Intelligent Systems, Control and Automation: Science and Engineering

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Rapid Roboting

Recent Advances on 3D Printers and Robotics

Springer

Intelligent Systems, Control and Automation: Science and Engineering

Volume 82

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ISSN 2213-8986 ISSN 2213-8994 (electronic)
Intelligent Systems, Control and Automation: Science and Engineering
ISBN 978-3-319-40001-3 ISBN 978-3-319-40003-7 (eBook)
https://doi.org/10.1007/978-3-319-40003-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Everyone needs time. Everyone likes to make things quickly, like the chef in a restaurant trying to organise all the preparations on a busy day. Everyone wants to have a detailed recipe for producing items efficiently and faster without losing quality, like the businessman. Everyone likes to be a pioneer in their field of expertise, like researchers working in a lab. But time is a killer. Everyone needs time.

This book aims to introduce the novel concept of Rapid Roboting, an analogy to the original idea of Rapid Prototyping, which was related to the quick building of prototype parts by machines reading data from a computer. Rapid Roboting is then the fast development of robots prototypes. The harmonical use of three enabling technologies supports this novel concept: Modular Open **Electronic** Hardware, Light **Programming** Languages and Additive **Manufacturing** in the context of robotics. By integrating those different technologies harmonically, it is possible to speed up the design process of robots, especially when testing new ideas on research or developing new robots for specific commercial purposes. When trying new concepts in robotics at the beginning of the design process, developing prototypes is an essential task for moving from the initial tests to more elaborated final prototypes. At this early stage, open-source electronics and light programming languages are convenient for speeding up the entire process. This book introduces Additive Manufacturing techniques and gives implemented examples of projects and research of the Rapid Roboting concept.

The audience can be university-level students interested in developing robots, researchers in computer science, mechatronics, electronics, small companies or start-up developing robotic applications or, in general, everyone interested in developing new robotic applications, having basic knowledge in the area.

This book is not for people interested in learning robotics from the beginning. It is a book for those who have already started the fantastic journey of changing the world by developing new robots. The book was a collaborative work of the editors and contributors from different institutions, research areas and countries, looking to the future and shaping it by developing new robotic applications. Before starting with the book, the editors would like to give special thanks to Michelle Viscaino for her valuable help in achieving this challenge.

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Acknowledgements

On behalf of the Editors, Prof. Dr. Gualtiero Fantoni (from the University of Pisa, Italy), Prof. Dr. Pablo Prieto (from the Federico Santa María Technical University, Valparaíso, Chile) and Prof. Dr. Fernando Auat (from the Federico Santa María Technical University, Chile), we would like to thank the contributors for such outstanding chapters:

- Prof. Dr. Eric MacDonald from the University of Texas, El Paso, USA.
- Prof. Dr. Miguel Torres Torriti from Pontificia Universidad Católica, Chile.
- Profs. Drs. María José Escobar, Sheila Lascano and Danilo Estay from Federico Santa Maria Technical University, Valparaíso, Chile, as well as Ph.D.(c) Mrs. Michelle Viscaíno and Mr. Javier Romero Schmidt.
- Prof. Dr. Cecilia Laschi from the National University of Singapore.
- Drs. Matteo Cianchetti and Mariangela Manti from Scuola Superiore Sant'Anna, Pisa, Italy.
- Dr. Marcello Calisti from the University of Lincoln, UK.
- Dr. Frédéric Alexandre, Head of the Mnemosyne Team, Inria Project-Team of the Inria Research Centre Bordeaux Sud-Ouest, France.
- Dr. Thierry Viéville, Researcher Senior at INRIA (National Research Institute in Computer Science and Control Theory), France.
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Acronyms

AANN	Adaptive artificial neural networks
ABS	Acrylonitrile butadiene styrene
AI	Artificial intelligence
AM	Additive manufacturing
ANN	Artificial neural networks
ASTM	American Society for Testing and Materials
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CLI	Command line interface
CNC	Computer numerical control
COM	Centre of mass
CPPN	Compositional pattern producing network
CT	Computed tomography
DARPA	Defense advanced research projects agency
DIY	Do it yourself
DoF	Degrees of freedom
DSP	Digital signal processor
FACE	Facial automation for conveying emotions
FDM	Fusion deposition modelling
FPGA	Field programming gate array
GOFAI	Good old-fashioned artificial intelligence
GP	Globus pallidus
GUI	Graphical user interface
HMI	Human-machine interface
IoT	Internet of Things
LGN	Lateral geniculate nucleus
LPL	Liht programming languages
MCU	Microcontroller unit
MODI	MODular intelligence
MOEH	Modular open electronic hardware
mPFC	Medial pre-frontal cortex

MPU	Microprocessor unit
MT	Manufacturing technologies
NEAT	Neuroevolution of augmenting topologies
OFC	Orbitofrontal cortex
PFC	Pre-frontal cortex
PLA	Polylactic acid
RAM	Random access memory
RGC	Retinal ganglion cell
ROS	Robot operating system
RP	Rapid prototyping
RTK	Real-time kinematics
SDM	Shape deposition manufacturing
SLA	Stereolithography
SLS	Selective laser sintering
SMS	Social meta scenes
SN	Subtantia nigra
STN	Subthalamic nucleous
TRL	Technology readiness level
UV	Ultra-violet
YARP	Yet another robot platform

Rapid Roboting: The New Approach for Quickly Development of Customized Robots

Fernando Auat, Pablo Prieto, and Gualtiero Fantoni

1 What Is Rapid Roboting

The *Rapid Roboting* concept is coined as an analogy to the original idea of Rapid Prototyping, which is the process of producing physical models fast by building parts layer by layer, by special machines that read the instructions from a computer representation of the intended piece. The original concept was later replaced by the Additive Manufacturing term and is currently known as 3D printing. Like any prototype, these models usually lack the high fidelity of the final product. However, they allow visualization, testing, and refinement at the early stages of product development.

Similar to Rapid Prototyping, Rapid Roboting benefits from early testing and refinements. For example, a new gearbox for a transmission, new sensors positioning, integrating electronic components in the robot structure, more efficient chassis for service robots, or a unique appearance for an interactive robot.

Rapid Roboting is then the fast yet accurate fabrication of specific-purpose robot prototypes or robotic solutions to research and industry-specific problems, leveraged by a group of three technologies: modular electronic hardware, light programming language, and manufacturing technologies, as shown in Fig. 1.

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_1

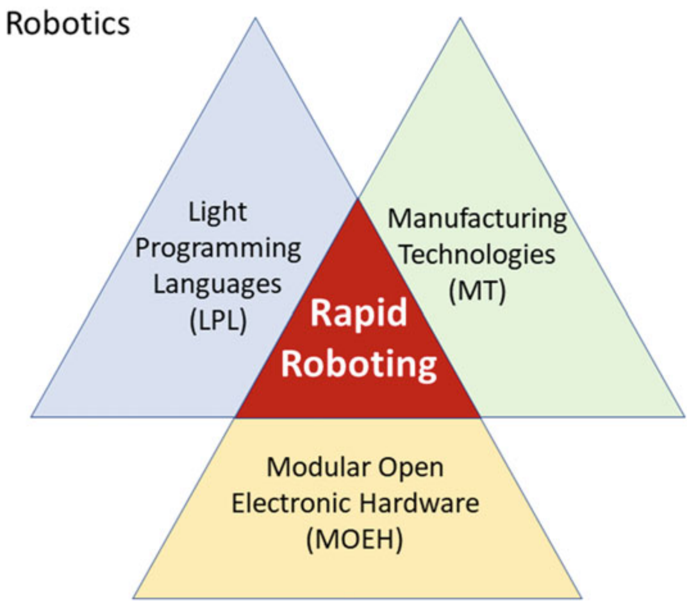

Fig. 1 Rapid roboting as a merge of existing technologies for rapid prototyping of robotic solutions

(1) Modular Open Electronic Hardware (MOEH): Cheap and widely available programmable boards, like Arduino or Raspberry Pi, allow testing minimal robot functionality essential for Rapid Roboting. Although these boards can have strong memory or processing capacity limits for the final product, they are good enough to test the central concept of the robot.
(2) Light Programming Languages (LPL): Programmable boards require a programming language to build the code loaded into the microprocessor to add the robot to the required functionality. Usually, all programmable boards come with their own programming language, but as is the case of Arduino programmable microcontrollers, the programming interfaces are becoming more intuitive. Thus, high specialization knowledge is no longer required, reaching then a vast market of users. An intuitive programming language is now a crucial part of the massification of a board.
(3) Manufacturing Technologies (MT): A wide range of techniques are currently available in a standard workshop. Plenty of hand and power tools can be used for building robot parts. However, technologies like additive manufacturing and laser cutter machines can speed up the development process. Digital 3D representations elements can be replicated several times accurately, and improvements after tests can be quickly implemented by rapidly building a new part considering new requirements and even in different materials.

Until now, most developments in robotics already include these three technologies. It is common to find Additive Manufacturing machines in labs dedicated to robotics. However, the designers, engineers, and researchers usually focus on software, electronic hardware, and parts design. *Rapid Roboting* aims to speed up the development of robot parts by integrating those different areas harmonically. And in this process, we find the core of *Rapid Roboting*: to allow designers—not necessarily robotic engineers or experts in the field—to a TRL 4 (technology readiness level) or TRL 5 of the technology in a fast and cost-efficient manner, ensuring that parts are rapidly designed, built and tested; that revisions are possible, considering improvements carried out through several prototypes; parts are efficiently manufactured with better precision than human hands making; more complex and integrated parts can be developed; it is possible to produce multi-material parts using one single manufacturing process and equipment, simplifying the resources; and those electronic components might be directly integrated at a physical level, during the manufacturing process.

2 What Has Been Done Before

Despite efforts in integrating these three technologies in a single method, where the robot parts are manufactured so that the electronics are embedded in the part and not added as a separated board, more work is necessary to enlace them harmonically in a general method.

Since many years ago, the Rapid Robotic concept has been present inside rapid prototyping techniques, as a set of methodologies used to build robots in research or teaching labs. Nowadays, we can find a 3D printer in almost every university lab. The try-and-error methodology for designing customized pieces has become so common that almost no prior specialized knowledge is required to start handling 3D printers. In this regard, several approaches bring 3D printers closer to the users. For small or medium-size pieces, 3D printers have almost replaced hand labor.

But the true capability of using rapid prototyping strategies to offer robotic solutions comes with the integration of electronics and programming skills. In recent years, the general practitioner has approached electronics from an engineering level using programming boards, such as Arduino, where users with almost no knowledge (or basic knowledge) of electronics can get a functioning prototype in a short time. Several books deal with such challenges, where the general audience can learn and be autodidactic. Finally, it required some level of programming skills. A programming language closes the gap between the chassis obtained through rapid prototyping, the electronics integrated into the robot and the motion or task that the robot should perform. Several frameworks do exist nowadays to deal with such challenges: the own programming framework of Arduino, as well as more advanced ones, such as the Robotic Operating System, specially designed to be the core of every robot platform.

3 What (New) It Is Proposed Here

In this book, we review the leading technologies required for rapid roboting, the advances made to integrate the different technologies, and some concept applications. We start with an overview of additive manufacturing techniques in chapter “Additive Manufacturing Enabling Technologies for Rapid Roboting”, which will lead to the most used techniques that are later applied to design robotic solutions. Chapter “Printing 3D Electronics for Robotics” offers a deep analysis of existing and cutting-edge techniques for printing 3D electronics; Chapter “Design of Mobile Robots” shows the fundamental concepts when creating a new robot, where we can find the integration of the three technologies mentioned herein: electronics, programming, and manufacturing. Chapter “Prototyping the Brain of a Robot” goes deep into programming a robot through the different languages and operating systems existing nowadays. Starting from chapter “Soft Robotics”, we show how rapid roboting is used in other dimensions of the robotics research field, specifically in soft robotics, bio-inspired robotics, and service robotics. We conclude the book with a chapter on rapid prototyping techniques applied to biomedical devices and our concluding remarks.

The information provided herein is intended to lead the engineer, researcher, or practitioner to this new and exciting field of rapid roboting, with a general overview of existing techniques, trends, and several case studies. Hopefully, the reader will realize the potential of these techniques to increase the TRL associated with their technology, as we did.

4 Summary of Each Chapter

Below, we present a brief description of each chapter, extracted from the chapters prepared by the authors and contributors.

Chapter: **Additive Manufacturing Enabling Technologies for Rapid Roboting**. This chapter aims to give a general description of the additive manufacturing process and its future trends, focused mainly on the rapid development of robots and have three main parts. The first part briefly describes the seven categories of Additive Manufacturing Technologies. Second, the landscape of active and expired key patents, providing a general picture of the present and future of the different technologies in terms of accessibility for small companies or researcher groups working on robotics. Finally, the impact of Additive Manufacturing on the leading market trends is discussed to shape the near future of its technologies in Rapid Roboting.

Chapter: **Printing 3D Electronics for Robotics**. With the current ability to print mechanical structures commercially, and with new enhanced fabrication technologies around the corner—currently being developed within research labs, soon it will be possible to print most—if not all of the robotics in a single non-assembly process (including more than just the structure). For this comprehensive fabrication approach, the Holy Grail would design a robot in CAD, press print, and five hours later return to find a fully functional robot prepared to crawl, walk, or fly out of the 3D printer. We show several cases in which robotics experts used 3D printing as a central element in the design and fabrication of advanced robots.

Chapter: **Design of Mobile Robots**. The design of a robot involves specialized knowledge from mechanical, electrical, and software engineering. Despite summarizing the wide variety of tools and knowledge is a challenging task, this chapter presents the main guidelines and recommendations for the design and rapid prototyping of mobile robots. The chapter reviews basic design rules, the fundamental robot components, the general hardware, and software architecture. The discussion includes aspects that are key to the selection of those components that ensure the robot prototype meets the motion specifications, such as the selection of computing platforms, the main types of mechanical transmissions, efficiency issues, the role of bearings, and other aspects concerning stability, overturning margins, controllability, and the motion dynamics. Finally, all the concepts and guidelines are employed in the design of a skid-steer mobile robot, which is presented as an example of rapid mobile robot prototyping

Chapter: **Prototyping the Brain of a Robot**. In this chapter, we will introduce several key points of this new discipline with particular focus on human-inspired cognitive systems. We will provide several examples of well-known developed robots, to finally reach a detailed description of a special case study: F.A.C.E., Facial Automation for Conveying Emotions, which is a highly expressive humanoid robot with a bio-inspired cognitive system. At the end of the chapter, we will briefly discuss the future perspective about this branch of science and its potential merging with the IoT, giving our vision of what could happen in a not-too-distant future.

Chapter: **Soft robotics.** This section is organized into two main parts: the first one focuses on different applications of the casting technique for developing different soft robots; the second one is an overview of the manufacturing procedures employed in soft robotics. We don't yearn to cover the entire state of the art but provide reader's guidelines to steer his research. Soft robots can be grouped into classes, according to their capabilities, as follows: locomotion, manipulation, and robots mimicking body parts (simulators). For each of these classes, we have identified key examples as means for describing the employed manufacturing procedure: (i) Locomotion—FASTT based on fiber-reinforced actuators; (ii) Manipulation—Octopus, STIFF-FLOP, Gripper that exploits different actuation strategies: cables, fluidic actuation combined with granular jamming and cable-driven under-actuation mechanism, respectively; (iii) Body parts simulator—Simulator of vocal folds that rely on the intrinsic mechanical properties of soft materials. The common denominator among these three classes is the design and prototyping of molds that replicate the shape of the robot. Molds could be made by common machineries (or also by traditional 3D printers) and were used as means for shaping the soft body.

Chapter: **Autonomous Service Units**. Autonomous robotics emerged as a research and development field nearly forty years ago, but only fifteen years ago, after the DARPA (Defense Advanced Research Projects Agency of the United States Department of Defense) challenge, autonomous mobile systems started to be considered as a solution to the transportation and service problem. This chapter is focused on autonomous (i.e., robotic) vehicles used as human transportation service from two points of view: on one hand, the autonomous vehicle that leads to intelligent transportation systems; on the other hand, autonomous vehicles used for rehabilitation or for enhancing mobility capabilities of their users. Both perspectives of autonomous systems are linked by the use of rapid prototyping techniques, aimed at converting a previously commercial product into a robotic system with a specific transportation usage. This chapter shows, in particular, two cases: two electric commercial vehicles (one golf cart and one car) converted into an autonomous robot for transporting people in cities or for executing specific tasks in sites, and an assistive vehicle (an electric scooter) used by people with reduced mobility. The design of the different components needed to achieve such automation is shown in detail herein.

Chapter: **Bio-inspired Robotics**. The fields of artificial intelligence and bio-inspired robotics have proven to cross several other fields of expertise including Cognitive Neuroscience. Here, we review principles of interaction between a natural (or artificial) organism and the environment where it lives. Then, we ask whether such structural coupling shapes the way it behaves. For instance, how the sensory processing of the external world controls actions, and finally, behavior? We remind the main sources of inspiration for bio-inspired robotics and relate them to currently active fields of research like Embodiment and Enaction. These latter concepts are illustrated by examples of recent research on two main aspects: (i) bio-inspired algorithms processing sensory signals coming from the outer world, and (ii) bio-inspired controllers based on human behavior and physiology. Finally, we include an example of a bio-inspired robot controller design based on the concepts here exposed.

Chapter: **Biomedical Devices: Materials, Fabrication, and Control**. In this chapter, we present an overview of materials used in rapid prototyping of biomedical devices, with their pros and cons, which are later used for implants of robotic prosthetic devices. Materials used in medical device must meet strict performance requirements through all their life cycle, design, manufacturing, packaging, shipping, use, end use. The selection of materials in biomedical field is strongly influenced by the application. In implants, the used materials must be corrosion resistance, biocompatible, bioactive, non-toxic, osseous integrated, with a good mechanical strength and wear resistance, because this material will be in contact with body fluids. A material with those characteristics is considered a biomaterial. In the case of prosthesis, the selection of a structural materials is focused in maximize the strength/weight ratio of the overall prosthesis. Another aspect is the manufacturability because the implant or prosthesis has to be cost effective. There is a big number of materials to choose, and each individual has particular needs. According to its chemical composition, the materials used in medical applications could be classified in metals, polymers, ceramics, and composite materials.

Chapter: **Future Trends**. Concluding remarks and future trends. In this chapter, we present a personal point of view of the editors about the future of rapid roboting in the academia and the industry, showing its potential as a fast TRL enhancer.

Additive Manufacturing Enabling Technologies for Rapid Roboting

Pablo Prieto

Abstract This chapter aims to give a general description of the additive manufacturing process and its future trends, focused mainly on the rapid development of robots and has three main parts. The first part briefly describes the seven categories of Additive Manufacturing Technologies. Second is the landscape of active and expired key patents, providing a general picture of the present and future of the different technologies in terms of accessibility for small companies or researcher groups working on robotics. Finally, the impact of Additive Manufacturing and the leading market trends are discussed to shape the near future of its technologies in Rapid Roboting.

1 Additive Manufacturing

Additive manufacturing involves a group of computer-controlled technologies that can fabricate objects by depositing layers of material, one on top of the previous one until a part is completed. In the beginning, these technologies were called Rapid Prototyping (RP) because they were mainly used to build prototype parts quicker than traditional techniques. Later, the Additive Manufacturing (AM) concept, which better describes the object building process, was adopted. Additionally, the 3D Printing concept has been adopted as well, especially by the general public.

AM is a key enabling technology for rapid roboting due to the lower cost and higher fabrication speed of parts compared to more traditional techniques such as manual model making or conventional CNC milling. Figure 1 shows a robotic quadratop chassis built using AM. The complete fabrication process took 2 days.

Figure 2 shows the complete process for designing an object to be produced, as a prototype or final part, using AM technologies. The process starts with the design concept (Fig. 1a). Next, a computer model representation is developed using Computer-Aided Design (CAD) technologies. After the CAD model is completed (Fig. 1b), the data is usually represented as a .stl file (Fig. 1c) and processed to describe each

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_2

Fig. 1 Rapid roboting of a robotic quadratop chassis developed in the product design engineering department at Universidad Técnica Federico Santa María, Chile. The robot intelligence was developed by the electronic engineering department from the same university

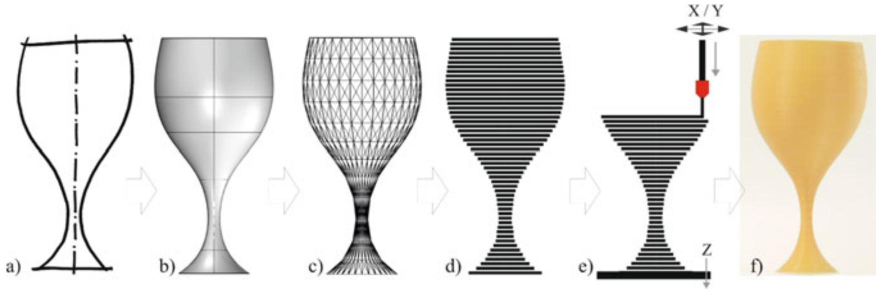
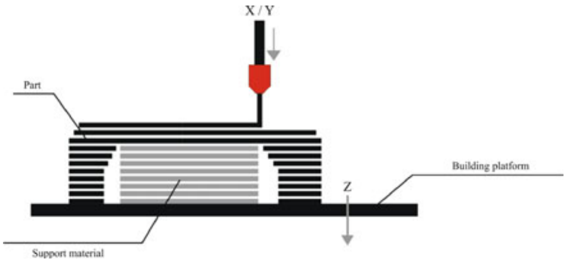


Fig. 2 **a** Original shape design **b** CAD model representation **c** STL file representation **d** Slicing **e** Manufacturing process **f** Final part

Fig. 3 Support material area



layer geometry for developing the tool path for depositing/tightening-up the material (Fig. 1d). Later, the object is built, layer by layer, using additive manufacturing (Fig. 1e). Usually, after the piece is made, a post-processing operation is needed to take off any remaining support material attached to the part, as shown in Fig. 1f.

The support material is the material deposited by the 3D printer to support areas where the geometry of the part under construction does not have any material deposited in the previous layer. For example, Fig. 3 shows a bridge-like structure where support material is needed to avoid the collapse of the central part of the object during its construction.

To build robot parts in a reduced time, avoiding the support material deposition as much as possible is recommended. In that way, the entire process is sped up because the fabrication process is quicker, and post-processing time is shortened. A basic rule for AM technologies that require support material is to avoid angles less than 45 degrees in geometries that increase its volume from the building platform to reduce support material. This is mainly applied for Material Extrusion technologies that are explained later.

To exploit the benefits of AM for the rapid development of robots, it is essential to understand the vast range of processes used for 3D Printing. To facilitate that quest, in 2009, the F42 subcommittee from the American Society for Testing and Materials (ASTM), an international organisation focused on technical standards, started the task of setting the standards for design, process, file formats, terminology, evaluation, and materials with regards to AM. The committee also defined seven categories that together constitute the full breadth of commercial AM technologies. The seven categories are Material Extrusion, Vat Photopolymerization, Powder Bed Fusion, Material Jetting, Binder Jetting, Sheet Lamination, and Directed Energy Deposition. They are described in the ASTM F2792-12a document [4]. Below, a summary of each is given.

Material Extrusion is the one where build material is selectively dispensed through an extrusion nozzle, for building a 3D part, as shown in Fig. 4. The most common implementation of this method involves the extrusion of thermoplastic material through a heated orifice. The materials available for this implementation tend to be functional thermoplastics, which are generally robust enough to withstand harsh environments, including chemical, mechanical, or temperature exposure.

Material extrusion processes are office- or home-friendly since they use office electrical supply, innocuous spooled thermoplastic feedstock, and no vacuum is required. The drawbacks of the technology include minimum features limited by the extrusion nozzle size and a rough surface finish due to stair-stepping effects. The mechanical strength suffers anisotropic weakness in the Z-direction based on layer-to-layer adhesion, but this improves with new materials such as Nylon 12 and new composites and post-processing improvements. This technology is well suited for robotics for the average DIY or industrial user with high-performance plastics available.

This process is the most suitable for rapid roboting projects, mainly because it is a simple technology, easy to implement, and the final parts are functional, cheap, and ideal for office environments.

Vat Photopolymerisation features a vat of liquid photocurable polymer that is selectively cured with an energy source such as a laser beam or other optical energy like a projection system, as shown in Fig. 5. The part under fabrication is typically attached to a platform that descends one cure depth after a layer is completed and the process is repeated. This technique benefits from feature sizes determined by laser beam width or optical resolution in the X- and Y-axes. The Z-axis is determined by the depth of penetration of the cure, which can be optimised with light-absorbing additives [9]. The advantage of this technique includes exceptional surface finish and high spatial resolution. The drawbacks include post-cleaning of uncured liquid materials. Additionally, the build materials are relegated to photochemistry with limited choices, and these materials may continue to cure when subjected to UV

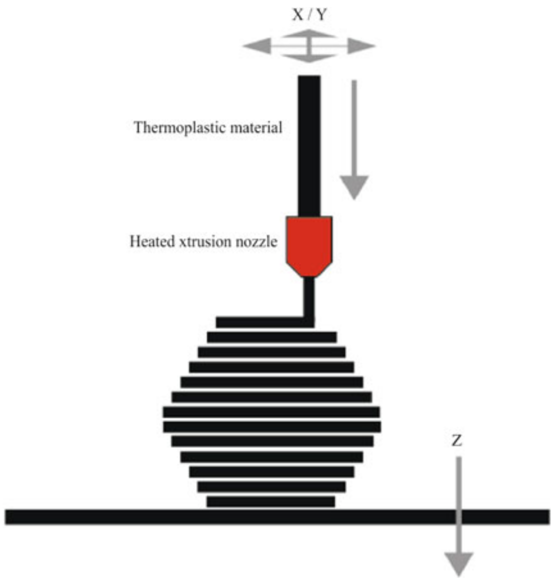


Fig. 4 Schematic of material extrusion technology

radiation—causing mechanical degradation or discolouring. For robotics requiring exceptional surface finish, however, this technology may be the best solution.

Powder Bed Fusion processes include selectively melting or sintering a layer of powder material using an energy source such as a laser or electron beam, as shown in Fig. 6. The powder bed is subsequently lowered by a fabrication layer thickness, and a rake or roller delivers a new powder layer with powder dispensed through a gravity-fed bin serving as material storage. The process repeats with the next layer, and unmelted powder in the bed acts inherently as support material for subsequently built layers. The advantages of this technology include (1) feature sizes determined by the energy source (width of the laser beam or electron beam) and the powder size, which are relatively small, (2) the reduction of z-strength anisotropy as interlayer adhesion is improved relative to *Material Extrusion*, and (3) the availability of high-performance materials (e.g., nylons and titanium) necessary for functional end-use parts. The disadvantage includes (1) powder waste, where powders may not be recyclable in the case of polymer fabrication, and (2) post-build cleaning involving powder removal from internal cavities. Given the strength of the resulting structures and the cost of the systems, powder bed fusion is generally well suited for industrial users but can be challenging to use in a hybrid manner with complementary manufacturing technologies.

Material Jetting uses ink-jetting technology to selectively deposit the build material with an immediate cure before applying subsequent layers. An example of this technology includes ink-jetting multiple photocurable polymers followed by the immediate total volume curing by a UV lamp attached to the front and back of the inkjet head, as shown in Fig. 7. With multiple materials, fabricated items can be

Fig. 5 Schematic of vat photopolymerisation technology

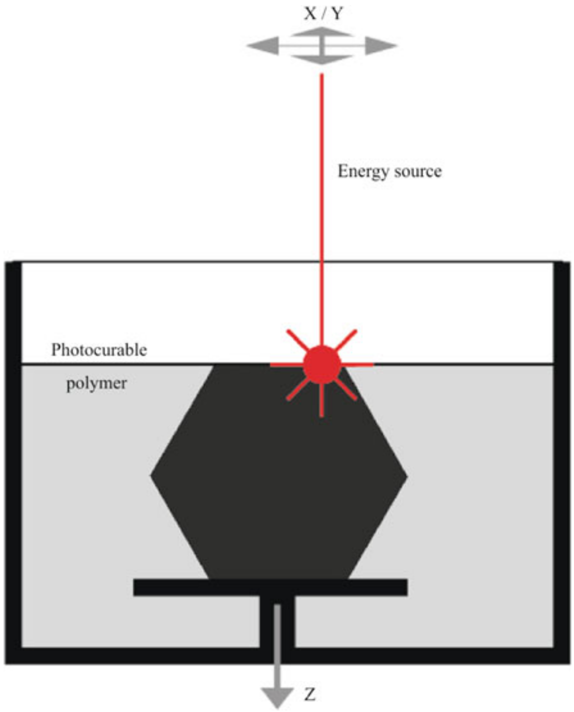
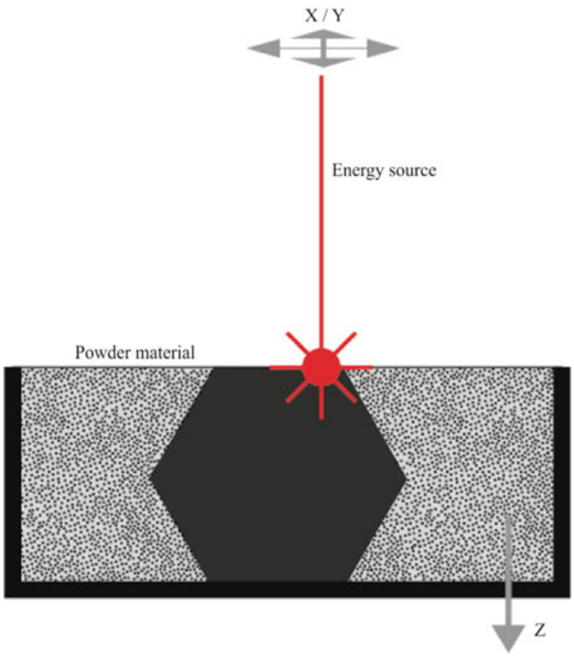


Fig. 6 Schematic of powder bed fusion technology



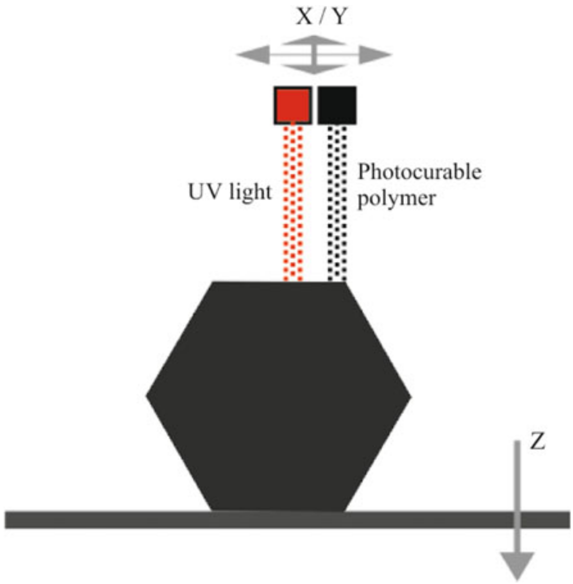


Fig. 7 Schematic of material jetting technology

multi-coloured, or materials can be chosen with varying stiffness properties. Ink-jetting is also naturally well suited for parallelism and thus can be easily scaled to more extensive and faster production and provides exceptional spatial resolution (25 μm feature sizes). Material jetting of photocurable polymers is confined to photo-chemistry and the associated material limitations. These materials may continue to cure in the presence of UV energy, which could cause discolouration or degradation.

Binder Jetting involves selectively ink-jetting a binder onto a layer of powder feedstock, as shown in Fig. 8. The additional powder material is then dispensed over and evenly as a layer by a rake or roller, and the process eventually creates a complete green body with many layers. One binder jetting technology requires a post-anneal furnace cycle for high-temperature materials (e.g., metals and ceramics) and an infiltration process to provide complete density parts due to the inherent porosity in the structure after binder removal. The system offers a vast range of materials with good resolution dictated by the ink-jetting. One other system can inkjet a variety of coloured binders (much like a commercial inkjet colour printer) into the powder and provide a full spectrum of colour throughout the structure for conceptual models.

Sheet Lamination is yet another additive manufacturing process in which individual sheets of material are bonded together to form three-dimensional objects, as shown in Fig. 9. After a new layer is bonded, the material is removed subtractively from the latter before applying the next layer. In one version, sheets of metal are bonded together using ultrasonic energy for welding. The ultrasonic process has been shown to produce metallurgical bonds between layers of aluminium, copper, stainless steel, and titanium. A subsequent subtractive process between layers adds internal structures and other complex geometries impossible with conventional

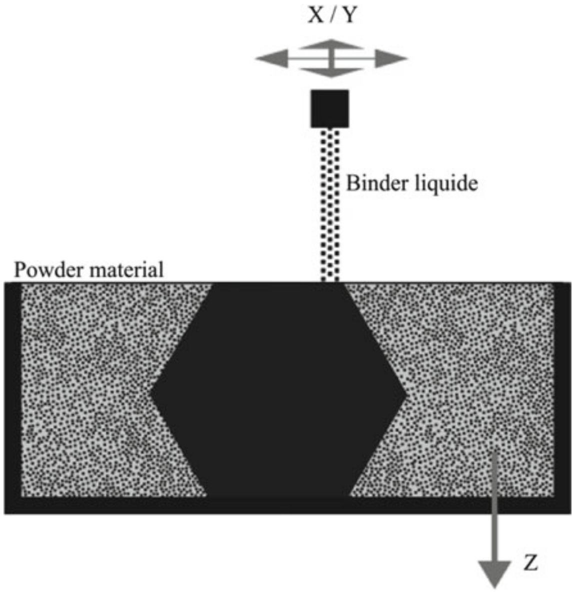


Fig. 8 Schematic of binder jetting technology

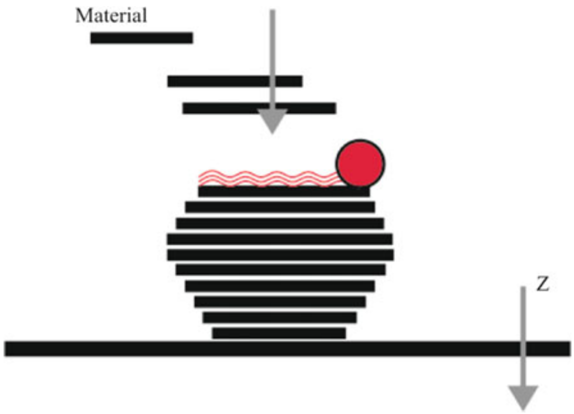


Fig. 9 Schematic of sheet lamination technology

subtractive processes alone. Sheet lamination often has limited choices for support material, and consequently, some geometries with overhangs may not be possible. Other versions of this technology include paper and polymer sheets bonded with adhesives. The main disadvantages of sheet lamination are the waste due to the subtractive processing and the lack of support material.

Directed Energy Deposition is an additive manufacturing process that focuses on material deposition and the energy source (typically a laser or electron beam) coincident with the surface being built, as shown in Fig. 10. These processes use powder or wire-fed metals, and one standard system is used to repair the high-value metal components used in engines that blow metallic powder towards the

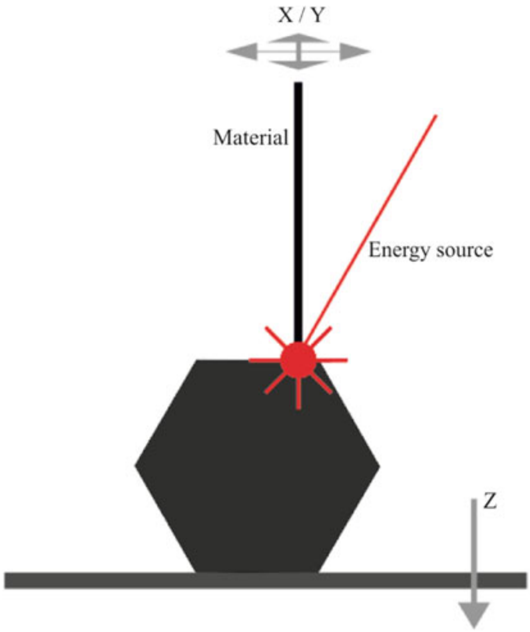


Fig. 10 Schematic of directed energy deposition technology

surface, where the powder is immediately melted with a laser beam. This technique is recognised for the high spatial resolution of metals but at generally low rates of material deposition. Another system uses a large evacuated chamber and a gantry to feed a metal filament to the surface of a metal structure under fabrication. An electron beam is focused on the surface at the point of contact of the filament—melting additional material to the surface. This technique provides high metal deposition rates over large volumes but at the expense of lower spatial resolution.

2 Additive Manufacturing Democratisation

In 2009, the first and more iconic patent on Material Extrusion expired, allowing new and low-cost open-source Fusion Deposition Modelling (FDM) machines to be available to almost everyone. Since then, a new era of AM democratisation has started, as several crucial patents have been expiring, allowing new small companies to produce cheap and improved 3D printers with different technologies.

In the following, a brief overview of some of the essential expired and active patents shaping the near future of low-cost technologies is presented. Figure 11 shows the presented patents, classified according to the ASTM categories, along with the original or current owner and dates of application and expiration.

2.1 Material Extrusion (ME)

The first key patent **US5121329A**—*Apparatus and method for creating three-dimensional objects* [10] was granted in 1992 to Stratasys Inc. and expired in 2009. This is an iconic patent that links a CAD representation to AM software to produce models through a nozzle that melts a thermoplastic material that is deposited, layer by layer, on a bed. After the expiration of this patent, Makerbot started the democratisation of AM with low-cost small machines, like the early Makerbot Cupcake CNC. This was a DIY machine built on the knowledge of RepRap [2] and Arduino open-source projects [3]. The RepRap project allowed enthusiastic makers to develop their 3D printers independently. In the following years, Makebot continued making AM available to bigger market segments by producing already assembled and easy-to-use machines. In the years after this iconic patent was granted, Stratasys Inc. and Arevo Inc. were granted patents that—at the time of writing—have recently expired, are about to expire, or still have several years of exploitation. Because of that, those patents have not impacted significant market segments. These patents are described below.

- The patent **US6004124A**—*Thin-wall tube liquefier* [34] was granted in 1999 to Stratasys Inc. and expired in 2018. It described a more detailed extrusion head system for liquifying a filament of thermoplastic material. The head is composed of a tube, preferably made of metal encased in a heating block and a nozzle. The formed extrusion head can receive two different materials, allowing to build multi-material pieces.
- The patent **US7297304B2**—*High-temperature modelling method* [36] was granted in 2007 to Stratasys Inc. and expired in 2020. It presents a special heating chamber isolated from the rest of the machine electronic control system. The chamber provides a stable building environment, reducing thermal contractions of the piece being built.
- The patents **US20040104515A1**—*High-Temperature modelling method* [37] and **US6722872B1**—*High-temperature modelling apparatus* [35] were granted to Stratasys Inc. in 2007 and 2005 and expired in 2020 and 2021, respectively. They present the method and the machine that deposits material from a dispenser head and a heated chamber. The dispenser deposits the material on a base. The motion components are external to the chamber and thermally isolated by a flexible ceiling.
- Finally, the patent **US10011073B2**—*Reinforced fused-deposition modelling* [7] was granted to Arevo Inc. in 2018 and will expire in 2034. This is similar to the previous patents described but has two novel characteristics. The first includes a needle in the nozzle containing one or more fibre strands to reinforce the final part. The second is the inclusion of a turntable that is coordinated with a robotic arm. The combination of those two characteristics should provide more accurate and robust parts.

2.2 Vat Photo Polymerisation

As it happened with FDM machines around 2010, the expiration of key patents is making some Vat Photopolymerisation machine prices drop drastically. Small companies are producing low-cost devices, like FormLabs that offers machines below 10.000 USD or Prusa Research that offers Prusa S1 with a price of around 2.000 USD. The latter is advertised as the first open-source stereolithography machine, and the creators present it as the mk3 of the SLA technology. Additionally, many small devices, mainly from China, have arrived in the market during the last 5 years at prices as little as 200 USD. Because of the low prices, this is another AM technology already available to almost everyone. The relevant patents for the advancement of these technologies are briefly described below.

- The patent **US4575330A**—*Apparatus for production of three-dimensional objects by stereolithography* [20] was granted to 3D Systems Inc. in 1986 and expired in 2006. This is one of the essential patents in the Vat Photopolymerisation area as it exposes the central concept of the technology. The final part is built by a cross-section pattern on the surface of a liquid capable of changing its state responding to external stimulation. The stimulation can be radiation, particle bombardment, or chemically induced. The process is performed in successive steps, submerging the part in the liquid at each layer.
- In 1996, 3D Systems Inc. was granted the patent **US5569349A**—*Thermal stereolithography* [5], which expired in 2013. In this patent, a technique for building support structures to the model during the stereolithographic process was proposed. The support material, which is different from the standard material, is added during the process. The support material then melts at a lower temperature than the material used for making the part, facilitating the post-processing task.
- The patent **US7158849B2**—*Method for rapid prototyping by using linear light as sources* [19] was granted to the National Cheng Kung University in 2007, and it will expire in 2024. It describes a building procedure that works by curing ultraviolet photosensitive layers, but instead of using an ultraviolet laser, it uses an ultraviolet Liquid Crystal Display.
- The patents **US9211678B2**—*Method and apparatus for three-dimensional fabrication* [15] and **US20160046072A1**—*Acceleration of stereolithography* [31] were both granted to Carbon Inc. in 2015 and 2018 and will expire in 2034 and 2036, respectively. They present a procedure to speed up the building process of stereolithography technology. The addition of a Lewis acid or an oxidisable tin to the polymerisable-liquid, speeds up the curing process. The critical issue in this patent is that continuum irradiation is possible, making a continuous building process feasible. Additionally, an essential enabling feature is described as a semipermeable plate that allows oxygen to go through. Managing both the oxygen as a polymerisation inhibitor and the ultraviolet sensitive resin in exact amounts at the right time is the key issue of this procedure for allowing the resin to fill the gap of the rising piece without curing.

2.3 Powder Bed Fusion

Similar to the democratisation process described for previous technologies, new Power Bed Fusion AM machines at decreased prices have appeared in the market after the expiration of essential patents in 2015 and 2017. For example, the 3D printer Lisa SLS is offered at around 7.500 USD Dollars, the Red Rock 3D at around 10.000 USD, and the Formlabs Fuse 1 at 17.500 USD. At the beginning of 2021, those prices are still high for small companies. However, as it happened with the FDM and stereolithography (also known as SLA) technologies, a significant price drop of new machines is expected to happen shortly. The first sign of this is the Open SLS project [1], which has spread essential knowledge for building Powder Bed Fusion machines, encouraging small companies to create new generations of low-cost devices. Relevant patents for this technology are described below.

- The patents **US5597589A**—*Apparatus for producing parts by selective sintering* [13] and **US5639070A**—*Method for producing parts by selective sintering* [14] were granted to the University of Texas System in 1997 and expired in 2014. They describe a machine that builds parts by sintering layers of powder with laser energy.
- In 1998, 3D Systems Inc. was granted the patent **US5733497A**—*Selective laser sintering with composite plastic material* [28], which expired in 2015. It presented a new composite powder-based material for laser sintering. The new material has a reinforcement powder, and the base material has a lower melting temperature. The final parts made with the unique powder material mixture have less distortion, easier rough breakout, and improved finishing.
- The patent **US6085122A**—*End-of-vector laser power control in a selective laser sintering system* [26] was granted to 3D Systems Inc. in 2000 and expired in 2017. The novelty of this patent lies in the control of the laser power according to the laser focal point speed and position. This improvement allows better quality parts in terms of homogeneity.
- The patent **US6215093B1**—*Selective laser sintering at melting temperature* from the Fraunhofer Society for the Demand of Applied Research [29] was granted in 2001 and expired in 2017. It presents a method and the device for building parts by melting metallic powder-based material, utilising a laser beam as a source of energy and having a protective gas atmosphere during the process. The produced models are very dense and have high strength.

2.4 Material Jetting

In 2019, two crucial patents expired. As a result, it is possible that in the next 10 years, new companies appear to fill available market gaps. Specifically, machines costing around 10.000 USD are capable of producing small parts at reasonable running costs. Objet Eden 260V from Stratasys is one of the cheaply available machines of this kind, but it is still inaccessible for small companies. The relevant patents for this technology are described below.

- The patent **US6259962B1**—*Apparatus and method for three-dimensional model printing* [18] from Stratasys Ltd. was granted in 2001 and expired in 2019. It protects the apparatus and the method for building parts by spreading material layer by layer utilising printing heads and curing the ultraviolet photosensitive material by using ultraviolet light.
- The patent **US7685694B2**—*Method for building a three-dimensional object* [38] was granted to Stratasys Ltd. in 2010 and is expiring in 2022. Its main focus is the deposition of two materials having different physical properties. One can be used for the building part and the second for the supporting structure.
- The patent **US8932511B2**—*Method of making a composite material by three-dimensional inkjet Printing* [30] from Stratasys Ltd. describes a method and apparatus to build parts with different materials, deposited by a head and cured by ultraviolet light. This patent opens the door for multi-material parts. The patent was granted in 2015 and is expiring in 2022.
- The patent **US10882245B2**—*Method of manufacturing three-dimensional object, liquid set for manufacturing three-dimensional object, device for manufacturing three-dimensional object, and gel object* [23] covers a method for depositing two different material components in different proportions, building a unique part having different physical properties when cured or hardened. Granted to Ricoh Co Ltd. in 2021, it is expiring in 2037.

2.5 Binder Jetting

A key patent expired in 2019, opening a route for the potential introduction of new low-cost machines, as happened with the previously discussed technologies. However, it is too early to asseverate that this will happen soon because it needs a particular dirty space, and the machines must be well maintained and clean. The ComeTrue® T10 Full-Colour Powder-based 3D Printer and the Partpro350 XBC from XYZprinting can be considered the new generation of Binder Jetting machines, but their prices start at 30.000 USD, still a high price for small companies. The relevant patents for this technology are described below.

- The patents **US6007318A**—*Method and apparatus for prototyping a three-dimensional object* [32] and **US5902441A**—*Method of three-dimensional printing* [8] were granted to 3D Systems Inc. in 1999 and expired in 2016. They provide a method and a machine for producing parts by applying a binder liquid on a layer of powder-based material. If the base material is white and the binder has different base colours, the final pieces can be in full colour.
- The patents **US20040012112A1** [11] and **US7037382B2** [12], both named *Three-dimensional printer*, improve the powder-based material management, clean the printing heads, detect a head failure, and take corrective measures automatically,

improving the reliability of the technique. 3D Systems Inc presented the patents. They were granted in 2006 and expired in 2017.

- The patent **US7291002B2**—*Apparatus and methods for 3D Printing* [33], from 3D Systems Inc. presents an apparatus and method for building parts by depositing a binder liquid on a powder-based material, adding several printing heads, and continuous printing on a rotary base. The patent was granted in 2007 and expired in 2025.

2.6 Sheet Lamination

In contrast to the cases previously discussed, the Sheet Lamination category has not been available as a low-cost alternative for small companies. Although the most straightforward technology in this category uses paper material and a thermosensitive glue for consolidation, the final part requires complicated post-processing that produces a high quantity of material that is wasted. Additionally, internal details are very difficult or impossible to build. Those aspects make this technology inappropriate for Rapid Roboting, especially if fully functional features are required. However, the ability to produce parts conformed by layers of different metals might be an exciting path for creating robot parts, especially if connected to the concept of embedded electronics in robot parts.

- The patent **US4752352A** from Cubic Technologies Inc. *Apparatus and method for forming an integral object from laminations* [16] was granted in 1988 and expired in 2006. It presents a method and the machine for building three-dimensional parts by lamination of the same or gradually varying shape. The apparatus has a supply material station, a workstation for shaping different layers, a control station, and an assembling station to stash the laminations in sequence and bond the laminations into the final part.
- The patent **US5192559A** from 3D Systems Inc. *Apparatus for building three-dimensional objects with sheets* [21] presents the conformation of three-dimensional objects through the superposition of sheets cut following the cross-section shapes. The sheets are then piled and integrated by a synergistic stimulation, like UV light for a sensitive binder. The patent is extensive and allows several materials and synergetic stimulation for cutting the sections and integrating the sheets. The patent was granted in 1993 and expired in 2010.
- The patent **US5730817A** from Cubic Technologies Inc. *Laminated object manufacturing system* [17] presents a method for making 3D objects by stacking a plurality of laminations. The system includes a two-dimensional proter to shape each layer from a sheet of material, like a laser-based one. Each shaped sheet is bonded to the previous one by a heat-sensitive adhesive. The patents also provide details of a control system that uses sensors to manage the temperature, pressure, layer thickness, and others. The patent was granted in 1998 and expired in 2016.

- The patent **US10293589B2** from Boeing Co. *System and method for additive fabrication using laminated sheets* [24] presents a method that first includes a computer application that generates the sections of the layers. The material sheet sections are later staked by using unique guides, and then the system uses thermal energy for consolidating the final part. The patent was granted in 2019 and is expiring in 2032.

2.7 Directed Energy Deposition

Finally, in the Direct Energy Deposition category, no low-cost machines are available yet. The complexity of precisely depositing material and applying an external energy source to conform the pieces, mixed with the gases created in the process (that need a particular chamber or external installation to evacuate gases), have hampered the massive penetration of those technologies at a low cost and for everyone. The significant advantage of this category is the excellent quality of the metal parts produced, which can be very important to create exact robot parts.

- The patent **2299747A**—*Method of forming structures wholly of fusion deposited weld metal* [22] presents a method and a machine for making metal parts providing a metal structure. The final piece is capable of resisting heavy stress and having different finishing. The process is based on successive arc welding on a non-adherent base. The process allows building parts to have different materials. The patent was granted to Babcock and Wilcox Co. in 1942 and expired in1959.
- The patent **10046419B2**—*Method and system for additive manufacturing using high energy source and hot-wire* [27] presents a method and apparatus that have a control system for building parts by applying high energy sources that melt material fed as a wire. The patent was granted in 2018 to Lincoln Global Inc. and is active until 2035.
- The patent **20160369399A1**—*Directed energy deposition with cooling mechanism* [25] presents a method and a system for making models by adding material through a nozzle onto a base and directly applying high energy. The material can be metal and applied as wire, metal powder projected, or others. The patent additionally includes a cooling system. The patent was granted to Rolls Royce Corp. in 2018 and is expiring in 2036.

3 Impact of AM on Rapid Robotic: Current and Future Trends

As can be noticed, several essential patents have been expiring in recent years, allowing the existence of the open source like RepRap project and companies like Formlabs

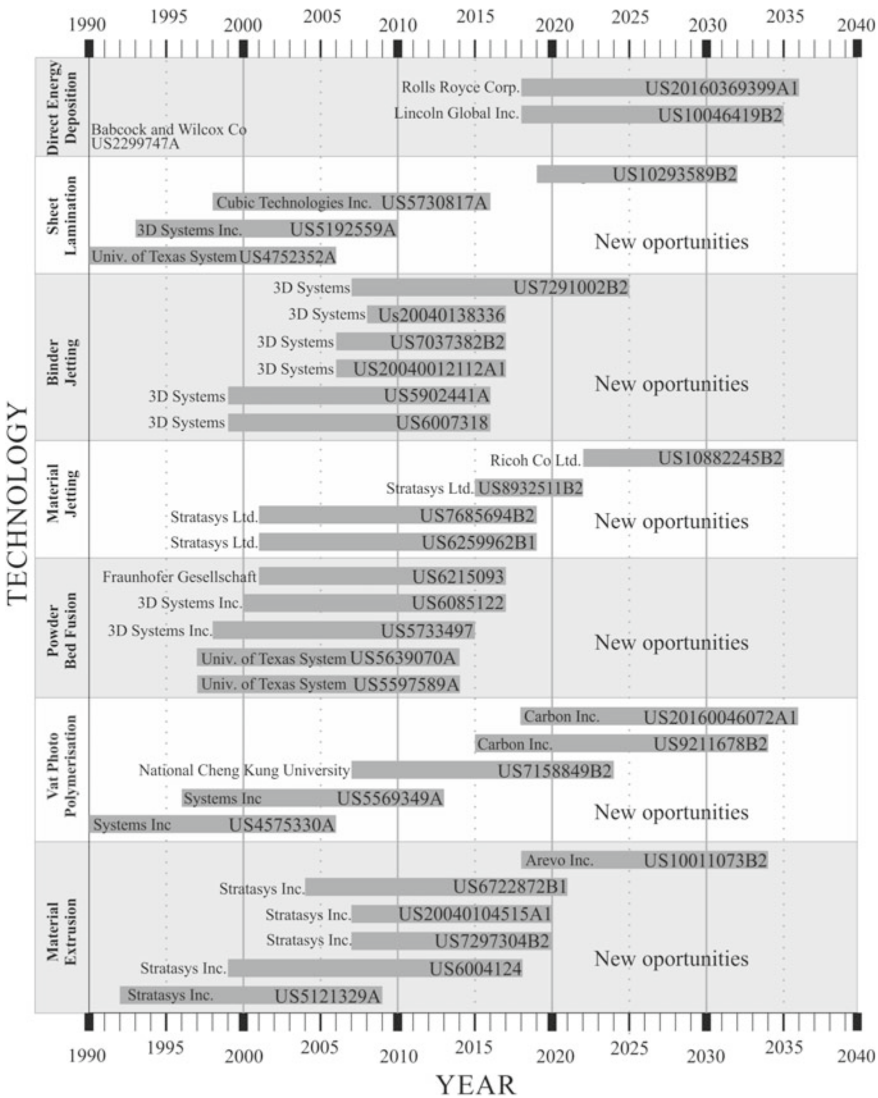


Fig. 11 AM patents, separated into categories. For each patent, the applicant and the protection period are given

to move the field forward by developing better and cheaper machines, like Formlabs 1, 2, and 3. Currently, it is easy to find small companies offering small size SLA machines capable of building accurate models at prices as little as 200 USD, an unthinkable price a few years ago. Another critical point has been the Do-It-Yourself (DIY) Open Electronics movements, which have released low-cost and easy-to-use boards—like Arduino—that have also helped spread the use of low-cost FDM 3D Printers.

Apart from the technologies available to produce low-cost 3D printers, new materials with new physical properties like strength, flexibility, and conductivity are also likely to improve and be widely available. Due to the future expiration of the patent US10011073B2 [7] focused on new parts having continuous fibre-reinforced composites, it is expected that new reinforced features will be available at a low cost for small companies and designers. For Rapid Roboting, this particular advance will provide comprehensive options for improving robot parts of big dimensions, especially those that provide mobility or mechanisms to robots.

As described in the chapter *Printing 3D Electronics for Robotics*, the integration of electronics in additive manufacturing is possible and brings substantial benefits for robot design and construction. Building single parts with embedded electronics simplifies the design, reduces the number of parts, and makes the logistics easier for the fabrication process.

From Fig. 11, several opportunities for developing new low-cost desktop 3D printers can be identified. For technologies like Material Extrusion and Vat Photopolymerisation, these opportunities have been already exploited, as demonstrated by the democratisation of crucial technologies like FDM, SLA, and LCD Photocuring to produce machines easily available online at very competitive prices. The main advantage for those AM segments is that they can be used in an office environment, in contrast with other technologies requiring special dirty spaces or special energy requirements.

For the rest of AM technologies (Material Jetting, Binder Jetting, Sheet Lamination, and Directed Energy Deposition), it is unclear whether they will significantly contribute to the rapid development of robot parts soon. In the Material Jetting category, it is possible to have low-cost desktop machines in the following years, but no companies working on it have been identified yet. In the Binder Jetting category, one of the most valuable features is producing full-colour models, an essential point for aesthetics but not for final fully functional parts. This technology can thus be beneficial for testing the aesthetics of robots but is not suitable to produce fully functional parts quickly. Additionally, most technologies in this category need a dirty space. Concerning the Sheet Lamination category, having machines capable of producing parts made of different materials at each layer can be beneficial for making conductive layers for integrating electronics. However, more development efforts are required to have this kind of machine widely available in the future. Finally, Direct Energy Deposition is a promising technology for Rapid Roboting, producing robust final robot parts, especially big components. However, low-cost desktop machines capable of operating in an office or small research labs are not on the horizon yet.

Another important trend can be found in the Wohlers Report 2021 [6], which shows how independent 3D printing service providers had quickly raised during the last years, including 2019 and 2020, the Covid-19 pandemic years. In the previous 7 years, independent services for 3D Printing went from less than 1.000 million USD to more than 5.000 million USD in 2020 [6]. 3D Printing services can be highly relevant for the Rapid Roboting concept implementation, especially for small companies or research centres. Instead of acquiring expensive or challenging to run AM machines, the files storing the description of parts with different materials and physical properties can be sent through the Internet. Because of the rapid development of courier services during the Covid-19 pandemic, the built part will be received back shortly after. Such services would also be suitable for small markets where independent 3D printing services might not be profitable. For those markets, having access to Cloud-based 3D printing services with international delivery would undoubtedly have a significant impact on AM democratisation.

Finally, it is worth mentioning the growing trend of using AM to produce final parts instead of testing or building prototypes. Such a trend has been fueled by developments in new materials and the increased reliability, production speed, and low costs of Fused Deposition Modelling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) technologies. Functional end parts built with those technologies are already a reality. Currently available FDM and SLA machines can be found at prices as little as 200 USD. SLS technology is also being used to offer new desktop machines, but the prices are still high (in 2021), starting at 5.000 USD. As it happened with Material Extrusion and Vat Photopolymerisation, it is expected that Powder Bed Fusion further enables the production of low-cost and high-quality machines in the next years.

References

1. OpenSLS (2021). https://github.com/MillerLabFTW/OpenSLS. Accessed 20 2021
2. RepRap (2021). https://reprap.org/wiki/RepRap. Accessed 20 2021
3. What is Arduino? guide introduction (2021). https://www.arduino.cc/en/Guide/Introduction. Accessed 20 2021
4. on Additive Manufacturing Technologies ACF, on Additive Manufacturing Technologies Subcommittee F42 91 on Terminology ACF (2012) Standard terminology for additive manufacturing technologies. Astm Int
5. Almquist T, Smalley D (1996) Thermal stereolithography. US Patent 5672312A
6. Associates W (2021) Wohlers report 2021
7. Bheda H (2018) Reinforced fused-deposition modeling. US Patent 10011073B2
8. Bredt J, Anderson T (1999) Method of three dimensional printing. US Patent 5902441A
9. Choi JW, MacDonald E, Wicker R (2010) Multi-material microstereolithography. Int J Adv Manuf Technol 49(5–8):543–551
10. Crump SS (1992) Apparatus and method for creating three-dimensional objects. US Patent 5121329A
11. Davidson T, Phillips R, Hernandes A, Russell D, Roche K, Zengerle W, Berlin A, Kinsley J, Sweet-Block B, Darul K (2006a) Three-dimensional printer. US Patent 20040012112A1

12. Davidson T, Phillips R, Hernandez A, Russell D, Roche K, Zengerle W, Berlin A, Kinsley J, Sweet-Block B, Darul K (2006b) Three-dimensional printer. US Patent 7037382B2
13. Deckard C (1997a) Apparatus for producing parts by selective sintering. US Patent 5597589A
14. Deckard C (1997b) Method for producing parts by selective sintering. US Patent 5639070A
15. DeSimone J, Ermoshkin A, Samulski E (2015) Method and apparatus for three-dimensional fabrication. US Patent 9211678B2
16. Feygin M (1988) Apparatus and method for forming an integral object from laminations. US Patent 4752352A
17. Feygin M, Shkolnik A, Diamond M, Dvorskiy E (1998) Laminated object manufacturing system. US Patent 5730817A
18. Gothait H (2001) Apparatus and method for three dimensional model printing. US Patent 6259962B1
19. Huang SJ, Wang CC, Lee SY, Wang CK, Wang CS, Chen CY, Chen CL, Lai WS, Hsieh C, Leu TS, et al (1996) Method for rapid prototyping by using linear light as sources. US Patent 7158849B2
20. Hull C (1986) Apparatus for production of three-dimensional objects by stereolithography. US Patent 4575330A
21. Hull CW, Jacobs PF, Schmidt KA, Smalley DR, Vinson WA (1993) Apparatus for building three-dimensional objects with sheets. US Patent 5192559A
22. Isaac H (1942) Method of forming structures wholly of fusion deposited weld metal. US Patent 2299747A
23. Iwata H, Norikane Y, Matsumura T, Niimi T, Naito H (2021) Method of manufacturing three-dimensional object, liquid set for manufacturing three-dimensional object, device for manufacturing three-dimensional object, and gel object. US Patent 10882245B2
24. Larsen TA, Romig E, Mitchell BJ (2019) System and method for additive fabrication using laminated sheets. US Patent 10293589B2
25. Ma K, Shuck QY, Bader JS (2018) Directed energy deposition with cooling mechanism. US Patent 20160369399A1
26. Manning GL (2000) End-of-vector laser power control in a selective laser sintering system. US Patent 6085122A
27. Matthews WT, Denney PE, Peters S (2018) Method and system for additive manufacturing using high energy source and hot-wire. US Patent 20150209905A1
28. McAlea KP, Forderhase PF, Ganninger ME, Kunig FW, Magistro AJ (1998) Selective laser sintering with composite plastic material. US Patent 5733497A
29. Meiners W, Wissenbach K, Gasser A (2001) Selective laser sintering at melting temperature. US Patent 6215093B1
30. Napadensky E (2015) Method of making a composite material by three-dimensional ink-jet printing. US Patent 8932511B2
31. Rolland J, DeSimone J (2018) Acceleration of stereolithography. US Patent 20160046072A1
32. Russell D, Anderson T, Bredt J, Vogel M, Seymour M, Bornhorst W, Hatsopoulos M (1999) Method and apparatus for prototyping a three-dimensional object. US Patent 6007318A
33. Russell D, Hernandez A, Kinsley J, Berlin A (2007) Apparatus and methods for 3D printing. US Patent 7291002B2
34. Swanson W, Hopkins P (1999) Thin-wall tube liquifier. US Patent 6004124A
35. Swanson W, Turley P, Leavitt P, Karwoski P, LaBossiere J, Skubic R (2004) High temperature modeling apparatus. US Patent 6722872B1
36. Swanson W, Turley P, Leavitt P, Karwoski P, LaBossiere J, Skubic R (2007a) High-temperature modeling method. US Patent 7297304B2
37. Swanson W, Turley P, Leavitt P, Karwoski P, LaBossiere J, Skubic R (2007b) High-temperature modeling method. US Patent 20040104515A1
38. Zagagi Z, Gothait H, Miller G (2010) Method for building a three dimensional object. US Patent 7685694B2

Printing 3D Electronics for Robotics

Eric MacDonald

Abstract With the current ability to print mechanical structures commercially, and with new enhanced fabrication technologies around the corner—currently being developed within research labs—soon, it will be possible to print most—if not all—of the robotics in a single non-assembly process (including more than just the structure). The Holy Grail for this comprehensive fabrication approach would be to design a robot in CAD, press print, and 5 hours later return to find a fully functional robot prepared to crawl, walk, or fly out of the 3D printer. We show several cases in which robotics experts used 3D printing as a central element in the design and fabrication of advanced robots.

1 Introduction

3D Printing was originally referred to as *Rapid Prototyping* in the 1980s. It was a technology that was generally relegated to quick fabrication of low-quality prototypes, allowing for form and fit to be evaluated for mechanical structures [9, 33]. The technology has evolved over the past three decades; spatial resolution, materials options, and mechanical strength have all improved in the commercial versions of layer-by-layer manufacturing, also known as *Additive Manufacturing*, which brings several significant advantages when considering building the mechanical components of robotic systems. The potential of *3D Printing* for more than just conceptual modelling but rather for end-use products is highlighted.

All of these terms, *Rapid Prototyping, Additive Manufacturing, and 3D Printing* refer to the same concept. More popularly, the technology is referred to as *3D Printing*, as the terminology provides a more intuitive understanding that a CAD model in a computer can be rendered as a mechanical structure. The technologies have matured, and a standards committee F42 from ASTM International has been formed

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_3

to help standardize the terminology, the file formats, and the evaluation procedures, among others.

The manufacturing has also expanded into other materials such as metals and ceramics, and consequently there is now a dramatically increased application space. Fabricated parts are now potentially targeted and robotics is central as illustrated by an example actuated robotic hand shown in Fig. 1a [15] and with significant research in applications for robotics in general for over a decade [4]. On top of that, the common DIY robotics user can now build complex and unique mechanical parts within their home with inexpensive plastics like ABS and PLA.

Simultaneously, a separate research community has focused on printed electronics in which conductive and semiconducting inks and pastes are micro-dispensed to create conformal or flexible electronics [3], as well as create sensors and actuators that are often the heart and soul of robotics since they provide the sensing, the motion, and the intelligence or autonomy of robots.

However, where these two technologies intersect is possibly the most promising area yet. This is where complex geometries are made possible by combining 3D printing with integrated or embedded electronics and sensors, allowing for volumetrically efficient and aerodynamic structures with multi-functional capabilities [6, 8, 14, 26, 27]. For example, a fractal antenna can be embedded within the wing of a robotic insect, providing electromagnetic functionality and simultaneously increasing the strength by introducing a metal wire into a thermoplastic structure as a composite for improved mechanical properties. Another example is illustrated in Fig. 1b, a gaming dice from the University of Texas at El Paso (UTEP). It was 3D printed with a microprocessor and accelerometer to identify motion, determine which side is up, and illuminate that top surface. Both figures demonstrate the profound potential that 3D printing has for the industry of robotics not only in terms of fast design iteration but also in terms of enabling new functionalities in complex geometries.

2 Traditional Additive Manufacturing and Its Suitability for Multi-functionality

To understand how robotics can be improved by 3D printing, we must first understand the vast landscape of processes that currently exist within the taxonomy that is the standard for 3D printing. From this perspective, we can describe the more advanced processes that enhance the existing commercial technologies to make 3D printed electronics and mechatronics.

The terminology standardization was developed by the F42 subcommittee, which was created in 2009 to set the standards for design, processes, file formats, terminology, evaluation, and materials with regards to Additive Manufacturing (AM). The subcommittee also defined a categorization of seven sub-technologies that together constitute the full breadth of commercial additive manufacturing techniques. The

Fig. 1 3D printed multi-functionality **a** Electronic gaming dice [17] and **b** Titanium prosthetic hand [15]

seven technologies are described in ASTM F2792-12a, the details of which are outlined below [10].

The most popular technology and possibly the most accessible to those in robotics is *Material Extrusion*, where building material is selectively deposited through an extrusion nozzle. The most common implementation of this method involves the extrusion of thermoplastic material through a heated orifice. The materials available for this implementation tend to be functional thermoplastics, which are generally robust enough to withstand harsh environments, like chemical, mechanical, or temperature exposure. Figure 2 shows a state-of-the-art materials extrusion production system from Stratasys.

Vat Photo Polymerization features a vat of liquid photo-curable polymer that is selectively cured with directed energy such as a laser beam or other optical energy, like a projection system. The system works at ambient temperatures and pressures which facilitates access to the vat for integrating other processes and hybridizing the system.

Powder Bed Fusion processes include selectively melting or sintering a layer of powder using an energy source such as a laser or electron beam.

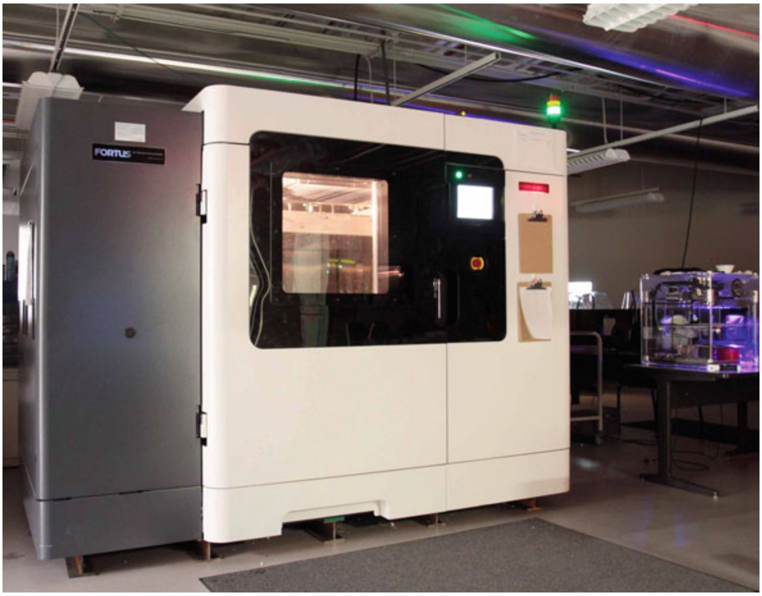

Fig. 2 Example of production printing system from Stratasys Fortus 900mc

Binder jetting involves ink-jetting a binder selectively onto powder. Additional powder is then dispensed by a rake or roller and the process eventually creates a complete green body with many layers. Both *Powder Bed Fusion* and *Binder Jetting* could potentially be integrated with complementary processes but powder processes in general are difficult to hybridize with ink dispensing and robotic placement processes.

Material jetting uses ink-jetting technology to selectively deposit the build material with an immediate cure prior to the application of additional layers. This technology can print multiple materials of varying stiffness and with a high resolution of ink jetting. Moreover, ink jetting can be used for conductive materials as well. The challenge with any ink-jetting process is that the viscosity of printable materials must be low for the technology to print well.

3 Multi-functional 3D Printing

Each of the standard commercial processes can be used directly for application in robotics: most of the processes have the ability to build hinges or even flexible sections to allow for linear or rotational actuation, or to be used simply to make single material mechanical pieces to be assembled within a robot. However, the possibility exists to further enhance these fabrication technologies with complementary manufacturing processes to embed components, wires, batteries, antennas, and other necessary subsystems required for completing a robot. In the next section, we will discuss these advanced *hybrid* versions of additive manufacturing.

3.1 Processes for 3D Printing Conductors Within Dielectric Structures

Back in the 90s, pioneering work included enhancing AM with embedded components [5], and these features required electrical connections if the components were electronic, electrical, or electromechanical in nature. Using conductive inks in 3D printing has been investigated with micro-dispensing [24], ink jetting [28], and aerosol jetting [22] onto stereolithography and materials extrusion pieces. Generally, this is accomplished on external surfaces after the fabrication is completed, but several examples have included interrupting and re-starting the fabrication, fully embedding components, and interconnecting within the 3D printed structure. Conductive inks have improved over the last three decades but still experience low conductivity when compared to traditional Printed Circuit Boards, which employ bulk copper. Others have implemented a Laser Direct Structuring technique where a plastic additive is included in the thermoplastic feedstock and can be activated selectively by a laser on an external surface. Subsequently, in an electro-less plating process we can add a high-density routing of bulk copper onto the laser-activated surface of the 3D printed structure. Low-temperature alloys have also been extruded [20] and injected [30] into thermoplastic structures to provide interconnect as an alternative to conductive inks. However, even though these alloys tend to have improved conductivity when compared to binder-loaded inks, the metals still fall short in comparison to copper, and the spatial resolution tends to be limited by the high viscosity.

A spin-off of a Harvard laboratory—Voxel8—provided the first commercial 3D printer based on materials extrusion, which includes a pneumatic ink dispensing system for printing conductive interconnect. The silver-based ink that is provided by the company in a proprietary cartridge is printed at room temperature and has a resistivity of 50×10^{-8} Ω-m (versus 1.7×10^{-8} Ω-m for bulk copper used in printed circuit boards), which can accommodate most low electrical current density applications in robotics. The ink is self-supporting and can span distances for structures with internal cavities that need to be bridged. The availability of this reasonably priced commercial system with embedded conductors and electronic components may be a major advancement for robotics. An example quadcopter is shown with an X-ray in Fig. 3

The University of Texas at El Paso (UTEP) has bypassed inks and embeds wires structurally within 3D printed thermoplastics by submerging the filament into the polymer substrate with selective heating of the metal either ultrasonically or through electrical current. Bulk copper has the advantage of providing the same conductivity as the plated copper used in traditional circuit boards. The wires come in a wide range

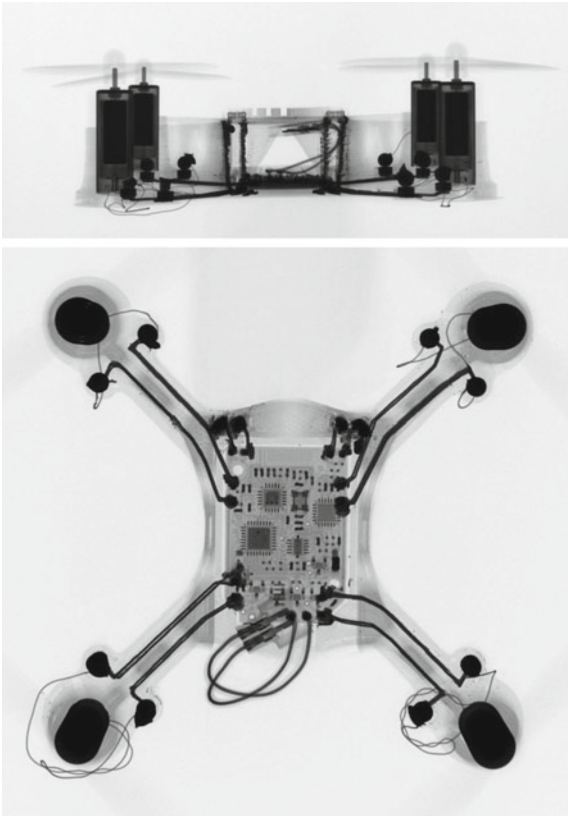

Fig. 3 Example of Voxel8 printing (courtesy of company)

of diameters ranging from 80 μm (and possibly smaller) to virtually any size as larger diameters can be easily accommodated by pre-printing perforations or trenches. The trenches minimize the substrate displacement as the metal is added to the structure and wires of almost any size can be press-fit into the substrate and then printed over for encapsulation. Once the wires are submerged, the substrate is left planar and further fabrication can continue without obstructions. Figure 4 shows wires embedded within a polycarbonate structure that was printed in a material extrusion system.

Given that these systems can provide bulk conductivity at virtually any cross-section, high-power applications like motors are now feasible. In fact, the UTEP's first application of the wires was a motor that was 3D printed in a non-assembly process [1], with electro-propulsion (Pulse Plasma Thrusters), and embedded within structures requiring high voltages (>1000 V) for ignition [18]. All electronics applications stand to benefit from this PCB-equivalent electrical performance, as there is a lower voltage drop across long leads that are now capable of carrying large electrical current reliably. A 200 mm long trace of 25 μm thickness and 100 μm of width, printed with commercially available inks, would result in a resistance of 10's of Ω.

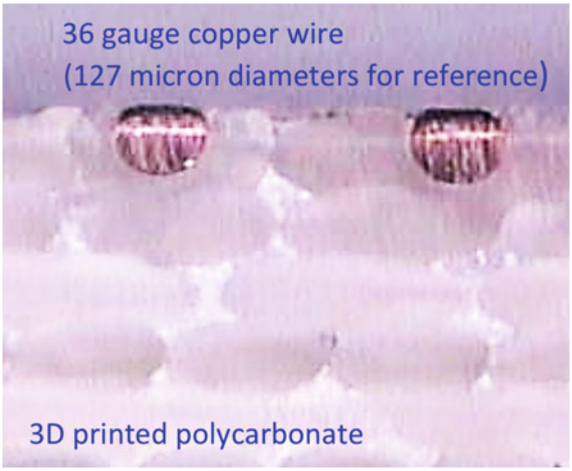

Fig. 4 Cross-section of embedded wires into 3D printed structure

This could be a problem if the trace is drawing 100's of mA on the order of 1.0 V of degradation at the destination.

Moreover, the embedded wires—serving as electrical interconnect—also provide an accidental benefit: providing increased mechanical strength by creating a plastic-metal composite—reinforcing the structure similar to rebar in concrete. Improvements in ultimate tensile strength have been reported in [6] and show that 3D printed structures, which are normally weaker than injection-molded plastic structures, can now exceed the performance of traditional injection mold manufacturing.

3.2 3D Printing Moving Assemblies

Most of the 3D printing processes provide a sacrificial support material that allows for overhanging features, and interconnected and interweaved physical components that are not physically bonded. This provides for relative motion between these sections. In this way, moving hinges, buttons, and gears can be fabricated to provide elbow or finger joints to enable robotic motion or to accept user input. The most famous example of this is the brain gear, which can be fabricated with many 3D printing technologies and is shown in Fig. 5.

In material extrusion, this can be accomplished with a water-soluble support material between the two hinge pieces or intentionally weak break-away pieces that can snap off and be sanded smooth. On the other hand, on powder bed fusion or binder jetting processes such as Laser Selective Sintering or Electron Beam Melting, the powder bed itself—if left unmelted—acts as a support material and only requires an escape path from the structure for removal. In the powder cases, sufficient design tolerances must be provided to ensure bonding between components does not occur.

Fig. 5 Well-recognized brain gear structure. Example shows multi-material extrusion fabrication in which any single red gear being rotated causes all to rotate while dark material remains stationary

In any of the 3D printing processes, two interlocking pieces can provide a wide range of smooth motion.

Another possibility for movement is to use multi-material systems to use a combination of flexible and stiff materials to provide selective flexibility. Material extrusion and material jetting processes both provide this capability. Elastomers are available commercially for material extrusion at reasonable expense, and material jetting provides a range of stiffness and colors in the photochemistry-based materials provided by companies like Objet (now Stratasys).

However, the simple capability for motion is not sufficient; an additional actuation device must be incorporated to control the motion similar to muscle moving bones in the skeletal system. 3D printing generally cannot provide this function, but components can be inserted into the structure either during the fabrication or afterwards including servos, linear actuators, flexing structures, pneumatics, etc. At least one research example has shown the creation of 3D printed motors, where fundamental components such as magnets, coils, and electronics have been incorporated to provide true 3D printed electromechanical actuation in a non-assembly 3D printing process [1]. Oak Ridge National Labs has shown metallic structures with internal meso-fluidic channels that enabled pneumatic actuation of robotic finger knuckle hinges [15], however, the actuation was controlled and powered externally.

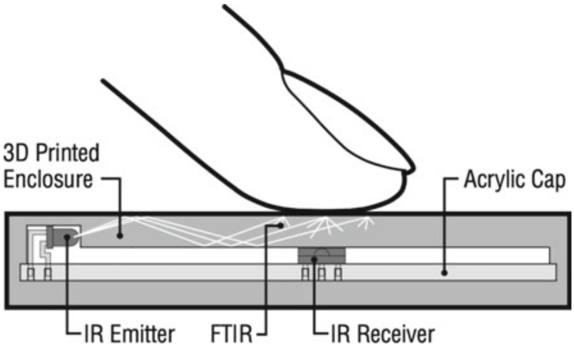

Fig. 6 Printed optics [34]

3.3 3D Printing Sensors

When talking about sensors embedded into 3D printed structures, significant research has focused on embedding sensors as well as directly 3D printing the sensors. Sensing tends to be concentrated into four areas for robotics: tactile, motion, vision, and hearing. While tactile sensing dominates the work so far in additive manufacturing, which is well suited for being 3D printed directly, the other three areas tend to be implemented by embedding traditional off-the-shelf devices into printed structures such as cameras or sensors.

Vatani et al. [31] presented conformal and compliant tactile sensors by using a micro-dispensing system to create a matrix of stretchable piezo-resistive lines. The intersections of these lines provide force information for a given location. In this report, nanocomposite lines were printed within a skin-like structure that was fabricated with 3D printing. The compliant 3D printed structure with orthogonal lines of sensing elements was capable of detecting and locating forces applied to the structure. The piezo-resistive sensing material was developed with the dispersion of multi-walled carbon nanotubes into a polymeric matrix with relatively uniform dispersion. Conductive networks are formed inside the polymeric matrix and external forces cause deformations, which result in an increase in the number of nanotubes in contact with one another. Consequently, a change in the resistivity for a given row and column can be measured and then associated with a known location in the robotic appendage.

Optical sensing of mechanical movement has also been implemented in structures using material jetting at Disney Research [34]. Inexpensive infrared emitter/receiver pairs can measure a wide range of environmental feedback by optically sensing through the semi-transparent 3D printed walls of the enclosure of the device. Integrating the sensors into the overall structure simplifies sensing and improves volumetric efficiency. However, the proposed techniques require that a transparent structure be fabricated, and currently this is only achievable in 3D printing with two liquid-based processes—stereolithography or material jetting. Based on photo-curable plastics, these two technologies provide sufficient transparency and clarity to serve as light guides; however, they are relegated to photochemistry, which can lead to reduced lifetimes of the device. This happens because curation continues after fabrication and it can reduce the efficiency of light transfer.

As illustrated in Fig. 6, the authors described a wide range of sensor applications including *displacement* monitoring where a light guide is mounted below the top of a transparent device, and when displaced, it changes the magnitude of light traversing between LEDs. *Push* and *pressure* sensing is where the application of a linear force moves the light guide. *Rotation* can be measured with a screw dial that lowers to move a light guide; as the screw dial lowers, the light path is obstructed and the attenuation can be measured. And finally, *Linear movement* is measured with a mechanical slider, as a light guide is traversed from one side to the other.

Muth et al. [21] reported creating stretchable sensors using 3D printing of a carbon-based ink within an elastomer. These were stretchable and allowed for strain gauge measurement. The sensor provides a stretchable device for soft robotics or robotic structures requiring flexibility for an improved range of motion. When strained beyond the limit, the printed carbon network is affected and particles are separated—increasing the resistance—this can be easily measured in a variety of ways. The printer allows for the sensor geometry to be tuned by controlling the cross-section. All printed sensors and devices are produced with a 3D printer that translates the dispensing syringe into a reservoir as a part of a process that later cures the structure.

Capacitive touch sensing has been shown by [26], where a copper wire or wire mesh is heated selectively and submerged into a 3D printed thermoplastic structure. This will act as a single plate of a capacitor, and its capacitance can be easily measured. A disruption in the electric field can indicate the presence of a new material in the vicinity of the sensor (Fig. 7). The report discusses 3D printed sensors like grip detection, keyboards, and even microfluidics sensors. The extension to robotics is obvious, for example, a sensor could be embedded during fabrication in the fingertips of an actuator (e.g., robotic hand) for feedback control.

Work is underway to increase the sensitivity, range of sensitivity, and also add sideways displacement and shear force measurement. All of these could be used to improve robotic hand motion and pressure control, with the increased sensitivity for the grasping and releasing of delicate objects.

3.4 3D Printing and Embedding of Batteries and Energy Sources

Currently, standard battery manufacturing can create custom-shaped lithium-ion batteries, which could be well suited for robotics in terms of the shape and energy density. However, this manufacturing technology is generally confined to high-volume production and requires expensive tooling such as molds. Both 2D and 3D printing research are attempting to enable the printing of batteries with custom forms, but the density of energy of these experimental batteries is dramatically less than commer-

Fig. 7 3D printed capacitive sensors with embedded wire mesh [26]

cial batteries and the reliability is unknown. Many reports of processes used to print batteries are confined to roll-to-roll technology [7, 11, 32].

Research does not necessarily support the requirements for full 3D freedom—as sheet formatting might be flexible (rolled or folded) but still remains 2D. Another option for 3D printing is to insert commercial batteries into the structure during the fabrication; sadly, many of the 3D printing processes that are well suited for robotics include a heated build envelope. Batteries—given their high energy density and sensitivity to temperature—can become unstable under these conditions [2]. Consequently, combining batteries and 3D printing is generally not possible unless limited to post-processing assembly or low-temperature 3D printing such as binder jetting or stereolithography. UTEP included commercial batteries as a post-process step in 3D printing using material extrusion on a Stratasys Fortus 400mc. Top lids were created to be placed above the battery after embedding into the structure, and a chemical process was used at low temperature to weld the plastic cap to the plastic structure—thus, fully embedding the battery into the structure after electrical connections had been established to the internal circuit. Micro-USB plugs and charging circuits were included to allow for the recharging of a test coupon used to prove space flight qualification for a NASA grant overseen by Glenn Research Center as shown in Fig. 8.

Another option is to integrate super-capacitors into the structure, which are far less sensitive to temperature in comparison to the chemical storage techniques used in commercial batteries. These capacitor approaches also provide fast charging times and can provide higher instantaneous power as required by the robotic electrical load. However, the energy density for ultra-capacitors is an order of magnitude less than commercial batteries, and the capacitors tend to be limited in the maximum voltages that can be stored. Furthermore, the capacitors are not only larger but are built in a pre-defined shape, which may not be well suited for the 3D printed structure in which it would be inserted.

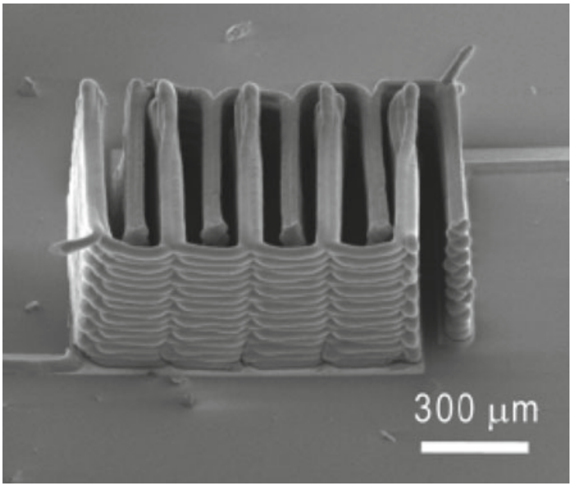

Fig. 8 3D printed Li-Ion battery [29]

Finally, 3D printed Lithium-Ion batteries have been demonstrated [29] used micro-dispensing to print high aspect ratio inter-digitated anodes and cathodes that when encapsulated with a liquid electrolyte, provide battery function as shown in Fig. 10. The aspect ratios of the patterned microelectrodes were as high as 11 for 16-layer electrode walls. Prior to the encapsulation, however, the microelectrode arrays were heated to 600°C in inert gas to remove the additives and sinter the nanoparticles. This high-temperature curing process would come before the direct printing within the 3D printed thermoplastic structures, since these structures would melt at such high temperatures. However, the idea of printing batteries in custom, arbitrary shapes could be completed as a separate process and then inserted or integrated within a 3D printed structure after the curing process was completed. The performance of the battery achieved an energy density of 9.7 Jcm^2 described in area rather than volume, rendering fair comparisons difficult with commercial batteries. Furthermore, if one cm^2 area were covered with a structure with an aspect ratio of 11, then this energy would be stored in 11 cm^3 providing a volume energy density of less than 1.0 J per cm^3. An equivalent commercial battery could provide 900 J cm^3 about three orders of magnitude better but without the freedom of printing to on-demand custom shapes. Clearly, as this demonstration was a first in the lab, significant optimizations remain, but 3D printed batteries still have a long way to go before being used in robotics (Fig. 9).

3.5 3D Printing Antennas

The increased interest in 3D printing is resulting in engineers reimagining the traditional manners in which antennas and electromagnetic devices are manufactured.

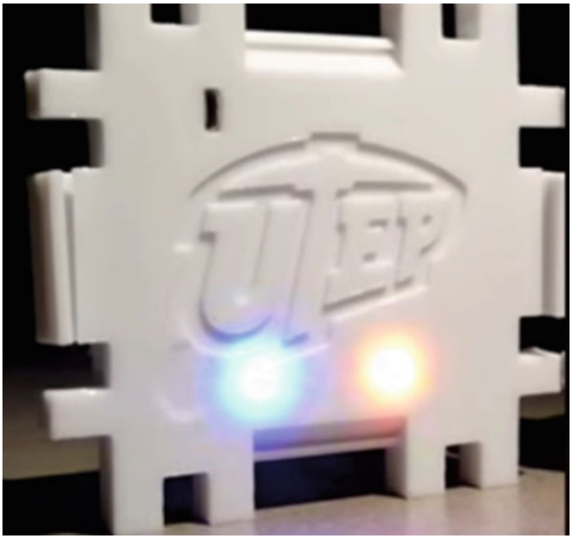

Fig. 9 3D printed electronics with embedded Li-Ion battery

Liang et al. [12, 13] and Shemelya et al. [26] used the enhanced 3D printing technology that embeds conductors to provide full spatial control of a combined dielectric and conductive structure with wires, meshes, and metallic foils in intricate 3D dielectric patterns (examples shown in Fig. 10). The ability to arbitrarily fabricate structures with complex topologies or geometries of interwoven dielectrics and conductors is enabling a new field of three-dimensional antennas—where structures can provide multiple frequency bands and maintain a small physical footprint, all while performing similarly to an electrically large antenna. The dielectric materials used in 3D printing can generally have a good electromagnetic performance with low loss tangents and a wide range of permittivity levels, allowing them to be physically small. Moreover, these antennas can be integrated into the structure (wing of plane, for instance), to save space and volume, and provide the extra benefit of improving the mechanical strength of the device by creating a composite structure. This also provides an interesting case of multi-functionality.

4 Examples of 3D Printing in Robotic Applications

With the current ability to print mechanical structures commercially, and with new enhanced fabrication technologies around the corner—currently being developed within research labs—soon, it will be possible to print most—if not all—of the robotics in a single non-assembly process (including more than just the structure). The Holy Grail for this comprehensive fabrication approach would be to design a robot in CAD, press print, and 5 hours later return to find a fully functional robot prepared to crawl, walk, or fly out of the 3D printer. The following examples are

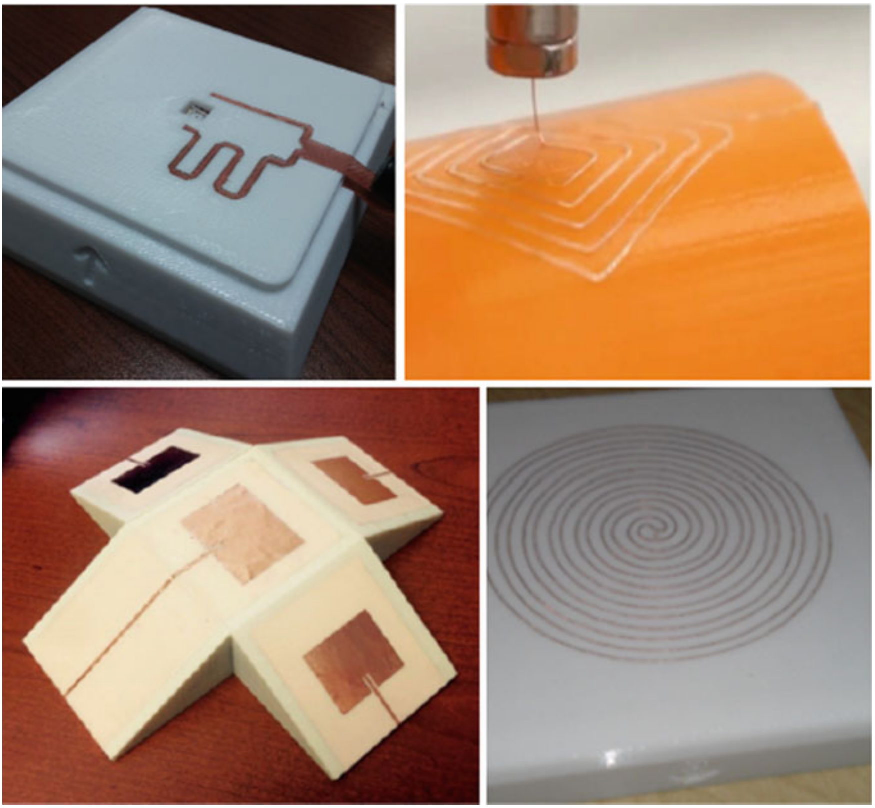

Fig. 10 3D printed antennas [13, 26]

cases in which robotics experts used 3D printing as a central element in the design and fabrication of advanced robots.

Some of the earliest work where additive manufacturing was reported to be used with robotics was in the late 90s [19]. It was generally relegated to mechanical structures, the fabrication of which provided for the rapid prototyping of the robots. However, the feasibility and utility of additive manufacturing of robots were manifest. Two processes were used: Stereolithography and Selective Laser Sintering. These were used to build mechanically mobile hinges and joints required for two robotic systems: a three-legged manipulator and a finger in a five-fingered hand.

In the second case, wires were embedded for actuation, which allowed for the digits to grasp. However, the actuation was not embedded within the structure—but rather implemented externally.

In the same timeframe [4], robots with legs with passive mechanical properties were inspired by nature. Using Shaped Deposition Modeling where castable polyurethane and sacrificial materials were deposited in layers, electronic and mechanical components were reported to have been inserted for the first time—

in the 3D printing world—during an interruption in the fabrication. By embedding these components into the structure, a new paradigm was created in which multi-functional devices could be fabricated directly from a CAD file with processes that were interrupted in order to integrate electronics and electromechanics.

The first soft robotics that was 3D printed [25] included a double-membrane antagonistic actuator fabricated with material jetting processes. Electrodes were embedded between the repeated layering of dielectric elastomers. When the structure was subjected to high voltages across the electrodes, it deformed and provided actuation. The problem with high voltages such as those required for this actuation is that generating them is difficult with traditional batteries and would require charge pumping or access to the grid. Other problems include the dielectric breakdown, which could lead to reliability challenges later. With the dielectric material being relegated to photochemistry in the case of material jetting of photo-curable elastomers, the material will continue to cure in the presence of UV light and potentially degrade or discolor.

In [23], a material jetting system was used to print a flapping-wing insect inspired by replicating the wing shape of real insects. An ornithopter with a mass of just less than four grams was fabricated using 3D printing, and it achieved an untethered hovering flight. The size and weight of the structure were significantly reduced with the design freedom and high resolution of material jetting. This demonstration helps highlight the use of additive manufacturing to miniaturize robotics—in addition to the advantages of rapidly prototyping robots or to design custom and complex structures.

The use of low-cost, open-source printing for the construction of a sophisticated under-actuated robotic hand was demonstrated in [16]. The project established the design of an adaptive, four-finger hand. They used simple 3D printed components, compliant joints, and commercially available devices. The authors promoted a series of open-source designs to be released. This was contributed to by the open-source user community and, consequently, provided a diverse database of robotic components accessible by all.

In [1], the fabrication of a high current ($>1\ A$) electromechanical device (i.e., motor) is described. It was achieved through a single hybrid AM build sequence using a low-cost printer. By embedding high-performance conductors directly into the thermoplastic FDM substrate, high-performance electromagnets could be activated

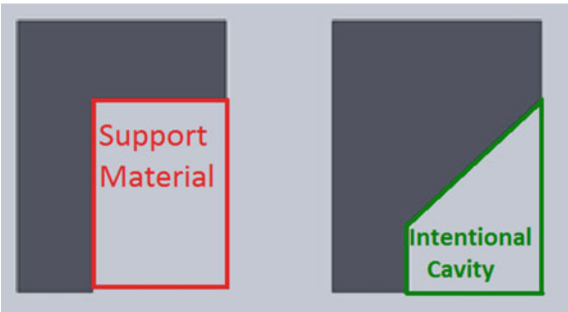

Fig. 11 45° rule [1]

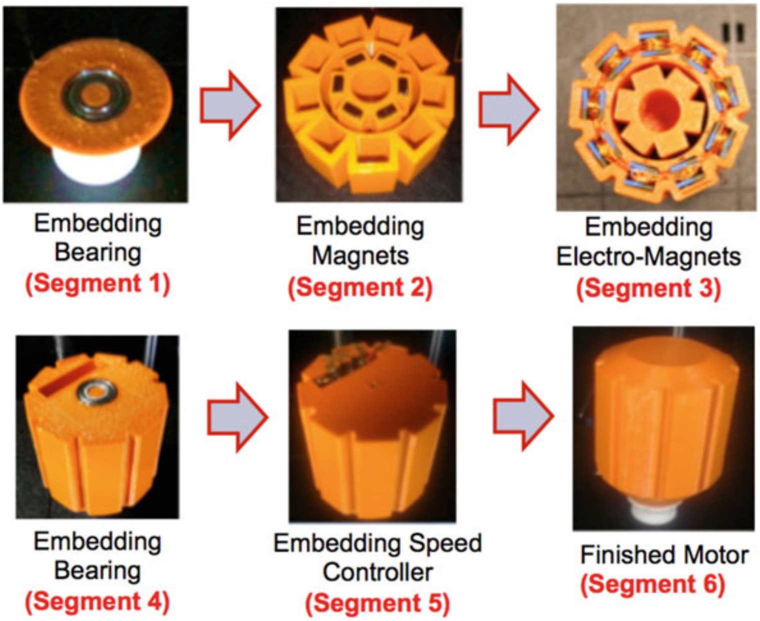

Fig. 12 3D printed motor [1]

and embedded within an external structure (stator). This structure included a moving rotating internal section (rotor) with embedded magnets. There were efforts put into eliminating the need for support material, even though there were internal cavities and overhanging structures. Since electronics were embedded, removal of water-soluble support was not possible as the water bath would result in damage to the components. Consequently, diligent use of the 45° rule was implemented to allow for the two mechanical structures to be constructed without support, and thus eliminating the sacrificial layer removal that would destroy the electronics. The 45° rule is illustrated in Fig. 11, and it states that when an overhanging feature does not exceed in more than 45° the support material, it is not necessary as the structure is self-supporting. Figure 12 illustrates the five different points in the material extrusion process in which the fabrication was interrupted and components and interconnect were inserted into cavities. The final motor was fully functional at the end of the print working at 8,000 RPM when powered by 12 V and a pulse width modulation signal. If a battery or ultra-capacitor had been included, the possibility of having a motorized robot exiting the 3D printer after completion of fabrication by walking or flying through the access point to the build camber will be possible.

5 Conclusions

Advancement in 3D printing will lead to the manufacture of fully functional robots, which will walk or fly out of a printer upon completion. Robot designers ranging from high school students to advanced researchers will have access to fabrication locally, and be enabled to iterate through designs, revolutionizing the design process. Online open-source design repositories will flourish, where designs will be offered to the community, and be improved further.

Components that cannot be fabricated directly—such as powerful motors, energy sources, and an armada of sensors—will be inserted, providing improved volumetric efficiency. With a ceaseless reduction in minimum feature sizes, robots will not just be more functional but span the full range of scale: there will be systems larger than cars down to micro-systems inspired by biological systems.

Many manufacturing challenges remain such as the need for additional materials, improved resolution, and anisotropy in strength; however, the exponentially increasing research focus on 3D printing processes ensures that the on-going evolution of these manufacturing systems will overcome these concerns.

References

1. Aguilera E, Ramos J, Espalin D, Cedillos F, Muse D, Wicker R, MacDonald E (2013) 3D printing of electro mechanical systems. In: Proceedings of the solid freeform fabrication symposium, pp 950–961
2. Balakrishnan PG, Ramesh R, Kumar TP (2006) Safety mechanisms in lithium-ion batteries. J Power Sources 155(2):401–414
3. Berggren M, Nilsson D, Robinson ND (2007) Organic materials for printed electronics. Nat Mater 6. https://doi.org/10.1038/nmat1817
4. Clark JE, Cham JG, Bailey SA, Froehlich EM, Nahata PK, Full RJ, Cutkosky MR (2001) Biomimetic design and fabrication of a hexapedal running robot. In: IEEE international conference on robotics and automation, 2001. Proceedings 2001 ICRA, vol 4. IEEE, pp 3643–3649. https://doi.org/10.1109/robot.2001.933183
5. Weiss LE, Merz R, Prinz F, Neplotnik G, Padmanabhan P, Schultz L, Ramaswami K (1997) Shape deposition manufacturing of heterogeneous structures. Nat Mater 16. https://doi.org/10.1016/s0278-6125(97)89095-4
6. Espalin D, Muse DW, MacDonald E, Wicker RB (2014) 3D printing multifunctionality: structures with electronics. Int J Adv Manuf Technol 72. https://doi.org/10.1007/s00170-014-5717-7
7. Gaikwad AM, Whiting GL, Steingart DA, Arias AC (2011) Highly flexible, printed alkaline batteries based on mesh-embedded electrodes. Adv Mater 23(29):3251–3255
8. Gaytan S, Cadena M, Karim H, Delfin D, Lin Y, Espalin D, MacDonald E, Wicker R (2015) Fabrication of barium titanate by binder jetting additive manufacturing technology. Ceram Int 41. https://doi.org/10.1016/j.ceramint.2015.01.108
9. Gibson I, Stucker B, Rosen DW (2010) Additive manufacturing technologies. Springer
10. International A (2012) ASTM F2792-12a, standard terminology for additive manufacturing technologies. ASTM Int https://doi.org/10.1520/F2792-12A
11. Kaltenbrunner M, Kettlgruber G, Siket C, Schwodiauer R, Bauer S (2010) Arrays of ultracompliant electrochemical dry gel cells for stretchable electronics. Adv Mater 22(18):2065–2067

12. Liang M, Yu X, Shemelya C, Roberson D, MacDonald E, Wicker R, Xin H (2014) Electromagnetic materials of artificially controlled properties for 3D printing applications. Antennas and propagation society international symposium (APSURSI). IEEE, pp 227–228
13. Liang M, Shemelya C, MacDonald E, Wicker R, Xin H (2015) 3D printed microwave patch antenna via fused deposition method and ultrasonic wire mesh embedding technique. IEEE Antennas Wirel Propag Lett 14:1346–1349
14. Lopes JA, MacDonald E, Wicker RB (2012) Integrating stereolithography and direct print technologies for 3D structural electronics fabrication. Rapid Prototyp J 18. https://doi.org/10.1108/13552541211212113
15. Love LJ, Lind RF, Jansen JF (2009) Mesofluidic actuation for articulated finger and hand prosthetics. In: 2009 IEEE/RSJ international conference on intelligent robots and systems, pp 2586–2591. https://doi.org/10.1109/IROS.2009.5353919
16. Ma RR, Odhner LU, Dollar AM (2013) A modular, open-source 3D printed underactuated hand. In: 2013 IEEE international conference on robotics and automation (ICRA). IEEE, pp 2737–2743
17. Macdonald E, Salas R, Espalin D, Perez M, Aguilera E, Muse D, Wicker RB (2014) 3D printing for the rapid prototyping of structural electronics. IEEE Access 2:234–242. https://doi.org/10.1109/ACCESS.2014.2311810
18. Marshall WM, Stegeman JD, Zemba M, MacDonald E, Shemelya C, Wicker R, Kwas A, Kief C (2015) Using additive manufacturing to print a cubesat propulsion system. In: 51st AIAA/SAE/ASEE joint propulsion conference, p 4184
19. Mavroidis C, DeLaurentis KJ, Won J, Alam M (2001) Fabrication of non-assembly mechanisms and robotic systems using rapid prototyping. J Mech Des 123(4):516–524
20. Mireles J, Kim HC, Lee IH, Espalin D, Medina F, MacDonald E, Wicker R (2013) Development of a fused deposition modeling system for low melting temperature metal alloys. J Electron Packag 135(1):011008
21. Muth JT, Vogt DM, Truby RL, Mengüç Y, Kolesky DB, Wood RJ, Lewis JA (2014) 3D printing: embedded 3D printing of strain sensors within highly stretchable elastomers. Adv Mater 26(36):6202–6202
22. O'Reilly MJ (2011) Aerosol jet printer as an alternative to wire bond and TSV technology for 3D interconnect applications. In: IMAPS international conference and exhibition on device packaging—in conjunction with the global business council, GBC 2011 spring conference, pp 135–138. www.scopus.com
23. Richter C, Lipson H (2011) Untethered hovering flapping flight of a 3D-printed mechanical insect. Artif Life 17(2):73–86
24. Rogers JA, Bao Z, Raju VR (1998) Nonphotolithographic fabrication of organic transistors with micron feature sizes. Appl Phys Lett 72(21):2716–2718. www.scopus.com, cited By :150
25. Rossiter J, Walters P, Stoimenov B (2009) Printing 3D dielectric elastomer actuators for soft robotics. In: Electroactive polymer actuators and devices (EAPAD) 2009, international society for optics and photonics, vol 7287, p 72870H
26. Shemelya C, Cedillos F, Aguilera E, Espalin D, Muse D, Wicker R, MacDonald E (2015) Encapsulated copper wire and copper mesh capacitive sensing for 3D printing applications. IIEEE Sens J 15. https://doi.org/10.1109/JSEN.2014.2356973
27. Shemelya CM, Rivera A, Perez AT, Rocha C, Liang M, Yu X, Kief C, Alexander D, Stegeman J, Xin H, Wicker RB, MacDonald E, Roberson DA (2014) Mechanical, electromagnetic, and x-ray shielding characterization of a 3D printable tungsten–polycarbonate polymer matrix composite for space-based applications. J Electron Mater 44. https://doi.org/10.1007/s11664-015-3687-7
28. Sirringhaus H, Shimoda T (2003) Inkjet printing of functional materials. MRS Bull 28(11):802–806
29. Sun K, Wei TS, Ahn BY, Seo JY, Dillon SJ, Lewis JA (2013) 3D printing of interdigitated li-ion microbattery architectures. Adv Mater 25(33):4539–4543
30. Swensen JP, Odhner LU, Araki B, Dollar AM (2015) Injected 3D electrical traces in additive manufactured parts with low melting temperature metals. In: 2015 IEEE international conference on robotics and automation (ICRA). IEEE, pp 988–995

31. Vatani M, Engeberg ED, Choi JW (2015) Conformal direct-print of piezoresistive polymer/nanocomposites for compliant multi-layer tactile sensors. Addit Manuf 7:73–82
32. Wendler M, Hubner G, Krebs M (2011) Development of printed thin and flexible batteries. Int Circ Graphic Ed Res 4:32–41
33. Wholers (2014) Wohlers Report 2014. Wohlers Associates Inc
34. Willis K, Brockmeyer E, Hudson S, Poupyrev I (2012) Printed optics: 3D printing of embedded optical elements for interactive devices. In: Proceedings of the 25th annual ACM symposium on User interface software and technology. ACM, pp 589–598

Design of Mobile Robots

Miguel Torres-Torriti

Abstract Virtual and physical rapid prototyping of mobile robots is often necessary not only in the development of research platforms, but also for validating commercial and customized mobile robot applications. The design of a robot involves specialized knowledge from mechanical, electrical and software engineering. Despite summarizing the wide variety of tools and knowledge is a challenging task, this chapter presents the main guidelines and recommendations for the design and rapid prototyping of mobile robots. The chapter reviews basic design rules, the fundamental robot components, the general hardware and software architecture. The discussion includes aspects that are key to the selection of those components that ensure the robot prototype meets the motion specifications, such as the selection of computing platforms, the main types of mechanical transmissions, efficiency issues, the role of bearings and other aspects concerning stability, overturning margins, controllability and the motion dynamics. Finally, all the concepts and guidelines are employed in the design of a skid-steer mobile robot, which is presented as an example of rapid mobile robot prototyping. A summary of the main conclusions and suggestions for further reading is presented in the last section.

1 Introduction

The design and development of robots involve a blend of skills and knowledge whose roots are in the disciplines of mechanical, electrical, computer and control engineering [24, 26]. Summarizing all the necessary aspects for designing and building industrial robots in one chapter is challenging. However, it is possible to provide an overview of the main design steps and recommendations, which should be easy to put into practice for the rapid construction of robot prototypes.

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_4

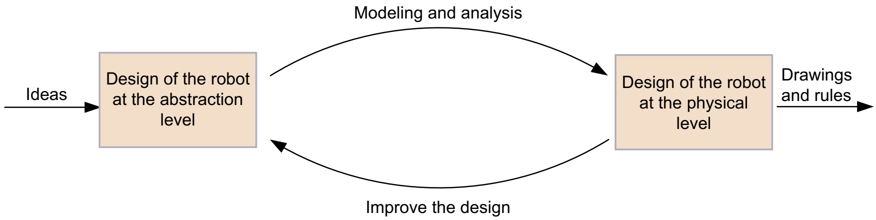


Fig. 1 The main phases of a design process

The *robot design process* is a series of steps, often iterative steps—that involve research, reasoning, analysis, modeling, verification and adjustments—by which the concept design that establishes the application requirements is transformed into a series of rules and plans structured for the construction of the robot. The iterative design process shown in Fig. 1 illustrates the two main phases starting from a statement of the requirements and general ideas that are transformed through a phase of *modeling and analysis* into a physical embodiement, which in turn provides useful information on the second phase to *improve the design* by making corrections to the initial concept design and specifications. The design process should not be confused with a trial and error process.

There are some basic rules for a good design that have been considered in the designs presented in this chapter and that are summarized as follows:

- Measure twice, cut once!
- KISS: Keep it simple, stupid!

> *Perfection (in desing) is attained not when there is nothing more to add, but when there is nothing more to take away.*
>
> *Antoine de Saint-Exupery*

- Be careful to not oversimplify!

> *Everything should be made as simple as possible, but not simpler.*
>
> *Albert Einstein*

- Rely on past experience! Do not re-invent the wheel!

> *The difference between theory and practice? In theory, there's no difference between theory and practice. In practice, there is.*
>
> *Benjamin Brewster*

The first rule comes from craftsmen and is often heard in mechanical workshops, but applies not only to the fabrication process. Either using basic formulas or advanced simulations, it is possible to *measure* and *predict* with different levels of accuracy the behavior of the robot even before building it. By following this rule, one can avoid purchasing wrong parts that do not satisfy the mechanical, electrical or computational requirements of the robot.

The second rule seems obvious. However, since robots are complex systems, it is easy to be drawn by complexity into designing and building something with many unnecessary parts or parts that are not necessary at least in a first prototype to carry out some physical verification quickly. So if the design is becoming complex, it is always good to pause and check if there are any parts that could be saved for some later stage after the minimal functionality has been tested.

The third rule is connected to the second one in the sense that simplifying the design does not mean one should forget the long-term target and the complete expected functionally. The second and third rules go together hand in hand.

The fourth rule can save a lot of time. Many design challenges and problems have already occurred in the history of humanity or are being faced currently in more than one place at the same time in our small world. So it is often a good practice to check the existing solutions, avoid past mistakes and use good ideas that can be found in books, papers and patents. If the solution exists commercially, try to use it because this will save time and money. Prototyping every single part from scratch is also risky because there are more chances of committing errors and not foreseeing problems that have already been encountered and solved in the commercial device.

These basic rules are so simple that it is often easy to ignore them. On occasions some people deliberately skip them because of overconfidence, thinking that spending time on the initial design is waste of time and that design problems can be solved along the way. This kind of thinking can easily mislead many people into the tempting idea that all designs and implementations can be solved merely by trial and error, but this is often a trap that finalizes in a dead-end that requires a complete redesign of the robot. In the next section, more formal robot design steps will be discussed always keeping in mind that the target is the one rapid roboting and quickly implementing a functional robot prototype.

2 Robot Design Fundamentals

This section covers the fundamentals of robot design. First, the steps of the design process are briefly reviewed in Sect. 2.1. In order to produce a design that complies with the specifications and is technically feasible, the designer must know what are the main parts, the hardware and software architecture of typical robots. The components of a robot and its architectural aspects are discussed in the subsequent Sects. 2.2 and 2.3. The motion model is explained in Sect. 2.4. Understanding the motion model is key to the correct selection of the motors and the electrical drives, the mechanical transmission and meeting the performance requirements. Other design considerations, such as the mechanical transmission, efficiency, the use of bearings, overturning, stability and controllability issues, as well as some aspects of rapid robot prototyping, are discussed in Sect. 2.5. Finally, the consequences of some of the typical design decisions on the robot performance are examined in Sect. 2.6.

2.1 Robot Design Steps

The robot design process in Fig. 1 typically involves the following main steps:

1. Define system objectives and specifications.
2. Identify system variables (inputs, outputs and disturbances).
3. Write the specifications for the variables (minimum, maximum, typical values and noise characteristics).
4. Establish the system configuration and identify the actuators.
5. Obtain or derive the mathematical models of the system, its sensors and actuators.
6. Define the hardware/software architecture and the adjustable parameters.
7. Optimize the parameters and analyze the system's performance. If the system fails to meet the expected performance, it will be necessary to repeat steps 4 through 7.

Defining system specifications requires to answer at least the following aspects:

- What is the robot's intended application and task to be solved.
- What is the robot's workspace and operation environment.
- What is the robot's payload capacity.
- What is the robot's expected operating speed (longitudinal and angular).
- What is the robot's level of intelligence, i.e. teleoperated, semi-autonomous or fully autonomous.
- What is the robot's communication architecture and system.
- What is the robot's energy consumption and operation time.
- What is the robot's set of physical requirements in terms of assembly simplicity, ease of operation and maintenance and safety to people; recyclability requirements and user interface aspects.

Once the above aspects have been defined and analyzed, then the physical aspects of the design have to be studied in detail as part of the iterative process. The physical aspects include among other things:

1. Structural definition.
2. Actuator and sensors selection.
3. Computers, control hardware and software selection.
4. Design of the user interface, also referred to as the *human-machine interface* HMI.
5. Definition of alarm conditions, backup procedures and display devices.

The full process of designing a mobile robot is illustrated in the robot design flowchart of Fig. 2, which was adapted from the design flow presented in [26]. The *preliminary design* phase in the robot design process of Fig. 2 can be considered the main part of a prototyping process if the construction of a functional prototype is included in each evaluation step. Functional prototypes allow to evaluate performance issues and correct them before investing in the *detail design* phase, production and documentation.

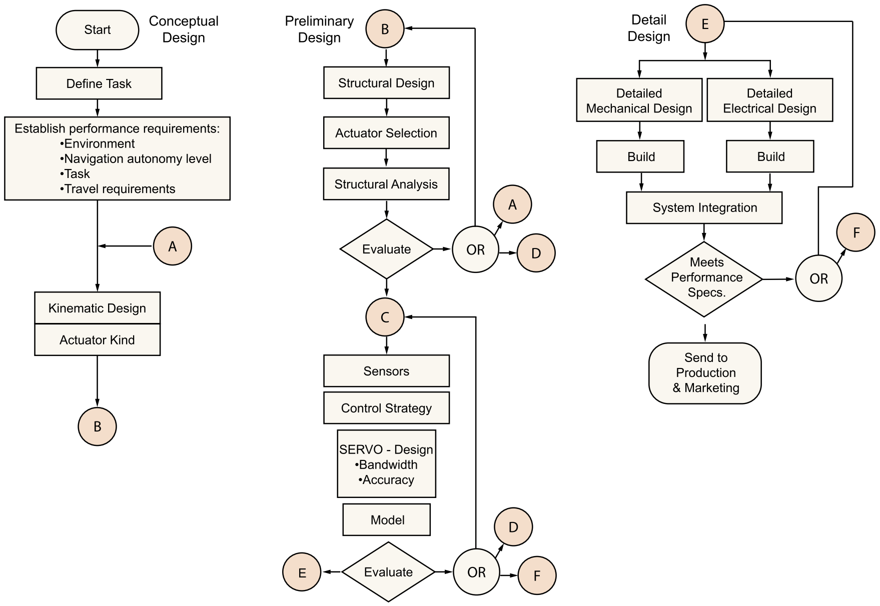


Fig. 2 Mobile robot design flowchart

The first step in preliminary design is the definition of the mobile robot's structure or morphology. This step cannot be completely decoupled from the actuator and sensors selection, because decisions on the latter have an impact on the robot's structure. Hence, it may be necessary to iterate over the kinematic design and the definition of the robot's morphology to achieve a feasible design. This motivates the discussion of the typical robot parts even before discussing the robot's kinematics and morphological aspects. The lack of knowledge about the parts of the robot leads to designs that often cannot be implemented and require many corrections to make them feasible.

2.2 *Robot Parts*

The main parts of a mobile robot are shown in Fig. 3. The essential parts of any mobile robot include the following:

- Wheels
- Hubs
- Bearings
- Gearboxes
- Motors/Actuators
- Motor mounts
- Power drives
- Batteries
- Computers
- Sensors
- Chassis
- Cable raceways

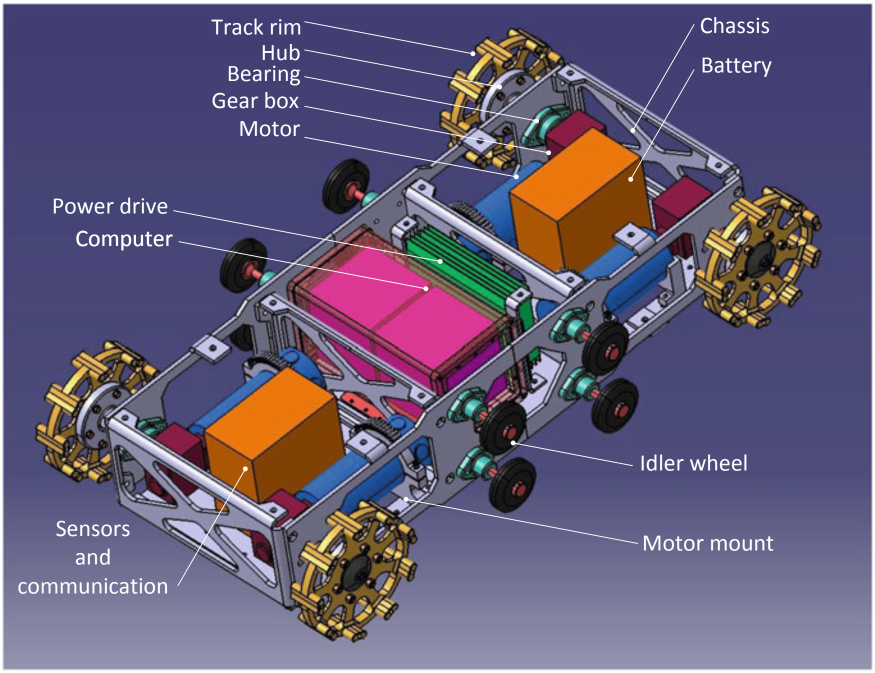


Fig. 3 Main parts of a mobile robot

Other parts that may need to be considered in some designs are the shear pins and break-away joints, which may act as mechanical fuses to prevent damages to the robot if there exists a chance of exposing the robot to large mechanical stresses.

2.3 Robot Architecture

The main parts of a robot mentioned in the previous section can be arranged into two main groups: (i) the hardware architecture and (ii) the software architecture.

2.3.1 Hardware Architecture

The hardware architecture comprises the mechanical components and morphology, as well as the control electronics, including electronic drives, communication interfaces, sensors and computers. A typical hardware architecture is illustrated in Fig. 4, which shows a block diagram with the main hardware components. Not all mobile robots necessarily have a navigation computer and a complete sensor suite with wheel encoders, range sensors (lidar, sonar or radar), an inertial measurement unit (IMU),

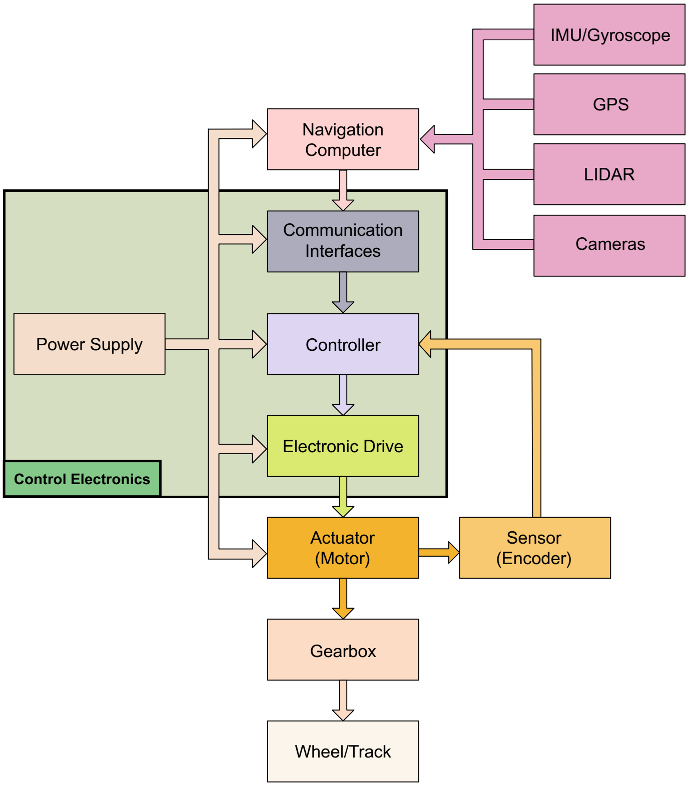
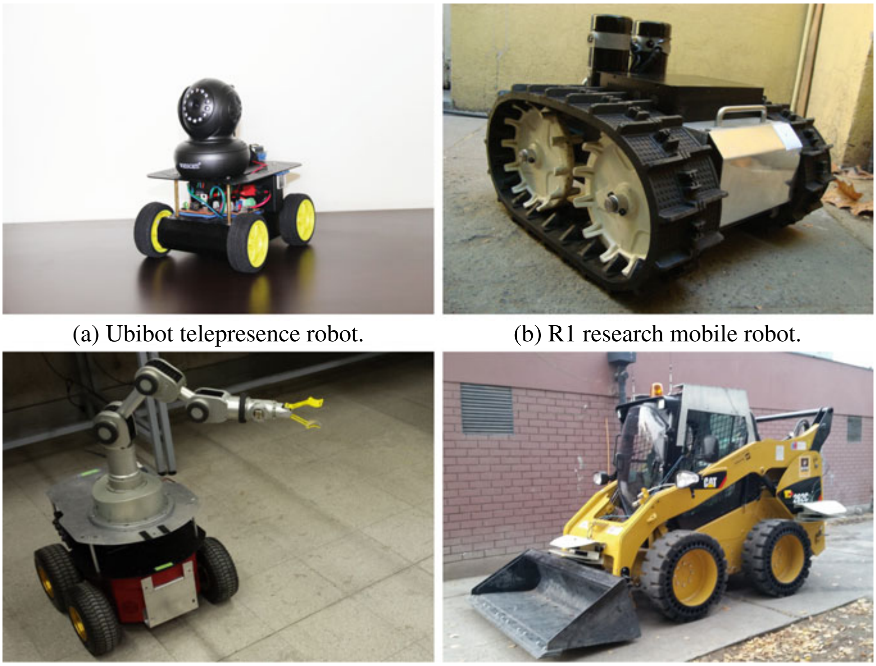


Fig. 4 Block diagram of the standard hardware architecture of a mobile robot

a gyroscope, a compass, a GPS and cameras, as depicted in Fig. 4. However, at least some of these sensors are necessary to provide displacement feedback and implement basic safety mechanisms in order to prevent collisions.

Figure 5 shows different examples of robots build from scratch (Fig. 5a and b) or assembled by integrating commercial platforms (Fig. 5c and d). In all cases, the hardware architecture of these robots can be described by the diagram in Fig. 4. An example of the design and hardware architecture of a skid-steer robot will be discussed in greater detail in Sect. 3. For another example that can be studied in detail, the interested reader on robot hardware architecture is referred to the open design of a low-cost mobile robot publicly available on the authors' website http://ral.ing.puc.cl/ubibot.htm, [22], with all the drawing and step-by-step assembly instructions for the mechanical, electrical and software components.



(a) Ubibot telepresence robot. (b) R1 research mobile robot.

(c) SSMM UC1 mobile manipulator. (d) R3 mining robot.

Fig. 5 Examples of skid-steer mobile robots

2.3.2 Software Architecture

There are different computing and software architectures for robots; see, for example, and [24, 25, Chap. 8]. Figure 6 shows a general software and computing architecture for mobile robots. Careful planning and well-thought-out design of the computing architecture allow to partition the code into modules or functional blocks with well-defined inputs and outputs that can be developed in parallel, tested and re-used, thus facilitating the development and maintenance of the system's software blocks.

The general software and computing architecture for robots that is illustrated in Fig. 6 has been divided into three levels: (i) the firmware or driver layer, (ii) the middleware or algorithm layer and (iii) the user interface layer. The firmware or driver layer is responsible for handling the interfacing with actuators and basic sensors of the robot. The firmware layer is the layer closest to the physical world and involves all the routines that manage the *transduction* or *input-output* processes by which logic signals are transformed into actions through the actuators, and analog or digital signals from the sensors are transformed into digital values. The software components of the firmware layer are hardware-dependent. However, the basic building blocks of this layer are often routines that take an actuator's desired position, velocity, acceleration or force and translate the value into a signal that produces the

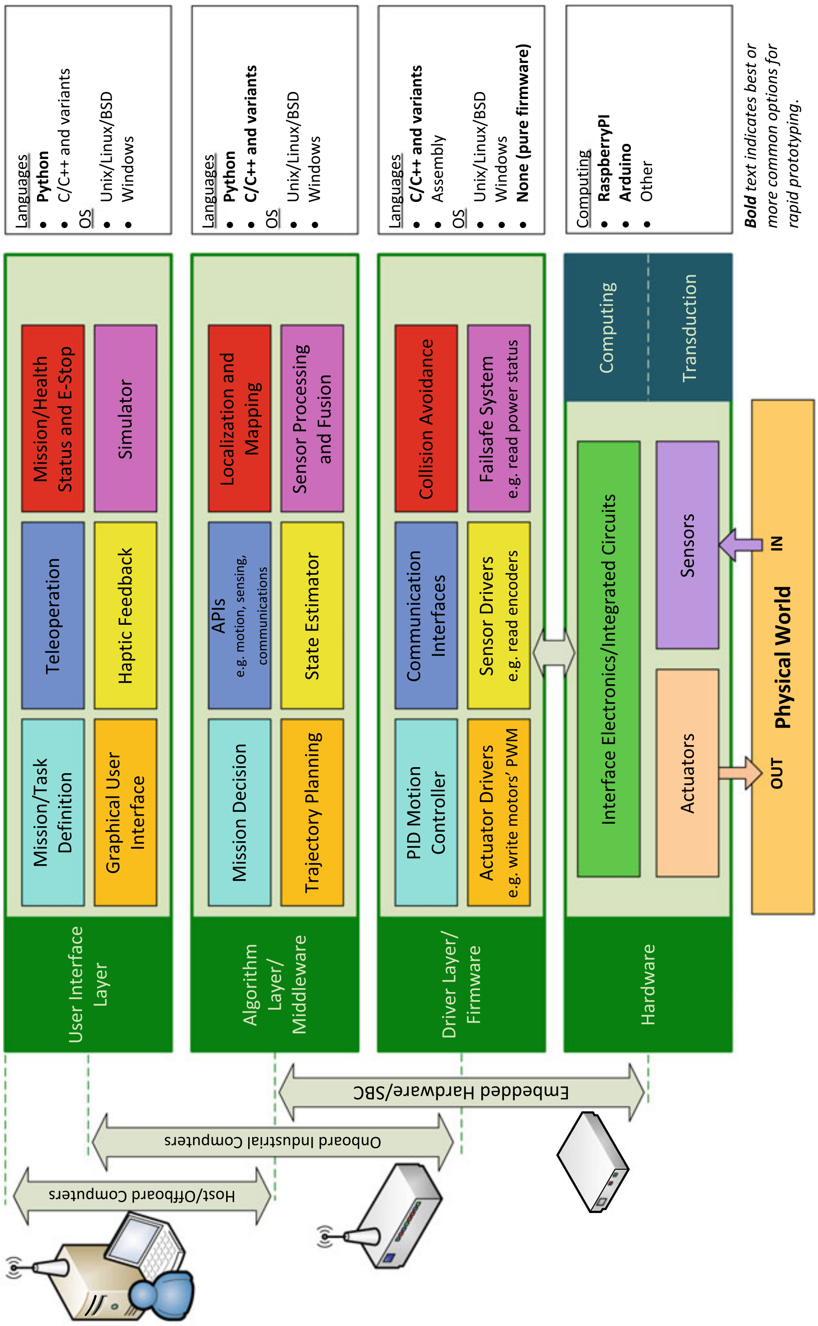


Fig. 6 General software and computing architecture of a mobile robot

corresponding actuation by adjusting some voltage or current amplitude, frequency or both. The firmware routines that control the actuators may include code to process the feedback from the sensors and close the loop in order to drive the actuators to a set-point specified by the user or some algorithm in the upper layer. Similarly, the firmware layer contains routines that instruct the hardware to read the raw sensor data from digital or analog-to-digital inputs and transform the data into values that can be used by the control routines in this or upper layers.

As just mentioned, the firmware layer is hardware-dependent. Industrial systems employ in general proprietary analog-to-digital and digital-to-analog conversion modules, data acquisition electronics and industrial-grade PCs. However, nowadays there exist two popular options: the Arduino and Raspberry Pi, which were conceived for the do-it-yourself-maker community. These platforms enable software-hardware interfacing in a relatively easy way at a low cost compared to industrial devices while providing the level of functionality expected from an embedded computer that must control and run the basic tasks of a mobile robot prototype. Choosing Arduino or Raspberry Pi depends on the project's requirements. Arduino is adequate when the main tasks are driving actuators and reading sensor data, with low power requirements, and the system must start quickly and operate with little or no human interaction. Unlike Arduino that is a microcontroller board that runs firmware directly, Raspberry Pi is a fully functional computer that runs an embedded Linux operating system. Therefore, Raspberry PI is suitable to implement functions of the higher layers of the software architecture shown in Fig. 6 and is very convenient for applications that require network connectivity, graphical output through a display and other functionality of a computer. Sometimes it is useful to combine the strengths of each platform, using Arduino to handle the hardware interfacing and all functions that need to run as soon as the device is powered on without having to wait for the whole operating system to boot and the Raspberry Pi to implement all higher level functions and provide network and user interface functionality.

The middleware layer contains all the algorithms that implement the main high-level tasks and functions of the robotic system. Routines in this layer take the sensors' measurements and make control decisions regarding the motion and task execution of the robot based on its sensors' feedback. The control decisions are transformed in this layer into low-level code that is sent to the drivers of the actuators running in the firmware layer. The middleware layer may include trajectory planning and tracking algorithms, localization and mapping routines, obstacle avoidance algorithms, state estimation and sensor processing routines. The high-level routines may also be collected into a programming library in the form of an application programming interface (API) that is independent of the physical hardware or platform. The API allows the developer to program the robot to perform more complex tasks.

The user interface layer is the highest layer of the computing architecture. This layer enables the user to interact with the robot locally or remotely on a PC connected to the robot over some network using input devices such as a joystick, keyboard, mouse or microphone and output devices like displays and speakers. The interface may be as simple as a command line interface (CLI) that uses text input and outputs only or a more complex graphical user interface (GUI) that displays virtual indicators showing the position and orientation of the robot, the robot location on a map, range scanner measurements, camera views and other state variables. A GUI typically provides inputs such as slide bars and buttons that allow the user to drive the robot, control its actuators and adjust its sensors. A teleoperated robot often involves a rich GUI that includes visual feedback from cameras. However, autonomous robots may not have a GUI, nor even a simple text-based user interface, and only provide developer interfaces.

A well-conceived software architecture should allow the developer to test the system with a simulated device without modifying any layers in the system except for the driver layer. To this end, the developer should clearly identify the physical input and output signals and write the software code blocks that implement the actual hardware interfacing with the physical world, as well as write similar blocks that simulate the physical connections in order to test the whole system using a software simulation of the physical devices.

The structure of the computing architecture presented in Fig. 6 provides the basis for a modular and reusable design. This is especially important because such a computing architecture design can help developers to work concurrently on different parts of the software and ensure code reusability that is important to speed up prototyping of the software components of the robotic system. On the other hand, changes or upgrades in the hardware that supports the functions at some level may require little or no modifications of the other layers, thus providing some independence between layers.

2.4 Robot Motion

This section summarizes the basic physical principles for the design of mobile robots, especially of differential-drive and skid-steer robots. The material in this section provides the basis to the solution of the fifth point of the robot design steps mentioned in Sect. 2.1 and the main part of the preliminary design process shown in Fig. 2, which is the selection of the actuators. Thus, the basic specifications that are obtained in steps 1–4 will be assumed to be known. The two main aspects that characterize the motion of mobile robots and land vehicles are their longitudinal motion, i.e. the motion along the driving direction, and their ability to turn, i.e. the change in heading. These two motion *modes* will be described by the so-called longitudinal motion model and the lateral or steering motion model. Both motion models are coupled, but for a preliminary design, it is possible to neglect the interaction forces. For an in-depth study of the motion models, the reader is referred to [1, 10, 21, 27, 31]. Since in general the ability of the robot to carry or pull a load is the first priority, the design must start by obtaining information about the power required to move the load in the purely longitudinal motion mode. Next, it is important to consider the lateral motion model because the location of the wheels or tracks for skid-steer robots has an effect on the robot's steering ability.

2.4.1 Longitudingal Motion and the Power Requirements

Regardless of the application details, the following data from steps 1–4 are necessary for the structural design, actuators' selection and calculating power plant requirements:

1. m: An estimate of the total mass of the robot including its actuators and the payload.
2. $\theta_{\max}$: The terrain's maximum slope angle.
3. $v : t \to v(t)$: A velocity profile that specifies the velocity of the robot v at each instant of time t. The designer should select the worst-case velocity profile, which is the one for which the robot is expected to achieve its maximum velocity in the shortest time interval required. From such specification, the largest acceleration that the robot will have to achieve can be calculated. An alternative is to directly impose a maximum acceleration value and infer the time the robot will take to achieve the maximum desired velocity. In order to facilitate computations by hand, a trapezoidal velocity profile, as shown in Fig. 7, is typically employed to obtain a gross estimate of the actuators' specifications prior to a detailed simulation. From this velocity profile, the following data can be obtained:
   - t_a, t_{cv}, t_s: the acceleration time interval $t_a = t_1$, the constant velocity time interval $t_{cv} = t_2 - t_1$ and the deceleration or stopping time interval $t_s = t_3 - t_2$.
   - $v_{\max}$: the maximum velocity.
   - $a = \frac{v_{\max}}{t_a}$: peak acceleration.

With the previous information, it is possible to obtain a gross estimate of the power that the actuators should deliver in order to move the robot. To rapidly obtain a gross estimate, it is assumed that the robot is a point mass, i.e. the masses of all the components and bodies that conform to the robot are summed up and treated as a single mass. Recalling that the kinetic energy of a body of mass m moving at speed v is given by

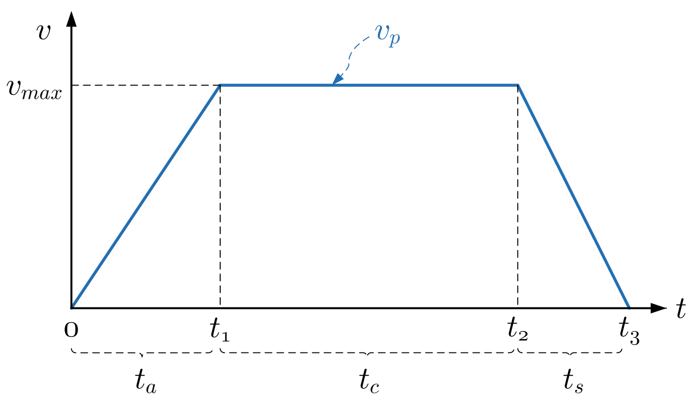


Fig. 7 Trapezoidal velocity profile

$$E_K \stackrel{def}{=} \frac{1}{2}mv^2, \tag{1}$$

while its potential energy by

$$E_P \stackrel{def}{=} mgh, \tag{2}$$

where h is the height of the body with respect to a reference level, the total energy of the body is then $E = E_K + E_P$. Recalling also that the rate at which energy is delivered is the instantaneous power, i.e. the amount of energy employed in the motion per unit of time:

$$P \stackrel{def}{=} \frac{dE}{dt} = \frac{d}{dt}\left(\frac{1}{2}mv^2 + mgh\right) \tag{3}$$

$$= mv\frac{dv}{dt} + mg\frac{dh}{dt} \tag{4}$$

$$= mva + mg\dot{h} \tag{5}$$

$$= F \cdot v + F_g\dot{h}. \tag{6}$$

In the last equations, $a = \frac{dv}{dt}$ is the acceleration (the rate at which the velocity v changes), $F = ma$ is the force that produces a change in the velocity v, $\dot{h} = \frac{dh}{dt}$ is the rate of change of the height h, g is the acceleration of gravity and $F_g = mg$ is the weight of the body, i.e. the force due to gravity. For simplicity of exposition, it will initially be assumed that the terrain is horizontal, thus the height is constant and its derivative is zero ($\dot{h} = 0$). With this assumption, $P = mva = Fv$; therefore, the computation of an estimate of the actuators' peak power can be obtained using Eq. (5) or (6) and hence requires either knowledge of the body mass m, its velocity v and acceleration a or the force acting on the body F and its velocity v. To make this clearer, let's consider the following examples: (1) a wheelchair, (2) a high-performance car and (3) a search-and-rescue robot. The specifications for each one of them are summarized in Table 1, together with the power requirements that can be estimated using Eq. (5) or (6).

If the terrain has a constant slope θ, then $\dot{h} \neq 0$, and it is necessary to consider also the energy required to move under the pull of gravity. Assuming that the robot has reached a constant longitudinal velocity v after accelerating a, the robot on an incline would have an ascent rate $\dot{h} = v\sin(\theta)$. Thus, the peak power would be

$$P = mva + mg\dot{h} = mva + mgv\sin(\theta). \tag{7}$$

Considering the search-and-rescue robot of the third example in Table 1 that could be capable of climing a slope of $\theta = 30°$, the power that the wheel motors would have to deliver increases by $mgv\sin(\theta) = 200 \cdot 9.81 \cdot 8 \cdot \sin(30°) = 7848$ W $= 10.5$ HP, so the total peak power of the motors should be $P = 9131$ W $= 12.24$ HP.

The power computed in (7) can also be obtained considering the force diagram for the mobile robot on a slope shown in Fig. 8. Neglecting the aerodynamic drag and friction forces, the main forces along the longitudinal axis of the robot are the motive force F_m and the projection of the gravity force on the longitudinal axis $mg\sin(\theta)$. The motive force F_m is produced by the motors and is equal to the motor torque multiplied by the wheel radius under the assumption of perfect traction without slippage and no viscous friction forces, i.e. $F_m = \tau_m r$, where τ_m is the motors' total torque and r is the wheels' radius. Newton's second law of motion states that the inertial force on the robot $F = ma$ is equal to the summation of all forces external forces:

$$ma = F_m - mg\sin(\theta). \tag{8}$$

Therefore, the motive force F_m that produces a net acceleration a is given by

$$F_m = ma + mg\sin(\theta). \tag{9}$$

Note that if $a = 0$, then $F_m = mg\sin(\theta)$ is the force that the motors must deliver to hold the robot fixed without rolling down the incline. The motors will have to deliver an additional force ma if the robot is required to increase its velocity with an acceleration rate a. The instantaneous power for the robot moving at a speed v under the action of the motive force F_m is $P = F_m v$. Comparing the power computed in (7) and the one computed as the product of the motive F_m expressed in (9) and the velocity v, it is possible to confirm that both approaches, one relying on energy principles that include the potential energy and the other relying on the force formulation, yield the same result as expected!

2.4.2 Lateral Motion and the Steering Ability

The forces produced by the wheels on each side of a skid-steer mobile robot are shown in Fig. 9. A difference between the total force of the left side F_l and the total force of the right side F_r makes the robot turn as shown by the torque balance equation:

$$J_r\alpha = \underbrace{F_r\frac{w}{2} - F_l\frac{w}{2}}_{\tau} - \tau_f, \tag{10}$$

where J_r is the moment of inertia of the robot about its center of mass (the origin of coordinate frame formed by axes $\mathbf{x}^r$ and $\mathbf{y}^r$), α is the angular acceleration, w and b are, respectively, the width and length of the robot and τ_f is the friction force caused by the lateral skid that arises due to the fact that the wheels' velocity and forces are not tangent to the curved trajectory that the robot is following, unlike a car with the Ackermann steering. The analysis of the friction and traction forces and their effects

Table 1 Examples of power estimation

Example	Specifications	Estimated Power
Wheelchair: An electric wheelchair must carry a person and some extra load that the person might carry, such as backpack. The average weight of a male adult is about 80 kg, and a carry-on luggage is typically less than 20 kg. The weight of the chair should also be included. If the chair is portable, the whole system should not weight more than 50 kg. Therefore the total weight including the person, should not exceed 150 kg. The wheelchair must gently accelerate and achieve a maximum speed that is similar or slightly higher than the standard walking speed. The average walking speed is 1.4 m/s, but it is desirable to have a chair that can move a bit faster at 2 m/s. In order to avoid sudden and strong accelerations that may cause the rider of the chair to feel uncomfortable, assume that the maximum speed will be achieved in 2 s.	$m = 150$ kg $v = 2$ m/s $t = 2$ s	$a = \frac{v}{t} = \frac{2}{2}$ $= 1\ \text{m/s}^2$ $= ma = 150 \cdot 1$ $= 150$ N $P = Fv = 150 \cdot 2$ $= 300$ W $= 0.4$ HP
High performance car: Consider a roadster that weighs 1,200 kg and accelerates from 0 to 100 km/h in 4 s.	$m = 1,200$ kg $v = 100$ km/h $= 27.78$ m/s $t = 4$ s	$a = \frac{v}{t} = \frac{27.78}{4}$ $= 6.94\ \text{m/s}^2$ $F = ma = 1,200 \cdot 6.94$ $= 8333.3$ N $P = Fv = 8333.3 \cdot 27.78$ $= 231.5$ kW $= 310$ HP
Search-and-rescue robot: Consider a robot that weighs 50 kg and has a payload capacity of 150 kg. Assume also that the robot should be able to move at a maximum speed of 8 m/s and achieve the maximum speed in 10 s.	$m = 50 + 150$ $= 200$ kg $v = 8$ m/s $t = 10$ s	$a = \frac{v}{t} = \frac{8}{10}$ $= 0.8\ \text{m/s}^2$ $F = ma = 200 \cdot 0.8$ $= 160$ N $P = Fv = 160 \cdot 8$ $= 1280$ W $= 1.72$ HP

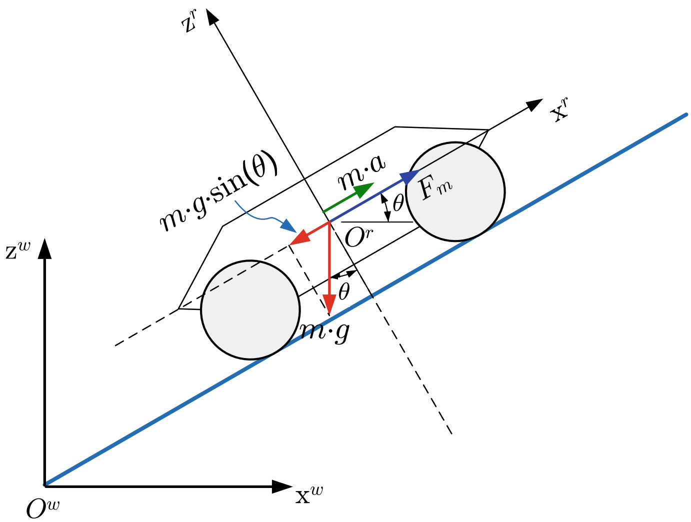


Fig. 8 Forces acting on the mobile robot on a slope

on the motion of skid-steer platforms can be found in more detail in [12, 17, 31]. For a preliminary design, the simplest assumption is to consider that these lateral forces are constant and they correspond to the static friction μN equally distributed among all the wheels or contact points of the threads, as shown in Fig. 9. Here $N = mg\cos(\theta)$ is the normal force produced by a terrain with slope θ as a reaction to the robot's weight. The static friction force μN only appears as a reaction when the object is displaced by an external force, such as the turning force τ produced by the wheels of the robot.

From Eq. (10), it is possible to see that if $F_l = F_r$, then the turning torque $\tau = 0$ and the robot does not turn. The friction torque τ_f only appears as a reaction when the heading rate of change or the torque τ are non-zero. Otherwise, the reaction forces are not generated. Hence, the robot turns left when $F_r > F_l$ or right when $F_l > F_r$. However, the turning capacity of the robot is reduced by the lateral skidding forces that generate the torque τ_f. The lateral forces can appear in any direction depending on the radius of curvature. The most demanding situation is when the robot turns in place, and therefore, the friction forces are tangent to the dotted circle shown in Fig. 9. In this situation, the total friction torque τ_f is given by

$$\tau_f = \sqrt{\left(\frac{b}{2}\right)^2 + \left(\frac{w}{2}\right)^2}\mu N. \tag{11}$$

The previous expression together with (10) provide some insight into some important design considerations for skid-steer robots:

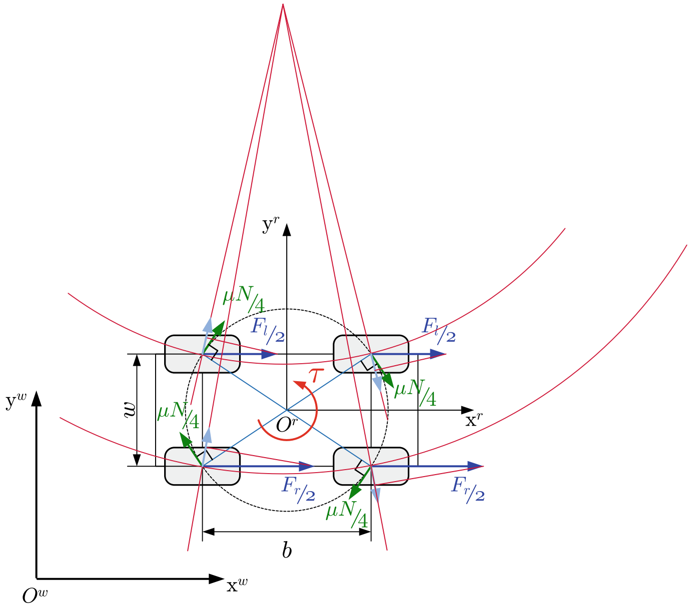


Fig. 9 Turning forces of a skid-steer robot

1. Thehe effect of the opposing skidding forces generating τ_f will be larger when the robot is bigger because the moment arm $\sqrt{\left(\frac{b}{2}\right)^2 + \left(\frac{w}{2}\right)^2}$ increases.
2. A larger width w for a given length b is better because this increases the effect of the forces F_l and F_r on the turning maneuver.
3. The ratio τ/τ_f between the effective turning torque and the skidding torque when $w \to \infty$ is in the limit:

$$\lim_{w\to\infty} \frac{\tau}{\tau_f} = \frac{\frac{w}{2}(F_r - F_l)}{\sqrt{\left(\frac{b}{2}\right)^2 + \left(\frac{w}{2}\right)^2}\mu N} = \frac{F_r - F_l}{\mu N}. \tag{12}$$

If $b \to \infty$, it is possible to see that the ratio τ/τ_f tends to zero, which is not ideal. So it is better to have a wider than a longer robot, as long as there are no lateral clearance restrictions, e.g. when the robot's width is limited because it has to pass through doors and narrow spaces. The previous ratio must satisfy $\tau/\tau_f > 1$ for the robot to be able to turn. This gives an additional power and force requirement for the actuators. Assuming $w >> b$, a rule of thumb when $F_l = -F_r$ is to have actuators capable of producing a force $F_r > \frac{\mu N}{2}$. The requirement that $\tau/\tau_f > 1$ with $F_l = -F_r$ implies that

$$\frac{\tau}{\tau_f} > 1 \Rightarrow F_r > \frac{\mu N}{2}\sqrt{\left(\frac{b}{w}\right)^2 + 1}. \tag{13}$$

The last equation shows that the ideal configuration would be the one for which $b = 0$ and $w = \infty$ as this would require the smallest force to turn the robot, i.e. as the skid-steer approaches a differential-drive robot, a smaller effort to make it turn will be required. It is to be noted that (13) provides the minimum condition to make the robot be able to turn and ensure that it can generate some turning acceleration $\alpha > 0$. However, the largest turning force a skid-steer robot will require occurs for the pure rotation ($F_l = -F_r$) with the additional requirement of complying with some specified angular acceleration α, which by Eq. (10) is

$$F_r = \frac{\mu N}{2}\sqrt{\left(\frac{b}{w}\right)^2 + 1} + \frac{J_r \alpha}{w}. \tag{14}$$

If the robot is of the skid-steer type, the total torque delivered by the motor(s) on the left or right side must be at least

$$\tau_{\min} \geq \min\left(r F_m/2,\ r F_r\right), \tag{15}$$

where r is the wheel radius and F_m and F_r are obtained from Eqs. (9) and (14), respectively. If the robot is a two-wheeled differential-drive robot, the friction does not affect the turning for wheels rolling without skidding, and the minimum torque of the chosen motors will have to satisfy

$$\tau_{\min} \geq \min\left(r F_m/2,\ r J_r \alpha/w\right). \tag{16}$$

From the previous condition, it is evident that making w as large as possible is convenient to reduce the turning torque required. However, the opposite conclusion can be drawn from the kinematic model of a differential-drive or skid-steer robot (when slippage is neglected):

$$v = \frac{\dot{\phi}_r r + \dot{\phi}_l r}{2}, \tag{17}$$

$$\dot{\psi} = \frac{\dot{\phi}_r r - \dot{\phi}_l r}{w}, \tag{18}$$

where $\dot{\phi}_r$ and $\dot{\phi}_l$ are the right and left driving wheel angular velocities. Considering Eq. (18), for motors that have a maximum rotational velocity $\dot{\phi}_{\max}$, the heading angular velocity $\dot{\psi}$ is maximized when $w = 0$. Therefore, there is a trade-off between minimizing the torque required to turn the robot and maximizing the turning velocity. This should become obvious when recalling that for a real system the power is limited to some value $P_{\max}$ and the instantaneous power for an in-place turn must satisfy $\tau\dot{\psi} < P_{\max}$. Hence, τ and $\dot{\psi}$ cannot be made arbitrarily large simultaneously without exceeding the maximum power constraint. Finally, it is to be noted that (15) and (16) provide gross estimates of the motor torques required for the worst-case situations.

A more detailed analysis through simulations would be required in order to optimize the motors' selection as briefly discussed in the next subsection.

2.5 Other Design Considerations

The implementation of a mobile robot must also consider the selection of adequate mechanical transmissions, the efficiency of the components, the use of bearings as an element to reduce efficiency losses due to friction and improve the structural integrity of the robot, overturning and stability conditions, controllability issues, as well as some aspects of rapid robot prototyping. All these aspects are discussed in this section to provide some insight into basic aspects that are often neglected, but that are important in a well-thought-out design.

2.5.1 Mechanical Transmission

In Sect. 2.4, all the power calculations were made as $P_{\text{out}} = F_{\text{out}} v_{\text{out}}$ considering the mechanical output of the robot using the values of the output force F_{out} and velocity v_{out} that the robot is expected to achieve in order to compute the robot's power supply requirements and motors' nominal power specifications. Calculations using output values are sometimes referred to as computations on the "load side". In the selection of the motors for a robot, the power delivered by the motor to the load must be equal to the power required by the load plus the mechanical power losses. For simplicity of exposition, let us assume the system has no power losses, then the motor must simply deliver an amount of power that is equal to the power required by the load. Denoting by P_{in} the power delivered by the motor, i.e. the mechanical input power supplied to the wheels or joints of the robot, then it would be necessary to select a motor that satisfies $P_{\text{in}} = P_{\text{out}}$. However, electric or combustion motors of a given power P_{in} typically rotate with a velocity ω_{in} and a torque τ_{in} that do not match the output angular velocity ω_{out} and output torque τ_{out}. To match the speed and torque requirements of the load, mechanical transmissions are required to convert the speed and torque of the motor. There exist different types of drive mechanisms whose main features are summarized in Table 2. Some examples of mechanical drives commonly employed in robotics are shown in Fig. 10. In general robot designers prefer stacked planetary gear transmissions or single-stage harmonic drives because of their compact, high-reduction, high-efficiency and low backlash characteristics [23].

The designer of the robot must always select an adequate transmission carefully not only because of the necessity of matching the motor (input) to the load (output) speed and torque specifications, but also to avoid damaging the motor if the transmission is undersized. For most applications, electric motors have a starting torque, i.e. the maximum torque that the motor can produce to start a rotational movement that is lower than the torque required by the load to start rotating. Depending on the

Table 2 Mechanical transmission summary

Name	Gear ratio N	Efficiency [%]	Advantages	Drawbacks
Input-Output Circular-Circular				
Spur gear	1–20	94–98	High torque	Backlash, noisy
Helical gear	1–20	94–98	High torque, lower backlash and noise, can change axles orientation by 90°	Require bearings
Bevel gear	1–5	94–98	Can change axles orientation by 90°	Backlash, noisy
Hypoid gear	10–200	80–95	Can change axles orientation by 90° with non-coplanar axes	
Epicyclic or planetary gears	10–100	90–99	High power density, low backlash, compact	Manufacturing complexity, lubrication
Worm gear and pinion	20–300	30–50	Not back-driveable, self-locking	Friction
Timing belt and pulley	1–10	90–98	Long distances between axles, low backlash	–
Roller chain and sprocket	1–10	90–98	Long distances between axles	Noisy
Bar linkages	1–5	90–95	–	Limited displacement
Cable drive	1–5	90–96	Long distances between axles	Deformation
Harmonic drive	30–320	70–90	No backlash, high gear ratio, high power density, extremely compact	Limited torque
Cyclo drive	3–119 (1-stage)	92–94	Low backlash,	Typically not back-
	10^6 (3-stages)	83–86	high gear ratio	drivable, vibrations
Input-Output Circular-Linear				
Leadscrew	–	20–50	Low backlash	Moderate Friction
Ballscrew	–	85–90	Low backlash	Low friction
Cam	–	75–90	Low backlash	Low friction
Rack and pinion	–	75–98	Moderate backlash	Friction
Input-Output Linear-Circular				
Crank-slider	–	75–85	–	Locking positions
Rack and pinion	–	75–98	Moderate backlash	Friction

application, the maximum torque when the rotational speed is zero is called stall torque or holding torque. The stall torque can be interpreted as the torque that must be applied by the external load to cause the motor stop rotating. When the peak torque is produced, the motor consumes the largest current that can flow through it given its winding resistance. This makes the motor windings to heat more due to the Joule-Lenz law, which states that the heating power of an electrical conductor

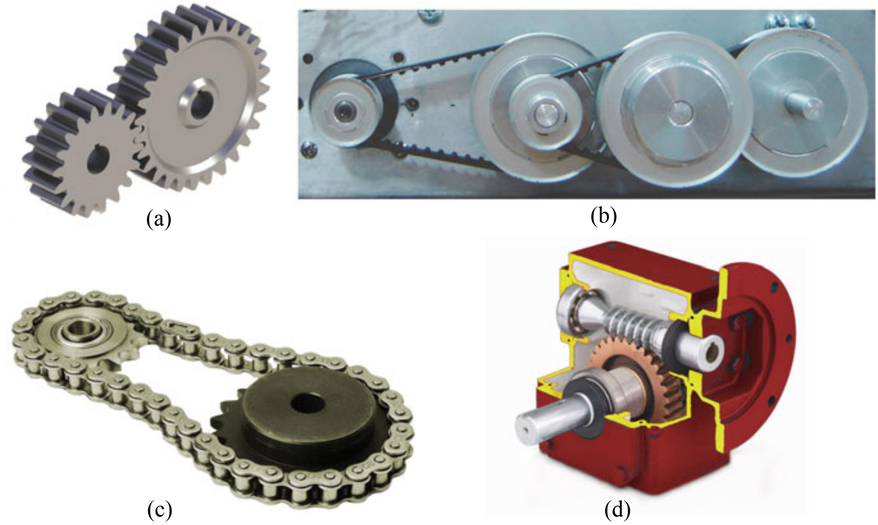


Fig. 10 Examples of drive mechanisms typically employed in robotics: **a** spur gears, **b** timing pulleys and belt, **c** sprocket and chain and **d** worm gear

is proportional to the squared current times the wire resistance. The heating for a few seconds can be enough to burn the insulating enamel or varnish of most electrical motors. The loss of insulation between wire loops produces a short circuit that decreases resistance further thus increasing the current until the wire melts. Hence, a correctly selected mechanical transmission is necessary to ensure the right torque is delivered to the load without stalling the motor and avoid damaging its windings.

For the different types of mechanical transmissions, e.g. gear trains, chain and sprockets, timing belts and pulleys and worm gears, it is possible to find a relation between the input and output velocity of the form:

$$N = \frac{\omega_{\text{in}}}{\omega_{\text{out}}},$$

where N is known as gear ratio or speed ratio. Often gearboxes are speed reducers, i.e. $\omega_{\text{in}} > \omega_{\text{out}}$ and $N > 1$. The gear ratio is written as $N : 1$, which can be read as one turn of the output requires N turns of the input. The power conservation in an ideal mechanical transmission requires that the speed reduction is compensated by an output torque increase:

$$\begin{aligned} P_{\text{out}} &= P_{\text{in}} \Rightarrow \tau_{\text{out}}\omega_{\text{out}} = \tau_{\text{in}}\omega_{\text{in}}, \\ \tau_{\text{out}} &= \frac{\omega_{\text{in}}}{\omega_{\text{out}}}\tau_{\text{in}}, \\ \tau_{\text{out}} &= N\tau_{\text{in}}. \end{aligned}$$

From the above equations, it is clear that for $N > 1$, the output speed is a reduction of the input speed $\omega_{\text{out}} = N^{-1}\omega_{\text{in}}$, while the output torque is an amplification of the input torque $\tau_{\text{out}} = N\tau_{\text{in}}$, and hence $P_{\text{out}} = \tau_{\text{out}}\omega_{\text{out}} = N\tau_{\text{in}}N^{-1}\omega_{\text{in}} = \tau_i\omega_{\text{in}} = P_{\text{in}}$. In a real mechanical transmission, power is lost due to diverse causes, such as friction, mechanical deformation, backlash and impact losses, thus $P_{\text{out}} < P_{\text{in}}$ for real systems. Some considerations on efficiency are discussed in the next Sect. 2.5.2.

2.5.2 Electrical and Mechanical Efficiency

In the design of a robot through rapid virtual and physical prototyping, power losses in the different stages should not be neglected. Considering the main hardware components discussed in Sect. 2.3 and shown in Fig. 4, it is possible to observe that the power supply must be able to provide not only mechanical power output $P_{\text{out}} = \tau_{\text{out}}\omega_{\text{out}}$, but also the energy consumed or lost in each stage.

The efficiency of a device, be it electrical or mechanical, is defined as the ratio between the power delivered by the device available as useful power and the total input power:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}.$$

In an ideal system, $P_{\text{out}} = P_{\text{in}}$, and therefore, $\eta = 1$, but in a real system, $0 < P_{\text{out}} < P_{\text{in}}$, and hence, $0 < \eta < 1$. For a device with efficiency η, an application with a specified output power P_{out} will require an input power $P_{\text{in}} = P_{\text{out}}/\eta$.

The power losses are equal to the difference between the input and the output power:

$$P_{loss} = P_{\text{in}} - P_{\text{out}} \;=\; P_{\text{in}} - \eta P_{\text{in}} \;=\; (1-\eta)P_{\text{in}}.$$

Considering the typical efficiencies of the main stages, the net efficiency η_{net} for a battery or fuel-powered system can be calculated as the multiplication of the efficiency of each stage as summarized in Table 3.

2.5.3 Bearings

Bearings are essential mechanical elements to reduce friction between moving parts and constrain their relative motion either to pure rotation about a fixed axis or translation along an axis. Often texts and information on the Internet about robot prototypes do not include information about bearings. In fact, many designs do not employ bearings or rely on the motor's internal bearings. Many robots built by hobbyists that use RC servos (servomotors for radio control) fall into this category, and since these robots are relatively small, they are able to work without additional bearings. However, this basic element can make a tremendous difference in a robot's performance

Table 3 Stage and net efficiency for battery- and fuel-powered mobile robots

Stage efficiency	Battery-powered	Fuel-powered
Motor η_{motor}	Electric motor η_{em}: • Brushless DC motor η_{bldc}: 90–96% • Brushed DC motor η_{bdc}: 75–85% • Induction motor η_{ind}: 88–94%	Internal combustion engine η_{ic}: 25–35%
Mechanical drive η_{md}	85–95%	85–95%
Electronic drive η_{ed}	94–98%	–
Net efficiency η_{net}	$\eta_{net} = \eta_{motor}\eta_{md}\eta_{ed} = 60-90\%$	$\eta_{net} = \eta_{motor}\eta_{md} = 21-33\%$

as bearings ensure that the motors find less rolling resistance and that they are not subject to excessive radial and axial loads that could damage them. In summary, the recommendation is to not overlook bearings as they improve structural strength and mechanical efficiency by reducing friction. The designer should always try to include bearings in the prototype, even in small robots that could be built using RC servos.

There exist various types of bearings. The most widely used bearings in mobile robots are plain bearings and rolling element bearings. Plain bearings are often referred to as bushings or bearing sleeves. These only have a bearing surface and do not have rolling elements. Thus, they are the cheapest and have a high-load carrying capacity, but have from two to ten times more friction than rolling element bearings and may suffer from stiction. On the other hand, rolling element bearings are more expensive and complex to manufacture, but have considerably less friction. Hence, rolling element bearings are significantly better for large moment loads. The family of rolling element bearings can be divided into two main types: (a) ball bearings and (b) roller bearings. Common ball bearing designs are the angular contact, the axial and the deep-groove radial bearing. In turn, roller bearings can be classified into different types according to the shape of the rolling element: cylindrical, spherical, tapered cone, needle and gear rollers. Figure 11 shows the main types of bearings. If the bearings are configured to support purely axial loads, then the bearings are called *thrust bearings* and can be built with rolling balls or spherical, cylindrical or tapered rollers as shown in Fig. 11c. Unlike most roller bearings that support radial or axial loads, tapered roller bearings support both radial and axial loads and can carry higher loads than ball bearings of the same size due to their greater contact area. However, due to their manufacturing complexity, tapered roller bearings are significantly more expensive than ball bearings. An economic alternative that can accommodate both radial and axial loads are the double-row angular contact bearings shown in Fig. 12. The capacity of double-row angular contact bearings to hold combined axial and

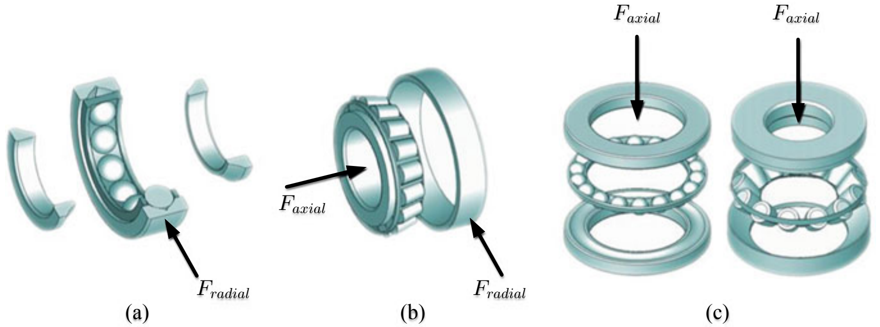


Fig. 11 Types of rolling contact bearings: **a** ball, **b** tapered roller and **c** ball and spherical roller thrust bearings

Fig. 12 Double row angular contact ball bearings

radial loads makes them a convenient bearing for the wheels axles in mobile robots as well the joints of robot arms.

2.5.4 Wheel Clearance, Overturning and Stability

Wheel clearance is important especially for robots that are intended to be operated outdoors on rubble and uneven terrain. The slopes that might be encountered must be also considered in the weight distribution of the internal components of the robot. Figure 13 illustrates these aspects. Overturning can occur either because the robot steps on some obstacles like a stone (see Fig. 13b), or the terrain slope is such that the angle α of the line that connects the left-most contact point with the center of mass (COM) and the horizontal axis exceeds 90° (see Fig. 13c), since the turning moment about the left-most contact point is $M_T = r\cos(\alpha)mg < 0$, when $\alpha > 90°$. If the robot width is w, the COM height is h and the terrain slope is θ, then $\alpha = \theta + \arctan(2h/w) < 90°$ implies that $\theta < 90° - \arctan(2h/w)$. Assuming that the robot has enough traction in order to hold its position without skidding on the slope or ramp, the design should optimize the weight distribution of the components inside the robot in such a way that minimizes h and maximizes w so that $\arctan(2h/w)$ is

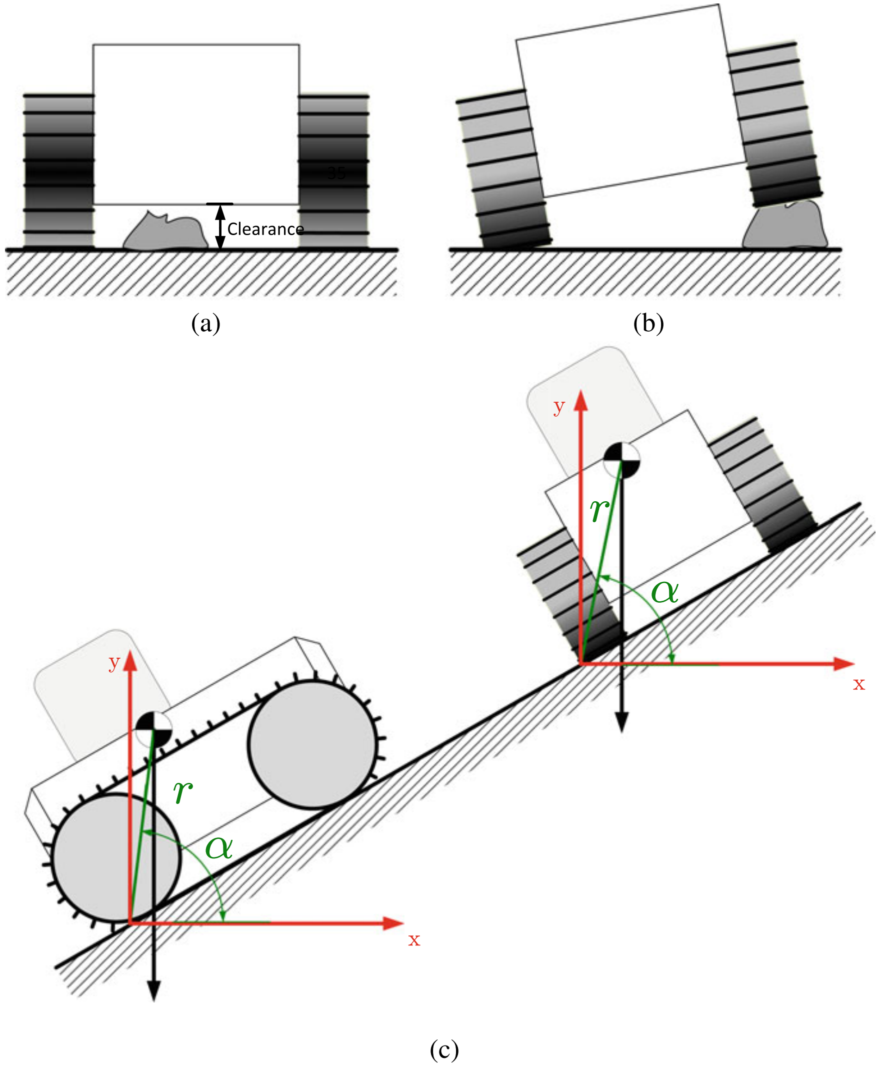


Fig. 13 Wheel clearance, overturning and stability of a mobile robot

reduced ideally to 0°. In practice $h > 0$ because of the wheel clearance constraints and the robot's width w must be smaller than a certain value $w_{\max}$, i.e. $w < w_{\max}$, in order for the robot to be able to drive across doors or passages of a specified width $w_{\max}$. It is to be noted that overturning and stability conditions can change significantly for mobile manipulator robots operating in uneven terrains with large loads depending on the arm position. Therefore, a careful design should take into account dynamic variations of the COM's position.

2.5.5 Controllability

The controllability of differential-drive and car-like mobile robots has extensively been studied in [7, 13, 14, 19] and references therein. In fact, the work in [13] shows the non-holonomic constraints of the car-like robot allow global controllability in the configuration space despite they reduce the instantaneous motions the robot can perform. The first-order kinematic model of the car-like robot satisfies the Lie algebra rank condition as long as the steering angle $\psi \neq \pm\frac{\pi}{2}$, and thus is controllable to a point everywhere in the configuration space, although it fails to satisfy Brockett's condition for smooth feedback stabilizability, i.e. the controllers stabilizing the robot to a point in the configuration space must be sought in the class of nonsmooth and/or time-varying feedback control laws; see [13] for further details. On the other hand, the car-like robot is also controllable to a trajectory and can be locally stabilized as may be proved by linearizing the system about a reference trajectory and verifying the controllability Gramian is nonsingular as shown in [13]. By relating the kinematic model of the differential-drive robot to that of the unicycle through a transformation of the input signals, similar techniques to those in [13] can be employed to show that the differential-drive robot is controllable to a point and about a trajectory [14]. The corresponding dynamic models inherit the structural properties of the kinematic models, in particular they can be shown to be small-time locally controllable [7].

2.5.6 Remarks on Rapid Construction of Low-Cost Robot Prototypes

An example that illustrates the design of a skid-steer robot prototype for quick and low-cost implementation is presented in Sect. 3. As mentioned in the fourth point of the basic design rules presented in the introduction, a good design borrows ideas from other successful designs. This saves time, helps to avoid mistakes and facilitates the process of learning to make better designs. Becoming a good designer is not just a matter of knowing all the concepts and theories behind, but also a matter of practical experience and skills. Therefore, studying other designs can help a lot to improve new designs and their implementation as prototypes. On the other hand, even if each prototype may have very specific and different requirements, all mobile robot designs always have to make choices about which control hardware and software should be used in the implementation of the prototype. There is no unique answer as to which is the best option, since the choice is often constrained by the prototype specifications. However, if the prototype has to be implemented quickly and at a low cost, there are some options that may come up first on the list in many situations. Some hardware and software suggestions are briefly discussed next.

It is possible to find different situations in which implementing a robot prototype quickly and at a low cost is often desired or necessary. The rapid development of low-cost mobile robot prototypes is not restricted to educational needs or the hobbyist world. Sometimes a low-cost prototype is required in addition to software simulations to validate physical aspects that cannot be fully captured by the simulation. When the rapid implementation and low cost are part of the design constraints, some design specifications and requirements of the final product can be sacrificed, typically physical ruggedness, software robustness and aesthetical aspects. Instead of an industrial- or military-grade computer, the designer may employ many alternatives available today for implementing embedded systems, such as TI MSP430, Arduino, ESP32, Raspberry Pi, BeagleBone, Gumstix, Intel Edison, Intel Galileo, Gizmo 2, PC104s and their variants. Some of these computing platforms run Linux or Windows operating systems. Some may be gone in ten years from now, and some others have already lost the popularity they had with the recent rise of open platforms like the Arduino project. In fact, in the late 90s, the PIC microcontrollers by Microchip started to gain popularity, and development systems based on these microcontrollers, such as the OOPic and Basic Stamp, were common platforms for rapid prototyping. Now their popularity has declined, but it is not clear for how long the existing technologies will hold their popularity in the rapidly evolving market of electronics and embedded systems.

If cost, ease and speed of implementation, flexibility, simplicity and availability of electronic interfaces that can be quickly integrated are the main criteria in the design and construction of the robot prototype, a good option is the Arduino Due as embedded computer to centralize the low-level control electronics. In other words, the Arduino Due can handle all the tasks grouped under the "control electronics" block in the hardware architecture diagram of Fig. 4 that are related to reading encoder signals, sending signals to the motor drives and receiving high-level motion commands from a radio controller or computer. Higher complexity functions can be implemented in a portable laptop computer, using languages such as Python. Both Arduino and Python share similar principles in their design philosophies which make them good choices for rapid prototyping. Some notable aspects of their design philosophies are that both aim at achieving results quickly and rely on the support and contributions of the community, thus they were made open in order to facilitate the implementation of new functionalities. Moreover, to achieve results quickly, Arduino and Python were made easy to learn and use. All the difficult details about electronics integration and software programming were hidden and solved in such a way that the user does not have to be an expert in electronics and programming to have a working system in a few hours. Additionally, access to low-level implementation details and "looking under the hood" is allowed, thus more advanced users can implement specific customizations. In summary, the outstanding features of Arduino on the hardware side and of Python on the software side are that they are simple to learn and use, modular, scalable, open and low cost. They are not optimized for performance or safety-critical applications, and therefore, if these aspects are fundamental requirements of the prototype, then Arduino and Python may not be the best choice. However, for most purposes, the initial prototype may sacrifice performance and robustness and leave optimizations and perfection for later pre-production prototype.

Finally, since hardware and software continuously evolve, it is a good idea to periodically check the Internet for comparisons and trends of the different single board computers and software development tools and languages. Some readers, for example, may prefer to devote more time to learning other prototyping systems such as Raspberry PI that may allow the implementation of prototypes that do not require an external PC as just suggested. However, in the case of robotics, the implementation of perception and high-level reasoning algorithms that endow the robot with some autonomy skills requires more computational power to support the algorithmic complexity that cannot be handled in real time by smaller single board computers due to speed or memory limitations.

2.6 Effects of Design Choices on Robot Performance

The longitudinal motion model given in Eq. (8) of Sect. 2.4.1 can be applied to differential-drive robots. Assuming the body mass is M, the left and right wheels' mass is m and that the wheels' angular velocity satisfies $\dot{\phi} = \mathsf{N}\dot{\phi}_m$. Here $\mathsf{N} = 1/N$ is the inverse off the gear ratio $N : 1$, the motors' angular velocity (input to the gearbox) is $\omega_{\text{in}} = \dot{\phi}_m$ and the wheels' angular velocity (output of the gearbox) is $\omega_{\text{out}} = \dot{\phi}$. Each wheel is modeled as disc of radius R with inertia moment:

$$J_o = \int_{p \in V} d(p, o)^2 \, dm \; = \; \int_0^R \int_0^{2\pi} r^2 \frac{m}{\pi R^2} r d\varphi dr \; = \; \frac{1}{2} m R^2.$$

Assuming the wheels roll without slipping, the kinetic energy of the robot with longitudinal velocity $v = R\dot{\phi}$ is given by

$$E_k = \frac{1}{2} M v^2 + \frac{1}{2} J_o \dot{\phi}^2 + \frac{1}{2} J_o \dot{\phi}^2 \; = \; \frac{1}{2}(M + m) R^2 \dot{\phi}^2,$$

while the potential energy can be assumed to be $E_P = 0$ for a robot moving on a surface with a slope angle $\theta = 0$. The Lagrangean in terms of the configuration variable $q = \phi$ and $\dot{q} = \dot{\phi}$ is the given by

$$L(\phi, \dot{\phi}) = E_K - E_P \; = \; \frac{1}{2}(M + m) R^2 \dot{\phi}^2.$$

Applying Lagrange's Principle, which states

$$\frac{d}{dt} \frac{\partial L(q, \dot{q})}{\partial \dot{q}} - \frac{\partial L(q, \dot{q})}{\partial q} = F_q,$$

it is possible to obtain the longitudinal motion equation:

$$(M + m) R^2 \frac{d\dot{\phi}}{dt} = \tau_{net}, \tag{19}$$

where τ_{net} is the net torque acting on the wheels. The torque τ_{net} is given by

$$\tau_{net} = 2\eta_{md} \tau_{bdc} \mathsf{N}^{-1} - 2\eta_{md} \tau_{fr} \mathsf{N}^{-1} - R F_{drag},$$

where $\tau_{bdc} = G_0 i_a$ is the brushed DC motor torque, G_0 is the torque constant, i_a is the armature current, η_{md} is the efficiency of the gearbox, $\tau_f = k_{fr}\dot{\phi}\mathsf{N}^{-1}$ is the motor's internal viscous friction, k_{fr} is the motor friction coefficient, $F_{drag} = k_d\dot{\phi}R$ is the aerodynamic drag force acting on the robot and k_d is the aerodynamic coefficient. On the othe hand, the brushed DC motor equation that relates the armature current i_a with the applied voltage V_a, is given by

$$L_a \frac{di_a}{dt} = V_a - G_0\mathsf{N}^{-1}\dot{\phi} - R_a i_a. \tag{20}$$

Equations (19) and (20) define the longitudinal motion dynamics of a simple two-wheeled differential-drive robot. The same model can be employed to describe the longitudinal dynamics of a skid-steer robot. The equations can be solved using numerical integration tools. An implementation of the equations in terms of block diagram using Matlab's Simulink® is shown in Fig. 14. The simulation of the model is a useful tool to find optimal design parameters, such as the optimal wheel radius R and the optimal gear ratio $N = \mathsf{N}^{-1}$. The simulation also allows to study the effects of parameter variations on the behavior of the robot, for example, to analyze the response of the robot designed to carry a certain load, when the load is changed, or analyze the motor currents when the robot gets stack against an obstacle and a blocked rotor condition occurs.

Simulation can save the time spent in trial and error redesign efforts and avoid errors derived from intuitive arguments that miss the underlying physics and lead to wrong conclusions. For example, if the objective is to maximize the speed of the robot, a purely kinematic reasoning would indicate that N should be larger than unity in order to amplify the motors' angular velocity and that the wheels' radius R should be as large as possible so that the longitudinal velocity $v = \dot{\phi}R$ is maximized. However, choosing $\mathsf{N} > 1$ causes an output torque $\tau_{\text{out}} < \tau_{\text{in}}$, and as the wheels' radius R increases, the wheels' inertia moment J_0 increases as well. Therefore, the ability of the robot to accelerate decreases as apparent from Eq. (19). On the other hand, if $\mathsf{N} << 1$, the motors' output torque $\tau_{\text{out}} >> \tau_{\text{in}}$, i.e. the robot will have a large driving torque, but the final velocity will be reduced significantly. For example, if the objective is to maximize the distance traveled in 10 s, there is an optimal gear ratio N and an optimal wheel radius for a 0.5 kg robot. The results for varying gear ratios $\mathsf{N} = \{1/20, 1/80, 1/160\}$ presented in Fig. 15 show in figure (c) that the gear ratio $\mathsf{N} = 1/80$ allows the robot to travel a distance of 1.4 m in 10 s, while the robot with $\mathsf{N} = 1/20$ only travels about 0.6 m and the robot with $\mathsf{N} = 1/160$ travels 1 m in the same period of time. This happens because the larger gear ratio $\mathsf{N} = 1/160$ results in a smaller final velocity as can be seen in Fig. 15f, despite the larger starting torque shown in Fig. 15b. On the other hand, the smaller gear ratio $\mathsf{N} = 1/20$ produces a smaller starting toque (see Fig. 15b), and despite the attainable final velocity in steady state is large, the smaller acceleration shown in Fig. 15b makes the robot take more than 10 s to achieve the larger steady-state velocity. The choice of such a small gear ratio is inadequate for a robot that must operate quickly in a confined space in which

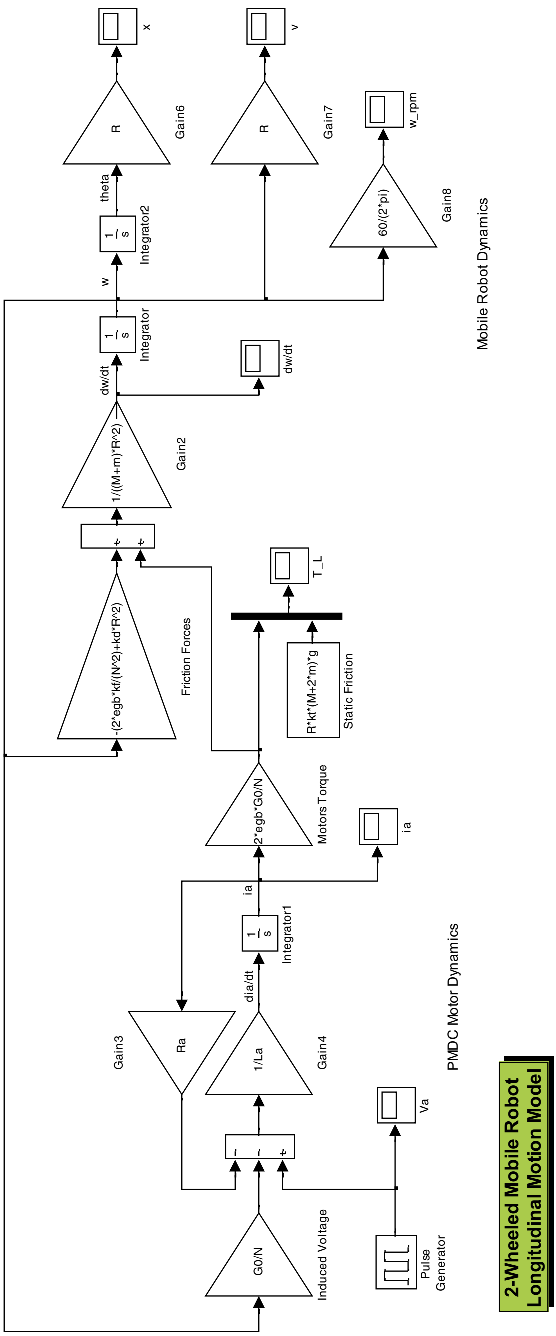


Fig. 14 Block diagram of the longitudinal motion model

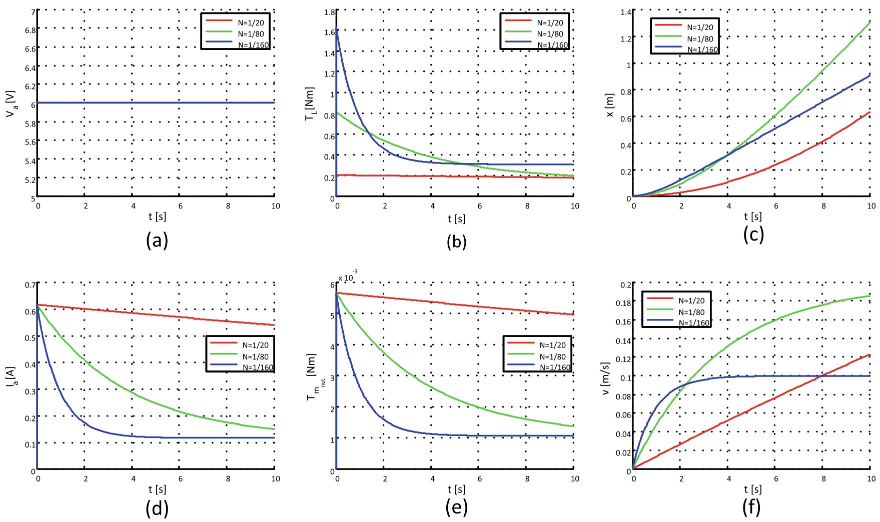


Fig. 15 Robot longitudinal response with different gear ratios [$N = 20 : 1, 80 : 1, 160 : 1$]: **a** applied motor voltage, **b** torque at the load side (wheels), **c** robot's position, **d** motor current, **e** motor torque and **f** robot's velocity

it does not have enough distance ahead to continue accelerating until the steady-state velocity is reached.

Similarly, the response of the robot with different wheel radius $R = \{1, 3, 25\}$ cm is presented in Fig. 16. Once again it is possible to observe in Fig. 16c that the optimal displacement in 10 s is achieved when the wheel radius is $R = 3$ cm. A smaller wheel radius produces a smaller tangential speed for a given angular velocity (see Fig. 16b), while a larger wheel radius increases the wheels' inertia and a reduced tangential force for a given torque because $F_{net} = \tau_{net}/R$, thus reducing the net longitudinal acceleration of the robot as can be seen from the smaller slope of the velocity curve for $R = 25$ cm in Fig. 16f.

Finally, variations of the robot's displacement and acceleration in 10 s for different robot loads are shown in Fig. 17. As expected, larger masses reduce the robot's net acceleration for the same applied motor voltage V_a. The selection of the appropriate motors for the robot must consider the robot's payload in order to meet displacement and attainable speed specifications in a given time period.

3 Design and Implementation of Mobile Robot Prototypes: *the R1 Skid-Steer Robot*

In this section, all the design concepts discussed in previous sections are employed in the design of the *R1 skid-steer robot* shown in Fig. 18, whose purpose is to serve as a

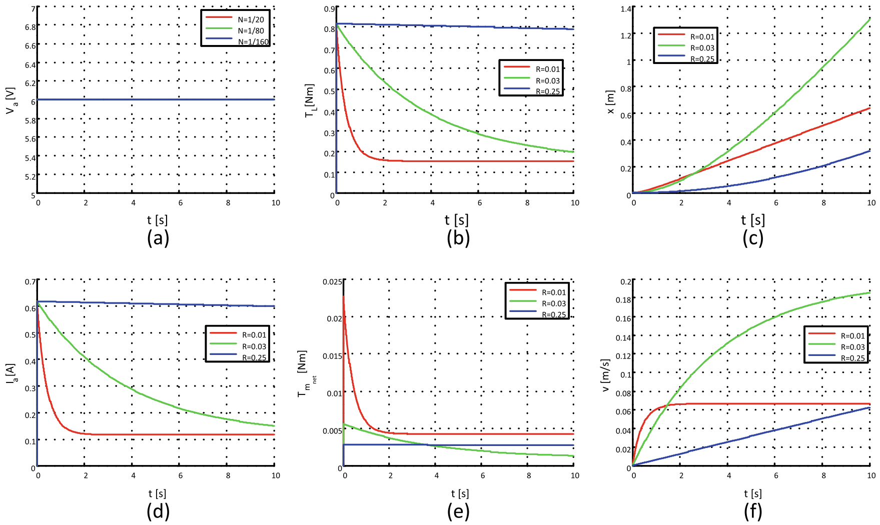


Fig. 16 Robot longitudinal response with different wheel radius [$R = 1, 3, 25$ cm]: **a** applied motor voltage, **b** torque at the load side (wheels), **c** robot's position, **d** motor current, **e** motor torque and **f** robot's velocity

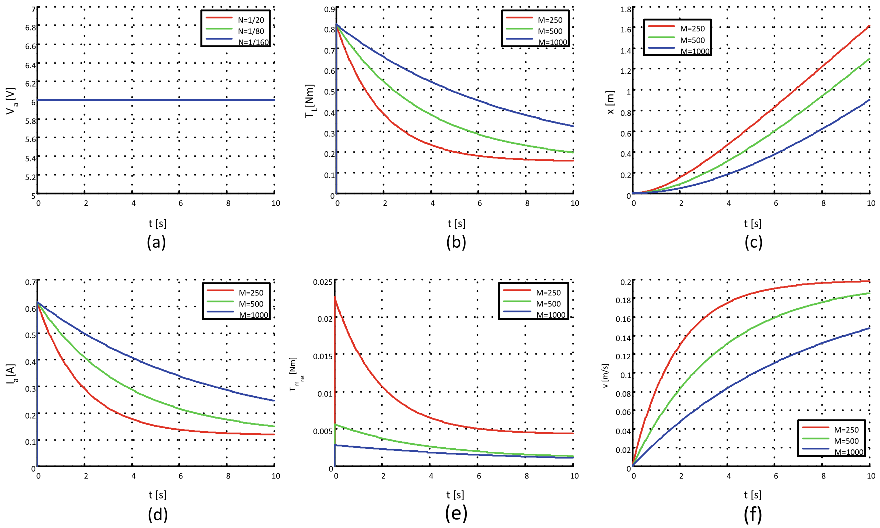


Fig. 17 Robot longitudinal response with different payloads [$m = 0.25, 0.5, 1.0$ kg]: **a** applied motor voltage, **b** torque at the load side (wheels), **c** robot's position, **d** motor current, **e** motor torque and **f** robot's velocity

mobile base for research on mobile manipulators operating in harsh environments in such applications as mining, search and rescue and agricultural tasks like harvesting, planting and agrochemicals spraying. The first step in the design process is to define the functional specifications of the robot and study existing solutions.

Design examples of tracked robots for harsh environments capable of traversing through rubble include Souryu-V [4], Helios IX [28, 29] and similar tracked robots [15]; see also references therein. There are also several commercial tele-operated tracked mobile manipulator robots, such as Packbot by Irobot, Talon by FosterMiller/QinetiQ, ANDROS Wolverine by Remotec/Northrup Grumman, XLP and MVF-5 DOK-ING robots, to name a few. For a discussion on robots for rescue, recovery and other hazardous operations, see [18, 24].

The design specifications of the R1 robot are summarized in Table 4. Using the equations presented in Sect. 2.4.1, the design specifications imply that each motor must have a peak power of 534.8 W, a peak torque of 42 Nm and a peak current of 22.3 A. If the robot is to operate continuously for one hour, the battery pack must have a charge equivalent to 44.6 Ah in order to supply enough current to both motors. Wheelchair motors model MCQ80 by Shenzhen Unite Industries Co., whose specifications are summarized in Table 5, was chosen to implement R1. The MCQ80 motor has half the required power to achieve the specified velocity and acceleration on a 20° incline. Therefore, the implemented skid-steer robot can meet the velocity and acceleration specifications if the slope is below 8°. Nonetheless, because of its threads and torque, the R1 robot can traverse short inclines with slopes angles above 8°, but at lower speeds and accelerations.

Once the main components for R1 were chosen, a diagram of the R1 architecture was made. The initial diagram depicting the hardware interconnections was drawn on a whiteboard as shown in Fig. 19. The hardware architecture diagram shows the batteries, microcontroller, h-bridges and the isolation circuit to separate the power from low current electronics. The schematic drawing of the final electronic hardware architecture is shown in Fig. 20.

Considering all the components, a case for the robot body of 400×230×180 mm was built using 10 mm thick 6061 aluminum sheets. The open body chassis and

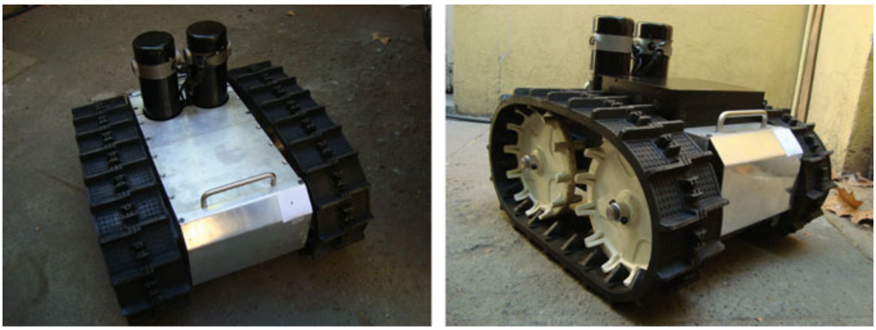


Fig. 18 Skid-steer robot R1

Table 4 Summary of the design specifications for the R1 skid-steer mobile robot

Criteria	Value
Mass	15 kg
Payload	85 kg
Maximum velocity	2.1 m/s
Maximum acceleration	0.4 m/s^2
Maximum incline	20°
Wheel radius	0.165 m
Total system efficiency	≥75%

Table 5 R1 motor specifications

Characteristic	Value
Motor type	Permanent magnet DC brushed motor
Model	MCQ80
Manufacturer	Shenzhen Unite Industries Co.
Nominal voltage	24 V
Output power	250 W
No load current	3 A
Maximum current	13 A
Gear ratio	32:1
Motor speed	3800 ± 100 RPM
Output speed	120 ± 3 RPM
Maximum output torque	43 Nm
Motor efficiency	≥78%
Motor weight	7.2 kg

the compartment for the robot's batteries and electronics are shown in Fig. 21. The MCQ80 motors have a gearbox with three spur gears and a worm gear connected to the motor. Figure 22 shows the clean gearbox without the gears grease. The wheel encoders are installed on the front wheels. The R1 robot can receive control signals through an XBee RF module or using a standard RC (radio control) receiver-transmitter pair. The R1 robot has been tested successfully with loads up to 80 kg on different terrains, including construction debris, sand, gravel, pebble and cobblestones. A short video of the R1 in operation can be found at https://youtu.be/EweQZVeKxec.

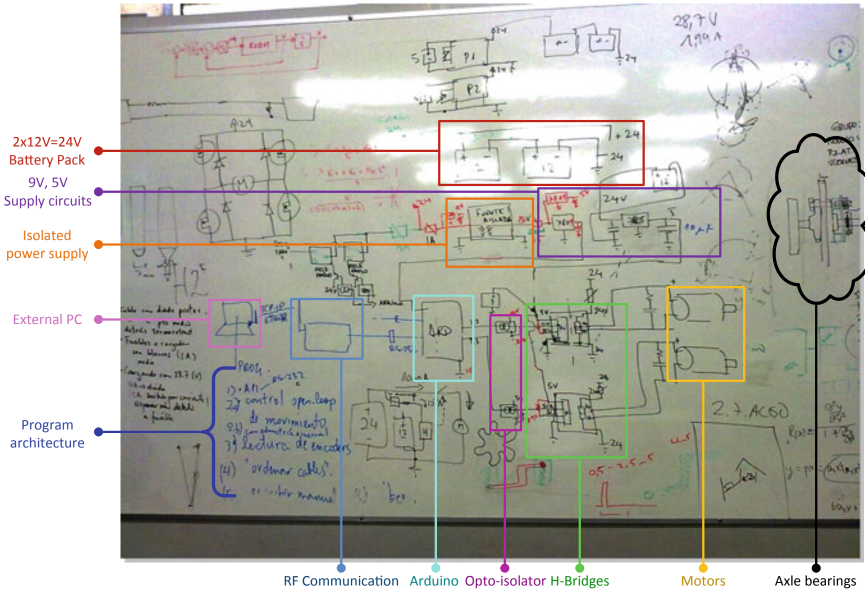


Fig. 19 Initial drawing of the electronic hardware architecture of the R1 robot

4 Conclusion and Further Reading

This chapter presented the main guidelines and recommendations for the design and rapid prototyping of mobile robots, including fundamental aspects concerning the basic design rules, the main parts of a robot, the general hardware and software architecture, the motion dynamics and the selection of the components that ensure the robot prototype meets the motion specifications, such as the main types of mechanical transmissions, efficiency issues, the role of bearings, and other aspects concerning stability, overturning margins, controllability and the selection of computing platforms. All the concepts and guidelines were employed in the design of the R1 skid-steer mobile robot, which was presented as an example of rapid mobile robot prototyping. The topics presented in this chapter should serve as a guiding tool for better virtual and physical prototyping of mobile robots, not only in the context of the development of research platforms, but also for validating commercial and customized mobile robot applications.

Information concerning mechatronic and robot design principles, procedures, methodologies and techniques is spread across an extensive number of textbooks and publications. The design of any mechatronic device involves different disciplines of engineering, and therefore, it is hard to find a single reference that could cover all aspects in depth. However, some books provide essential knowledge and guidelines in a concise and rigorous manner. Regarding general robot engineering and design aspects, with an emphasis on components, construction and practical

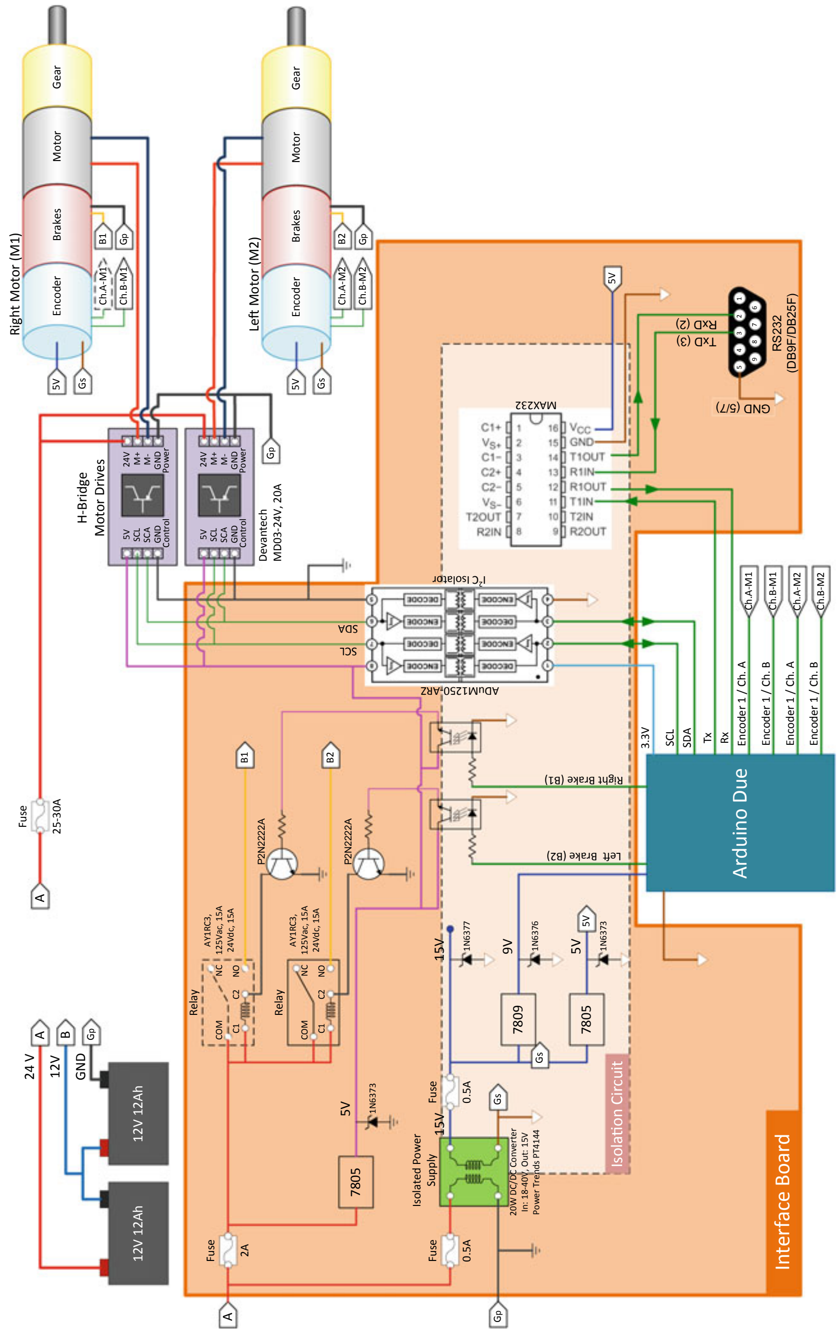


Fig. 20 Electronics architecture of the R1 robot

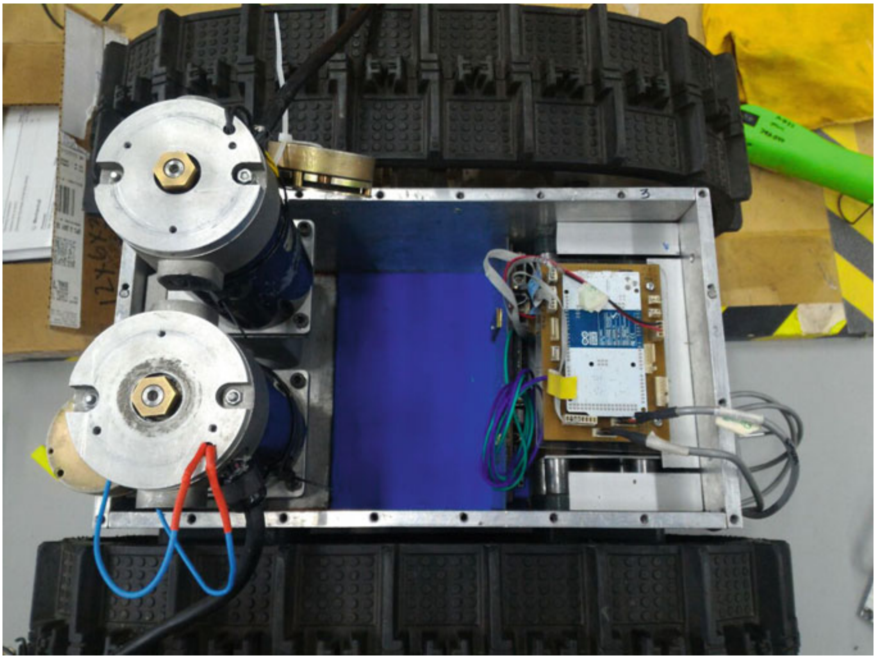


Fig. 21 Compartment for batteries and electronics of the R1 robot

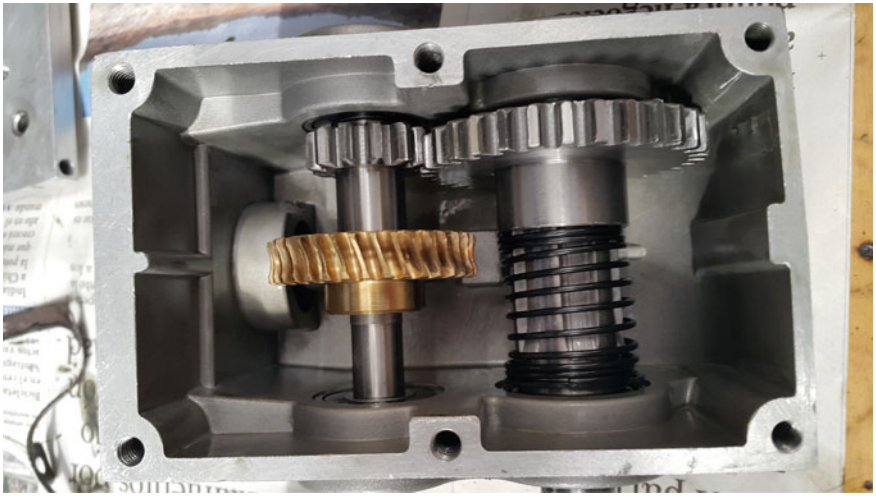


Fig. 22 Gearbox of the R1 robot composed of a worm gear and spur gears

operation issues, the books [11, 26] are a good place to start if the aim is industrial-grade robot construction. The books [11, 26] only cover the design and engineering of robot manipulator arms, but the concepts and tools can also be applied or extended to the design of mobile robots. The classic books [16, 30] are aimed at an audience of hobbyist and non-specialist, but may serve also as an introduction to the practical construction of wheeled mobile robot prototypes and small scale proofs of concept. On the other hand, a standard formal introduction to current mobile robots can be found in [25] with an emphasis on basic components, kinematics and computational aspects pertaining to the tasks of perception and autonomous navigation. The book [25] does not focus on hardware design and implementation, but together with [11, 16, 26, 30] provides the basis for the design and construction of autonomous wheeled mobile robot prototypes.

On the general topic of the engineering design process, some useful references include [2, 6, 9, 20]. In particular, the paper [6] discusses the similarities in the development process specific to disciplines of mechanics, electronics and software engineering and how this process must be coordinated in the design of a mechatronic device, such as a mobile robot.

Concerning the modeling of mobile robots, the references are [1, 24, 27]. A detailed review concerning the tools for simulating mobile robots is found in [27]. An important aspect to consider is the control laws that enable the robot to track a reference trajectory. A discussion on the controllability and control laws can be found in [13] for unicycle, differential-drive and car-like mobile bases. Several discrete-time path tracking controllers have been proposed in the last decade. A comparative review of different controllers and their application to field robots can be found in [5]. Most of the work concerning the controllability of mobile robots and the proposed control laws only consider kinematic models because of the complexity of the dynamic models, which makes it hard to obtain closed-form expressions. On the other hand, for most mobile robots, it is often possible to assume from a practical perspective that the dynamics is correctly handled by the low-level first-tier control loops that manipulate torques and forces applied through the actuators to obtain almost instantaneously a specified motion velocity. Making this assumption is possible because mobile robots in general move relatively slow compared to the response time of the actuators. Therefore, it is possible to assume that the manipulated variables that produce changes in the trajectory of the robot are velocity commands. Although neglecting the dynamics works reasonably well in practice, the robot designer should not forget that the robot must be designed and built so that the assumption does not deviate much from reality. Thus, the designer of the robot will require the knowledge of the real forces and inertias involved in the motion of the robot, so that the actuators and power supplies can be sized correctly. In this context, a note of caution to the reader and designer is not to forget that an accurate dynamic description of the robot is essential in a good design even if many texts in robotics treat it superficially or simply do not mention it at all. Two textbooks that provide all the mathematical tools to rigorously develop the dynamic models of mobile robots are [3, 8].

References

1. Aguilera-Marinovic S, Torres-Torriti M, Cheein FA (2016) General dynamic model for skid-steer mobile manipulators with wheel-ground interactions. IEEE/ASME Trans Mechatron (99):1. https://doi.org/10.1109/TMECH.2016.2601308
2. Albano LD, Suh NP, Pecht M, Slocum A, Jakiela M, Lewis K, Mistree F, Rao JJ (1999) Mechanical engineering handbook. CRC Press LLC, Boca Raton, Chap Engineering Design, Chap, p 11
3. Angeles J (2014) Fundamentals of robotic mechanical systems, 4th edn. Mechanical engineering series (Book 124). Springer New York, Inc., Switzerland. https://doi.org/10.1007/978-3-319-01851-5
4. Arai M, Tanaka Y, Hirose S, Kuwahara H, Tsukui S (2008) Development of souryu-iv and souryu-v: serially connected crawler vehicles for in-rubble searching operations. J Field Robot 25(1–2):31–65. https://doi.org/10.1002/rob.20229
5. Auat-Cheein F, Scaglia G (2014) Trajectory tracking controller design for unmanned vehicles: a new methodology. J Field Robot 31(6):861–887. https://doi.org/10.1002/rob.21492
6. Bernardi M, Bley H, Schmitt B (2004) Integrating a mechatronics-oriented development process into a development department. In: Proceedings of the 37th CIRP international seminar on manufaturing system. Budapest, Hungary, pp 265–270
7. Campion G, Chung W (2008) Springer handbook of robotics. Springer, Chap 17: Wheeled Robots, pp 391–409
8. Featherstone R (2008) Rigid body dynamics algorithms. Springer, New York, USA
9. Gausemeier J (2002) From mechatronic to self-optimization. In: Proceedings of the 20th CAD-FEM user meeting 2002. http://www.sfb614.de/doku/vonderMechatronikzurSelbstoptimierung.pdf
10. Jazar RN (2014) Vehicle dynamics, 2nd edn. Springer, New York, USA. https://doi.org/10.1007/978-1-4614-8544-5
11. Klafter RD, Chmielewski TA, Negin M (1989) Robotic engineering: an integrated approach. Prentice Hall
12. Kozlowski Krzysztof, Pazderski Dariusz (2004) Modeling and control of a 4-wheel skid-steering mobile robot. Int J Appl Math Comput Sci 14(4):477–496
13. Luca AD, Oriolo G, Samson C (1998) Robot motion planning and control, Springer, Chap 4: feedback control of a nonholonomic car-like robot, pp 171–253
14. Luca AD, Oriolo G, Vendittelli M (2001) Ramsete: articulated and mobile robotics for services and technologies, Lecture notes in control and information sciences, vol 270, Springer, chap 8: control of wheeled mobile robots: an experimental overview, pp 181–226
15. Ma J, Luo J, Pu H, Peng Y, Xie S, Gu J (2014) Design, simulation and manufacturing of a tracked robot for nuclear accidents. In: 2014 IEEE international conference on robotics and biomimetics (ROBIO), pp 1828–1833. https://doi.org/10.1109/ROBIO.2014.7090601
16. McComb G (2011) Robot builder's bonanza. McGraw-Hill Education TAB
17. Mohammadpour E, Naraghi M, Gudarzi M (2010) Posture stabilization of skid steer wheeled mobile robots. In: 2010 IEEE conference on robotics automation and mechatronics (RAM), pp 163–169. https://doi.org/10.1109/RAMECH.2010.5513194
18. Murphy RR, Kravitz J, Stover SL, Shoureshi R (2009) Mobile robots in mine rescue and recovery. IEEE Robot Autom Mag 16(2):91–103. https://doi.org/10.1109/MRA.2009.932521
19. Oriolo G (2014) Encyclopedia of systems and control, Springer, chap wheeled robots, pp 1–9. https://doi.org/10.1007/97814471510291781
20. Pahl G, Beitz W, Feldhusen J, Grote KH (2007) Engineering design, a systematic approach, 3rd edn. Springer
21. Rajamani R (2012) Vehicle Dynamics and Control, 2nd edn. Mechanical Engineering Series, Springer, New York, USA
22. Retamales F, Torres-Torriti M (2016) Ubibot telepresence mini-robot. http://ral.ing.uc.cl/ssmm.htm

23. Sensinger JW, Lipsey JH (2012) Cycloid versus harmonic drives for use in high ratio, single stage robotic transmissions. In: 2012 IEEE international conference on robotics and automation (ICRA), pp 4130–4135. https://doi.org/10.1109/ICRA.2012.6224739
24. Siciliano B, Khatib O (eds) (2008) Springer handbook of robotics. Springer, Berlin, Heidelberg
25. Siegwart R, Nourbakhsh IR, Scaramuzza D (2011) Introduction to autonomous mobile robots. The MIT Press, Intelligent Robotics and Autonomous Agents series
26. SRI International (1988) Robot design handbook. McGraw-Hill
27. Torres-Torriti M, Arredondo T, Castillo-Pizarro P (2014) Survey and comparative study of free simulation software for mobile robots. Robotica FirstView:1–32. https://doi.org/10.1017/S0263574714001866, http://journals.cambridge.org/articleS0263574714001866
28. Ueda K, Guarnieri M, Hodoshima R, Fukushima EF, Hirose S (2010) Improvement of the remote operability for the arm-equipped tracked vehicle helios ix. In: 2010 IEEE/RSJ international conference on intelligent robots and systems (IROS), pp 363–369. https://doi.org/10.1109/IROS.2010.5650826
29. Ueda K, Guarnieri M, Inoh T, Debenest P, Hodoshima R, Fukushima EF, Hirose S (2011) Development of helios ix: an arm-equipped tracked vehicle. J Robot Mechatron 23(6):1031–1040
30. Warren JD, Adams J, Molle H (2011) Arduino robotics. Technology in Action, Apress
31. Wong JY (2008) Theory of ground vehicles

Prototyping the Brain of a Robot

Daniele Mazzei, Lorenzo Cominelli, and Nicole Lazzeri

Abstract In this chapter, we will introduce several key points of this new discipline with a particular focus on human-inspired cognitive systems. We will provide several examples of well-known developed robots, to finally reach a detailed description of a special case study: F.A.C.E., Facial Automaton for Conveying Emotions, which is a highly expressive humanoid robot with a bio-inspired cognitive system. At the end of the chapter, we will briefly discuss the future perspective about this branch of science and its potential merging with the IoT, giving our vision of what could happen in a not-too-distant future.

1 Introduction

> *"Individual's interaction with computers, television and new media are fundamentally social and natural, just like interactions in real life. ... Everyone expects media to obey a wide range of social and natural rules. All these rules come from the world of interpersonal interaction, and from studies how people interact with real world. But all of them apply equally well to media..."*
> (The Media Equation Theory, Revees and Nass 1996) [1].

Humans have an innate tendency to the anthropomorphism of the surrounding entities [2], regardless they are living or non-living beings. Similarly, we have always been

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_5

fascinated by the creation of machines that have not only human traits, but also emotional, sensitive and communicative capabilities similar to humankind.

This was clearly highlighted by the imagination of artificial creatures able to interact with us and to move around our physical and social spaces, which has inspired writers, producers and directors since the dawn of the science fiction genre: from the robots in Karel Capek's R.U.R. to the Frankenstein monster of the Mary Shelley's novel, from the Star Wars's droids R2-D2 and C-3PO to the positronic robots of the Asimov's short stories up to the Philip K. Dick's replicants, science fiction novels, plays and movies have illustrated us how this robotic technology may live together with us and benefit society but also raise questions about ethics and responsibility.

In the last decades, this imagination has become reality with the enormous advances in hardware performance, computer graphics, robotics technology and artificial intelligence (AI). Different reasons can guide researchers in building a robot able to interact with people in a human-centred way. We are a profoundly social species and understanding our sociality can help us to better understand ourselves and our humanity [3]. Such robots can be a test bed for modelling human social behaviours, and the parameters of those models could be systematically varied to study and analyse behavioural disorders [3]. If it is possible to interact with social robots in a natural and familiar way, they can be used to enhance the quality of our life. In the future, a personal social robot could assist people in a wide range of activities, from domestic to service tasks up to educational and medical assistance. Moreover, according to the emerging trend of the Internet of Things (IoT) and the evolution of smart environments that receive and process a huge set of data, a humanoid could become the next generation of interfaces for enabling humans to relate with the world of information by means of an empathic and immediate interaction.

As a consequence, due to its importance and peculiarity, this has become a tangible research field: Cognitive Robotics.

In this chapter, we will introduce several key points of this new discipline with a particular focus on human-inspired cognitive systems. We will provide several examples of well-known developed robots, to finally reach a detailed description of a special case study: F.A.C.E., ***Facial Automaton for Conveying Emotions***, which is a highly expressive humanoid robot with a bio-inspired cognitive system. At the end of the chapter, we will briefly discuss the future perspective about this branch of science and its potential merging with the IoT, giving our vision of what could happen in a not-too-distant future.

2 The Mind of a Robot

Before dealing with principles and methods to follow, in order to build the mind of a robot, we should examine what we mean when we use the word "mind" or "brain" in the context of humanoid robots. There are still important scientific trends supporting pure biomimetics with the certainty that a successful artificial intelligence would be possible only by means of a faithful reproduction of the biological human brain structure. Nonetheless, in the last decade, the investigation of the main human brain functions and a more general study of human behaviours have led to the development of simplified models that produce good results. Several examples will be discussed and described in the next sections. From now on, we will use the term "mind" as a computational infrastructure designed for controlling a robot in order to make it able to interpret and convey human-readable social cues and to express a variety of behavioural and communicative skills, especially aimed at attracting people in social interactions.

As a consequence of its complexity, the creation of a cognitive architecture for robots requires additional knowledge from different research fields, such as social psychology and affective computing and also computer science, AI. The contributions of each of these fields have repercussions on the design of the underlying control framework. Social psychology provides information on how people react to stimuli that represent guidelines for modelling the robot's behaviour. Computer science deals with the development of software systems that control the behaviour of the robot and its interaction with people and the world. Affective computing is a new interdisciplinary field focused on simulating empathy in machines [4], i.e., giving machines the ability to interpret the emotional state of humans and adapt their state and behaviour to them. AI is fundamental for enhancing capabilities and believability of the robot using models and algorithms to iteratively learn from human behaviours, to process environmental cues and information about the interlocutors' affective state and finally to determine the action to take at a given moment on the basis of the current social context.

On the other hand, we must be careful to move not-too-far away from the biological model. For instance, neuroscience has taught us that the human intelligence does not depend on monolithic internal models, on a monolithic control and on a general-purpose processing [5]. Humans perceive the world and their internal state through multiple sensory modalities that in parallel acquire an enormous amount of information used to create multiple internal representations. Moreover, behaviours and skills are not innate knowledge but are assimilated by means of a development process, i.e., performing incrementally more difficult tasks in complex environments [5]. There is also evidence that pure rational reasoning is not sufficient for making decisions since human beings without emotional capabilities often show cognitive deficits [6].

Following this bio-inspired direction, over the last 60 years, AI has dramatically changed its paradigm, from a computational perspective which includes research topics, such as problem-solving, knowledge representation, formal games and search techniques, to an embodied perspective which concerns developing systems in the real physical and social world that must deal with many issues extraneous to the first perspective.

This new multidisciplinary field called "embodied artificial intelligence" started to acquire another meaning in addition to the traditional algorithmic approach also known as GOFAI (Good Old-Fashioned Artificial Intelligence): it designates a paradigm aimed at understanding biological systems, abstracting general principles of intelligent behaviour and applying this knowledge to build intelligent artificial systems. This is definitely more than a good compromise.

On this research line, promoters of the embodied intelligence began to build autonomous agents able to interact in a complex, dynamic and hostile world, always taking the human being as a reference point. An autonomous embodied agent should be able to act in and react to the environment by building a "world model", i.e., a dynamic map of information changing over the time acquired through its sensors. As in the human being case, the body assumes a key role in the exchange of information between the agent and the environment. The world is affected by the agent through the actions of its body and the agent's goal (or we can say "intentions") can be affected by the world through the agent's body sensors. However, building a world model also requires the ability to simulate and make abstract representations of what it is possible to do in certain situations that means "having a mind".

In order to underline the importance of the body in this process of representation, we need to cite one of the major figures who outlined the tight bond between mind and body, as Antonio Damasio:

> "*Mind is not something disembodied, it is something that is, in total, essential, intrinsic ways, embodied. There would not be a mind if you did not have in the brain the possibility of constructing maps of our own organism. [...] you need the maps in order to portray the structure of the body, portray the state of the body, so that the brain can construct a response that is adequate to the structure and state and generate some kind of corrective action.*"

In conclusion, we claim that, by combining the biological and robotic perspectives, building an intelligent embodied agent requires both a body and a mind. For a robot, as well as in the human case, the body represents the means through which the agent acquires the knowledge of the external world, and the mind represents the means through which the agent models the knowledge and controls its behaviour.

2.1 Robot Control Paradigms and Cognitive Architectures

From a robotic point of view, humans are sophisticated autonomous agents that are able to work in complex environments through a combination of reactive behaviours and deliberative reasoning. A control system for an autonomous robot must perform tasks based on complex information processing in real time. Typically a robot has a number of inputs and outputs that have to be handled simultaneously and it operates in an environment in which the boundary conditions determined through its sensors change rapidly. The robot must be able to react to these changes in order to reach a stable state [7].

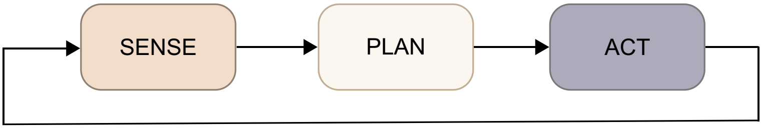

Fig. 1 The Hierarchical paradigm based on a repetitive cycle of SENSE, PLAN and ACT

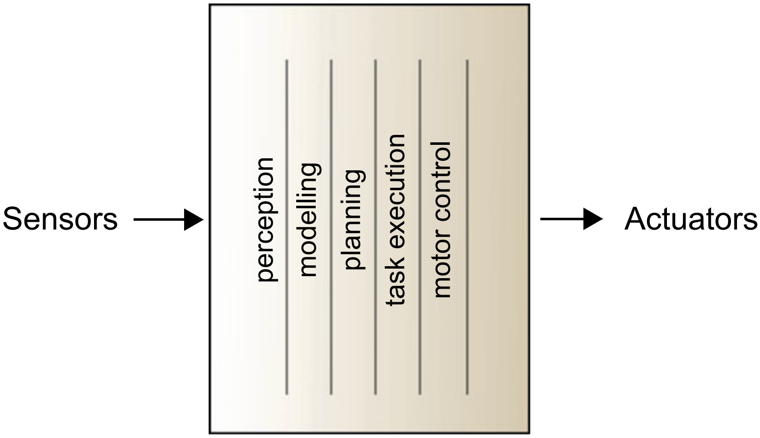

Fig. 2 Example of traditional decomposition of a mobile robot control system into functional modules

Over the years, many approaches have been used in AI to control robotic machines. The three most common paradigms are the *Hierarchical*, the *Reactive* and the *Hybrid Deliberate/Reactive* paradigm. All of them are defined by the relationship among the three primitives, i.e., SENSE, PLAN and ACT, and the processing of the sensory data by the system [8].

2.1.1 The Hierarchical Paradigm

The *Hierarchical paradigm* is historically the oldest method used in robotics since 1967 with the first AI robot, Shakey [9]. In the Hierarchical paradigm, the robot senses the world to construct a model, plans the next actions to reach the goal and finally acts to carry out the first directive. This sequence of activities is repeated in a loop in which the goal may or may not have changed (Fig. 1).

Figure 2 shows an example of Hierarchical paradigm characterized by a horizontal decomposition as designed by Rodney Brooks [10]. The first module consists in collecting and processing the environmental data received through the robot's sensors. The processed data are used to either construct or update an internal world model. The model is usually constituted by a set of symbols composed of predicates and values which can be manipulated by a logical system. The third module, i.e., the

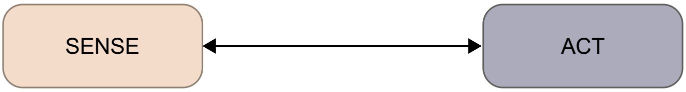

Fig. 3 The Reactive paradigm based on a direct link between SENSE and ACT

planner, uses the world model and the current perception to decide a feasible plan of actions to be executed to achieve the desired goal. Once a suitable set of actions has been found, the fourth and fifth modules execute the actions by converting the high-level commands into low-level commands to control the actuators of the robot. This process is repeated continuously until the main goal of the robot has been achieved.

Using a top-down design and sequential modules, the Hierarchical paradigm lacks robustness because each subsystem is required to work; therefore, the failure of any one of the sub-modules determines the failure of the whole chain. Moreover, it needs higher computational resources due to the modelling and planning phases.

2.1.2 The Reactive Paradigm

Starting from the 1970s, many roboticists in the field of AI explored biological and cognitive sciences in order to understand and replicate the different aspects of the intelligence that the animals use to live in an "open world" overcoming the previous "closed world" assumption. They tried to develop robot control paradigms with a tighter link between perception and action, i.e., SENSE and ACT components, and literally threw away the PLAN component (Fig. 3).

From a philosophical point of view, the *Reactive paradigm* is very close to the *Behaviourism*'s approach and theories [11]. In this paradigm, the system is decomposed into "task-achieving behaviours" which operate in parallel and independently of any other behaviours. Each "behaviour module" implements a complete and functional robot behaviour rather than one single aspect of an overall control task, and it has access to sensors and actuators independently of any other modules. The fundamental idea of a behaviour-based decomposition is that intelligent behaviour is not achieved by designing one complex, monolithic control structure but by bringing together the "right" type of simple behaviours, i.e., it is an emergent functionality.

The *subsumption architecture* developed by Rodney Brooks in 1986 [10] is perhaps the best-known representative of the Reactive paradigm for controlling a robot. The model is based on the fact that the cognition can be observed simply using perceptive and action systems that interact directly with each other in a feedback loop through the environment. The subsumption architecture is focused around the idea of removing centralized control structures in order to build a robot control system with increasing levels of competence. Each layer of the behaviour-based controller is responsible for producing one or a few independent behaviours. All layers except the bottom one presuppose the existence of the lower layers, but none of the layers presupposes the existence of the higher layers. In other words, if the robot is built

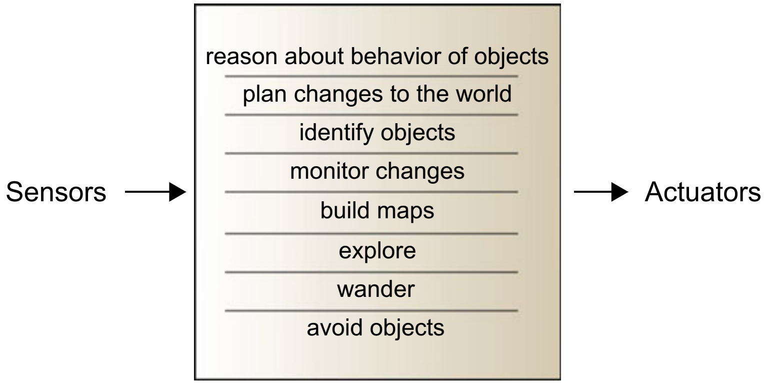

Fig. 4 Example of decomposition of a mobile robot control system based on task-achieving behaviours

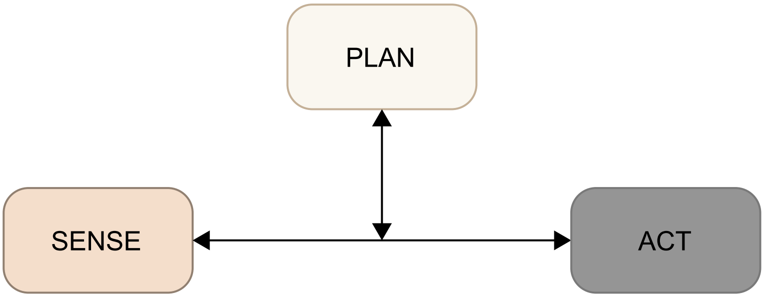

Fig. 5 The Hybrid Deliberative/Reactive paradigm which reintroduces the PLAN component and combines a behaviour-based reactive layer with a logic-based deliberative layer

with a bottom-up approach, each stage of the system development is able to operate. This architecture entails that a basic control system can be established for the lowest hardware level functionality of the robot, and additional levels of competence can be built on the top without compromising the whole system. Figure 4 shows an example of a behaviour-based decomposition of a mobile robot control system with the subsumption architecture.

2.1.3 The Hybrid Deliberate/Reactive Paradigm

Since the Reactive paradigm eliminated planning or any reasoning functions, as a consequence, a robot with this kind of control architecture could not select the best behaviour to accomplish a task or follow a person on the basis of some specific criteria. Thus, at the beginning of the 1990s, AI roboticists tried to reintroduce the PLAN component without disrupting the success of the reactive behavioural control which was considered the correct way to perform low-level control [8]. From that moment, architectures that used reactive behaviours and incorporated planning activities were referred to as using a Hybrid Deliberative/Reactive paradigm (Fig. 5).

The *Hybrid Deliberative/Reactive* paradigm can be described as PLAN, then SENSE-ACT: the robot first plans how to best decompose a task into sub-tasks, then it decides what are the suitable behaviours to accomplish each sub-task. The robot instantiates a set of behaviours to be executed as in the Reactive paradigm. Planning is done at one step while sensing and acting are done together. The system is conceptually divided into a reactive layer and a deliberative layer.

In a Hybrid Deliberative/Reactive system, the three primitives are not clearly separated. Sensing remains local and behaviour specific as it was in the Reactive paradigm but it is also used to create the world model which is required by the planning. Therefore, some sensors can be shared between the model-making processes and each perceptual system of the behaviours. Instead, other sensors can be dedicated to provide observations which are useful for world modelling and are not used for any active behaviours.

Here, the term “behaviour” has a slightly different connotation than in the Reactive paradigm: if “behaviour” indicates a purely reflexive action in a Reactive paradigm, the term is nearer to the concept of “skill” in a Hybrid Deliberative/Reactive paradigm.

On the basis of Brooks’ theory, the robot cognitive system can be divided into two main blocks: the *Low-Level Reactive Control* and the *High-Level Deliberative Control*.

The Low-Level Reactive Control is managed by a dedicated animation engine designed to receive and merge multiple requests coming from the higher layer composed of multiple modules. Since the behaviour of the robot is inherently concurrent, different modules are expected to send requests for movements, and parallel requests could interest the same actions and generate conflicts. Thus, the animation engine is responsible for mixing reflexes, such as eye blinking or head turning to follow a person, with more deliberate actions, such as facial expressions. For example, eye blinking conflicts with the expression of a surprise since normally amazed people react by opening their eyes wide.

As the robot’s abilities increase, it becomes difficult to predict the overall behaviour due to the complex interaction of different modules. Acting in a dynamic environment requires the robot to record the observed facts for updating its internal state, to plan events for deciding when to act and to manage goals for resolving conflicting behaviours. Therefore, knowledge processing systems are becoming more and more important resources for robots that perform challenging tasks in complex environments. Such systems are used to emulate the reasoning process of human experts through decision-making mechanisms in which expert knowledge in a given domain is modelled using a symbolic syntax [12]. These systems called *expert systems* are functionally equivalent to a human expert in a specific problem domain in terms of its capability to reason over representations of human knowledge, to solve the problem by heuristic or approximation techniques and to explain and justify the solution based on known facts. These considerations led to choose an expert system to implement the High-Level Deliberative Control.

Expert Systems

In his book "Introduction to Expert Systems", Peter Jackson wrote a good definition of an *expert system*, defined as "a computer system that emulates the decision-making ability of a human expert" [13]. The main difference between expert systems and conventional computer programs is that the roots of expert systems lie in many disciplines among which the area of psychology concerning with human information processing, i.e., the cognitive science. Indeed, expert systems are intrinsically designed to solve complex problems by reasoning about knowledge, represented as if-then-else rules, rather than through conventional high-level procedural languages, such as C, Pascal, COBOL and Python [14].

The first expert systems were created in the 1970s and rapidly proliferated starting from the 1980s. Expert systems were among the first truly successful forms of AI software [15]. Expert systems were introduced by the Stanford Heuristic Programming Project led by Feigenbaum, who is sometimes referred to as "the father of expert systems". The Stanford researchers tried to identify domains where expertise was highly valued and complex, such as diagnosing infectious diseases (MYCIN) [16] and identifying unknown organic molecules (DENDRAL) [17].

An expert system is divided into two subsystems: the *Inference Engine* and the *Knowledge Base*. The knowledge base is represented by facts and rules that can be activated by conditions on facts. The inference engine applies the rules activated by known facts to deduce new facts or to invoke an action. Inference engines can also include explanation, debugging capabilities and conflict resolution strategies.

A widely used public-domain software tool for building expert systems is CLIPS (C Language Integrated Production System). CLIPS is a rule-based production system developed in 1984 at NASA's Johnson Space Center. Like other expert system languages, CLIPS deals with rules and facts. Asserting facts can make a rule applicable. An applicable rule is then fired. Rules are defined using a symbolic syntax where information is described as a set of facts and decisions are taken through a set of simple rules in the form: ***IF*** *certain conditions are true* ***THEN*** *execute the following actions*.

In a Hybrid Deliberative/Reactive architecture where an expert system can be used to implement the High-Level Deliberative Control, data perceived and elaborated by the sensor units is streamed through the connection bus of the cognitive subsystem and then asserted in the rule engine as knowledge base (facts) generating the first part of the robot cognition, i.e., the *(primary cognition)* [6]. In this case, the robot's behaviour is described through a set of primary rules which are triggered by the facts that are continuously asserted and can fire the assertion of new facts, i.e., the *(secondary cognition)* [6], or can call actuation functions which change the robot state, i.e., the *(motor control)*. Facts of the secondary cognition are analysed by a higher level rule set which represents the *emotion rules set*. The emotion rule set triggers events that are related to the secondary cognition such as the emotional state of the robot, a parameter that can influence its behaviour.

An example of a cognitive architecture based on a rule-based engine is described in detail in Sect. 5.3.

3 Embedded Systems for Robots Control

An embedded system is a microprocessor-based system that is built to control specified real-time functions. The normally used soft-core processing hardware includes microcontrollers and microprocessors, FPGAs, digital signal processors (DSPs) and application-specific integrated circuits (ASICs), each of which has its own properties.

3.1 Microprocessors Verses Microcontrollers

There has always been confusion between the two terms "microprocessor" and "microcontroller". Many times they are mistakenly used as if they were the same thing. In fact, both of them have been designed for real-time application and share many common features, but at the same time, they have important differences:

Microprocessor (MPU) is an integrated circuit which relies only on a CPU, i.e., processing powers such as Intel Pentium or Core, ARM Cortex, without including a RAM, a flash ROM or other peripherals on the chip which must be added externally by system designers to provide program and data storage according to the needs of the specific application.

A **Microcontroller** (MCU) has a CPU, in addition to a fixed amount of RAM, ROM and other peripherals all embedded on a single chip. For this reason, it is also referred to as a minicomputer or a single-chip computer. Nowadays, different manufacturers produce many different versions of MCUs with a wide range of features. Some of the most important manufacturers are ATMEL, Microchip, TI, Freescale, Philips and Motorola.

MCUs use an on-chip flash memory where a program is stored in order to perform specific tasks. Specific tasks mean applications where the relationship between the information given as an input and given back as output is known, e.g., keyboards, mouse, washing machine, digicam, pendrive, remote, microwave, cars, bikes, telephone, mobiles and watches. Since the applications are very specific, they need a minimum amount of resources, such as RAM, ROM and I/O interfaces, and can be embedded on a single chip. This in turn reduces not only the size and the cost, but also the start-up period because the program code is easier and can be quickly executed.

On the contrary, MPUs are designed for applications where tasks are not specific and require higher processing ability, such as developing software, games or websites, editing photos and writing documents. Therefore, MPUs typically use external ICs such as NOR flash, dual data rate (DDR) RAM, power management ICs, analog-to-digital converters (ADCs), codecs and touch-sense controllers. The clock speed of MPUs is higher than the one of the MCUs. In fact whereas MCUs operate from a few MHz to 30–50 MHz, today's MPUs operate above 1GHz as they perform complex tasks.

Therefore, MCUs and MPUs have completely different approaches. The most obvious consideration is about performance which can be compared as MIPS—

millions of instructions per second. MPUs offer more processing power than MCUs which can be a decisive factor for the development of mathematically intensive or complex animation-based applications. On the flip side, if real-time deterministic behaviour is primarily important, MCUs will be a better choice. Regarding the memory, in MCU, built-in flash memory provides high-performance code execution but represents a practical limitation due to the finite space of the total available memory space. Most Flash MCU devices on the market have from 8 Kbytes to 2 Mbytes of on-chip program memory which can double, or even quadruple, the speed at which the system can access data compared to the nominal flash speed but this amount of memory can be a limiting factor, for example, the Linux kernel alone, without application code, can be 1 to 5 MB. On the contrary, in MPUs, programs can be stored in non-volatile flash but must be transferred into an external DRAM memory for high-speed execution which means faster execution of the code but longer boot time. Due to the sophistication of the applications, OSs and hardware involved, MPUs require complex file and memory management functionality that implies an increment of costs. Another consideration is about the power consumption. MCUs are typically orders of magnitude below the MPUs which make them suitable for a wide range of products designed especially for ultra-low-power applications. Although some low-power modes are available, the use of external memories makes it tricky.

In conclusion, it is evident that, according to their different features, comparing microcontrollers and microprocessors in terms of cost is not justified. Undoubtedly, a microcontroller is cheaper than a microprocessor. However, microcontroller cannot be used in place of microprocessor, and using a microprocessor in place of a microcontroller is not advised as it makes the application quite costly.

3.2 FPGAs, DSPs and ASICs

Digital signal processors (**DSPs**) are designed to have embedded multipliers and DSP blocks, which allow complex arithmetic operations to be performed, so they are easy for high-level programming applications. When compared with MCUs, one of the primary advantages of DSPs is the availability of a single cycle multiply and accumulation operation. Also, DSPs have parallel processing capabilities and integrated memory blocks, which largely enhance the processing speed. Some DSP architectures, called digital signal controllers (DSC), are optimized for control applications and contain control-oriented peripherals such as PWM generators, watchdog timers and fast response interrupts. However, DSPs require much higher costs compared with FPGAs. Usually, DSPs are applied for image and audio signal processing when the use of MCUs is not possible due to computational limitations. Their primary application type in the industry is motor controller.

FPGAs were developed for digital embedded systems based on the idea of using arrays of custom logic blocks (LBs) surrounded by a perimeter of I/O blocks (IOBs), all of which could be assembled arbitrarily. FPGAs take the advantage of high operation speed, reconfiguration capability, a very large number of components and supported protocols. In embedded systems, FPGAs are used in two ways: either to implement the desired functionalities directly in the digital logic or to implement the architecture of a microprocessor—so-called soft processor core—and desired microcontroller peripherals. The latter scenario became very popular in recent years as the FPGA prices reduced significantl, and could compete with MCUs. The use of FPGAs allows also for the easy design of additional custom hardware accelerators that implement in hardware certain time-consuming computations. Rodriguez-Andina et al. presented a thorough study of the evolution of capabilities of FPGAs and design tools [18].

As another competitive type of implementation platform for embedded systems, Application-Specific Integrated Circuits (**ASICs**) have the advantages of high-quality performance, low power consumption and low cost. In order to expedite the design process, ASICs are built from the composition of so-called standard cells. Over the years, the design tools improved while maximum complexity and functionality increased. Current designs may include standard cells such as up to 32-bit processors, ROM, RAM, EEPROM, Flash and other large complex blocks. The use of ASICs is feasible only for manufacturing high quantity and long series due to higher initial engineering cost [19].

3.3 Choosing the Correct Platform

An attribute that is difficult to determine is the required processing performance any given design might require. Processing power, measured in terms of Dhrystone MIPS (DMIPS), helps quantify these criteria. For example, an ARM Cortex-M4-based microcontroller such as Atmel's SAM4 MCU is rated at 150 DMIPS while an ARM Cortex-A5 application processor (MPU) such as Atmel's SAMA5D3 can deliver up to 850 DMIPS. One way of estimating the DMIPS required is by looking at the parts of the application that may be performance hungry. Running a full operating system (OS), such as Linux, Android or Windows CE, for your application would demand at least 300–400 DMIPS. For many applications, a straightforward RTOS might suffice and an allowance of 50 DMIPS would be more than adequate. Using an RTOS also has the benefit that it requires little memory space; a kernel of just a few kB being typical. Unfortunately, a full OS demands a memory management unit (MMU) in order to run; this in turn specifies the type of processor core to be used and requires more processor capability.

For the above-mentioned reasons, MCUs and MPUs are mainly used for robot's peripheral parts such as hands or skin [20] or in swarm robotics for designing distributed embedded intelligence [21, 22].

On the contrary, DSPs and FPGAs are more suitable in systems where analog control is primarily important. Examples are control of motors that have to move significant weight such as arms and legs for locomotion and microrobotic systems when some hardware features may need to be reconfigured over time.

4 Software for Robot Cognitive Systems

The human being can be seen as a distributed system composed of multiple subsystems working independently but communicating with each other at different scales and levels, e.g., apparatus, organs, cells and molecules. We have discussed about the "director" of this orchestra, mentioning also the importance of the body as more than a media, but rather as an essential part for the existence of the mind as we know it. Now we cannot avoid to spend some words about what can be defined as the third fundamental part of a human (or a human-inspired) being: the communication.

Taking inspiration from our brain and our body, humanoid robots are conceived as modular systems. Robots can always be described as composed of parts that constitute the sensory apparatus, the motor apparatus and the cognitive system which in turn are divided again into modules that receive, process and stream information. Such a modular and distributed architecture allows both the simultaneous functioning of many simple features and the fulfilment of very complex tasks that require high computational costs. Robustness and responsiveness can be guaranteed specifically thanks to the distribution of the workload among the subsystems that compose the overall architecture. Everything related to the management of the intercommunication among the subsystems is what, in computer science, is called *middleware*. The key feature of a robotics middleware is to give a handy API and automatism as much as possible. Moreover, the middleware also has to support cross-platform compilation and different programming languages.

In the following, we will provide a brief explanation about the functioning and usage of the two most widely used and successful middleware.

4.1 Yet Another Robot Platform (YARP)

If data is the bloodstream of your robot, then YARP is the circulatory system.

YARP[1] (Yet Another Robot Platform) is an open-source framework that includes a set of libraries, protocols and tools to cleanly decouple sensors, processors and actuators from software architecture [23]. The main goal of YARP is supporting the distributed computation over an inter-process communication infrastructure in order to provide a foundation that makes robot software more stable and long-lasting by supporting incremental architecture development. YARP is written in C++ and is cross-platform.

YARP manages the connections through special *Port* objects. A port is an active object managing multiple asynchronous input and output connections for a given unit of data. An input port can receive from multiple connections while an output port can

[1] http://www.yarp.it/.

send data to many destinations. Both input and output ports can use different rates on different protocols (e.g., TCP, UDP and multicast). Normally communication is fully asynchronous which means that messages are not guaranteed to be delivered but losing one message does not compromise the integrity of the system. Indeed, typically systems based on sensor data privilege fast exchange of updated data rather than processing every bit received. Therefore, YARP ports are targeted at dealing with recurrent and updated messages. In case of necessity, message delivery can be guaranteed, but at the cost of introducing a coupling between processes.

YARP ports support a set of primitive data types whereas more complex data types need specializing the port template for the new type and providing serialization and deserialization functions. Ports are implemented as C++ templates and specialized to the type of the data to be transmitted or received [23].

A name server manages all the Ports on the network by mapping their symbolic name into the triplet (IP address, port number and interface name) which is necessary to establish socket communication between two endpoints.

YARP represents an easy-to-use and simple open-source framework that allows programmers to decouple sensors, processors and actuators from the software infrastructure making it flexible and reliable.

4.2 Robot Operating System (ROS)

ROS[2] (Robot Operating System) is an open-source meta-operating system designed to meet a specific set of challenges encountered when developing large-scale service robots. ROS provides libraries and a set of tools to help software developers create robot applications. Key features are modularity, flexibility and portability which allow research groups to share parts of the systems in the form of ROS packages. ROS was designed to be language-neutral and currently supports four programming languages: C++, Python, Octave and LISP, with other language ports in various states of completion [24].

A system based on ROS normally has a peer-to-peer topology with a number of processes potentially running on a number of different hosts. No server is present; therefore, ROS provides a sort of lookup mechanism called the name service, or master, used by the processes to find each other at runtime.

Four concepts are fundamental in the ROS: nodes, messages, topics and services. Processes that perform computations are called *nodes* which correspond to a "software module" from the point of view of a modular architecture and a system is typically composed of many nodes. Communication among nodes is based on the exchange of *messages* which are strictly typed data structures and support standard primitive types. A node sends a message by publishing it to a given *topic*, i.e., a named bus. A node that subscribes to a topic means that it is interested in receiving the related kind of data. Multiple publishers and subscribers can exist to publish

[2] http://www.ros.org/.

and/or subscribe to multiple topics. Finally, request/reply among the nodes is done via a *service*, which is defined by a pair of messages: one for the request and one for the reply. A providing ROS node offers a service under a string name, and a client calls the service by sending the request message and awaiting the reply.

Collaborative development of a system based on ROS is supported through the use of packages which are simply a directory that contains an XML file describing the package and stating any dependencies. Packages can wrap existing software, build nodes for use in ROS graphs or provide libraries and standalone executables. The packaging system allows the building of ROS-based software to be partitioned into small, manageable chunks, each of which can be maintained and developed independently by its own team of developers [24].

5 Case Studies

This section briefly presents examples of existing complex architectures for controlling humanoid social robots. The first example is Kismet [3], belonging to the category of the cartoon-like robots that is focused on building a socially intelligent machine able to communicate with and learn from people and to express its personality through facial expressions. The second example is iCub [25], a full-body humanoid robot, more focused on building cognitive capabilities based on enactive development by means of the interaction with the environment. The last example is F.A.C.E. [26], a humanoid social robot that is characterized by its extreme aesthetic similarity to a real woman and its ability to reproduce realistic facial expressions and social behaviours.

This choice is dictated by the fact that building a humanoid robot is a long-term project which involves scientists from different academic fields who can integrate technical knowledge of hardware and software, psychological knowledge of interaction dynamics and domain-specific knowledge of the target application [27]. Therefore, the process of building such robots requires many prototyping steps by facing new challenges unique to social robots, such as sensory information processing, multimodal human communication design and application of behavioural models based on acceptable rules of social norms. Indeed, robots with social abilities are designed to interact and cooperate together with humans in a shared space. This means that a social robot must be able to express its own state and perceive the state of its social environment in a human-like way in order to act successfully. Bionics research is focusing on the development of the so-called "social intelligence" for autonomous machines in order to make these social robots able to establish life-like empathic relationships with their partners. The term "social intelligence" implies the ability to interact with other people or machines, to interpret and convey emotional signals and to perceive and react to interlocutors' intentions for maintaining the illusion of dealing with a real human being.

From the technical point of view, the following milestones have to be achieved in the design and development of the mind of a social robot:

1. A distributed modular architecture that allows the design of the system as multiple abstract and physical layers with parallel processing and distributed computational load;
2. An imperative control architecture aimed at controlling the low-level procedure like motor control, sensors reading, kinematics calculation and signal processing;
3. An hardware/platform/robot-independent architecture that can be easily ported on various platforms and consequently used in various research, commercial and therapeutic setups;
4. A deliberative reasoning architecture aimed at implementing the behavioural model;
5. An intuitive and easy-to-use behavioural model definition language that allows neuroscientists and behavioural psychologist to convert their theoretical models into executable behaviour for the robotic platform;
6. A object-oriented storage system on which data of heterogeneous categories can be stored without the need of a preliminary database structuring procedure;
7. A pattern-matching engine able to conduct search and analysis procedure not necessarily describable with the Boolean comparison or mathematical analytics;
8. An high-level perception system aimed at extracting high-level social, emotional and empathic parameters from the robot perceived scene with particular focus on the interpretation of humans' emotional and behavioural signs.

In summary, some requirements are mandatory for developing a social and emotional intelligence of a humanoid robot: a sensory apparatus able to perceive the social and emotional world, an actuation and animation system able to properly control the robot's movements and gestures, but also a "smart brain" able to manipulate the incoming flow of information in order to generate fast and suitable responses. All these features make these robots powerful research tools for studying human intelligence and behavioural models by investigating the social dynamic of human-robot interaction [3, 28, 29].

5.1 Kismet, a Cartoon-Like Robot with Social Intelligence

Kismet is the first robot designed to explicitly engage people in natural and expressive face-to-face interactions, and it is widely recognized as the pioneering effort in the new field of social robotics. The design of Kismet was inspired by infants, who "*are born as a coherent system, albeit immature, with the ability to respond to and act within their environment in a manner that promotes their survival and continued growth.*" [3]. Kismet's appearance has been thought to encourage people to treat it as if it were a very young child or infant. Kismet can communicate its emotional state and social cues to the social partner through face, gaze direction, body posture and voice.

The underlying architecture of Kismet was designed on the basis of behavioural models and mechanisms of living creatures referred to by Cynthia Breazeal as the

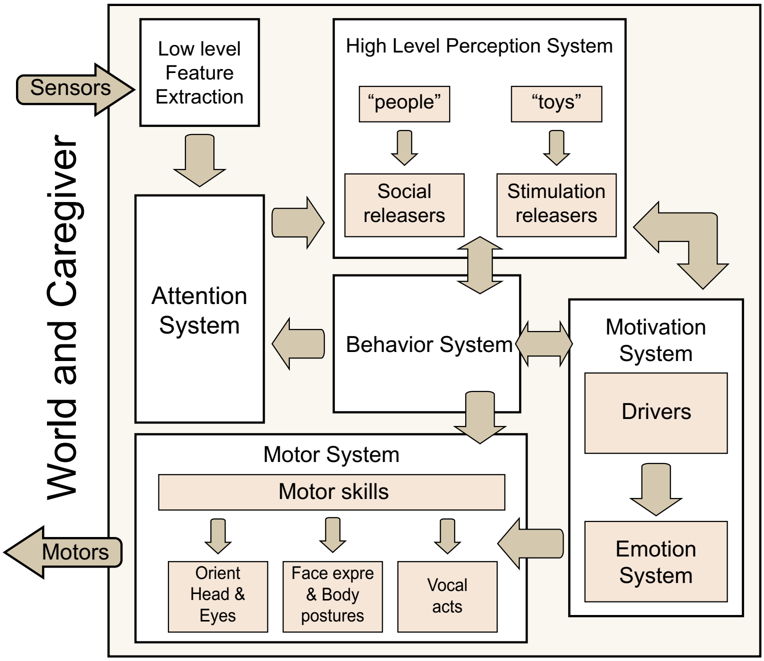

Fig. 6 The framework used for designing Kismet's synthetic nervous systems

robot's synthetic nervous system (SNS). Kismet's SNS is a modular system that includes six modules (Fig. 6):

1. The low-level feature extraction system is responsible for acquiring the raw sensory information and extracting those features that are relevant for the behaviour of the robot. From the earliest stages of development, human infants can discriminate between social stimuli, such as faces or voices, and salient non-social stimuli, such as brightly coloured objects, loud noises or large motion [3]. Therefore, the detection of the eyes as visual cues or the recognition of vocal effect as auditory cues may be interesting perceptual cues from the point of view of Kismet.
2. The high-level perception system is responsible for generating perceptions that are behaviourally relevant starting from the low-level features of the target stimuli identified by the attention system. Each behaviour and emotive response has a corresponding releaser, i.e., a collection of feature detectors used to identify a particular object or event of behavioural significance. A releaser will determine if all perceptual conditions are right for the response to become active. In that case, active responses are passed to their corresponding behaviour process in the behaviour system and also to the affective appraisal stage where they can influence the emotion system [3].
3. The attention system receives the low-level visual perceptions and selects the ones that are particularly salient or relevant at that time. The selection of perceptual

stimuli can depend on different factors, e.g., someone that suddenly appears or something that has a special significance for the robot or has an inherent saliency can attract the robot's attention. On the basis of the stimulus considered to be the most salient, the robot can organize its subsequent behaviour around it.

4. The motivation system regulates and maintains the "well-being" state of the robot varying from an alert state when it is interacting well with people and a mildly positive affective state when the interactions are neither overwhelming nor under-stimulating [3]. The nature of the robot is defined by its "needs" which influence its behaviour since it acts to satisfy them. The motivation system consists of two related subsystems: drives and emotions. Kismet's drives model critical parameters necessary to the homeostatic balance which have to be maintained within a bounded range. Kismet's emotions are idealized models of emotions and arousal states which serve in social contexts to respond in an adaptive manner.
5. The behaviour system implements and arbitrates between typical competing behaviours of infants. Each behaviour is viewed as an independent goal-directed entity that competes with other behaviours. Behaviours are organized into competing functional groups where each group is responsible for maintaining one of the three homeostatic functions: to be social, to be stimulated by the environment and to occasionally rest [3]. Each functional group consists of an organized hierarchy of behaviour groups each of which represents a competing strategy for satisfying the goal of its parent behaviour. Kismet uses an arbitration mechanism to determine which behaviour has to be activated and for how long: at the behavioural category level, it selects the functional group which represents the need to be satisfied; at the strategy level, it decides which behaviour group belonging to the winning functional group is the winner and finally, at the level task, it selects one of the behaviours belonging to the winning behaviour group.
6. The motor system is responsible for commanding the actuators in order to carry out the task selected by the behavioural system and to convey the affective state established by the motivation system. Kismet's architecture includes the vocalization system to express utterance, the facial animation system to orchestrate facial expressions and lip synchronization and the oculo-motor system to reproduce human-like eye movements and head orientations. At a given time, concurrently active behaviours may compete for the same actuators; therefore, the motor skills system is responsible for appropriately blending the motor actions. The motor skills system is also responsible for smoothly transitioning between sequentially active behaviours in a timely manner so as to not disrupt the natural flow of the interaction. Finally, the motor skills system is responsible for moving the robot's actuators to convey the appropriate emotional state of the robot.

Kismet is mainly designed to model the social interaction between an infant and its caregiver [3]. Kismet is not used to perform specific tasks but its cognitive system is motivated by basic drives which are typical for a child, i.e., thirst, hunger and fatigue. The modular architecture is structured to provide Kismet with the ability to express life-like qualities, to perceive and understand the complexity of human social behaviours and to adapt to the current social scenario by changing its behaviour by means of a physical body that allows the robot to be socially situated with people.

5.2 iCub, a Full-Body Robot with Cognitive Capabilities

iCub is an infant-like robot with the motor and cognitive abilities of a two and a half years-old child. The development of iCub is based on replicating the learning process that a real child goes through from a dependent, speechless newborn into a walking, talking being [25]. The physical appearance of iCub with its 90cm of height reflects the age of a baby. A semi-transparent mask with luminous colour light-emitting diodes highlights the eyebrows and the mouth to smile and frown.

The fully articulated body makes iCub able to crawl and sit. The robot is equipped with human-like senses [25]: a stereoscopic vision by two cameras mounted on moving ocular bulbs with eyelids; an auditory system with two microphones mounted on the head; an vestibular system using an inertial sensor that provides absolute orientation and angular acceleration; a proprioceptive perception to detect the position of all joints and a tactile system based on capacitive sensors on the hands which provides contact and pressure information.

Taking inspiration from psychological and neuroscience studies about the development of babies, iCub's brain is provided with a rich set of innate action and perception abilities that a newborn would be able to do, such as recognizing a human face and detecting objects against a background [25]. More complex cognitive abilities would be learned over time through an increasing development process.

The software architecture provides the basic control of the hardware based on the YARP middleware [23], an open-source software library that supports distributed computation with a special focus on robots. All data are exchanged as IP packets over a GBit Ethernet connection. The lowest level filters the information acquired through the sensory system to determine the most salient signals to be sent to the cognitive architecture (Fig. 7).

The cognitive architecture includes three main levels:

- the multi-functional perceptuo-motor circuits represent all the abilities that can be considered innate and initially planned in neonatal development, such as the basic ability to re-orient the gaze towards local perturbations in the tactile, auditory and visual field or more complex ability to detect human faces and follow the eyes. These circuits operate concurrently, competitively and cooperatively; therefore, specific mechanisms are required to specify which skills are selected and uninhibited [30];
- the modulation circuits receive data from the lower level and compare those data with combinations of actions and sensory information that iCub has encountered before deciding the next action. It is based on the mechanism by which the agent achieves an increasingly greater degree of anticipation and simulation as it learns and develops with experience [30];

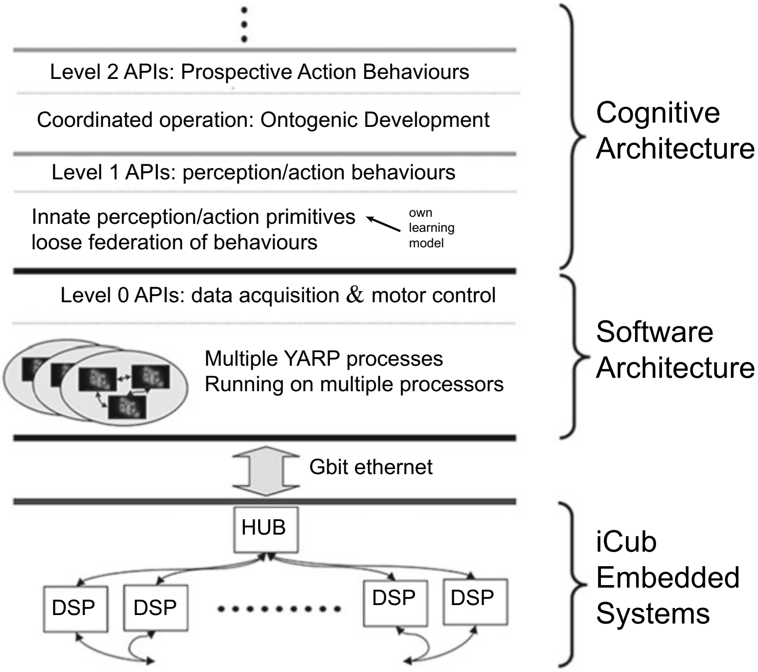

Fig. 7 The software control architecture of iCub

- the self-modification circuits explore and predict new perceptual possibilities not on the basis of an objective environment, but on the basis of the prior experience and the space of possible actions that the system can engage in while still maintaining the consistency of the coupling with the environment [30]. The information is sent down to the middle level to help determine the robot's next action.

iCub has been developed with the aim of studying and reproducing the self-development process of a child. Its cognitive architecture is based on the concept of an enactive system, which is a system able to experience and assimilate, anticipate and predict, learn and develop autonomously. Five concepts define the enactive cognitive science [31]: embodiment, i.e., a physical entity that interacts with its environment; experience, i.e., the history of interaction with the world; emergence, i.e., the development of cognitive behaviours from the dynamic interplay between component parts; autonomy, i.e., self-generating identity and self-regulation of homeostasis and sense-making, i.e., generation of knowledge autonomously by acting in the world. From this point of view, cognition is the process whereby an autonomous system adapts to its environment through a continuous process of self-organization. Thus, the embodiment becomes fundamental to make the robot able to move into the space, manipulate the environment and experience from these manipulations (Fig. 8).

Fig. 8 The F.A.C.E. humanoid robot

5.3 *F.A.C.E, a Realistic Humanoid Robot with Expressive Abilities*

F.A.C.E. (Facial Automaton for Conveying Emotions) is a humanoid robot with a believable facial display system based on biomimetic engineering principles equipped with a passive articulated body [26]. The latest prototype of the head has been fabricated by David Hanson[3] through a life-casting technique. It aesthetically represents a copy of the head of a female subject, both in shape and texture, and the final result appears extremely realistic. The actuation system is controlled by 32 electric servo motors which are integrated into the skull and the upper torso mimicking the major facial muscles. Thanks to the physical and mechanical characteristics of the materials, F.A.C.E is able to reproduce a full range of simulated human facial expressions in an extremely realistic way.

The android is equipped with a rich set of sensors to acquire information from the environment. Raw data are processed and organized to create "metamaps", i.e., structured objects of itself, of the world and of its social partners which together form the knowledge base. The knowledge representation as structured objects offers the advantage to manipulate the information at a higher level of abstraction and in a more flexible and natural way thanks to the usage of a rule-based declarative language. The application of rules to the existing knowledge produces new structured information that can also be decoded to be processed again by a procedural language.

[3] http://www.hansonrobotics.com/.

As in the human nervous system, planning is the slowest part of the control. Rule-based expert systems can deal with a huge amount of rules but require time to compute the final action. In the meanwhile sensors and actuators have to be linked through direct communication channels to perform fast reactive actions. Thus, a Hybrid Deliberative/Reactive paradigm that supports heterogeneous knowledge representations is a good solution for designing a control architecture of a social robot. Integrating a logic-based deliberative system with a behaviour-based reactive system ensures that the robot can handle real-time challenges of its environment appropriately while performing high-level tasks that require reasoning processes [32].

In this way F.A.C.E. has the ability to react immediately to simple visual and auditory stimuli, e.g., an unexpected noise or a sudden movement in the scene, and, at the same time, to process high-level information that requires more reasoning starting from the acquired raw data. The result of this slower but more complex reasoning process can modulate or even change completely the behaviour of the social robot.

Sensing the Social World

In their semiotic theories, Uexküll and Sebeok define the concept of *Umwelt*, that is the *self-centred world*. According to Uexküll, organisms can have different Umwelten, even though they share the same environment [33].

We perceive the world through our senses that interpret it creating a subjective point of view of the environment around us which includes objective data such as colours, light and sounds and subjective information such as the tone of voice or the body gestures of our interlocutors. Similarly, the perception system of a social robot cannot be limited to the acquisition of low-level information from the environment but it has to extract and interpret the social and emotional meaning of the perceived scene. A robot observing people talking has to deduce who is the speaker, their facial expressions, their gender, their body gestures and other significant data useful to understand the social context. All this information has to be analysed through the "body filter", i.e., from the robot's point of view [34].

The F.A.C.E. control architecture is equipped with a Social Scene Analysis System aimed at acquiring "the robot Umwelt" by extracting social information related to the current context. The perception system of F.A.C.E. control architecture creates contextualized representations of F.A.C.E.'s Umwelt called Social Meta-Scenes (SMS). High-level information such as postures, facial expression, age estimation, gender and speaking probability is extracted to be "projected" into the cognitive system of F.A.C.E. which becomes aware of what is happening in the social environment (Fig. 9).

Reasoning and Planning: The Social Robot Awareness

Animals show awareness of external sensory stimuli. Human beings are also aware of their own body states and feelings related to the social context [35]. In the context of social robots, awareness is not just being conscious of motors positions. It includes the capability to perceive the inner state, or "unconscious proprioception", evolved as a consequence of the exteroceptive sensory stimulation. The continuous generation

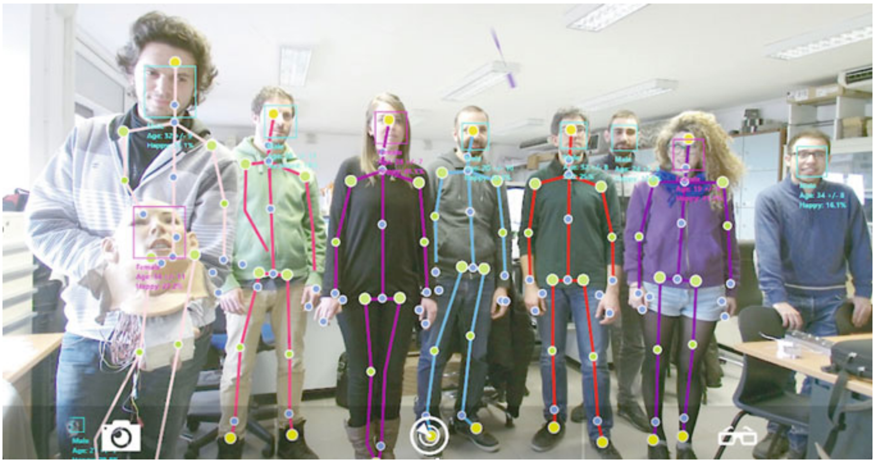

Fig. 9 The F.A.C.E. Scene Analysing System is tracking some interlocutors at "Enrico Piaggio" Research Center (University of Pisa, Italy). Faces are recognized and highlighted with squares (blue for male and pink for female) together with social information like estimated age and estimated facial expression. Body skeletons of the two closest subjects are also highlighted with red lines

of inner state representations is the core of a suitable cognitive system that allows the social robot to project itself into the social context [36].

In a similar manner, the mind of F.A.C.E. has been conceived for making the robot participate in the social environment interpreting the social cues and interacting with the other interlocutors in an active way. Its mind has been biomimetically designed on the basis of the formalization of Damasio's theory presented by Bosse et al. [37], who provided fundamental indications for the implementation of the three main concepts of Damasio's theory, i.e., *emotion*, *feeling* and *feeling of a feeling*. The cognitive system has also been conceived to endow the robot with a primary and secondary cognition, that is in line with what Damasio defines as the *Proto-Self* and the *Self* of a human being. Indeed, all the information gathered by the perception system of the robot, e.g., noise level, sound direction, RGB images and depth images, is processed and identified only if inherent with templates that are pre-defined in the cognitive block. In case of a successful match, this chunk of raw low-level information becomes an entity of the world perceived by the robot, such as a subject or a particular object. The robot itself is also an entity of its own world, and its "bodily" state is continuously perceived in terms of power consumption or motor position for example. This is the first layer of the F.A.C.E.'s knowledge that can be defined as the primary cognition or the *Proto-Self*. By the comparison between the robot's personal state and this primary information about the surrounding scenario, F.A.C.E., by means of its rule-based reasoning capability, has the possibility to invoke an immediate action, but is also able to build new knowledge. This is the second layer of the F.A.C.E.'s knowledge, produced by its symbolic rule-based reasoning and the fundamental relation between the robot's state and the robot's social world, i.e., the

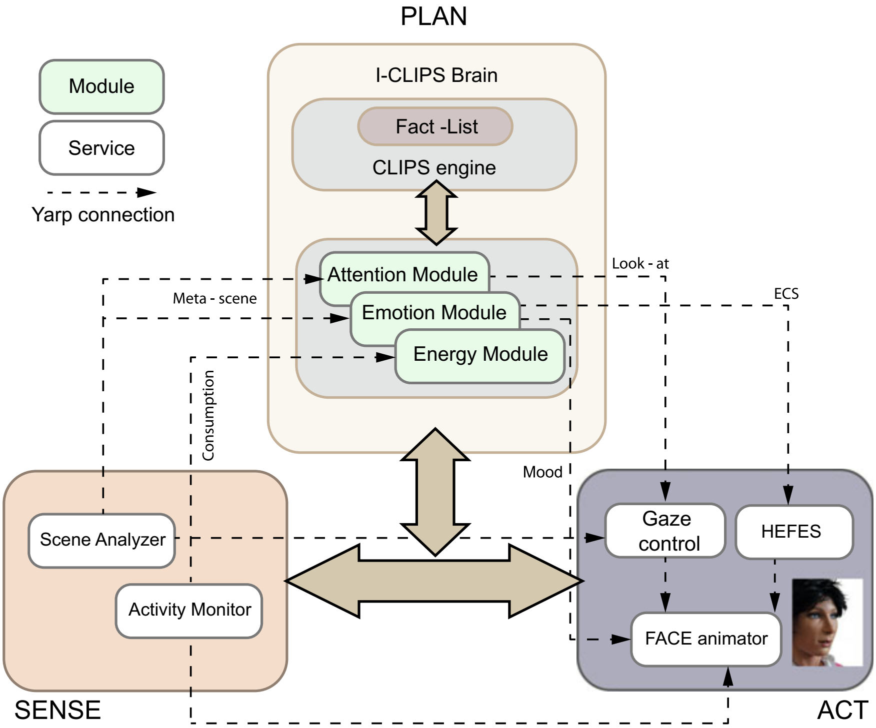

Fig. 10 The F.A.C.E. Cognitive System proto-self

robot's *Umwelt*. This secondary higher level of knowledge can be considered as an *Extended Consciousness* [38], that is what leads humans to the creation of a *Self*, the simulation of a journey that starts from a perceived bodily state to a conscious feeling, passing through emotions.

The F.A.C.E.'s cognitive architecture is based on a Hybrid Deliberative/Reactive paradigm [39]. It is highly modular by encapsulating functions into single modules. Procedural modules collect and elaborate raw data gathered from sensors or received from the other modules while declarative modules process high-level information through a rule-based language.

The proposed architecture, as shown in Fig. 10, can be described taking into account the three main functional blocks: SENSE, PLAN and ACT.

The sensory subsystem acquires and processes incoming data and makes the output available both to the actuation subsystem which manages fast and instinctive "stimulus-response" behaviours (SENSE-ACT) and to the deliberative system which creates metamaps of the social world and the robot itself (SENSE-PLAN). Based on these metamaps, the deliberative system plans and computes the next goal (PLAN-ACT). For example, an unexpected sound could change the robot's attention suddenly without taking care of the rest of the current scene or the total energy consumption of the robot interpreted as "fatigue" could influence its actuation system directly. The deliberative system uses the same information to reason and decide the next action according to the current knowledge of the robot.

The system includes a set of *services*, standalone applications interconnected through the network. Each service collects and processes data gathered from sensors or directly from the network and sends new data over the network. The information's flow through the network is formalized as XML packets that represent a serialized form of structured data objects. This information's management through structured data packets makes it possible to create a modular and scalable architecture by developing services that can receive and send data through the network using different programming languages and hardware devices.

The network infrastructure is based on YARP, the open-source middleware designed for the development of distributed robot control systems [23]. YARP manages the connections by using special *Port* objects. A port is an active object managing multiple asynchronous input and output connections for a given unit of data. Each service can open many different YARP ports for sending and receiving data through the network. Each structured data object is serialized as an XML packet and sent over the network through a dedicated YARP port. Vice versa, each structured object received from the network through a YARP port is deserialized in the corresponding structured object.

The current stage of the architecture includes the following services (Fig. 10).

SENSE

Scene Analyser: it is the core of the SENSE block. It processes the information acquired through the Microsoft Kinect Camera[4] to extract a set of features used to create a *meta-scene* object. The extracted features include a wide range of high-level verbal/non-verbal cues of the people present in the environment, such as facial expressions, gestures, position, speaking identification and a set of the most relevant points of the scene calculated from the low-level analysis of the visual saliency map. Finally, the meta-scene is serialized and sent over the network through its corresponding YARP port. Details of the Scene Analyser algorithms and processes are reported in [40].

Power Supply: it is the energy monitor of the F.A.C.E. robot. This service manages the connection with the robot power supply and monitors the current consumption and the voltage levels of the four power channels of the robot. The power supply service calculates the robot power consumption in Watt with a frequency of 1 Hz and serializes this information to be sent over the network.

Gaze Control: it is the control system of the robot's neck and eyes [40]. This module receives meta-scene objects which contain a list of the persons in the field of view of the robot, each of them identified by a unique ID and associated with spatial coordinates (x,y,z). The Gaze control service is also listening to the *"look at"* YARP port used by the deliberative subsystem to send the ID of the subject

[4] https://developer.microsoft.com/en-us/windows/kinect.

towards which the robot must focus its attention (the attention model is described in detail in [39]).

F.A.C.E. Animator: it is the low-level control system of the F.A.C.E. robot. This service receives multiple requests coming from the other services such as *facial expressions* and *neck movements*. Since the behaviour of the robot is inherently concurrent, parallel requests could generate conflicts. Thus, the animation engine is responsible for blending multiple actions taking account of the time and priority of each incoming request.

ACT

HEFES (Hybrid Engine for Facial Expressions Synthesis): it is a software engine deputed to the emotional control of the F.A.C.E. robot [26]. This service receives an ECS (Emotional Circumplex Space) point (v,a) expressed in terms of *valence* and *arousal* according to Russel's theory called "Circumplex Model of Affects" [41] and calculates the corresponding facial expression, i.e., a configuration of servo motors, that is sent over the network to the F.A.C.E. animator.

PLAN

I-Clips Brain: it is the core of the PLAN block. This service embeds a rule-based expert system called the I-CLIPS Brain and works as a gateway between the procedural and the deliberative subsystems [39].

In the proposed cognitive architecture, the sensory system could also be partially simulated giving the agents the possibility to perceive in-silico parameters such as their own heartbeat, breathing rate and stamina. These in-silico senses can be used to create the virtual proto-self extension which can be used to develop more complicated cognitive models which take into account inner states like "stamina".

Thanks to this control architecture and to its unique sensory and actuation system, F.A.C.E. is a robot with incredible expressive capabilities. The F.A.C.E. robot has been used in robot-therapy experiments with children suffering from Autistic Spectrum Disorders [42], and currently, it is involved in an European Project called EASEL (Expressive Agents for Symbiotic Education and Learning)[5] in which the robot interprets the role of a synthetic tutor for teaching pupils. In more recent studies, F.A.C.E. has been used as a highly technological and expressive robotic platform which is becoming very useful for cognitive robotics and research about the implementation of cognitive models in social robots [43].

6 A Future Possibility for Social Robotics

We provided social robotics' definitions, descriptions, methods and use cases. Clearly, this field is a proper universe unto itself, and it is unfeasible to summa-

[5] http://easel.upf.edu/.

rize all in one chapter, but we hope to have provided a good enough smattering about how to develop the brain and mind of a robot.

Now, we want to conclude this chapter with a huge possibility that opens to this area in conjunction with the emergence of important new fields. Indeed, there is no need to investigate the state of the art in scientific literature to observe some phenomena that are forcefully becoming parts of our everyday life.

The Internet of Things (IoT), for instance, is no longer a futuristic scenario. In a few years, billion of objects, animals and people will be provided with unique identifiers and the ability to transfer data over a network without requiring a human-to-human or human-to-computer interaction.

Kevin Ashton, cofounder and executive director of the Auto-ID Center at MIT, first mentioned the Internet of Things in a presentation he made to Procter and Gamble. Here's how Ashton explains the potential of the Internet of Things:

> *Today computers—and, therefore, the Internet—are almost wholly dependent on human beings for information. Nearly all of the roughly 50 petabytes (a petabyte is 1,024 terabytes) of data available on the Internet were first captured and created by human beings by typing, pressing a record button, taking a digital picture or scanning a bar code. The problem is, people have limited time, attention and accuracy—all of which means they are not very good at capturing data about things in the real world. If we had computers that knew everything there was to know about things—using data they gathered without any help from us—we would be able to track and count everything and greatly reduce waste, loss and cost. We would know when things needed replacing, repairing or recalling and whether they were fresh or past their best.*

A *thing*, in the Internet of Things, can be a person with a heart monitor implant, a farm animal with a biochip transponder, a car with built-in sensors to alert the driver when tire pressure is low or any other natural or man-made object that can be provided with an IP address and the ability to transfer data over a network.

IPv6's huge increase in address space is an important factor in the development of the Internet of Things. The address space expansion means that we could *"assign an IPV6 address to every atom on the surface of the earth, and still have enough addresses left to do another 100+ earths"*. In other words, humans could easily assign an IP address to every "thing" on the planet. This recent revolution of the IoT, which has given objects the possibility to exchange and gather information through and from the Internet, cannot be kept separated from the robotics research. A new generation of smart objects able to analyse the environment and interact with users in various manners and through various communicative channels has to be designed. This new population of smart entities connected with social robots would represent a sort of ecosystem on which social humanoids could act as the main interface thanks to their enhanced communicative capabilities.

Such a network will have the capability to analyse the human environment from various points of view extending the robot's perceptual capabilities. The fusion of the Internet of Things with emotionally and socially driven artificial intelligence for humanoids will bring robots to really become useful, increasing their acceptability by humans. This process is opening the opportunity to develop user-oriented scenarios (e.g., smart home/office [44]) in which an heterogeneous collection of objects becomes able to collect, exchange, analyse and convey information.

In summary, everything that we are using every day, such as laptops, cell phones, computers and other objects, and almost every place in which we live, e.g., airports, houses, offices and cities, are becoming "smart". We can say that we will live soon in a *Smart World*. Every part of this world will be identified with a unique ID and connected to the Internet, generating new information, continuously and without any need for our involvement. This leads to the well-known issue of the *Data Deluge* [45–47] that can be summarized, in addition to the obvious problems of security and privacy, in two simple questions—*Where can I store all this?*—but even more important—*What does it mean?*—that shall be read as—*How can it be useful for me?*. It is clear that to cope with such a huge dataset, we will need a middle layer, a filter or better an interface between human beings and the world of information. There must be some kind of artificial intelligence, something that we could consider as a personal artificial and intelligent butler who must be able to process all data about our house, our work and our everyday life activities, selecting what information is important now and here for a specific *me*.

At this point, an open question naturally arises: Is there a machine or an interface to deal with this work better than a Social Robot? This question should be answered considering that it is a high-tech object already endowed with the capability to read a wide range of signals and communicate naturally and emotionally, just as we do among human beings.

We believe that this could be an excellent opportunity for the future of Social Robotics.

References

1. Reeves B, Nass C (1996) The media equation: how people treat computers, television, and new media like real people and places. Cambridge University Press, New York, NY, USA
2. Hutson, M.: The 7 laws of magical thinking: how irrational beliefs keep us happy, healthy, and sane. Penguin (2012)
3. Breazeal, C., Scassellati, B.: f4 challenges in building robots that imitate people. Imitation in Animals and Artifacts 363 (2002)
4. Picard RW (1997) Affective computing. The MIT Press, Cambridge
5. Brooks RA, Breazeal C, Marjanovic M, Scassellati B, Williamson MM (1999) The cog project: Building a humanoid robot. In: Nehaniv C (ed) Computation for metaphors, analogy, and agents, vol 1562. Lecture notes in computer science. Springer, Berlin, Heidelberg, pp 52–87
6. Damasio A (1994) Descartes' error: emotion, reason, and the human brain. Grosset/Putnam, New York

7. Arkin RC, Mackenzie DC (1994) Planning to behave: a hybrid deliberative/reactive robot control architecture for mobile manipulation. Int Symp Robot Manuf Maui, H I:5–12
8. Murphy RR (2000) Introduction to AI robotics, 1st edn. MIT Press, Cambridge, MA, USA
9. Nilsson, N.J.: Shakey the robot. Technical Report 323, AI Center, SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025 (1984)
10. Brooks R (1986) A robust layered control system for a mobile robot. IEEE J Robot Autom 2:14–23
11. Arkin, R.C.: Behavior-based robotics. MIT Press (1998)
12. Giarratano JC, Riley GD (2005) Expert systems: principles and programming. Brooks/Cole Publishing Co., Pacific Grove, CA, USA
13. Jackson P (1986) Introduction to expert systems. Addison-Wesley Pub. Co., Reading, MA
14. Giarratano JC, Riley G (1998) Expert Systems, 3rd edn. PWS Publishing Co., Boston, MA, USA
15. Leondes CT (2001) Expert systems, six-volume set: the technology of knowledge management and decision making for the 21st century. Academic
16. Shortliffe EH, Davis R, Axline SG, Buchanan BG, Green CC, Cohen SN (1975) Computer-based consultations in clinical therapeutics: explanation and rule acquisition capabilities of the mycin system. Comput Biomed Res 8:303–320
17. Lindsay RK, Buchanan BG, Feigenbaum EA, Lederberg J (1993) Dendral: a case study of the first expert system for scientific hypothesis formation. Artif Intell 61:209–261
18. Rodriguez-Andina JJ, Moure MJ, Valdes MD (2007) Features, design tools, and application domains of fpgas. IEEE Trans Ind Electron 54:1810–1823
19. Fasang PP (2009) Prototyping for industrial applications [industry forum]. IEEE Ind Electron Mag 3:4–7
20. Salih JEM, Rizon M, Yaacob S, Adom AH, Mamat MR (2006) Designing omni-directional mobile robot with mecanum wheel. Am J Appl Sci 3:1831–1835
21. Magnenat S, Rétornaz P, Noris B, Mondada F (2008) Scripting the swarm: event-based control of microcontroller-based robots. In: SIMPAR 2008 workshop proceedings
22. Dorigo M, Floreano D, Gambardella LM, Mondada F, Nolfi S, Baaboura T, Birattari M, Bonani M, Brambilla M, Brutschy A et al (2013) Swarmanoid: a novel concept for the study of heterogeneous robotic swarms. IEEE Robot Autom Mag 20:60–71
23. Metta G, Fitzpatrick P, Natale L (2006) YARP: Yet Another Robot Platform. Int J Adv Rob Syst 3:43–48
24. Quigley M, Conley K, Gerkey BP, Faust J, Foote T, Leibs J, Wheeler R, Ng AY (2009) Ros: an open-source robot operating system. In: ICRA workshop on open source software
25. Natale L, Nori F, Metta G, Fumagalli M, Ivaldi S, Pattacini U, Randazzo M, Schmitz A, Sandini G (2013) The icub platform: A tool for studying intrinsically motivated learning. In: Baldassarre G, Mirolli M (eds) Intrinsically motivated learning in natural and artificial systems. Springer, Berlin, Heidelberg, pp 433–458
26. Mazzei D, Lazzeri N, Hanson D, De Rossi D (2012) Hefes: a hybrid engine for facial expressions synthesis to control human-like androids and avatars. In: 2012 4th IEEE RAS & EMBS international conference on biomedical robotics and biomechatronics (BioRob). IEEE, pp 195–200
27. Glas D, Satake S, Kanda T, Hagita N (2011) An interaction design framework for social robots. In: Proceedings of robotics: science and systems, Los Angeles, CA, USA
28. Breazeal C (2003) Emotion and sociable humanoid robots. Int J Hum Comput Stud 59:119–155
29. Breazeal C (2005) Socially intelligent robots. Interactions 12:19–22
30. Vernon D, Metta G, Sandini G (2007) The icub cognitive architecture: Interactive development in a humanoid robot. In: IEEE 6th international conference on development and learning. ICDL, pp 122–127
31. Vernon D, Sandini G (2010) Embodiment in cognitive systems: on the mutual dependence of cognition & robotics. In: Embodied Cognitive Systems. Gray, J. and Nefti-Meziani, S. pp 1–12
32. Qureshi F, Terzopoulos D, Gillett R (2004) The cognitive controller: a hybrid, deliberative/reactive control architecture for autonomous robots. In: Innovations in applied artificial intelligence. Springer, pp 1102–1111

33. Von Uexküll J (2014) Umwelt und innenwelt der tiere. Springer
34. Pfeifer R, Lungarella M, Iida F (2007) Self-organization, embodiment, and biologically inspired robotics. Science 318:1088–1093
35. Critchley HD, Wiens S, Rotshtein P, Öhman A, Dolan RJ (2004) Neural systems supporting interoceptive awareness. Nat Neurosci 7:189–195
36. Parisi D (2011) The other half of the embodied mind. Embodied and grounded cognition
37. Bosse T, Jonker CM, Treur J (2008) Formalisation of damasio's theory of emotion, feeling and core consciousness. Conscious Cognit 17:94–113
38. Damasio A (2010) Self comes to mind : constructing the conscious brain, 1st edn. Pantheon Books, New York
39. Mazzei D, Cominelli L, Lazzeri N, Zaraki A, De Rossi D (2014) I-clips brain: a hybrid cognitive system for social robots. In: Biomimetic and biohybrid systems. Springer, pp 213–224
40. Zaraki A, Mazzei D, Giuliani M, De Rossi D (2014) Designing and evaluating a social gaze-control system for a humanoid robot. IEEE Trans Hum-Mach Syst PP: 1–12 (2014)
41. Russell JA (1980) The circumplex model of affect. J Pers Soc Psychol 39:1161–1178
42. Mazzei D, Billeci L, Armato A, Lazzeri N, Cisternino A, Pioggia G, Igliozzi R, Muratori F, Ahluwalia A, De Rossi D (2010) The face of autism. In: The 19th IEEE international symposium on robot and human interactive communication (RO-MAN 2010). IEEE Computer Society publisher, pp 791–796
43. Cominelli L, Mazzei D, Pieroni M, Zaraki A, Garofalo R, De Rossi D (2015) Damasio's somatic marker for social robotics: preliminary implementation and test. In: Biomimetic and biohybrid systems. Springer, pp 316–328
44. Atzori L, Iera A, Morabito G (2010) The internet of things: a survey. Comput Netw 54:2787–2805
45. Bell G, Hey T, Szalay A (2009) Beyond the data deluge. Science 323:1297–1298
46. Hey AJ, Trefethen AE (2003) The data deluge: An e-science perspective. In Berman F, Fox GC, Hey AJG (eds) Grid computing - making the global infrastructure a reality. Wiley, pp 809–824 Chapter: 36
47. Anderson C (2008) The end of theory: The data deluge makes the scientific method obsolete

Soft Robotics

Matteo Cianchetti, Mariangela Manti, Marcello Calisti, and Cecilia Laschi

Abstract This chapter is organized into two main parts: the first one focuses on different applications of the casting technique for developing different soft robots; the second one is an overview of the manufacturing procedures employed in soft robotics. We don't have the ambition to cover the entire state of the art, but we aim to provide readers with guidelines to steer their research. Soft robots can be grouped into classes, according to their capabilities, as follows: locomotion, manipulation, and robots mimicking body parts (simulators). For each of these classes, we have identified key examples as means for describing the employed manufacturing procedure: (i) Locomotion—FASTT based on fiber-reinforced actuators; (ii) Manipulation—Octopus, STIFF-FLOP, Gripper that exploits different actuation strategies: cables, fluidic actuation combined with granular jamming and cable-driven under-actuation mechanism, respectively; (iii) Body parts simulator—Simulator of vocal folds that rely on the intrinsic mechanical properties of soft materials. The common denominator among these three classes is the design and prototyping of molds that replicate the shape of the robot. Molds could be made by common machinery (or also by traditional 3D printers) and were used as means for shaping the soft body.

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_6

1 Introduction

The increasing development of soft robotics technologies enables a new trend in the manufacturing processes and materials compatible with dedicated fabrication procedures employed for creating soft-bodied systems. Soft robots embed the main subsystems of a traditional robot, i.e., the actuation unit, sensors, and control units with the power source in their compliant body. In this configuration, soft matter creates the linkage between these components by adapting casting, laminated or adhesive techniques. On the contrary to traditional robots, soft ones-being made of compliant materials rely on non-traditional fabrication procedures, thus opening the doors to new challenges for designing and manufacturing soft robots. A smart combination of different soft materials into the desired shape is key to complete something able to face and negotiate different scenarios, exploiting its shape and intrinsic mechanical properties.

Traditional soft robots manufacturing techniques are casting, shape deposition manufacturing (SDM), and soft lithography [1, 2]. The most used, and traditionally also the simplest, is casting. This technique is not a soft-purpose fabrication method, and in fact, it was used for the first time more than 6000 years ago. It has several pros, such as high accuracy, a vast amount of different soft materials available, the speed of fabrication, and the fact that it is a well-known procedure. However, it also features several cons and difficulties: the casting of soft materials should be often performed under vacuum to expel undesired air bubbles; particular shapes are difficult to obtain through a mold; and curing must be accurately controlled, in particular, when it is performed in two or more steps (i.e., for example in the case of second casts to enclose additional components) [3]. Multi-material parts are common for soft robots, but sometimes they are physically unfeasible with this manufacturing process.

The other very common fabrication technology is the SDM. It is conceptually similar to additive manufacturing: a first layer of supporting material (which will be further removed) is placed onto the working space, then a layer of structural material is deployed and shaped (by using common machines, e.g., CNC milling). Later, another supporting substrate layer is placed, and the process goes on until the piece is completed [4]. Due to the layer-by-layer deposition, multi-material parts are extremely easily fabricated. Moreover, it is possible to easily embed stand-alone components, such as complex circuitries. SDM produces accurate pieces, but it suffers from a very long fabrication time, and the layer-to-layer connection is sometimes critical (and requires adequate heating of the previous layer).

Finally, soft lithography is used to produce soft robots with channels inside elastomeric materials. This is usually a two stages process where an open-channel part is extracted from a mold, and then it is cured onto a flat layer, which produces the final, closed-channel structure. The open-channel and the flat layer should be made of materials that allow reliable adhesion, and it is common to cure only partially the open-channel, and then to use prepolymer as adhesive between the two parts. This process requires appropriate infrastructures and skills, and moreover, since it uses a mold, is subject to the same limitation affecting casting.

This chapter is organized into two main parts: the first one focuses on different applications of the casting technique for developing different soft robots; the second one is an overview of the manufacturing procedures employed in soft robotics. We don't yearn to cover the entire state of the art but provide to reader's guidelines to steer his research.

2 Manufacturing Procedures for Soft Robots

Soft robots can be grouped into classes, according to their capabilities, as follows: locomotion, manipulation, and robots mimicking body parts (simulators). For each of these classes, we have identified key examples as means for describing the employed manufacturing procedure.

1. Locomotion—FASTT based on fiber-reinforced actuators.
2. Manipulation—Octopus, STIFF-FLOP, Gripper that exploits different actuation strategies: cables, fluidic actuation combined with granular jamming, and cable-driven under-actuation mechanism, respectively.
3. Body parts simulator—Simulator of vocal folds that rely on the intrinsic mechanical properties of soft materials.

The common denominator among these three classes is the design and prototyping of molds that replicate the shape of the robot. Molds could be made by common machinery (or also by traditional 3D printers) and were used as means for shaping the soft body.

2.1 Locomotion

2.1.1 FASTT

FASTT is a tetrapod robot that relies on the use of fiber-reinforced bending actuators for moving on different grounds. These elements consist of a core bladder reinforced with a strain-limiting layer and inextensible fibers. Due to the complexity of the actuator, the mold design of the actuator has to be done by taking into account the manufacturing procedure without overlooking the involved soft materials.

As mentioned in [5], the manufacturing procedure for developing fiber-reinforced actuators is completed into five steps, by involving specific components for each one, as follows:

1. *Core mold:* The core element of the actuator has a semi-cylindrical shape with an internal channel and it is made of soft matter.
2. *Strain Layer:* This is a key element of the actuator because checks and defines the actuator performances. The strain layer, placed on the base of the actuator,

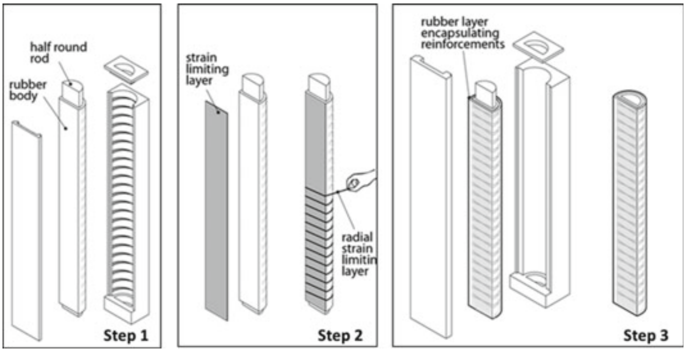

Fig. 1 Main steps for fabricating a single fiber-reinforced actuator. Adapted from Soft robotics toolkit

is made of an inextensible material in order to prevent and avoid its lengthening during the inflating phase.

3. *Fiber reinforcement:* An extensible kevlar thread is wrapped around the actuator (made of the semi-cylindrical chamber with the inextensible layer). The wire line draws a path that avoids lateral expansion of the chamber during the inflating phase. It allows to steer the energy in the desired direction.
4. *External skin:* A thin external layer of soft material is poured on the fiber reinforcement in order to encapsulate the wire to the underlying body within the entire actuator.
5. *End-caps:* The chamber is closed plugging-in the two end-caps at both ends. One of them is equipped with a hole for the connection to the air source.

The manufacturing procedure is multiphase; the single actuator ideally takes long time but you can make multiple actuators in parallel. The fabrication procedure is summarized in the following three steps (see Fig. 1, adapted from soft robotics toolkit[1]):

Step 1: casting of the actuator's body into a dedicated mold;
Step 2: wrapping fiber around the actuator;
Step 3: casting a bottom layer of silicone to embed the fabric to the actuator's body.

The fiber-reinforced actuators are highly adaptable to different movements. The secret in the manufacturing process; in particular, in the strain-limiting components of the actuator (the inextensible layer and fibre wrapping). By changing the configuration of the inextensible layer and the arrangement of the fiber reinforcement, different bending motions can be achieved: bending, extension, and twisting (Fig. 2). Moreover, starting from these actuation modes, a more complex and custom actuator might come out by combining them along the actuator length. It's fantastic because

[1] https://softroboticstoolkit.com/.

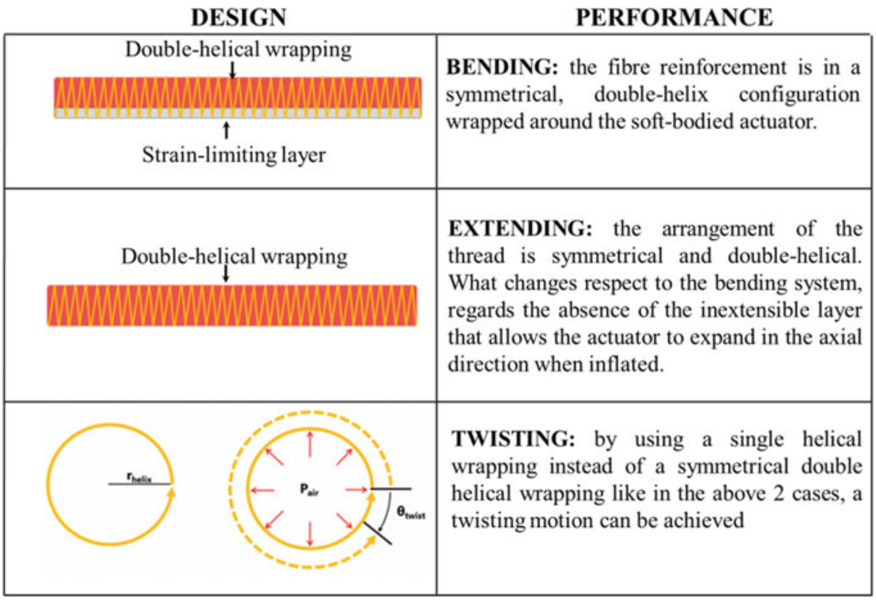

Fig. 2 Bending, extending, and twisting actuators

you don't need additional elements to arrange them into a smart configuration for this purpose.

Another technical parameter that can be changed during the designing and manufacturing phase of the soft actuator is the morphology of the air chamber. Different designs can be experienced as follows: circular, rectangular, and semi-circular. It means that we can finalize the actuator shape according to the expected motion.

The circular actuator is capable of applying the highest bending torque for a given pressure, but it also has a high resistance to bending, making it the least efficient system among the three shapes. The rectangular and semi-circular shapes have roughly similar efficiency. However, the rectangular cross-section deforms into a quasi-circular shape when pressurized, while the other two cross-section types maintain their original shapes.

In addition, by changing the material whose the actuator is made of, different performances can be obtained. Actually, the Dragon Skin (Smooth-On Inc.) series has been selected to make the soft-bodied actuator; the suitable material should rely on a trade-off between softness and hardness for the actuation performances. As a consequence, different silicones (Dragon Skin 30, Dragon Skin 10 Medium) can be used during the manufacturing phase, according to the required features.

The outer skin layer, for embedding the fiber reinforcement, has been made with a more soft material such as EcoFlex 20 or Dragon Skin 20. The low elasticity of the silicone allows to compact the design without altering the actuation performances due to the stiffness variation of the material.

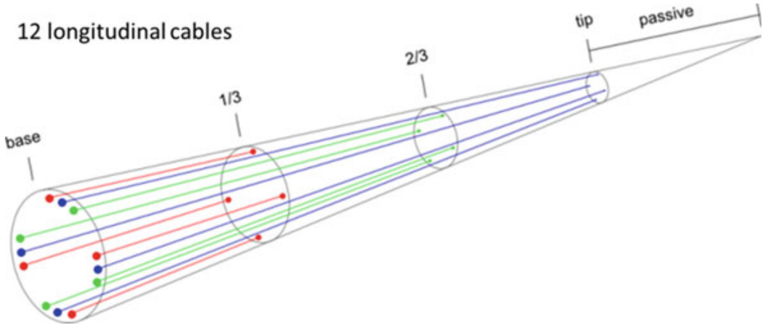

Fig. 3 Sketch of the soft arm showing the arrangement of the cables within the soft body

2.2 Manipulation

2.2.1 Octopus

Different technologies have been used to carry out biologically-inspired soft robots, by mimicking both the soft-bodied structure and the actuation elements. The manufacturing process involved in the development of soft arms OCTOPUS-like is manual and multi-steps, based on casting procedure due to the need of embedding active elements into the soft body.

The starting point of the arm fabrication requires a mold that replicates the arm shape where the soft material is poured. This has been designed taking into account both the desired final shape and also the removing phase of the mold with respect to the total length of the arm. As shown in the picture (Fig. 3), the arm has a conical body shape that is 450 mm in length, where 12 longitudinal cables were lodged [6].

Cables are arranged along the arm and they are anchored in a group of four at different levels (1/3, 2/3 and tip with respect to the total length), as a consequence, we designed a multi-section mold with variable cross-section along its length. The proximal portion of the arm where cables come out is rigid and filled with silicone, as shown in Fig. 4

Another expedient that we introduced during the prototyping phase regards how to interface the actuation cables with the silicone body. The active cables, after few cycles, can damage the arm by cutting the silicone. In order to avoid this issue, we inserted cables inside silicone guides where the cable can freely move, without moving along the entire body. The external guide is perfectly engaged to the arm and cutting stresses are mitigated, thus preventing relative movements between the two parts.

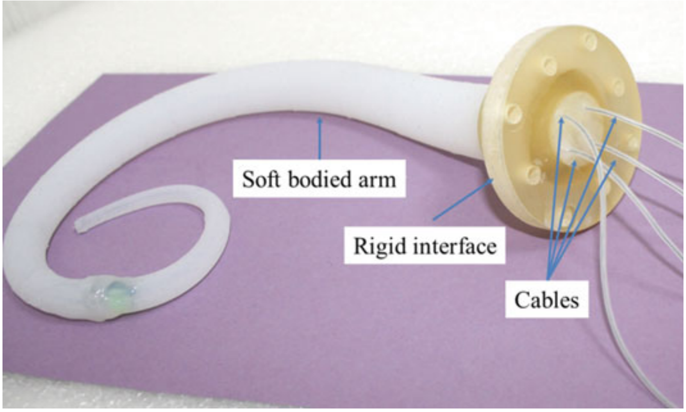

Fig. 4 A cable-driven soft arm prototype

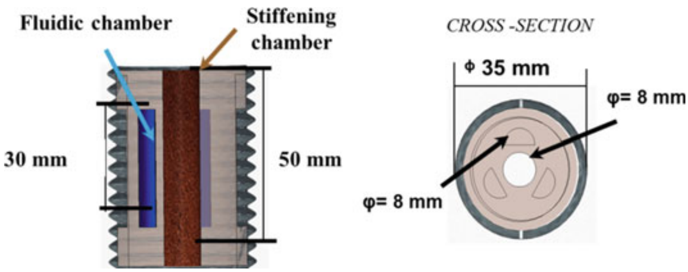

Fig. 5 Stiff-flop module design [7]

2.2.2 Stiff-Flop

The STIFF-FLOP surgical manipulator is a modular manipulator for minimal access surgery. It is ideally composed of repetitive units with the same structure and functionalities, which are integrated together with rigid interfaces. The basic element is a soft module (Fig. 5) that combines three flexible fluidic actuators placed at 120° for guaranteeing omnidirectional bending and elongation capabilities with a central channel for the granular jamming chamber. This latter implements stiffness changing.

Granular Jamming One of the main challenging aspects of a soft robot is its capability of changing and adapting its stiffness with respect to the environment. For this purpose, in the soft robotics field, particular attention has been focused and devoted to the investigation and elaboration of new solutions and technologies for this purpose. Among the suitable strategies, researchers thought to embed a granular jamming-based solution for providing a variable stiffness to the STIFF-FLOP manipulator. The jamming phenomenon has gained attention from roboticists due to its capability of enabling a reversible transition between a fluid-like to a solid-like material, just acting on the boundary conditions of the system. Vacuum triggers the stiffness variation of the soft body with no volume variation, due to an isometric (in an efficient system) modification. There exist two systematic approaches to the jamming activation: granular and layer jamming. The global effect is the same for both configurations, they differ for the matter involved in the system (particles and sheet, respectively) and how these interact. In the STIFF-FLOP endoscope, they used an internal chamber jamming-based for changing and adapting the stiffness to the environment. Even if the macroscopic effect of the jamming phenomenon is simple, because it is given by a phase transition of the matter, at the microscale the mechanism is a complex combination of multiple effects. In the last ten years, scientists focused on modeling the phenomenon through constitutive laws [8] and state equations [9] for describing physical effects [10]. Moreover, despite the investigation from a physics standpoint, more comprehensive studies have been carried out by researchers on the role played by the structural elements (particle shape, friction, density and number of particles, the role played by the membrane) [11, 12] that promote the transition from a fluid-like to a rigid-like behavior, by interacting. Up to now, we experienced that coffee grounds work well with a latex membrane due to the relative friction between constituents.

Authors have developed and experienced three different fabrication techniques for the stiff-flop module, each one is contextual to the dimension of the module and arrangement of its components within it. In the following section, we will provide a schematic view of the three manufacturing methods for each generation of prototypes.

2.2.3 Manufacturing Procedure I

The manufacturing procedure (Fig. 6), entirely manual, is based on the use of molds designed with CAD software. Referring to the detailed documentation in [13], a single module derives from seven sequential steps

1. Preparation of the silicone for the module
2. The fabrication of the silicone module begins with the assembly of the dedicated mold and a first silicone casting phase, for building the actuation chambers. After that, the mold is rearranged for completing the silicone module itself. At this stage, the representative element is built: it has three equally spaced pneumatic chambers, equipped with the tube hole for the inflation phase through the air source, and the internal channel to host the membrane for the granular jamming mechanism
3. Insertion of the tube to the pressurized chambers by using silicone glue to link the cured silicone with the external surface of the tube
4. Preparation of the crimped braided sheath in order to obtain a bellows-type structure, as shown in [13] to be used as lateral constraint. The containment structure is obtained by applying to the sheath a mechanical deformation in the vertical direction and by saving the permanent deformation with a thermal treatment

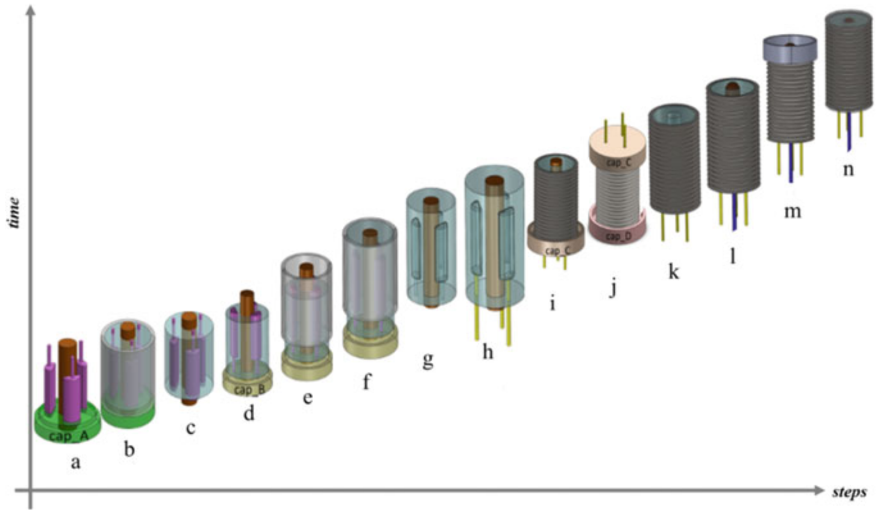

Fig. 6 Manufacturing procedure I for the single module. Insertion of the chambers and the stiffening cylinder into cap_A (**a**), first silicone casting (**b**), removal of shells and cap_C (**c**), introduction of cap_B (**d**), reposition of the shells (**e**), second silicone casting (**f**), removal of shells, cap_B and chambers (**g**), insertion of the tubes (**h**), insertion of cap_C and sheath for its fixing on the bottom side (**i**), insertion of cap_D and sheath for its fixing on the top side (**j**), removal of cap_D and stiffening cylinder (**k**), insertion of the granular jamming membrane (**l**), closing of the semi-rings around the module (**m**), final module (**n**) [14]

5. The external sheath is wrapped around the silicone module and embedded into the soft-bodied element by using silicone
6. Fabrication of the granular jamming membrane using a dedicated mold and commercial latex
7. After curing, the membrane is filled with granular matter, inserted into the central channel, and connected to the hosting site through silicone glue

2.2.4 Fabrication Procedure II

The second generation of STIFF-FLOP prototypes has been fabricated by using the 3D printing method. It uses rigid material (Vero White Plus RGD835) combined with a rubber-like material (Tango Plus FLX930). The basic idea is to replicate the pneumatic chambers with a compliant material constrained into a rigid cylinder. Different design patterns have been tested in order to obtain the same bending performances, thus overcoming possible fragilities introduced during the multi-step procedure (Fig. 7).

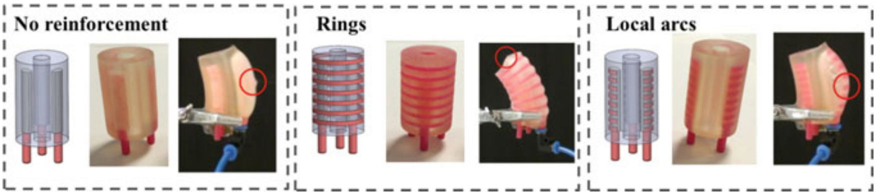

Fig. 7 Manufacturing procedure II for the single module. Vero White Plus RGD835 printed together with Tango Plus FLX930

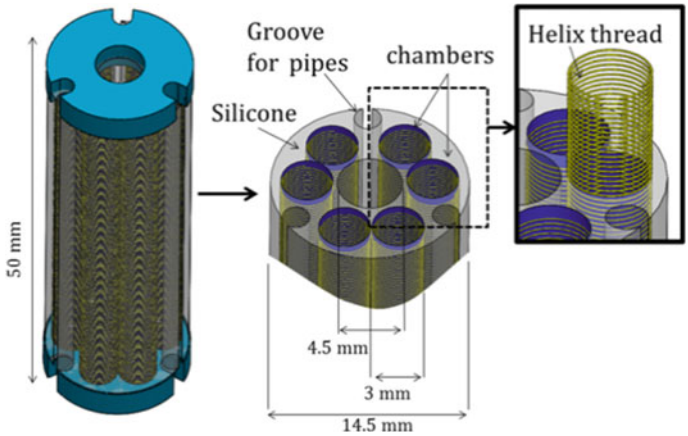

Fig. 8 Miniaturized version of the STIFF-FLOP module

2.2.5 Fabrication Procedure III

The final STIFF-FLOP module has been miniaturized in order to address the technical requirements for a surgical endoscope. It implies that the manufacturing procedure has been revised and adapted to this improved final version shown in Fig. 8.

The third manufacturing procedure experimented by the authors pours silicone into dedicated molds, thus requiring multiple steps (Fig. 9). Firstly, chambers are made by wrapping a thread around an internal core; they are later placed inside the mold, thus confining the silicone body. After that, the second mold for creating the inner layer of silicone is inserted; as the last step, the module is confined with the caps where pipes are fixed.

2.2.6 Gripper

The casting procedure has been employed for making three different generations of soft fingers, in order to meet and satisfy the technical requirements involved in manipulation tasks. In particular, the soft-bodied finger has to be both structurally

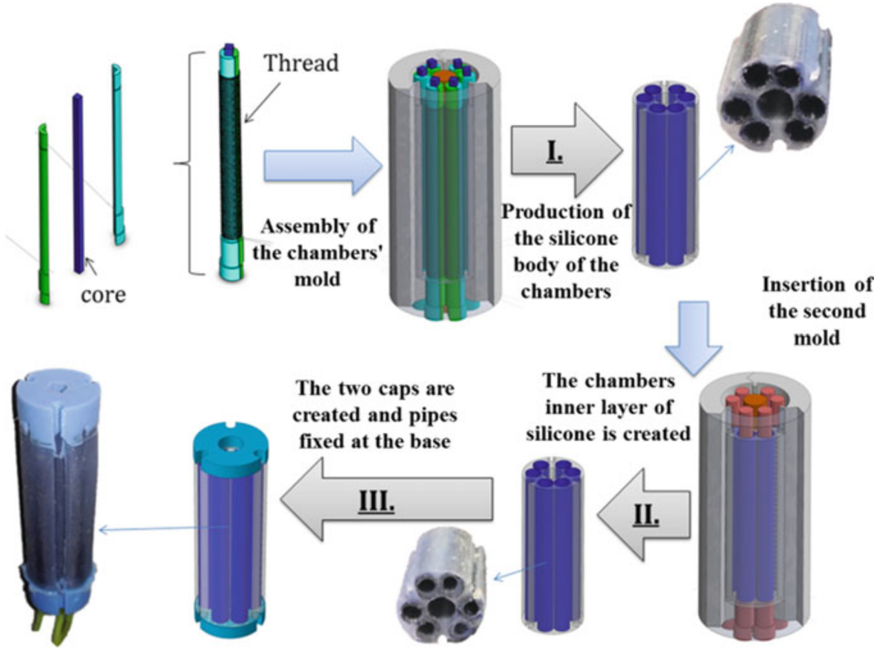

Fig. 9 Manufacturing procedure III for the miniaturized version of the STIFF-FLOP module

rigid and soft for adapting to the surface without damaging the object. We will explain the three design and fabrication procedures, going through the first prototype up to the optimized one, in terms of soft material (Fig. 10). The common denominator among these elements is the use of a finger mold with embedded cables, for recreating holes in the polymerized version that will host the actuation cable.

Soft finger version 1: This finger is entirely made of Dragon Skin 30 (Smooth-On Inc.) and it embeds a spring on the upper portion of the finger. Firstly, this finger is entirely made of Dragon Skin 30 (Smooth-On Inc.) and it embeds a spring on the upper portion of the finger. Firstly, silicone is poured into the phalange's section and polymerized. After that, we put the spring on the dorsal portion of the structure and then we have covered it with additional silicone, thus filling the mold, silicone is poured into the phalange's section and polymerized. After that, we put the spring on the dorsal portion of the structure and then we have covered it with additional silicone, thus filling the mold.

Soft finger version 2: The second finger has been entirely made in Smooth-Sil 950 (Smooth-On Inc.); it being more rigid, is able to confer structural stability to the finger, thus allowing it to remove the spring on the upper side.

Soft finger version 3: The last finger version derives from a combination of the previous two soft materials. In particular, we used the Dragon Skin 30 for the phalanges, while the Smooth-Sil 950 for the dorsal portion.

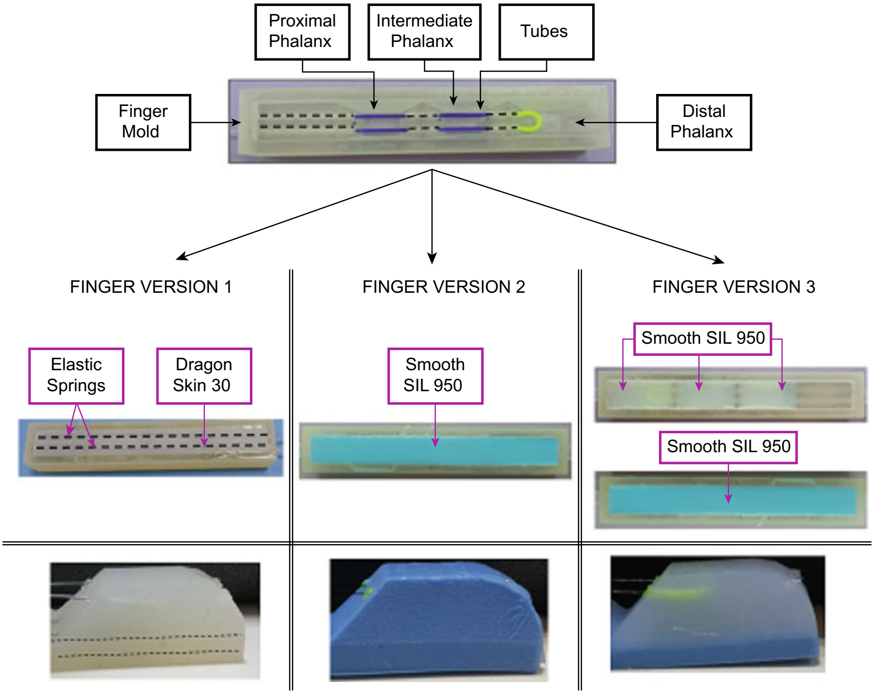

Fig. 10 The three versions of the soft finger. (1) Dragon Skin 30 with elastic springs; (2) Smooth-Sil 950; (3) Dragon Skin 0 in combination with Smooth-Sil 950 [15]

2.3 *Body Parts Simulator*

2.3.1 Vocal Folds

Biological vocal folds are made of soft tissues that are arranged on three levels, with different geometry and mechanical properties (Fig. 11). In order to meet the biological requirements of the natural vocal folds, in terms of viscoelastic properties, and the geometrical ones, we mainly focused on the identification of suitable soft materials to make the soft structure and on the design of an ad hoc casting procedure to build the multi-layered physical counterpart.

We faced a double challenge: the first one regarding the identification of the suitable elastomers for the present purpose; the second one consists of the design and development of the multiphase casting procedure, driven by the final shape of the system.

The vocal fold CAD model was used to create 3D printed molds for the fabrication procedure of the layered structure. We have used a fixed framework as support, combined with the dedicated changeable elements to produce the cover, ligament, and body portion, respectively.

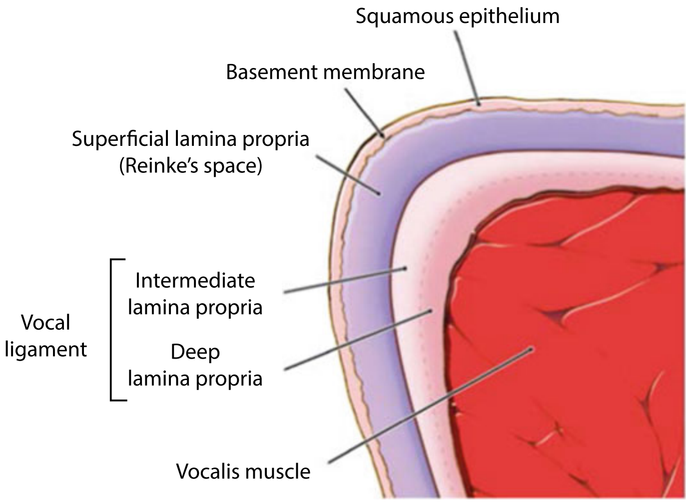

Fig. 11 Coronal section through the free edge of the vocal fold, demonstrating the layered microanatomical structures that allow vibration [16]

As shown in Fig. 12, we started from the external layer of the vocal fold, representing the cover that undergoes vibrations during the oscillation phase. After the curing time for the cover section, we have removed the cover layer mold and we have inserted the ligament layer. This phase has to be carefully done in order to guarantee a constant adhesion of the first layer to the external fixed framework. The last step regards the body layer manufacturing. We remove the ligament layer mold and insert the body one in order to confine the internal section. After pouring the proper silicone, the vocal fold is ready and can be removed from the mold. Thanks to this guided and accurate manual multiphase manufacturing procedure, we are able to have a direct control on the shape of the single layer, without introducing an excess of material or irregular shapes.

Each color corresponds to a portion of the multilayer vocal fold, with an accurate reproducibility level with respect to the anatomical layered structure. The ability to maintain, as much as possible, the dimension of the original shape is mandatory for obtaining vibration performances close to the biological model [15].

3 Manufacturing Strategies for Soft/rigid Interface

To the best of our experience, the multiphase casting procedure has been well strengthened; it allows to build multi-material body parts by embedding the actuation/sensing unit in the robot's body. Despite that, the multiphase casting procedure has constraints, especially when the soft matter has to be linked with a rigid frame: this aspect still represents an open issue. For this purpose, challenging and complex

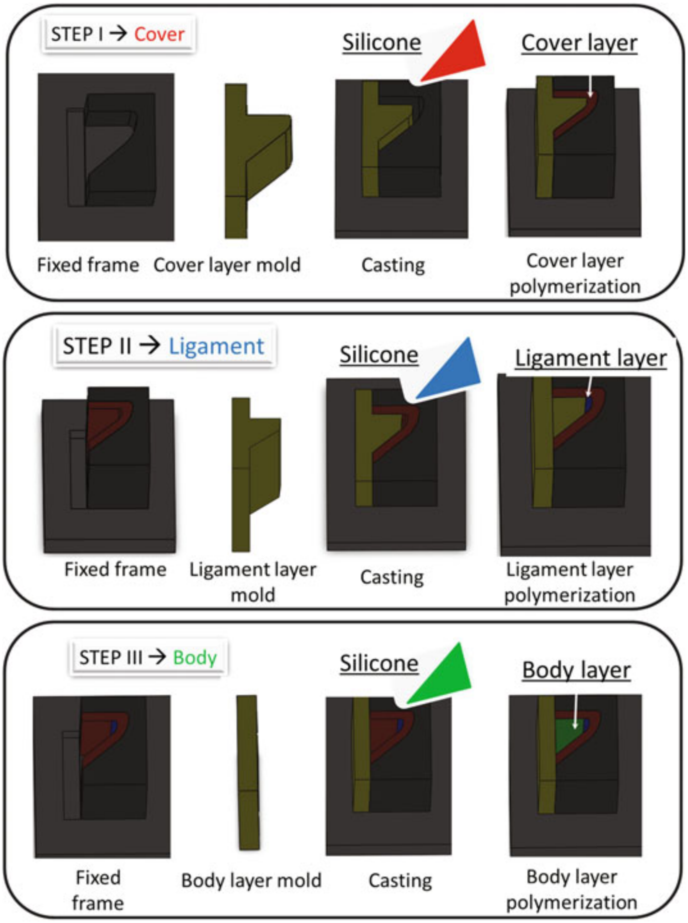

Fig. 12 The three main phases of the casting procedure for the multilayer vocal folds. **a** Cover layer, **b** ligament layer, **c** body layer casting procedure. The vocal fold CAD model with the layered structure with the silicone prototype

fabrication processes and interfacing techniques are required. The problem can be partially overcome by designing *ad hoc* smart features on the rigid frame that allow the soft material of anchoring itself to it by increasing the adhesion between the two parts. This methodology stands as a first attempt and produces a soft/rigid interface which is not stable, especially if the connection undergoes cyclic stresses and fatigue. In this view, multi-materials 3D printers are showing promising features by establishing a new trend for the manufacturing of soft robots.

4 Soft 3D Printing

Soft robotics changed the archetype of robot in many ways. Robot's body morphed from the classical metallic, machine-like body to a wide spectrum of compliant blob-like, amoebe-like, worms, octopus, fish, and many more *like* shapes. Mechanical design methodology changed from traditional approaches to integrated body-behavior evolutionary design methods [17], where the soft matter plays a fundamental role. Actuators always act also as structural elements [18], and the interaction among deformable bodies, actuation strategies, and environmental forces should be taken into account to obtain different behaviors yet without increasing control complexity beyond a manageable level [19]. Eventually, this paradigm shift generates amazing different designs, ranging from bioinspired to complex evolved ones [20].

Such huge diversity evokes novel fabrication methods which could satisfy designer dreamed morphologies. Luckily, a powerful, flexible, and cheap method is rapidly rising in the manufacturing domain, and it could shine on soft robots too: it is the additive manufacturing, also known as 3D printing. Although the majority of the 3D printers are devoted to the fabrication of rigid materials (such plastics, resins, metals or alloys), there are specific printers which can produce also rubber-like objects. This fabrication method, in particular for soft robots, is quite young and it is starting right now to expose its full potential.

Additive manufacturing solves most of the problems of the other fabrications methods (i.e., casting, soft lithography, and SDM). Multi-materials 3D printers blend two resins to obtain materials which can range from rubber-like soft skins to ABS-like plastic components. Moreover, the transaction among materials with different elastic modules can be almost continuous, allowing to explore the whole spectrum of nonlinear stress–strain relationships [21, 22]. However, although the additive manufacturing allows complex multi-material designs, it limits the number of different materials that can be used. Another significant limitation of additive manufacturing is the high cost of the materials and of the printing machines. We envisage that both these limitations will be mitigated as the technology will further progress, and multi-material 3D printers will be commonly available in the next future.

In the next sections, we are going to introduce the most popular 3D printers, then the soft materials currently used, and finally we will illustrate two significant use cases, which represent two applications of 3D soft-printing.

4.1 Multi-material 3D Printers

Single material 3D printers are now very common, and the cheapest printer can cost less than 100 euros. Conversely, multi-material 3D printers are still rare and expensive, and also very few can print soft materials. The two most renowned printers currently available belong to Stratasys and 3D Systems companies.

The first one is the Stratasys Objet Connex printer series. It was the first 3D printer class that used a gamut of diverse materials which can produce also soft objects. It uses a proprietary material of the Tango family, and it blends up to three different kinds of resins to obtain variable stiffness. The base materials, Table 1, can be combined in several ways to produce a gamut of elastic properties.[2]

The second one is the 3D Systems Projet 5500X. It uses a VisiJet®composite material which can be used to produce ABS-like, Rubber-like or Polycarbonate-like materials. Also, in this case, it is possible to blend the materials to obtain ad hoc characteristics: the base material properties can be inspected in Table 2, while the composite ones can be obtained from the producers website.[3]

Both printers work with UV curable materials. The working principle is very similar to one of the FDM printers, however, the deposited materials require UV light to cure, but this technology produce printed pieces with extremely thin layers whose definition can be compared with the one obtained by lithography. The working principles are reported in Fig. 13.

It is essentially the same process as FDM, with the main difference that an additional passage is required to cure the deposited material. The reported 3D printers integrate the UV lamp (one or two lamps) close to the extruder, so that the time from deposition to cure is reduced.

Along with the commercial solutions, a few research groups are trying to develop multi-material printers that are affordable yet as versatile as the professional ones. MIT, Chulalongkorn University, and Tsinghua University are developing a multi-material 3D printer. This printer is remarkable since it features more than 10 different materials which can be mixed together (compared to the low number of materials proposed by the other commercial solutions). Moreover, the developers claim that the production cost will be quite competitive, around 7000 USD [23].

4.2 Soft Materials for 3D Printers

It is worth mentioning that multi-material printers are not the only way to digitally fabricate soft robots. Specifically, an alternative approach is to use rubber-like soft materials that can be printed with traditional 3D printers. This approach is followed by NinjaFlex, Lay-series filament, Soft PLA, PolyMaker PolyFlex, Flex TPU, and many others.

While these filaments have fixed stiffness, they have the undebatable advantage of working with low-cost 3D printers. Considering that most of the printer producers are also proposing multi-extruder printers, this could be a cost-effective solution when design constraints are not extremely demanding. The most commonly reported problem, however, is that such filaments—as they derive from the viscoelastic characteristic of the material—can, in awful situations, occlude the extruder.

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[2] www.stratasys.com.

[3] http://www.3dsystems.com/materials/professional.

Table 1 Rubber-like material available for the Objet Connex

TANGOBLACKPLUS FLX980 and TANGOPLUS FLX930					
	ASTM	UNITS	METRIC	UNITS	IMPERIAL
Tensible strength	D-412	MPa	0.8-1.5	psi	115–220
Elongation at break	D-412	%	170–220	%	170–220
Comprenssive set	D-395	%	4–5	%	4–5
Shore Hardness (A)	D-2240	Scale A	26–28	Scale A	26–28
Tensile Tear resistance	D-624	kg/cm	2–4.	Lb/in	18–22
Polymerized density	ASTM D792	g/cm^3	1.12-1.13		
TANGOBLACK FLX973					
Tensible strength	D-412	MPa	1.8-2.4	psi	115–350
Elongation at break	D-412	%	45–55	%	45–55
Comprenssive set	D-395	%	0.5-1.5	%	0.5-1.5
Shore Hardness (A)	D-2240	Scale A	60–62	Scale A	60–62
Tensile Tear resistance	D-624	kg/cm	3–5	Lb/in	18–24
Polymerized density	ASTM D792	g/cm^3	1.14-1.15		
TANGOGRAY FLX950					
Tensible strength	D-412	MPa	3–5	psi	435–725
Elongation at break	D-412	%	45–55	%	45–55
Comprenssive set	D-395	%	0.5-1.5	%	0.5-1.5
Shore Hardness (A)	D-2240	Scale A	73–77	Scale A	73–77
Tensile Tear resistance	D-624	kg/cm	8–12	Lb/in	50–60
Polymerized density	ASTM D792	g/cm^3	1.16-1.17		

Table 2 Base material properties of the 3D Systems ProJet 5500X

Properties	ASTM	Base materials		
Material Name		VisiJet CR-WT	VisiJet CR-CL	VisiJet CF-BK
Description		Rigid ABS-like	Rigid Polycarb-like	Flexible Rubber-like
Appearance		White	Clear	Black
Cartridge Quantity kg		2	2	2
Density@ 80°C (liquid), g/cm^3	D-4164	1.04	1.04	1.04
Tensile Strength, MPa	D-638	56	56	2.2
Tensile Modulus, MPa	D-638	2400	2400	0.7
Elongation at Break, %	D-638	8.1	13	290
Flexural Strength, MPa	D-790	74	75.00	0.5
Flexural Modulus, MPa	D-790	2500	2500	5.5
Heat Deflection Tmp.@ 0.45 MPa, °C	D-648	54	54	n/a
Impact Strength (Notched Izod), J/m	D-256	18	18	n/a
Shore Hardness (A), Scale A	D-2240	n/a	n/a	63
Shore Hardness (D), Scale D	D-2241	83	83	n/a
Glass Transition, Tg °C	DMA, E°	43	43	n/a

4.3 3D Printing Applications

Although the vast majority of soft robots are still fabricated with traditional methods, the adoption of additive manufacturing raises interesting possibilities. Among the already cited practical advantages, there are also unique designs that can be realized only with additive manufacturing technologies. Here, we present two use cases that describe, respectively, the high-fidelity reproduction of multi-material, compliant objects, and the design process which relies on continuum variation of the material properties.

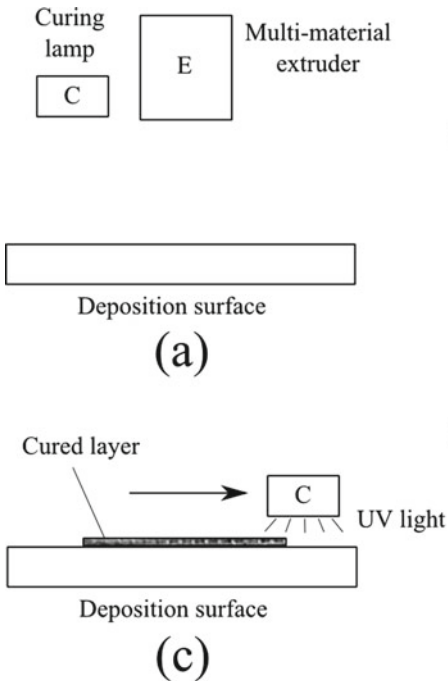

Fig. 13 Working principle of UV curable additive manufacturing: in addition to the extruder, the 3d printer also uses a curing lamp **a** to print an object, a first layer is deposited over the deposition surface by the extruder **b** while a UV lamp cures the layer (**c**), then the next layer is deposited possibly onto the previous one (**d**) and the cycle is repeated until the object is finished

4.3.1 Prototyping of Soft Objects

Unleashing the full potential of multi-material 3D printing will allow us to accurately replicate compliant objects with nonlinear behaviors. A seminal example of this application is presented in [21]. Basically, the authors knew the strain/stress curve of the desired object for several spot locations, and they had a library with several strain/stress curves for different base materials. By comparing the behavior of a single spot on the object with the materials' library, they found the appropriate material for each voxel of the digital model. Noticeably, an overall mesoscale nonlinear behavior can be approximated by the behaviors of diverse basic materials at a microscale (i.e., printed by Objet Connex). To print the final object, the authors followed several steps. In the first one, a generic material is represented by the linear relationship:

$$\sigma(u) = E\epsilon(u) \tag{1}$$

where E is a 6×6 matrix which relates the stress and strain vectors, while u is the displacement field. The trick to obtain a nonlinear behaviour is to explicitly define the stress–stress relationship E as a function of the local strain:

$$E = E(\epsilon(u)) \tag{2}$$

Simulated deformations, with finite element method (FEM), of the modeled material were compared with actual experiments on base materials to find the properties, $E(\epsilon(u))$, which furnishes the optimal matching.

Once the base materials are correctly modeled, a combinatory optimization algorithm is used to search the best microscale arrangement of the base materials which produces a desired mesoscale deformation. Similar to the previous step, a FEM model is simulated with a particular design (design means, in this case, material selection and distribution), and the force-displacement behaviour is compared with actual experiments on the target object. Once the best design is found, a volumetric model comprising position and properties of the material is obtained, which can be directly used as input in the additive manufacturing machine.

A final evaluation is performed comparing the printed and the target object, which proves a quite good reproducibility of multi-material, compliant objects. The readers interested in details should refer to Bickel et al. [21].

4.3.2 Exploiting Soft Material Variation in the Design

While in the first use-case, the 3D printer was used to replicate the material behaviour of a known object, it is possible also the converse case: to simulate a desired behaviour which should be used as design target, and then to build the actual prototype. Additive manufacturing allows to exploit local deformation of soft robots to optimize certain characteristics of manipulating or moving robots.

In particular, in [22] was studied the distribution of nine levels of different stiffness to optimize the performance of a jumping soft robot. The performance was evaluated as the length of the jump and reaction force on landing. The robot was made of two principal components: a deformable membrane that allows to push the ground and jump, connected to a semi-spherical top which can be made of different materials. The authors tested three different designs of the semi spherical top: a completely rigid one, an almost completely soft one, and a gradient-based one. Examples of the robots are depicted in Fig. 14.

The simulations of the robots were performed initially with finite element analysis (FEA), with nonlinear characterization of the constituent materials performed by mechanical testing on Instron 5544. Then prototypal counterparts were built with Objet Connex 500.

Both simulations and experimental results with the robot demonstrate that the rigid top allows for longer jump than soft counterparts, however, the landing provokes significant damages to the robot structure. Conversely, despite reducing the

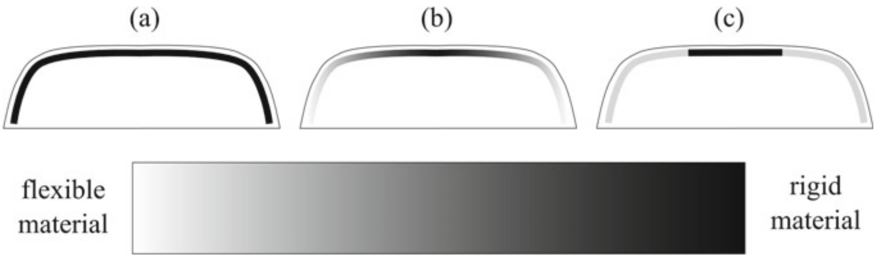

Fig. 14 Three different designs were tested for the top part of the jumping robot: a fully rigid top (**a**), a gradient-based top (**b**), and a center-rigid edge-flexible top (**c**). The gradient-based top provides a trade-off among jumping efficacy and robot robustness

performance of the locomotion, gradient-based top allows to significantly reduce the damage at the impact of the robot, that performed several jumps (more than the double of the rigid counterpart) without damages.

This paper presents a remarkable use of additive manufacturing technology that incorporates a *compliant gradient* in the design itself. Such, almost continuous, property change can be exploited only if a fabrication method allows to reproduce easily and reliably the material distribution and properties. To this purpose, additive manufacturing could be a paradigm shift of soft robots fabrication, which will impact not only the physical realization of the prototype, but also the very design principles.

5 Conclusion

The present chapter gives an overview of the manufacturing processes currently used for the development of soft robots; and different approaches and techniques that have been enabled by recent advances in this field. We also reviewed the state-of-the-art manufacturing techniques used to create robots at a nano and microscale, that do not scale well into systems that work with the meter scale and vice versa. Conversely, the soft 3D printing technology is still unable to deliver elastomer materials with mechanical properties close to those produced with the poured rubber technique. However, the ability to print very soft materials together with ad hoc designs based on material blending opens novel opportunities for soft robot designers and gives a chance for proper exploitation of soft bodies. A multi-material 3D printing machine removes the mold stage, reducing design-to-prototype time and increasing design space. Soft robotics is walking toward a new era of advanced *robotic materials* that will be able to embed sensors, actuators, computing and communication elements.

References

1. Rus D, Tolley MT (2015) Nature 521(7553):467
2. Cohen E, Vikas V, Trimmer B, McCarthy S (2015) In: International design engineering technical conferences and computers and information in engineering conference, vol 57137. American Society of Mechanical Engineers, vol 57137, p V05BT08A015
3. Arienti A, Calisti M, Giorgio-Serchi F, Laschi C (2013) In: 2013 OCEANS-San Diego. IEEE, pp 1–7
4. Merz R, Prinz F, Ramaswami K, Terk M, Weiss L (1994) In: 1994 international solid freeform fabrication symposium
5. Ansari Y, Shoushtari AL, Cacucciolo V, Cianchetti M, Laschi C (2015) In: Conference on biomimetic and biohybrid systems. Springer, pp 13–25
6. Calisti M, Arienti A, Giannaccini ME, Follador M, Giorelli M, Cianchetti M, Mazzolai B, Laschi C, Dario P (2010) In: 2010 3rd IEEE RAS & EMBS international conference on biomedical robotics and biomechatronics. IEEE, pp 461–466
7. Ranzani T, Gerboni G, Cianchetti M, Menciassi A (2015) Bioinspirat Biomimet 10(3):035008
8. Forterre Y, Pouliquen O (2008) Ann Rev Fluid Mech 40:1
9. Mills P, Snabre P (2009) Eur Phys J E 30(3):309
10. Goren L, Aharonov E, Sparks D, Toussaint R (2011) Pure Appl Geophys 168(12):2289
11. Zhang J, Majmudar T, Sperl M, Behringer R (2010) Soft Matter 6(13):2982
12. Jiang A, Ranzani T, Gerboni G, Lekstutyte L, Althoefer K, Dasgupta P, Nanayakkara T (2014) Soft Rob 1(3):192
13. Ranzani T, Cianchetti M, Gerboni G, De Falco I, Menciassi A (2016) IEEE Trans Rob 32(1):187
14. De Falco I, Gerboni G, Cianchetti, A. Menciassi, J Vis Exp: JoVE (105) (2015)
15. Manti M, Hassan T, Passetti G, d'Elia N, Cianchetti M, Laschi C (2015) In: Conference on biomimetic and biohybrid systems. Springer, pp 64–74
16. Simpson B, Rosen C (2008) Operative techniques in laryngology, pp 3–8
17. Corucci F, Calisti M, Hauser H, Laschi C (2015) In: Proceedings of the 2015 annual conference on genetic and evolutionary computation, pp 145–152
18. Cianchetti M, Calisti M, Margheri L, Kuba M, Laschi C (2015) Bioinspir Biomim 10(3)
19. Calisti M, Corucci F, Arienti A, Laschi C (2015) Bioinspir Biomim 10(4):046012
20. Cheney N, MacCurdy R, Clune J, Lipson H (2014) ACM SIGEVOlution 7(1):11
21. Bickel B, Bächer M, Otaduy MA, Lee HR, Pfister H, Gross M, Matusik W (2010) ACM Trans Gr (TOG) 29(4):1
22. Bartlett NW, Tolley MT, Overvelde JT, Weaver JC, Mosadegh B, Bertoldi K, Whitesides GM, Wood RJ (2015) Science 349(6244):161
23. Sitthi-Amorn P, Ramos JE, Wangy Y, Kwan J, Lan J, Wang W, Matusik W (2015) ACM Trans Gr (Tog) 34(4):1

Autonomous Service Robotics

Michelle Viscaíno, Javier Romero, and Fernando Auat

Abstract Autonomous robotics emerged as a research and development field nearly forty years ago, but only fifteen years ago, after the DARPA (Defense Advanced Research Projects Agency of the United States Department of Defense) challenge, autonomous mobile systems started to be considered as a solution to the transportation and service problem. This chapter is focused on autonomous (i.e., robotic) vehicles used as human transportation service from two points of view: on one hand, the autonomous vehicle that leads to intelligent transportation systems; on the other hand, autonomous vehicles used for rehabilitation or for enhancing mobility capabilities of their users. Both perspectives of autonomous systems are linked by the use of rapid prototyping techniques, aimed at converting a previously commercial product into a robotic system with a specific transportation usage. This chapter shows, in particular, two cases: two electric commercial vehicles (one golf cart and one car) converted into an autonomous robot for transporting people in cities or for executing specific tasks in sites; and an assistive vehicle (an electric scooter) used by people with reduced mobility. The design of the different components needed to achieve such automation is shown in detail herein.

1 Introduction

Transportation systems worldwide are facing challenges from a multidisciplinary perspective. First, the strong commitment of developed countries to reduce the carbon print, such as the case of countries that belong to the European Union, who

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_7

proposed to ban fossil fuelled vehicles by 2035 [1]. Policies such as the previous one implies that not only governments have to adequate their regulations, but also society and its consumption habits and the economy, since, for many countries, fossil oil and its derivatives are one of their main commodities [1]. Second, for the case of ground transportation, specifically, for the transportation of people, vehicles manufacturing has been growing in the last 70 years, where market preferred its own transportation directives instead of using public systems [21]. The latter led to a worldwide vehicle population of approximately 5.5 billion cars, driving in 2019 (without considering cars that were discarded, public transportation, machinery, and other fuel-based transportation systems). From the previous statement, it is clear that the reduction of the carbon print in transportation systems, or the ambitious goal of banning fossil oil as fuel by 2035, will cause an impact in several dimensions of our way of living and our economic systems.

The constant traffic jams (commonly present in great cities) has motivated the development of driving tools to aid drivers in finding the shortest paths to reach work or home, such as Waze, Google Maps, and other internet-based solutions (for further details, the reader is encouraged to take a look at [3, 13, 18, 27]). Such tools do not only help drivers in specific routes they are taking, but also the traffic data and geo-located information collected while using such applications, have allowed an enormous amount of historical driving data that can be used to statistically model the traffic in any city and to prevent jams where possible, even if such tools increased the length of the route. Furthermore, such data also allows to build consumption maps. When using fossil fuel, a consumption map can be used for estimating the pollution in a city [2, 20], impacting the real state value and the location of refuel (gas) stations.

Unlike combustion engines, electrically powered motors can be found more and more often in transportation vehicles. They started in small and green applications (wheelchairs, golf cars, and mobile robots) and now the market is moving towards electric cars [12]. In this regard, electric vehicles still have to face one of the most important challenges when compared to combustion engines: the autonomy of the batteries. Currently, electric vehicles cannot compete in autonomy with combustion engines: a fossil fuelled vehicle has an average autonomy of 400 km, with four people—of average weight—inside; whereas an electric commercial car reaches around 150 km with a single person inside [14]. Although the latter has been changing in the last years, it is unlikely to think that combustion engines can be replaced today by electric ones and that our ways of living would be the same [17]. But electric cars do have several other capabilities that fuelled cars do not have: the fact that being electric makes it capable of being fully automated and integrated into the grid: the car might become an IoT (Internet of Things) device [11]. The latter is one of the main advantages of electric cars, since an actuator, that transports people, can be part of the Internet revolution. One of the main drawbacks, as was previously stated, is the autonomy, and from there, several questions arise: how the cars will be re-charged? How the energy/power will be managed (not only the motion consumes electric energy, but also all the auxiliaries, such as air conditioned, lights, radio, among others)? Where to place charging stations, which technology will be used (there are currently no regulations on this matter, as there are for fuelled cars [9])?

Electric vehicles also have an important advantage when compared to vehicles with combustion engines. The automation of electric vehicles is easier [6, 16]. In a car with a combustion engine, each element of the driving system (the acceleration and brake pedals, the wheel, among others) need their own actuator, which is usually electric-based [16]. In an electric vehicle, the automation of the acceleration can be directly solved through the vehicle's own electronics, as shown in [6, 16]. The brake is usually mechanic (including hydraulic ones) and as the wheels, require of an electric actuator. The entire automated system with sensors can be integrated into a single processing unit or even connected into the Cloud for autonomous navigation tasks. Such is the case of the commercial vehicles available today in several countries, as the ones provided by Tesla Company [5], or the vehicles developed by Google, Uber, and others, just to mention a few. It is to be noted that not all the electric vehicles available today are automated: their automation correspond to the regulations of the country where it is commercialized and the availability of smart cities or intelligent transportation facilities, as reported in [8, 11].

Autonomous electric vehicles can be used for urban transportation (the well known autonomous cars [8] or automated trains [26]); for rural applications, there are some approaches such as the service units developed by [15, 25, 28], where they perform a previously given task in mining or agriculture. Additionally, we can find autonomous vehicles assisting people with some impairment, such as the case of autonomous (e.g., robotized) wheelchairs [4, 7, 10]. In this chapter, we will focus on three specific cases: one service unit used for field tasks, one electric autonomous car, and one automated scooter. The three service units have been used for research purposes. The approach followed in this work answers the following question: how rapid prototyping techniques can help in the automation of commercial electric vehicles without interfering with the product delivered by the manufacturer? Therefore, our aim is to add value without taking value from the commercial product. To this end, we focus this chapter on the different stages of the automation of the three mentioned vehicles, where rapid prototyping played a crucial role.

2 The Autonomous Service Unit

As an example of using rapid prototyping techniques when automating a service unit, we present herein the commercial electric car Cushman Hauler Pro, which was used for terrain modeling, autonomous navigation, power consumption performance evaluation, among other tasks [22–24]. The car was equipped with an onboard computer Nvidia Jetson TX2 and a set of sensors to measure different data associated with the vehicle. The sensors installed were an RTK (Real Time Kinematic) device NavCom SF-3040, a Stereolabs ZED camera, and a voltage and current sensor system for the batteries. Figure 1 summarizes the architecture of the system.

Fig. 1 System architecture. The vehicle is equipped with a ZED camera to obtain RGB-D data, an RTK for position and velocity estimation, and current and voltage sensors to estimate energy consumption. All the sensors connected to a Jetson TX2 are working on Ubuntu 16.04 under ROS operating system

Each sensor was used to measure data from the terrain and the vehicle itself which was then processed to estimate data on the vehicle-terrain interaction. All devices were implemented on ROS, or Robot Operating System, which allows to record all the information sampled with their respective time-stamps. Table 1 shows the main characteristics of each component of the architecture.

Table 1 Characteristics of the system and sensors

Characteristic	Description
Cushman hauler pro	
Motor	16.7 kW at peak torque
Electric system	72V DC
Max. speed	23.34 Km/h ± 0.80 Km/h
Curb weight	669 kg
ZED camera	
Range	From 0.5 to 20 m
Resolution	420 p, 720 p 1080 p and 2 k
Frame rate	Up to 100 fps
Communication	USB 3.0 port
Navcom SF-3040	
Accuracy RTK	Horizontal: 1 cm + 0.5 ppm
(<40 km)	Vertical: 2 cm + 1 ppm
Data rate	1 Hz, 5 Hz and 10 Hz
Communication	Serial port through USB
Voltage and current sensor	
Voltage range	From 15 to 80 V
Current range	From −300 to 300 A
Precision	12 bits ADC
Sampling rate	800 Hz average
Communication	Serial port through USB
Nvidia Jetson TX2	
GPU	NVIDIA Pascal^{TM}, 256 CUDA cores
CPU	HMP Dual Denver 2/2 MB L2 + Quad ARM\textregistered A57/2 MB L2
Memory	8 GB 128 bit LPDDR4 59.7 GB/s

2.1 Hardware

This section describes more in-depth the hardware involved in the automation of the service unit.

2.1.1 Jetson TX2

The Jetson TX2 is an embedded platform designed for artificial intelligence (AI) work in real-time. Two main parts comprise this developer kit, the carrier board and the processing module itself.

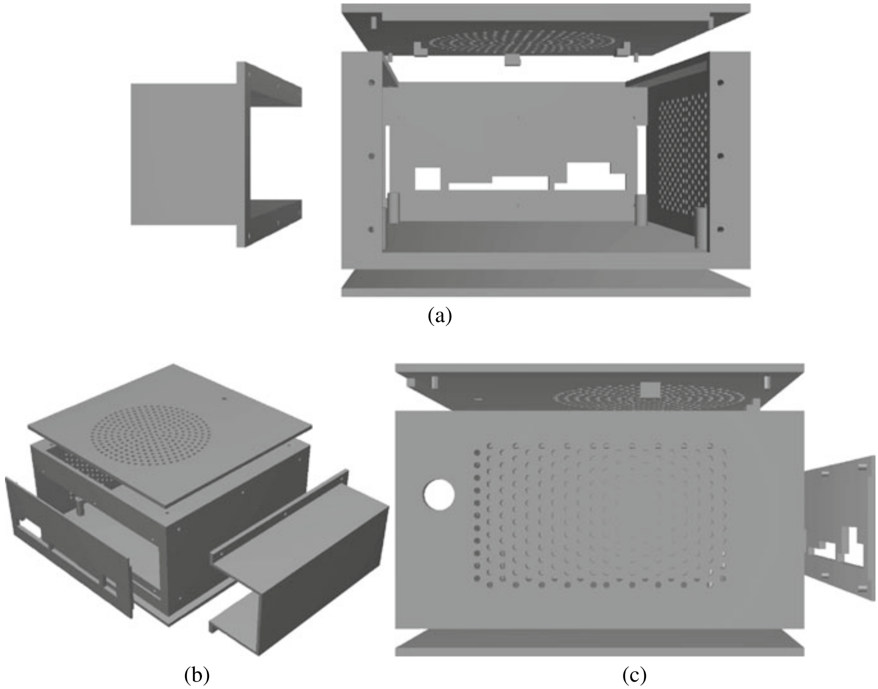

Fig. 2 3D model of the printed case. **a** Front view, **b** top back-side view and **c** side view of the case

The carrier board includes all the necessary connections and interfaces to allow the user to develop embedded software in this device. It can be mounted on any mini-ITX capable case and includes Ethernet, USB 2.0 and 3.0, HDMI, SD card, and Wi-Fi antenna ports on the backside. During automation of the service unit, we designed a 3D printed a custom case, Fig. 2 shows different views of the 3D model, while Fig. 3 shows a picture of the printed case.

The module contains all the processing power, which includes the mentioned characteristics in Table 1. The most important feature is the Nvidia Pascal GPU with CUDA support which allows this device to be a powerful tool for parallel processing and deep neural networks.

2.1.2 The RTK

The Real Time Kinematic or RTK used here is the NavCom StarFire SF-3040, which comprises a base and rover devices. The base was mounted on a static pole, while the rover was installed on the vehicle. Table 1 shows some of the most important features of this device pair. Figure 4 shows the installation of the RTK over on the vehicle.

Fig. 3 Jetson TX2 mounted in the front panel of the electric vehicle on a custom 3D printed case. The case also includes a mounting hole for a tripod head to install a camera in case the vehicle used is more compact and space for a battery on the side

This device combination allows for sub-metric measurements of the position of the vehicle. We use the localization for three purposes, the first for vehicle localization, the second for velocity estimation of the vehicle, and lastly to geolocalize each image of the terrain taken and classified.

2.1.3 Camera

The camera used corresponds to the ZED camera by Stereolabs, a stereo camera designed for use outdoors. The ZED is a 2 k resolution stereo camera designed for depth sensing and motion tracking. Using binocular vision, the camera allows to measure objects in a range of 0.5–20 m as fast as 100 frames per second, depending on the resolution used, indoors, and outdoors. Figure 4 shows the installation of the camera on top of the vehicle.

Using the included Software Development Kit or SDK, it is possible to obtain and save depth information on each of the frames taken in real time. The SDK is compatible with both the Jetson series of embedded systems of Nvidia and with ROS. The SDK for this camera also includes more capabilities, which were not used in this work, for example, spatial mapping and visual odometry, these features may allow to improve and expand this work in the future.

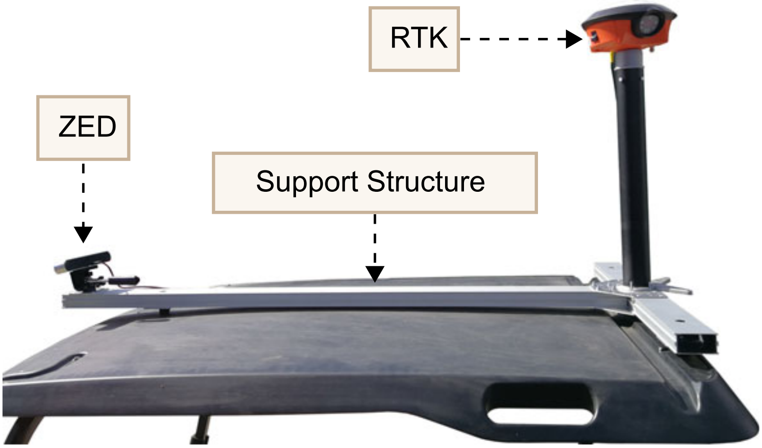

Fig. 4 Top view of the service unit's ceiling with the RTK and the ZED camera installed on it, using a supporting structure

2.2 *Software*

This section gives a description of the software environment used for the automation of the service unit. The focus of this part is on the acquisition and recording of the data in each experimental test.

The software architecture is divided in three parts: data logging, preprocessing, and processing. Figure 5 shows a diagram that represents each of these divisions. The following subsections will describe each of the parts, how they work, and their function.

2.2.1 Data Logging

Data logging of the sensors corresponds to the first part of the system. Schematic 1 in Fig. 5 shows this process. As shown in the figure, each of the sensors is connected to the main computer which runs ROS.

Each sensor has a Node, or ROS process, associated with it, that allows to save the data acquired with the sensor in the computer. The main advantage of using this method is that ROS allows to save each sample with a time-stamp, which also allows the user to synchronize or later re-run the experiments as required.

The nodes used are:

- nmea_navsat_driver: this node connects through the serial port with the RTK and publishes over a topic called `\ fix` which contains longitude, latitude and altitude measured by the RTK system and logged with the time-stamp for each sample.

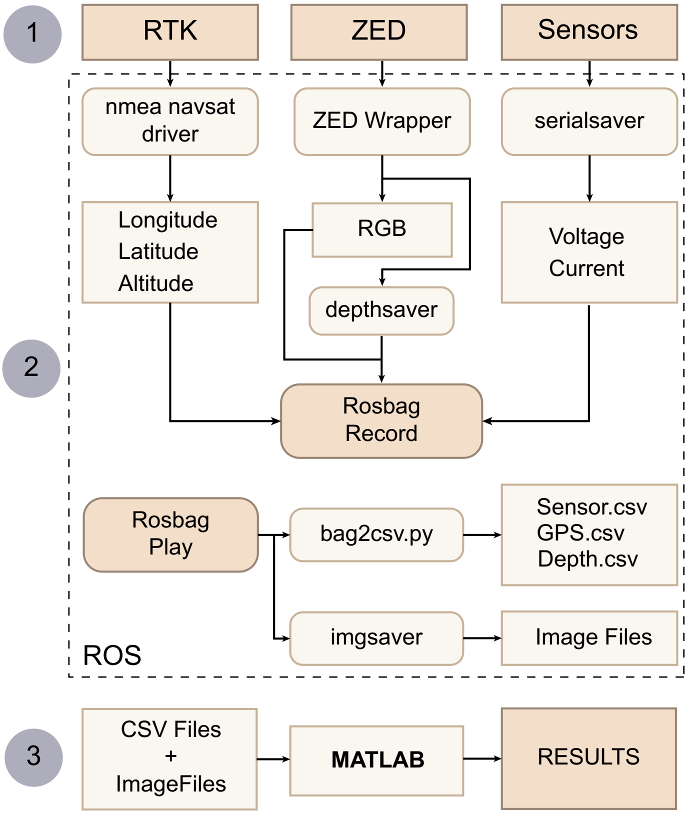

Fig. 5 Software architecture used in this work (1) corresponds to data logging, (2) to Preprocessing of data, and (3) Processing of the data for results. Rounded rectangles correspond to nodes or ROS packages, light gray rectangles to data. Pointed line square surrounding schematics (1) and (2) correspond to the main computer running ROS. Dark gray sharped rectangles with outline correspond to the different hardware used, MATLAB square is indicated with the same color because it was run in a different computer hardware than the rest of the system

- ZED_wrapper: this is a package that lets the user utilize all of the ZED SDK capabilities through ROS. It publishes all the necessary data in different topics (e.g., `zed\rgb\image_rect_color` publishes the rectified image captured by the left camera)
- serialsaver: this node captures the information sent by the voltage and current sensor through serial port, parses it and publishes in a topic called `\serial\sensorser` which contains voltage and current measurements.
- depthsaver: this is a secondary node that subscribes to the ZED depth topic and takes only a segment of the depth information given. After extracting the required segment, which corresponds to 600 samples within a rectangle of 1200×200

pixels centered on the image, a message is published in the topic `\depth\array` in the form of a vector containing all these depth samples.
- Rosbag: this is a ROS package that allows to save all the topics required by the user in a file with file-type `.bag`. This file contains all the information published in the topic and the corresponding time-stamps in a way that it is easy for the user to repeat the experiments performed or extract information for off-line processing. Record is the command that allows the user to save the information.

The result of this first stage of the process is a `.bag` file. Second stage, Preprocessing the data, is in charge of this data extraction.

2.2.2 Preprocessing

This stage is the shortest and its purpose is to prepare the files containing all the data to be read and processed in the last stage. Schematic 2 in Fig. 5 shows this process.

The nodes used are:

- Rosbag: this package is used again in this part, though the Play command is used. This command allows the user to reproduce a `.bag` file simulating the original experiment. It is also possible to configure the sampling rate and other parameters on this replaying.
- bag2csv.py: this is a small script that allows the user to extract each topic in separate `.csv` files. The topics that can be extracted in this manner must contain text or numbers, topics with other types of data (e.g., images) cannot be saved in this manner.
- imgsaver: this node allows the user to save each image frame from the `.bag` file into an image file with `.png` file-type. It also saves a `.csv` file with the time-stamps for each image.

After this second stage of the process, the results are four `.csv` files corresponding to voltage and current sensor data, localization data, and depth data. It also generates image files for each frame captured by the camera during the experiment.

2.2.3 Processing

The last stage corresponds to Processing. In this stage, the data obtained from the previous one is, as the name says, processed. We use the results from each experiment for further analysis and study, namely estimating models for each terrain measured and Energy consumption prediction with these models. Schematic 3 in Fig. 5 shows this process.

As can be seen in the figure mentioned, this stage comprises entering the data extracted in the previous stage to MATLAB and obtaining the final results. Inside MATLAB, we use several processes to clean, filter, synchronize, and classify all the data. Figure 6 shows a diagram that resumes the processes executed and their order.

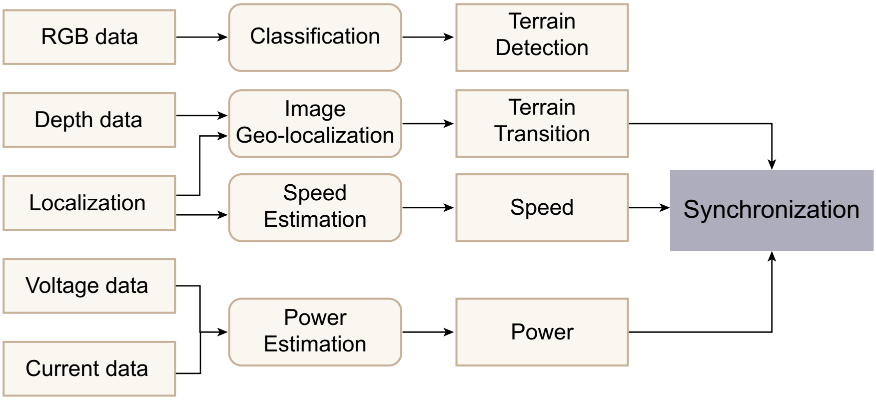

Fig. 6 Diagram of the processes performed inside MATLAB for each experiment

3 The Autonomous Car

An electric car is a vehicle propelled by one or more electric motors, which are powered by electric energy from batteries housed inside the vehicle.

This type of vehicle has the advantage that its electric motor provides instant torque, is more efficient than internal combustion engines, does not pollute, and is much easier to build and maintain than an internal combustion engine.

Although the first electric automobile appeared in the 1880s, due to recent developments in batteries, (which have made it possible to increase the amount of stored energy, lower costs and increase the life span of the car), is that electric cars are gaining importance again, slowly succeeding in displacing internal combustion vehicles.

The 100% electric vehicle Renault Twizy, is a small car designed for urban areas, which started in 2009 as a concept for the Frankfurt Motor Show, and it is marketed since 2012 mainly in European countries, where it has managed to sell more than 18,000 units accumulated until 2017. Figure 7 shows a picture of the electric car, whereas Table 2 summarizes the main mechanical and electrical features of the Twizzy.

3.1 The Brake

The Twizy vehicle has a hydraulic braking system, with a single-circuit configuration. In this type of configuration, there is only a single brake fluid circuit, where the pressure from the brake pedal is transmitted to the other pistons which actuate the brake presses. Some vehicles, in order to increase the the robustness of the system against possible fluid leaks in the brake circuit (which may render the brake system useless), contain independent brake circuits, which consist of two hydraulic circuits

Fig. 7 Picture of the electric car Twizzy, by Renault

Table 2 Characteristics of the Twizzy

Characteristic	Description
Twizzy, by Renault	
Motor	Electric, synchronous
Power	20 HP
Torque	57 Nm
Transmission	Reduction, with one march ahead and one reverse
Max. speed	80 Km/h
Autonomy of the battery	100 Km
Battery	Ion-lithium 6.1 kWh
Break	Regenerative
Acceleration	Electronic, resistive type
Charging	220 V/10 A

actuating separately the front and rear brakes. If there is a leak in one of the circuits, the other continues to function.

One of the important features, present in most electric vehicles (including the Twizzy), is regenerative braking. Since an electric vehicle uses an electric motor to convert the energy into kinetic energy, the process of regenerative braking uses the opposite process. The electric motor absorbs the vehicle's kinetic energy and converts it into electrical energy. This energy can then be stored again in the vehicle's own batteries increasing the vehicle's autonomy. However, there are some limitations to the use of regenerative braking. One of these is given by the system's capacity to absorb the energy it generates. Since the batteries have a charging power limit, if this limit is exceeded, the batteries could be damaged. This is why part of the energy it regenerates can be lost. Thus, some vehicles include some type of resistor that burns the excess energy, or, as in the case of the Twizzy electric vehicle, regenerative braking is partially disabled, also changing the behavior of the car.

Figure 8 shows the original pedals from the Twizzy. When automating the vehicle one of the constraints was to implement a system such that the brake pedal could be either actuated or pressed by a driver, we designed the adaptation shown in Fig. 9. Such adaptation, printed using a 3D printer, was positioned on the top of the pedal and allowed for the two functions previously mentioned. To govern the brake, we installed a linear actuator, whose response time—for the actuator at full length—was less than 0.5 s, which was required by the Chilean traffic regulations.

3.2 The Traction Velocity

As mentioned above, the Renault Twizy electric vehicle has an electric accelerator, which can be operated directly on the vehicle, without having to couple an electro-mechanical system as in the case of the brake pedal seen above. Figure 10 shows a lateral, top, and connected view of the acceleration pedal into the vehicle's bus. The connection is a set of resistances arrangement which were previously identified. To be able to govern acceleration, we developed another electronic interface, using an Arduino Mega platform. Such interface interprets our velocity commands and converts them into voltage levels which are later input into the vehicle's bus. Figure 11 shows a scheme of the interface designed for controlling the acceleration pedal.

Since we are able to command acceleration via the computer, in order to close the loop and have wheel velocity readings, we installed an encoder at the rear wheel. Such encoder provides of dead-reckoning estimates of the vehicle and allows us to implement different control strategies to test the performance of the automated system, as we did in [19]. Figure 12 shows a picture of the encoder placed at the right rear wheel.

Fig. 8 Original brake and acceleration pedals from the Twizzy

3.2.1 The Heading

In this particular case, we designed a similar gear as the one shown later in this work, in Sect. 4.3.1, where we printed two gears and adapted one of them to a servomotor. The other one was installed on the vehicle's wheel. The interface to govern the heading was the same used to govern the brake, shown in Fig. 11.

4 The Autonomous Assistive Vehicle

For implementation of the proposed system and real-world experimentation, a modified robotic scooter is used, shown in Fig. 13. The scooter is equipped only with exteroceptive sensors, and does not possess proprioceptive sensors for measuring velocity, pose, or any internal condition.

Fig. 9 Adaptation of the brake, using 3D printing

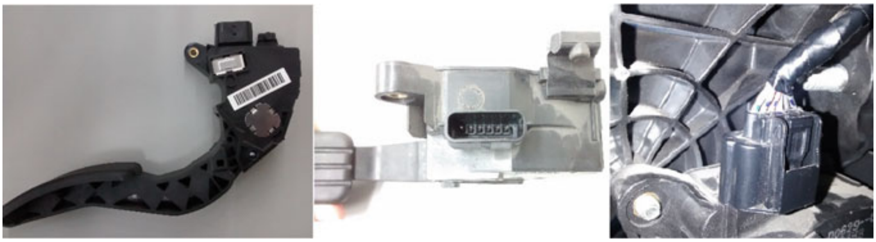

Fig. 10 Different snap-shots of the acceleration pedal and its electronic connection to the vehicle bus

4.1 Motors and Encoders

The scooter is equipped with a bipolar stepper motor to control linear speed when in motion. A calibration stage allows a rough mapping of the motor's position and the robot's stationary linear speed. The driver for this motor connects via USB to the processing unit (in this case, a portable computer). Additionally, an unipolar DC motor is mounted onto the scooter's front steering axis via two gears. This allows the system to automatically control the vehicle's steering angle from the computer. This motor counts with an encoder that, after calibration, allows a rough measurement of the steering angle in real time. The driver also connects to the computer via USB.

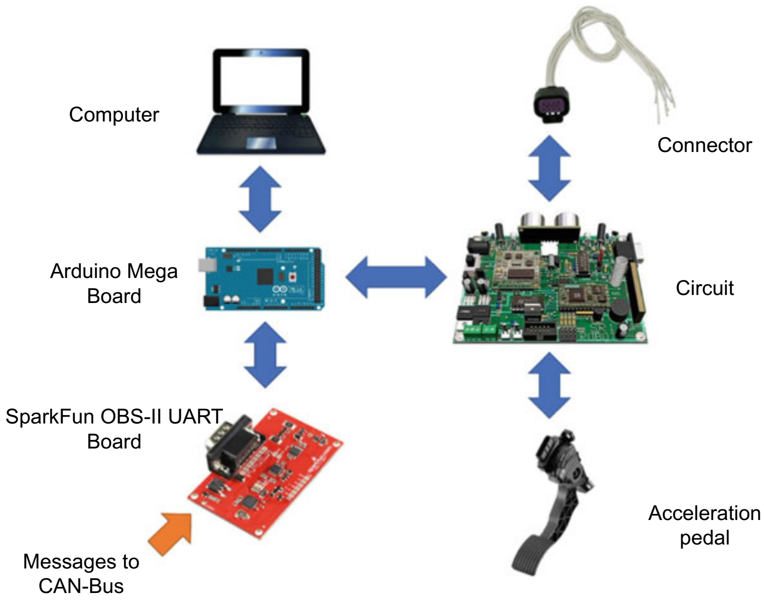

Fig. 11 Interface based on Arduino Mega to connect the computer into the vehicle's CAN bus, to thus control the acceleration via programming

4.2 Sensors

The only exteroceptive sensor mounted on the scooter is an Hokuyo laser range finder,This allows measurement in 240 deg, up to 4 m from the laser.

4.3 Communication System

In order to communicate the main program (in charge of controlling the vehicle, monitoring all activity, running mapping and path planning algorithms, among others) with the sensors and hardware onboard the scooter, shared memory is used. All motor drivers are written in C++, and via shared memory communicate with the main program. The same approach is used to read and buffer all laser scans, which can be read by the main program at any time. The basic architecture is shown in Fig. 14.

4.3.1 Mechatronics Design and Assembling

Using the capabilities of rapid prototyping, the mechatronization of the scooter was rapidly achieved in terms of functionality and costs. For example, Fig. 15 shows

Fig. 12 Installation of an encoder at the rear wheel for positioning purposes

several snapshots of the gears developed to control the vehicle's heading. One gear was designed to be placed at the scooter's clamp, whereas the other gear was located at the bottom engine, in charge of controlling the degrees of turning of the system. Although the accuracy of the movement is mainly given by the bottom engine, the teeth of the gears had a slight backslash to avoid jamming. As can be seen, both gears were especially designed for the needs of automation of the scooter.

A few things are worth mentioning about the mechatronized scooter:

- The system is controlled by an Arduino microcontroller connected to a laptop.
- One back wheel, as shown in Fig. 15 (bottom, left) has a potentiometer, acting as an encoder, for wheel velocity estimation.
- The front chassis has the electronics: a LiDAR, the microcontroller, the batteries, among others.
- The velocity of the vehicle is controlled via a servo-motor, through a PWM signal from the microcontroller.
- The gears were designed and printed in our 3D printers, whereas the rest of the chassis was made of aluminum.
- The entire system was adapted to the scooter without changing the manufacturer's specifications.

Fig. 13 Picture of the automatized scooter

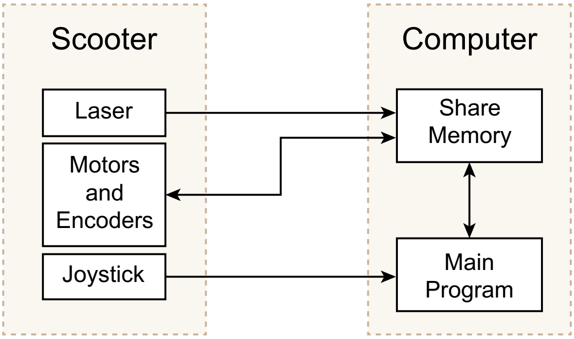

Fig. 14 Layout of the communication system

4.4 Human–System Interface

Though a robot's capacity to predict a user's intention has been addressed as an important challenge, the user's capacity to correctly interpret the robot's actions, understood as manifestations of intentional states, is equally important for satisfactory and sustainable human–robot interaction. A GUI (graphical user interface) was designed to provide feedback to the user, in terms of the machine's interpretation

Fig. 15 Different snap-shots of the mechatronized scooter

of a given scenario. This feedback comes in the form of a map of the environment with visual representations of the vehicle's future state, the current path, possible destinations, currently preferred areas of navigation, among others. It also displays messages in the form of text, but this can be improved via automatic voice generation. In addition, the user may select automatic destinations from the interface for autonomous or semi-autonomous modes. Despite the importance of an adequate interface in terms of increasing a user's trust in the system, as well as reducing frustration due to poor human–robot communication, this was not the main focus of this research. Additionally, the user can control the vehicle through a joystick in manual mode and interact with the system in semi-autonomous modes.

4.4.1 General System Architecture

The general system architecture is shown in Fig. 16. The robot uses a laser range sensor to scan the environment. This data is processed by the localization and mapping module to estimate the robot's location and generate a map for path planning and displaying information to the user via a GUI. Users receive and use feedback from the environment and the GUI to generate navigation intentions using a joystick, which translates into control commands via the Controller Module. If manual mode is selected, the joystick-generated control command drives the assistive robot directly. If autonomous navigation is selected (a goal must be set) the Path Planner Module determines a safe trajectory for the vehicle, which the Controller Module translates into control commands for each sampling time. In this mode, the joystick plays no role. Finally, if collaborative control is selected, the joystick not only influences control directly, but serves as input for the Path Planner Module (assisted autonomous

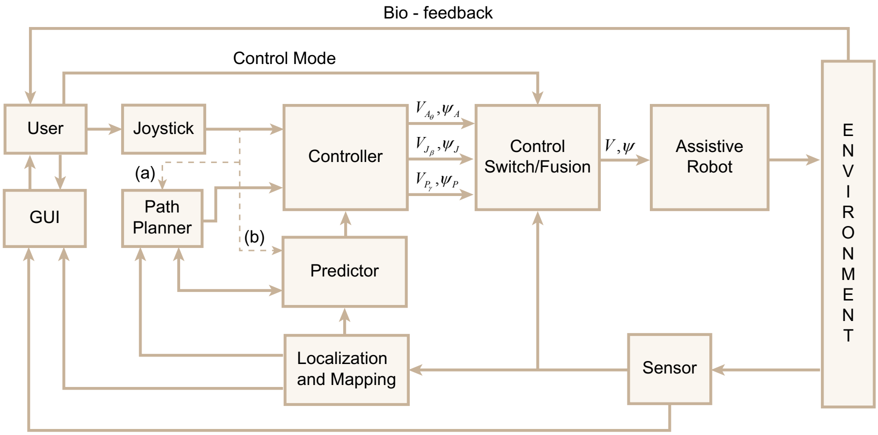

Fig. 16 General control scheme implemented on the assistive vehicle to allow autonomous navigation at different modes

mode) or to the Prediction Module (assisted manual mode). These modules interpret the joystick movements so as to aid the user during navigation. Up to three different control commands (linear speed and steering angle) are generated independently, corresponding to manual control (what the user wants), autonomous control (what the machine wants), and the predictor module (what the machine thinks the user wants). These three are switched and combined in accordance with the selected control mode and sent to the motor control unit to act on the vehicle.

4.4.2 Control Modes

Four control modes are available to the user, offering different levels of autonomy. This can be switched at any time using the GUI available onboard the vehicle.

1. Manual mode: The user has complete control of the vehicle via joystick. No collision detection systems are available, thus allowing the user to navigate and push objects if necessary.
2. Assisted manual mode: The user controls the vehicle via joystick, and the predictor module uses the user's control command, the estimated pose, and map information to estimate the future trajectory. If the path is deemed safe, the mode is indistinguishable from manual mode. If a future collision is detected, the map information is used to generate a safe path in the direction of the user's command.
3. Assisted autonomous mode: This mode requires the user to set a destination on the map offered by the GUI. The robot will navigate autonomously with the information provided by the path planner and localization and mapping modules. In particular, Dijkstra's Algorithm is used to calculate the optimal path to the goal. The user may use the joystick to take control of the vehicle at any time,

while simultaneously re-defining transition weights on the Dijkstra nodes, thus conditioning the autonomous behavior.

4. Autonomous mode: The user sets a destination on the map and the robot navigates autonomously. The user has no means of intervening in the navigation, other than stopping the vehicle if necessary. This mode is implemented primarily for testing and comparison purposes.

5 Concluding Remarks

In this chapter, we have shown three cases where rapid prototyping was used to develop autonomous robots used for research purposes, but the aim of providing a service, i.e., to assist a person or a process.

The autonomous service unit consisted of an electric golf car. The rapid prototyping techniques were especially focused on solving the sensor placement on the chassis of the vehicle and to develop a case to contain all the electronic devices. The main outcomes were that we were able to locate the GNSS antenna, the stereo camera, and other sensors in a quick yet efficient manner. The system was tested in the field and the main results were published in [22–24].

The autonomous car is an iconic case study: the electric vehicle Twizzy by Renault was purchased by the Advanced Center for Electrical and Electronic Engineering, Federico Santa Maria Technical University, Chile in 2017, and it became the first electric vehicle fully automated in the country. The rapid prototyping techniques allowed us to design the piece for the brake pedal: the assembled piece should allow one person to still press the brake since Chilean regulations do not allow yet autonomous cars on the streets. Therefore, a person should always be behind the wheel. The designed piece was installed onto the brake pedal without affecting the pedal's functioning. Additionally, the linear actuator used to automate the brake was selected according to the Chilean response time regulations: the brake should be pressed at full length in less than 0.5 s. Additionally, we used rapid prototyping techniques to install the motor that controls the heating system, without modifying the vehicle as it is delivered from the manufacturer. The scientific results achieved with the automated Twizzy can be seen here [19].

The assistive vehicle was also automated using rapid prototyping techniques. The system was specially designed to enhance the mobility capabilities of the users. The main challenge was the designing of the gear system to control the clamp. The electronics were placed at the front of the vehicle and the powering was external to the vehicle's own batteries. The main outcomes of this system were published in [10]. In particular, an extensive human–machine study was conducted to validate the usability of the four navigation strategies programmed in the vehicle.

It is worth noticing that all the vehicles or systems presented herein are electric-based. Unlike combustion engines, electric motors allow for a quick electronic or electric modification or assembling, there are almost no vibrations (less dynamic complexities) and the vehicle can be later programmed. From an electric basis of the vehicle, the electronics are designed to read its sensors and control its actuators. Later, a control strategy is implemented on a programmed board (such as a microcontroller or even a computer). Finally, a navigation strategy is developed. Such a strategy might be integrated into the cloud, making the vehicle one more device of IoT (Internet of Things), which is the current trend as was detailed in the introduction. When working with combustion engines, the challenge is even bigger (reaching an electronic basis for developing autonomous behavior requires further development and often changes in the chassis). But current carbon prints regulations are making such engines obsolete.

Acknowledgements This work was partially supported by Basal Project FB0008, CONICYT-PCHA/Doctorado Nacional/2018-21181420.

References

1. Carey N, Steitz C (2021) EU proposes effective ban for new fossil-fuel cars from 2035. Accessed 14 July 2021. https://www.reuters.com/business/retail-consumer/eu-proposes-effective-ban-new-fossil-fuel-car-sales-2035-2021-07-14/
2. Arango I, Lopez C, Ceren A (2021) Improving the autonomy of a mid-drive motor electric bicycle based on system efficiency maps and its performance. World Electric Veh J 12(2):59
3. Ashfaq R, Saleem M (2019) Use of global navigation satellite system (gnss) software defined receiver (sdr) for determining the 3d real time position variation in dense urban areas by averaging method. In: 2019 sixth international conference on aerospace science and engineering (ICASE), IEEE, pp 1–9
4. Bastos-Filho TF, Cheein FA, Müller SMT, Celeste WC, de la Cruz C, Cavalieri DC, Sarcinelli-Filho M, Amaral PFS, Perez E, Soria CM et al (2013) Towards a new modality-independent interface for a robotic wheelchair. IEEE Trans Neural Syst Rehabil Eng 22(3):567–584
5. Betz S (2021) The top 21 self-driving car companies paving the way for an autonomous future. Accessed 22nd July 2021. https://builtin.com/transportation-tech/self-driving-car-companies
6. Buechel M, Frtunikj J, Becker K, Sommer S, Buckl C, Armbruster M, Marek A, Zirkler A, Klein C, Knoll A (2015) An automated electric vehicle prototype showing new trends in automotive architectures. In: 2015 IEEE 18th international conference on intelligent transportation systems, IEEE, pp 1274–1279
7. De la Cruz C, Bastos TF, Cheein FAA, Carelli R (2010) Slam-based robotic wheelchair navigation system designed for confined spaces. In: 2010 IEEE international symposium on industrial electronics, IEEE, pp 2331–2336
8. Eppenberger N, Richter MA (2021) The opportunity of shared autonomous vehicles to improve spatial equity in accessibility and socio-economic developments in european urban areas. Eur Trans Res Rev 13(1):1–21
9. European Commission (2021) Electric vehicle charging - standards for recharging points for e-buses. Accessed 22nd July 2021. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12906-Electric-vehicle-charging-standards-for-recharging-points-for-e-buses_en
10. González E, Cheein FAA (2018) Preliminary results on reducing the workload of assistive vehicle users: a collaborative driving approach. Int J Soc Robot 10(5):555–568
11. Guevara L, Auat Cheein F (2020) The role of 5g technologies: challenges in smart cities and intelligent transportation systems. Sustainability 12(16):6469
12. EA (2021) Global EV Outlook 2021, IEA, Paris. Accessed 22nd July 2021. https://www.iea.org/reports/global-ev-outlook-2021

13. Irie K, Tomono M (2012) Localization and road boundary recognition in urban environments using digital street maps. In: 2012 IEEE international conference on robotics and automation, IEEE, pp 4493–4499
14. Isorna Llerena F, López González E, Caparrós Mancera J, Segura Manzano F, Andújar J (2021) Hydrogen vs. battery-based propulsion systems in unipersonal vehicles–developing solutions to improve the sustainability of urban mobility. Sustainability 13(10):5721
15. Jeon CW, Kim HJ, Yun C, Han X, Kim JH (2021) Design and validation testing of a complete paddy field-coverage path planner for a fully autonomous tillage tractor. Biosyst Eng 208:79–97
16. Jeong S, Jang YJ, Kum D, Lee MS (2018) Charging automation for electric vehicles: is a smaller battery good for the wireless charging electric vehicles? IEEE Trans Autom Sci Eng 16(1):486–497
17. Malmgren I (2016) Quantifying the societal benefits of electric vehicles. World Electric Vehicle J 8(4):996–1007
18. Muramatsu S, Tomizawa T, Kudoh S, Suehiro T (2017) Mobile robot navigation utilizing the web based aerial images without prior teaching run. J Robot Mechatron 29(4):697–705
19. Prado AJ, Michałek MM, Cheein FA (2018) Machine-learning based approaches for self-tuning trajectory tracking controllers under terrain changes in repetitive tasks. Eng Appl Artifi Intell 67:63–80
20. Raboaca MS, Bizon N, Grosu OV (2021) Optimal energy management strategies for the electric vehicles compiling bibliometric maps. Int J Energy Res 45(7):10129–10172
21. Rfidtires (2021) How many cars are there in the world today? Accessed 22nd July 2021. https://www.rfidtires.com/how-many-cars-world.html
22. Romero Schmidt J, Eguren J, Auat Cheein F (2019) Profiling the instantaneous power consumption of electric machinery in agricultural environments: an algebraic approach. Sustainability 11(7):2146
23. Schmidt JR, Cheein FA (2019) Assessment of power consumption of electric machinery in agricultural tasks for enhancing the route planning problem. Comput Electron Agric 163:104868
24. Schmidt JR, Cheein FA (2019) Prognosis of the energy and instantaneous power consumption in electric vehicles enhanced by visual terrain classification. Comput & Electr Eng 78:120–131
25. Shojaei K (2021) Intelligent coordinated control of an autonomous tractor-trailer and a combine harvester. Eur J Control 59:82–98
26. Xu Z, Qu D, Hong J, Song X (2021) Research on decision-making method for autonomous driving behavior of connected and automated vehicle. Complex Syst Complexity Sci 18(3):88–94
27. Yadav R, Kishor G, Kashyap K, et al (2020) Comparative analysis of route planning algorithms on road networks. In: 2020 5th international conference on communication and electronics systems (ICCES), IEEE, pp 401–406
28. Zangina U, Buyamin S, Aman MN, Abidin MSZ, Mahmud MSA (2021) Autonomous mobility of a fleet of vehicles for precision pesticide application. Comput Electron Agric 186:106217

Bio-inspired Robotics

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Abstract The fields of artificial intelligence and bio-inspired robotics have proven to cross several other fields of expertise including Cognitive Neuroscience. Here, we review principles of interaction between a natural (or artificial) organism and the environment where it lives. Then we ask whether such structural coupling shapes the way it behaves. For instance, how the sensory processing of the external world controls actions, and finally, behavior? We remind the main sources of inspiration for bio-inspired robotics and relate them to currently active fields of research like Embodiment and Enaction. These latter concepts are illustrated by examples of recent researches on two main aspects: (i) bio-inspired algorithms processing sensory signals coming from the outer world and (ii) bio-inspired controllers based on human behavior and physiology. Finally, we include an example of a bio-inspired robot controller design based on the concepts here exposed.

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_8

1 Introduction

Robots are powerful and reliable systems and perform better than humans in several domains, for example, considering very precise manipulations in stereotyped tasks. In other domains, their performances remain very poor and disappointing. It is often said that they lack intelligence that a biological system would display for such cases and this has opened a multifarious activity of research to associate robotics with theoretical biology and artificial intelligence.

At the birth of computer science, defining intelligence as a Physical Symbol System opened the field of Artificial Intelligence (AI) [83]. Indeed, computers have all the characteristics of a Physical Symbol System: they encode symbols (variables), combine them into structures (expressions), and manipulate them with processes (programs) to produce new expressions. Consequently, the fathers of AI thought that, if intelligence has also these characteristics, a computer will implement them and become an intelligent machine. In spite of many successes of traditional AI, it is known today that this view is too narrow. One weakness is the Symbol Grounding Problem defined by Harnard [43]. For example, performing scene interpretation in computer vision, you might want to manipulate the rule: "chairs are generally close to tables" to disambiguate some images and you will face a typical problem of this domain, not linked to the intelligent interpretation of scenes but to the low level grounding of the symbols (chair, table) in the data (set of pixels). Another limitation is the Frame Problem and has been illustrated by Searle's Chinese Room [90], where an agent in a room can answer in Chinese to requests and appear as intelligent only by manipulating syntactic rules without any knowledge of the Chinese language. This problem is very significant in domains like automatic language processing where some problems need to be solved with the knowledge of the semantic of a sentence and not only its syntax.

These problems certainly arise from a too introspective view of human intelligence: To us, intelligence means formal reasoning and we minimize if not forget other central characteristics. In these examples, the (not so) intelligent system does not understand what it is doing and has no knowledge about the meaning of its responses for the environment and for itself. A deeper analysis of these problems also evokes intentionality and awareness, but we will not address these concepts here, since some tasks considered in the domain with the same concerns aim at reproducing the behavior of insect and it is not clear if these animals have intentionality and awareness in their classical meaning. In any case, even without these philosophical considerations, it became clear to many researchers that one important problem was about the relation of the agent with its environment: To approach this fundamental characteristic of intelligence, it is important that the environment be significant for the agent itself and not for the human designer.

This analysis was considered important at the birth of Embodied AI when researchers began to embed AI in robots. It was reasoned that, since robots have bodies with sensors and actuators to interact directly and meaningfully with their environment, they were certainly good solutions to address real AI tasks. At that time, R. Brooks wrote an important publication [16] where he argued that, instead of building abstract and hierarchical representations, just defining several elementary loops between sensors and actuators could result in more complex behaviors, from the interactions between these loops. In addition, these behaviors were shown to be more robust and flexible, due to the coordination of elementary reactive mechanisms and not to the abstract integration of all possible cases in formal rules in a central controller. The important concept here is that of emergence. A behavior seen as intelligent by an observer is not synonymous of an intelligent internal mechanism to emulate it, but results from a set of asynchronous loosely coupled processes relating the perception of the environment to actions modifying it. As a simple illustration of this principle, some of us were recently involved in modeling certain characteristics of eye movements like preference to certain patterns or positions in the visual field [103]. Whereas some models explain such phenomena by complex high-level rules, we have shown that just taking into account low level characteristics like the non homogeneous distribution of sensors in the retina and some characteristics of neuronal dynamics could explain the same target selection principles in a more parsimonious way.

A step further, it could be asked to embodied AI to propose a generative process. Since it appears that the so-called intelligent behaviors can result from parallel exchanges of information and mechanics principles between the agent and its environment through its sensors and actuators, in a reverse engineering view, it might be asked, for a behavior under study, to enumerate the information processing principles of perception and dynamical system approaches of action that might make this behavior emerge. Whereas embodied AI has proposed many studies exemplifying this process [76], the conceptual framework had to be enlarged to really propose a general roadmap to tackle such questions, referring to enactive cognitive science [110].

Enaction goes deeper into the principles of embodied AI by proposing, based on biological consideration, a global view of the system, seen as an organism exchanging with its environment. Whereas embodiment mainly insists on the consequences of having a body situated in the environment, enaction adds principles as autonomy at different time scales and ecological meaning and soundness of the behavior in the environment. In short, these principles arise from a more biological view of what is called intelligence in the natural world. Concerning autonomy, the main idea is that an intelligent system must survive and adapt to a changing world by itself. This leads to consider intelligence at three time scales, in the immediate present (an intelligent system must display an intelligent decision at each time step), in ontogeny (an intelligent system must develop from initial conditions and learn the changing world), and in phylogeny (reproduction is also an intelligent behavior). Ecological meaning considers the following question: why should an agent display an intelligent behavior? Basically, the answer is: Because it has needs, motivations, and goals. These should be specified and the agent should be able to perceive them and to compare them with the results of its deliberations and actions, as a major source of information for learning when they are not fulfilled. This principle is also an important source of autonomy since goals and evaluation of the capacity to reach them are defined by the system itself. Ecological soundness aims at specifying an intelligent behavior, stressing the need to match the complexity of the task, the morphology of the actuators, and the level of description of information representation in the sensory part. This is a good way to ensure efficiency of the implementation of the task without dependencies to lower or higher levels of description.

Altogether with inspiration from biological sciences, these principles are at the root of enactive cognitive science and have made possible many studies in robotics including developmental and evolutionary robotics. In the present chapter, we propose to exemplify these principles and to go deeper into several aspects. In the first section, we will propose some more considerations on sensorimotor relations and enactive principles. In the second section, we will present in more details some realizations for information processing on the sensory perceptive side and in the third section, we will consider control of action. Though these examples are good illustrations of current approaches of getting more inspired from life to design intelligent systems, we will also discuss in the concluding sections of the grand challenges that remain to be addressed to go further in that direction.

2 A Sensorimotor Account of Behavior

2.1 Enaction

> *Perception consists in perceptually guided action... ...we must see the organism and environment as bound together in reciprocal specification and selection... ...Cognitive structures emerge from the recurrent sensorimotor patterns that enable action to be perceptually guided.*
>
> Francisco J. Varela (1991)

A key point introduced by Francisco Varela was the importance of action to build our perceptive world, he liked to call this *Enaction* [110, 111] (see Fig. 1). In this context, *the organism and environment are bound together in reciprocal specification and selection* [110] wherein they become dependent upon each other.

To understand sensory systems, the neurophysiology, computation or philosophy explanations are unsatisfactory [105]. The sensory experience of the world is built in the course of animal action through a network consisting of multiple levels of interconnected, sensorimotor subnetworks [110] in a brain that supports the behavioral response (e.g., food selection, intra- and/or inter-specific recognition). A series of classical studies on motor- or sensory-deprived experiences support the enactive position. In a sensorimotor task, a group of kittens actively explore the environment, and thus their brains develop neuronal selectivity to orientation, movement, and depth. However, a similar but passive group does not develop neuronal selectivity and has low visual capabilities (Hubel and Wiesel [45]). Along with similar results on bird

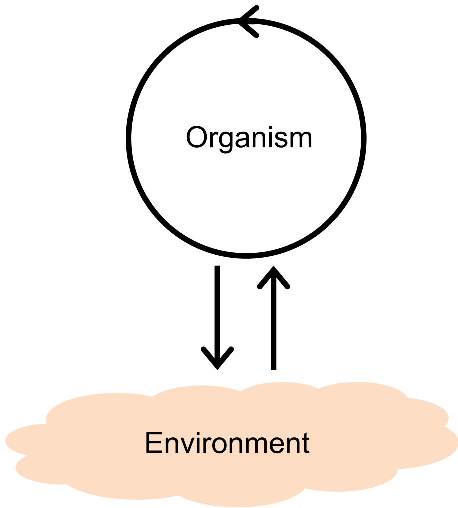


Fig. 1 Enaction was introduced by Varela, Thompson, and Rosch (1991), to account for the relationship or coupling maintained between an organism and its environment from where mutual co-specification and actions would emerge

song, social or sexual imprinting and visual binocularity, neurobiologists coined the concept of *critical period* to refer to the postnatal period of brain maturation that is sensitive to the sensorimotor experience of the environment. This is the period when the plasticity of the brain can be shaped through interaction with the natural world. On other hand, O'Regan and Noe [73] used a similar approach to enaction where they propose *seeing as a way of acting* through considering the laws of physical contingencies relating light and reflectance as a propriety of an object surface.

Here, we review the participation of sensorimotor loops and enactive vision. At a more practical level, we wish to discuss about the sensorimotor constraints to be considered in the design of robotics bio-inspired solutions.

A sensorimotor system is the result of evolution, development, learning and adaptation processes acting at different time scales and behavioral task repertoire [106]. From computational consideration, they can be modeled from optimal principles, including predictions regarding the behavior of a given system. Furthermore, as far as visual tasks are concerned an action-based account of perception still remains mostly studied only separately from the input-to-perception and output-to-action perspectives. Complex organisms actively explore their environment and the understanding of the neural mechanisms underlying such relations would help to assess the interweaving between the nature of perception and their application such as an efficient construction of artificial cognitive systems that can match, for example, a natural exploratory behavior.

In doing so, robots become sensitive to environmental, physical, and dynamic characteristics using their computational and physical constraints [102]. In [77], according to experiments with a simulated head, the authors concluded that sensorimotor laws possess intrinsic properties related to the structure of the physical world in which an organism's body is embedded (but see for a more general discussion [12, 13]).

An important challenge in cognitive robotics is how to achieve autonomous, hopefully "human" inspired, behaviors. On one hand, a top-down approach to behavior for any natural system has been so far unsuccessful. Otherwise, the embodiment of the system, with particular attention to its morphology, environmental interactions, and the physical constraints that ultimately shape the system seems a more promising alternative. More recently considered, the exploitation of a direct link between embodiment and information flow can induce statistical regularities enhancing information processing.

From an engineering point of view, embodied action [110] means that a sensorimotor behavior will turn to be self-calibrated [112] in the function of its internal (e.g., visual sensors) and external parameters, during the action.

2.2 Modeling Sensorimotor Interactions

The dual model of human behavior studied in psychology and the neural mechanisms involved in human decision-making process have inspired a series of robot controllers designed to better interact with the environment and to adapt to the changing environments. Here, we briefly summarize some of the applications of the principles described in Sect. 4 in robotics controllers.

2.2.1 Robot Controllers Based on Layered Models

Most of the layered architectures proposed for robot controllers are somehow inspired by psychological studies, where the human thought is presented as a dual-processing system including reactive and deliberative actions. In psychology, the most acceptable schemata for the separation between reactive and deliberative actions is generated as a result of more than one underlying process. Specifically, [98] analyzed the most prominent dual-process models of human thought, finding that they are based and controlled by two principles [98]:

1. One principle based on information processing, which is structured by language, sensory inputs, and symbolic representations either of the outer world or experience under conscious or unconscious states.
2. One principle based on the associative mode of the symbolic links generated, which are learned over many experiences, created by similarities/differences or any other relation, which is mostly automatic and unconscious.

The principles here described form part of the so-called dual-process model of the human behavior which has a long story in psychology research. The information processing in these dual schemata can be either sequential or parallel. The authors in [101] propose a parallel processing generating dynamic responses with different time

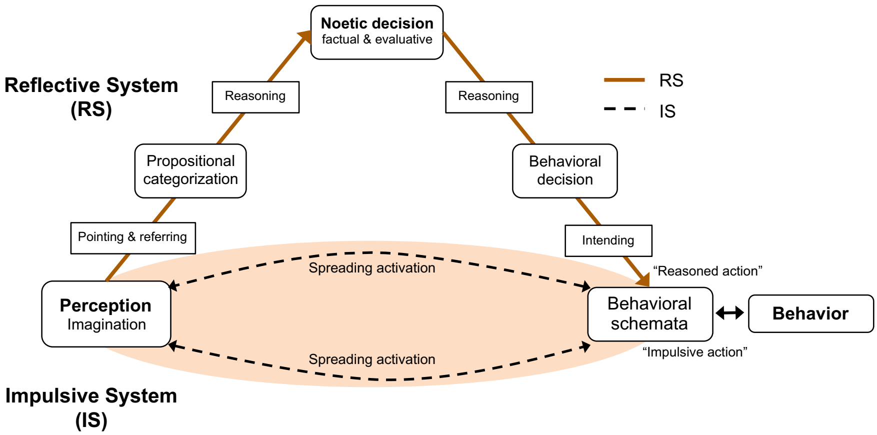
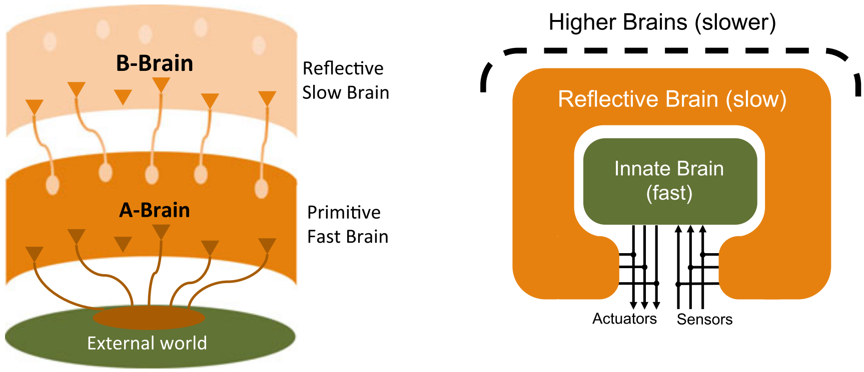


Fig. 2 Dual model of the human behavior proposed by [101]

scales. The dual schema proposed by the authors is grouped in two pathways: (i) *a reflective pathway* which creates the symbolic representations of the outer world in a conscious manner, and, (ii) *an impulsive pathway* which quickly generates behavior according to an internal direct map learned through associations and experience. A diagram showing the model of human behavior described by [101] is shown in Fig. 2.

This dual-processing of the human thought inspired the AI approach proposed by [4, 15], where the processes are layered and organized according to a behavior-based paradigm. Thus, the lower layers are occupied by higher priority processes and always active (e.g., danger avoidance), while the higher layers are capable of more specific and complex behaviors that may or may not be activated. This pioneering work marked the beginning of a large amount of robot architectures requiring both: a fast reaction and complex capability, and represent the main motivation behind the reactive-deliberative type of robot control architecture [47].

Extending the idea of dual-processing, a family of bio-inspired approaches models human thought as a stack of layers with increasing complexity working in parallel. This hierarchical architecture is the one originally stated by Marvin Minsky [68, 69], defining an A-brain which connects the artificial brain to the real world through sensors and actuators. Following the hierarchy, there also exists a B-brain which considers the output of A-brain as input information. B-brain does not know the existence of the real world and governs the A-brain behavior (see Fig. 3a). Additional layers could be also defined following the same paradigm. Following this idea, each layer only reacts to the state of the underlying layer which is certainly an abstract representation of the outer real world. In fact, in [96] (and later in [97]), Singh and Minsky presented an improvement of [68] proposing a model formed by six layers including deliberative, reflective, and self-reflective computations.



(a) (b)

Fig. 3 Brain-based architectures used as robot controllers. **a** Layered brain proposed by Minsky [68, 69]. **b** Robot controller architecture implemented by [117]

Applying Minsky's ideas in robotics, the authors [117, 118] proposed a robot controller inspired by this layered artificial brain structure, in particular, using two brain layers: A-brain and B-brain. Nevertheless, the limitation of this approach is the representation of the outer world done by the A-brain. As the output of the A-brain defines the behavior of the subsequent brain layers, if this output is not complex or accurate enough, the artificial brain will fail in many behaviors. Many sensors are needed in order to obtain and to generate a good representation of the sensed world done by the A-brain, and if this fails, a direct connection of the inputs/outputs is needed to the B-brain. To overcome this limitation, the authors connected both A-brain and B-brain to the external world as it is represented in Fig. 3b.

Similar ideas of a layered artificial brain representing different levels of cognition have been proposed by Davis in [25]. The author reviews a generalized architecture for cognition based on control states, which includes goals, reflexes, desires, and impulses. At a given moment, more than a control state can be present in the system (see Fig. 4), and they can be sometimes antagonistic or complementary. Both, a perceptual act or an internal process can trigger a perceptual state. The control processes lying on each cognitive layer (reflective, deliberative or reactive layers) have different time dynamics. Tasks needing a rapid response of the system are processed in the reactive layer. Deliberative layer deals with processes (control states) with slower dynamics. This architecture is somehow governed by the reflective layer, in which inputs are the internal states of the underlying layers and outputs are caught by modifying the internal state of the deliberative layer. Moreover, Davis also proposes a method for social cooperation between agents by using a centralized deliberative agent and local reactive controllers for each agent.

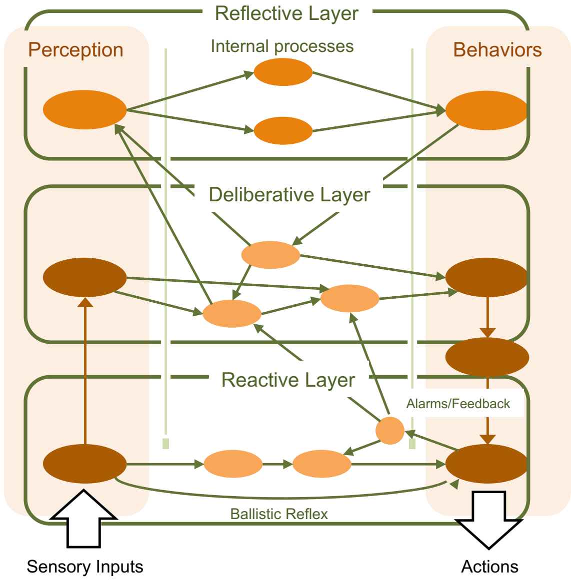


Fig. 4 Diagram of the generalized cognitive architecture proposed by [25]. The processing of perceptual inputs, either coming from the sensory inputs or the internal analysis is processed in three different scales: *reactive* layer, *deliberative* layer, and *reflective* layer (image adapted from [25])

2.2.2 Robot Controllers Based on Neural Mechanisms

Another source of inspiration for the bio-inspired robot controllers is the study of the brain from its neural mechanisms point of view. Damasio and Carvalho [24] described the nature of feelings from a perspective including dual processing. According to them, reactions obey action programs that are executed without any kind of deliberation, due to hard-wired systems present in our bodies, thanks to evolution. There are two main types of action programs: drives and emotions. Drives are aimed to satisfy basic and instinctual physiological needs like hunger, thirst, and libido. Emotions, on the other hand, are action programs that are mostly triggered by external stimuli. When an action program is activated, it produces a change in our current body state. This change is detected by our interoceptive system (collection of nerves dedicated to detect changes in body state), and a feeling is triggered. Damasio and Carvalho define feelings as the mental experiences that accompany body states. Thus, their model proposes a duality between conscious and unconscious experiences, being in this case, feelings and action programs. A robot architecture that uses these ideas as starting point to generate a bio-inspired controller is presented in [81].

Getting into details of neural mechanisms, the stack of layers with increasing complexity proposed by [69] can be mapped to the hierarchical processing of the sensory systems in the mammalian brain (see more details in Sect. 3.1). Briefly, sensory systems process incoming information in different brain areas of increasing complexity, where only the first layer in this hierarchy has a *direct* connection of the outer world. Kurzweil, inspired in this processing schema proposed in [56] his own theory declaring that our brains work as a dense pattern recognizer, i.e., in a multi-scale fashion and with different time scales. He also demonstrates the viability of his proposal by the implementation of the SIRI personal assistant, which uses multi-level pattern recognition and a constant learning process through the use of Hidden Markov Models.

If we now consider the neural circuit in charge of decision-making process, which includes brain areas such as the basal ganglia and prefrontal cortex (PFC), another interesting approach is the one proposed by Krichmar in [54]. In this architecture, a neurorobotical system is presented as a test platform for the study of the generation of curious and anxious behaviors in humans. To do so, variations in the levels of dopamine and serotonin are artificially generated and then studied the effects that these variations produce in the simulated medial prefrontal cortex (mPFC) and orbitofrontal cortex (OFC). The work of Krichmar is part of the so-called Brain-Based Robotics, a recent trend in which neural models of the brain are embedded into robotic platforms in order to generate brain-based controllers. A vast collection of examples of brain-based robot architectures is presented in [55].

In the last few years, the modeling of robot controllers considering brain areas involved in the dopamine influence, such as basal ganglia, has been vastly studied under the reinforcement learning paradigm. Looking for a reward is one of the main motivations of the reactive mammalian decision-making circuitry and what is basically catching the modeling of the basal ganglia [41, 78]. For instance, [39] developed a robot controller based on a model of basal ganglia for a survival task. They showed that this type of model correctly allowed the behavior to switch between different options, differentiating from a classical Winner-takes-all mechanism. The authors observed that using the basal ganglia model, the feedback loop can induce a *behavioral persistance* which is sometimes necessary when a decrease in the drive is observed, and it is observed in several animal behaviors. Models where more than a single loop is involved, suggest that the neural mechanism of decision making resolves competition between different actions available in complex scenarios. Following this, the authors in [78] proposed a robot controller based on a model of the basal ganglia inspired in animal behavior. The behavior observed in the robot matches the behavior of the animal when they are confronted in complex scenarios with multiple alternatives. Similarly, [66] presented the Psikharpax project, where an artificial rat equipped with a sensory-motor system attempts to have autonomy and some capabilities observed in real rats. The neural mechanism ruling artificial rat behavior is based on a model of the *basal ganglia-thalamus-cortex* loop.

The modeling of internal nuclei of basal ganglia has been also accomplished by authors working with robot controllers. For instance, modeling internal nuclei of the basal ganglia, such as the subthalamic nucleus (STN), the globus pallidus (GP), and the substantia nigra (SN), the authors in [114] proposed a behavior-based robot controller where parameters of the model where optimized by genetic algorithm. The simulated robot successfully switched between the six possible behaviors accomplishing the assigned task.

3 Sensing and Modeling Perceptual Input: Vision

One of the main domains where biological inspiration could be applied to robotics is in vision. Vision is one of the most important sensory inputs in humans and in many animals, needing in some cases (e.g., monkeys) up to half of the cortical areas fully dedicated to this sensory input [63]. Studying vision and its underlying mechanisms could certainly unveil how the brain, and more specifically the sensory systems in general, works. This understanding can be applied to the development of new algorithms and technologies that can be exploited in the robotic industry.

3.1 Understanding Mammalian Vision

The computation of visual information, in mammals, starts with the retina in the eye. The retina is highly packed and structured in three cellular and two synaptic layers, with a rich diversity of neuronal types. This thin layer of neural tissue is an arrangement of 5 different neuron types with a clear structure: photoreceptors, bipolar cells, horizontal cells, amacrine cells, and retinal ganglion cells (RGCs). RGCs are particularly important because they convert the electrical activity gathered by all the other cells types in electrical pulses (spikes) traveling to the visual cortex through the optic nerve.

The classical view of retinal processing is related mostly to contrast equalization and real-world conversion from light to spikes, but only to do this, maybe we do not need 5 different neuron types, around 10 types of bipolar cells, 50 types of amacrine cells, and another 20 types of RGCs. A few years ago, [33, 40] reviewed the last findings in the retina, highlighting the fact that it does not only equalize contrast: the retina also extracts different and complex features from input images most of them related to complex motion patterns. More lately, using micro-electrode array technology for retina in-vitro, it has been shown that a single functional type of RGC paves the entire visual field [94], i.e., if each RGC functional type is associated with the computation of a certain image feature, each part of the visual field is being processed, in parallel, by 20 different visual computation machines!

The output of the retina (see [116] for a review on standard biological and computational aspects) is thus formed by about 20 different types of spiking RGC [59]. The classical categories of midget and parasol RGC form the parvocellular and magnocellular pathways through the lateral geniculate nucleus (LGN). More recently, the attention has been turned to several other types of ganglion cells present in small numbers but with an important associated function and also non-standard responses from ganglion cells in general.

At present, in vertebrates the description and function of a diversity (n = 15–20) of RGC (the 0 or 1 (spike) output of the retina to the brain) poses an important challenge for the characterization of early-visual processing [61]. In that line of research, it is still missing a precise description of their: (i) morphology and physiology; (ii) functional physiological fine-tuning mechanism to create diverse parallel visual stream; (iii) neural coding capacity at the individual and population level [23, 33, 60, 115]. From an engineering point of view, a sensory design should display neural coding capacity, constrained by signal compression and transmission through a limited channel capacity, in order to match "informational" signals from its natural environment [5, 8, 93]. In its engaging framework, adequacy between environment signals and sensory design, [8] proposes that the optimal "sensory biological solution", embedded in an intricate chemical and electrical neural network, should, before signal transmission, decrease the intrinsic redundancy and noise of natural scenarios. More recently, [7] revisited the concept of "redundancy" proposing that the nervous system should exploit (and not eliminate) redundancy originating from the statistical properties of natural signals. This is a key aspect to be taken into account in our formalization.

The fact that RGC could be an independent encoder as well involved in population coding is a key issue in order to improve the state of the art regarding early-vision mechanisms. The latter issue is still a large debate in biology, including the fact that with natural movies, RGC seem to act as independent encoders [72], while other observations show that standard RGC types tend to fire together (synchrony) and dynamically adapt their response to light or obscurity [62]. The importance of correlations for an entire population of neurons has been addressed in the retina using high-density array of electrodes (Multielectrodes MEA) with 16–256 electrodes in a (e.g.) 1×1 mm) where most of the neurons in a small area (<500 mm) have been recorded (methodology available to one author of this paper). This new paradigm allows to exhibit correlated responses, in the presence or absence of light [28, 65] with different time constants resulting from a mechanism involving: (i) a common photoreceptors input source through bipolar cells (broad); (ii) amacrine through gap junctions with RGC (medium); (iii) through gap junction between RGC (narrow) [14]. Those different mechanisms are serious candidates at the origin of neural synchrony [33, 71, 72]. In salamander and guinea pig, for instance, a maximum entropy model using weak pairwise correlations, predict 90% of the multi-spiking structure of a large retinal population [86] and 99% of a complete ON and OFF primate parasol cells population [94]. It has generalized several statistical tools [20] allowing to further investigating these aspects at a higher level of generality.

At a computational level, the evidence that retinal cells process the visual information far beyond the common view of "X versus Y (i.e. parvo versus magno)" standard cells in vertebrates is well established. As reviewed in [40], ganglion cells visual pigments can be also responsible for different types of computation: regulating photo-dependent circadian behavior, directional selectivity, motion detection and discrimination, including response anticipation for movement or omitted flashes. The last example includes sophisticated RGC responses for temporal pattern recognition [87], detection and prediction of periodic patterns [88] and motion reversal detection [89].

As pointed out by [40], the non-standard behaviors of RGCs are revealed by using natural stimulus corresponding to dynamic visual scenes [61]. This is a crucial point: when using standard artificial stimuli, only "standard" ganglion cells behaviors are detected. However, when using stimuli corresponding to natural images statistics (e.g., pink noise stimuli) or dynamics [9], it is clear that non-standard behaviors become visible, with the consequence that the visual processing and related neural dynamics are completely different.

Beyond the retina, the spikes sent through the optic nerve are received by the lateral geniculate nucleus (LGN) in the thalamus and then projected to the visual cortex, specifically primary visual cortex (V1). Located in the occipital lobe, V1 is divided into six different functional layers, from layer 1 up to layer 6. The magnocellular input from LGN is received by Layer 4Cα, while the parvocellular inputs are received by layer 4Cβ. This fact inspired the classical but controversial idea of two different cortical systems to process the visual information [67, 108]: ventral and dorsal stream. Ventral stream is located at the temporal lobe and mainly formed by areas such as V1, V2, V4, PIT or TEO, AIT or TE, and it is mostly related to form, color, and texture processing. Dorsal stream, located at the parietal lobe, manages motion information and it is formed by V1, MT, MST, LIP, VIP, and PP.

The hierarchical organization of the visual system allows the system to compute more complicated visual features covering wider visual areas and gaining the size and position invariance of most of the features detected.

If we focus on the motion processing performed by the dorsal stream, when we move up in the visual system hierarchy, some rules start to emerge in its design: each cell gathers a subset of neuron responses of the underlying layers (architecture many-to-one), and context normalization is performed by center-surround mechanisms. Center-surround mechanism at the level of MT visual area, where motion information is computed, allows the system to detect features related to motion contrasts, of motion singularities of the visual scene that could be useful for pattern categorization.

3.2 From the Classical Artificial Vision Early-Vision Front to Enactive Vision

Since David Marr [58] paradigm, where computer vision was described as a pipelined 2D to 3D feed-forward process, artificial vision has developed far beyond. Complex computational problems such as visual sensor calibration and self-calibration, stereo and motion computation, visual object segmentation and recognition have been solved [64]. The ground of the different frameworks essentially formalizes the geometry of multiple images [32], while artificial vision is also seen as an active process [17, 112]. This last view has then been revisited in terms of enactive vision [102].

A step further, non-trivial architectures including feedbacks and distributed computations have been designed on well-founded variational mechanisms [6], with the capability to perform real images and image sequences analyses with a high level of accuracy. This includes visuomotor tasks [85], sensory systems becoming able to exploit characteristics of the environment in coherence with their own computational constraints. Finally, the biological plausibility of such visual computations has been addressed, building a concrete link based on our knowledge of the related biological mechanisms [112]. Such formalism has been considered within the recent KEOpS[1] project, in order to work with the most advanced and efficient framework.

These models allowed exploring many aspects of computer vision, from the most technological (e.g., robotic implementation) to the most fundamental (distributed implementation and interaction of modal information flows), including the most philosophical (the link to enaction). These sources of inspiration have been highly useful in this project, and particularly the modular approach, extensively used in cortical modeling [2, 3] and put to the forth here at the retina level. This includes the comparative analysis of novelty detection models derived from machine learning mechanisms [51] considering the diversity of non-standard behaviors of retina cells.

However, a common drawback of the reported framework is the over simplification of the early-visual front-end [34]. Since the profound synthetic view proposed by Koenderinck on this subject [42], almost all authors consider this crucial processing step as completely described by some variants of Linear-Nonlinear (LN) models. This restrictive model has several drawbacks, one being to limit the visual cues information available from a classical view of the visual stream (magno and parvo pathways). In this KEOpS project, the goal was precisely to go beyond this aspect of the state of the art.

At a functional level and in coherence with what is described in Sect. 2.2, it is known (see [19] for a review and numerical simulations) that two pathways interact. The fast (i.e., impulsive) early-visual pathway mainly fed by bistratified ganglion cells projects onto the so-called konio cells. It provides raw and uncertain "alarms", i.e., visual event detection. This information combines with the paro/magnocellular visual pathways. This interaction leads to an efficient and complex fully distributed algorithm of visual event detection, as sketched out in Fig. 5. Beyond the will of functional modeling of the brain mechanisms, it provides a challenging architecture for embedded robotics vision, since it appears that this mechanism also works with complex real image sequences, as shown in Fig. 6.

Natural image sequences [37, 95] can be segmented in (low-level) basic structural properties that are critical cues for visual categorization (e.g. contrast, color, texture), among them: "power spectra signature" [107]; "modal structural regularities" [52]; "natural modes" [11]; "modular and local-processing architecture" [44]. This latter work shows how second-order statistics (i.e. pixel correlation) help to identify low-level structures, directly connected to categorization/localization performance in humans. Automatic high-level gesture recognition in natural scenarios have been also successfully addressed [113]. In order to go beyond, higher statistical orders, like Independent Component Analysis (ICA) have to be considered since (i) it is known that it accurately represents local Receptive Fields (RF) [79], (ii) it is deeply linked with sparse coding [21], as observed in the retina and beyond, when natural scenarios stimulus are used [9, 61].

[1] https://project.inria.fr/keops.

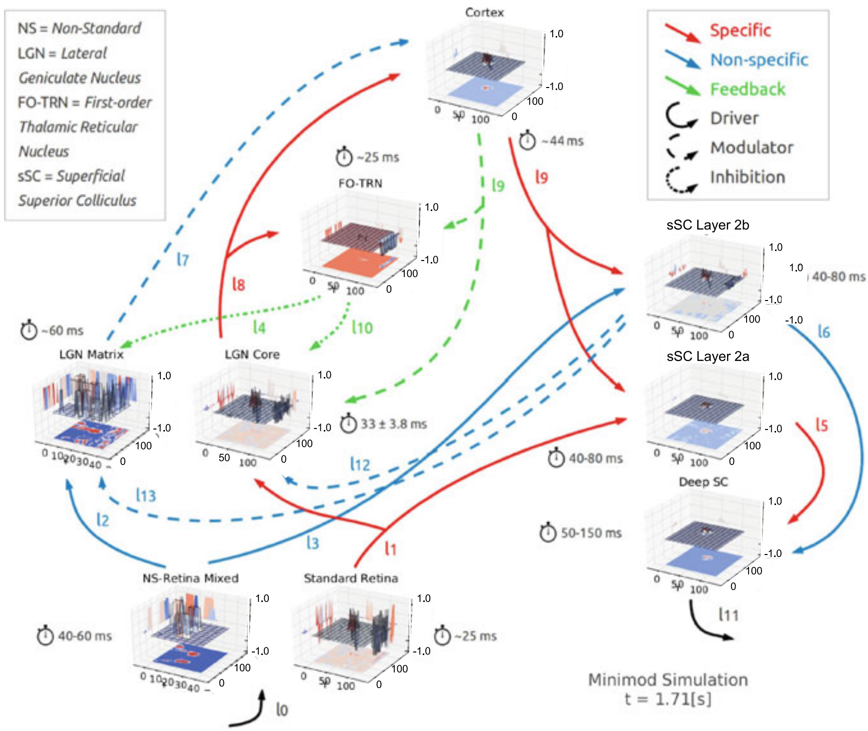


Fig. 5 A functional model of early-vision feedback interactions in the thalamus, combining raw fast visual event detection with finer local visual analysis, from [19]. The non-standard (NS) visual pathway projects onto the matrix part of the primary thalamus (namely the Lateral Geniculate Nucleus LGN) with diffusely and widely projecting neurons, while the standard visual pathway projects onto the core part of the LGN with a much finer topographic projection. In a nutshell, the former acts as a fast modulator of the cortical activity, allowing to rapidly take visual alarms into account and feedbacks onto the latter pathway in order to confirm/cancel the event, with, e.g., a direct action on the superior colliculus (sSc), as far as exploration saccade generation is concerned. This algorithmic mechanism is fully distributed and emerges from the interaction between these cortical maps activities

Regarding robust natural image scene analysis, the sensory layers must take into account (i) the noise corruption and (ii) scene complexity but also the fact that (iii) natural image statistics is quite specific [46]. Noise corruption is efficiently managed by nonlinear anisotropic diffusion filtering [6] and it has been shown that such filtering is compatible with biologically plausible implementations [53]. A key result from [107] shows that second-order statistics is sufficient and efficient to detect global natural image categories, while [104] has numerically demonstrated that when considering nonlinear anisotropic diffusion filtering, local image categories can also be efficiently detected, as illustrated in Fig. 7. The fact that such rather sophisticated event detection mechanisms can be implemented in a two layers network compatible with the retina architecture, in contrast with very efficient but much heavier pro-

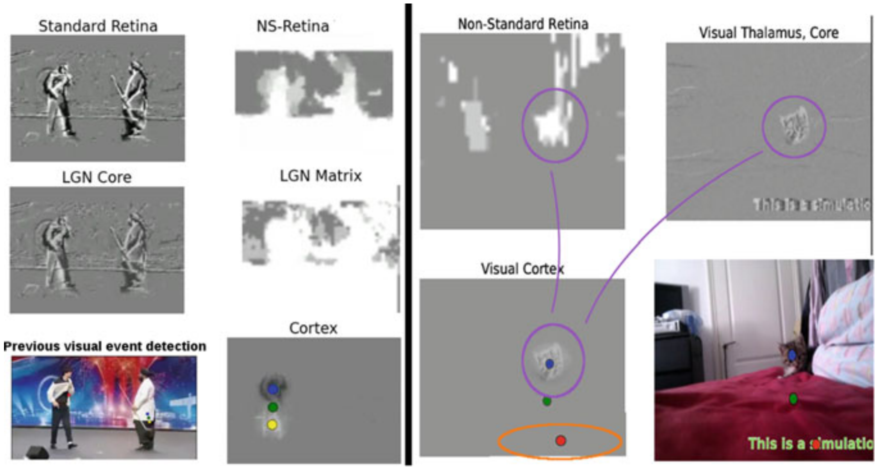


Fig. 6 Two examples of visual analysis of a real complex image sequence. *Left view*: In the previous time instant, the right-hand side person has been detected since it performed an intrusion in the scene, while the system switched to the left-hand side person that initiates a *simulated* aggressive reaction to this intrusion. The standard retina pathways simply detect contrast and motion, while the non-standard pathway roughly detects two diffuse visual events. The core/matrix interaction allows the system to isolate these two visual events and switch from one to another. *Right view*: The system is focusing on the cat (acting as the predator), which has been segmented by a cooperative behavior between the non-standard retina pathway projecting on the LGN matrix (not represented) and the LGN core. When a distractor occurs (here, the scrolling text banner at the video bottom) the cortex maintains two regions of interest and has to rapidly gaze on the distractor before coming back on the original visual event, as observed in the model simulation

cessing using deep-networks as in [31], is a crucial fact for real-time bio-inspired robotics. However, in indoors artificial environments, standard filtering techniques are sufficient, the combination of nonlinear diffusion/segmentation mechanisms with statistical learning methods [104] being to be kept for outdoors conditions.

3.3 *Computational Neuroscience Approach of Sensory Systems*

Many authors have shown that keeping only some basic concepts about retina operation, it is possible to implement a fast feedforward categorization system based only on the activation of the first independent retinal neurons (rank coding). Using Difference of Gaussian (DoG) as spatial kernels and a bank of different spatial extent, [82, 109] proposes a system where the input image is convolved with this filter bank obtaining a ranking of neurons with highest (or earliest) activation. This ranking of neuron, called *rank coding*, is then used for rapid object categorization of natural images. A schema of this algorithm is shown in Fig. 8, which shows how an input

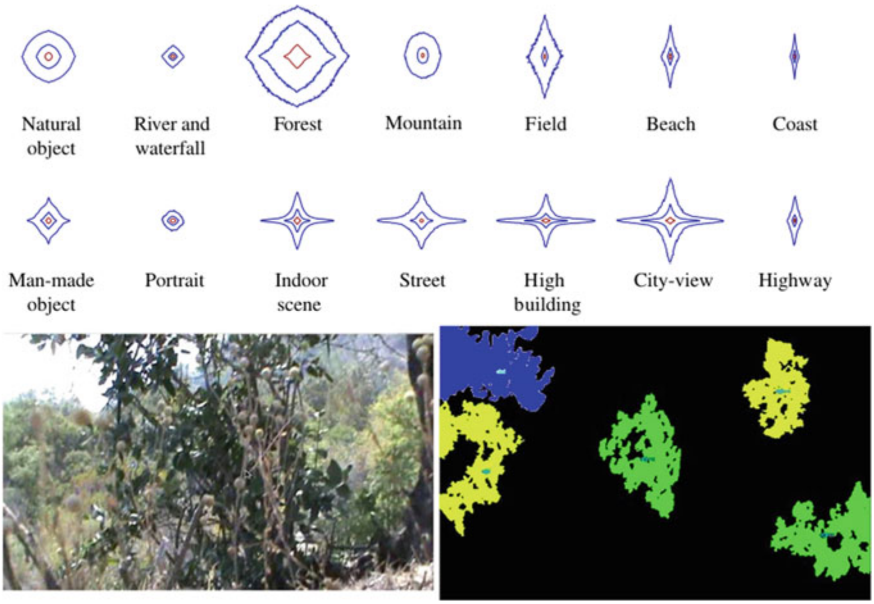


Fig. 7 Top view: The magnitude 2D spectrum signature of a natural image is a relevant cue to detect the image category, from [107]. This is a crucial result for contextual visuomotor reflexes. Bottom views when considering a complex and rather spurious visual scene (left bottom view), the previous result still holds locally and (in the left bottom view) the scene main elements (namely here: sky in blue, landscape in yellow and trees in green) are properly labeled, from [104]

image is encoded by a bank of DoG filters representing different types or retinal ganglion cells. Considering only a small subset of the first cells generating a response, it is possible to reconstruct the input information and recognize the original image. In Fig. 8, we show the image reconstruction considering only the number of cells corresponding to the 1%, 5%, 10%, and 20% of the total image pixels (683×384).

Following these ideas: motion detectors with increasing complexity, architecture many-to-one, and center-surround mechanisms, [29, 30] proposed a bio-inspired architecture to categorize action videos. Both, V1 and MT were modeled using neural networks where neuron activity was computed starting from local motion information in the input videos (see Fig. 9). Using a hierarchical feedforward model the system here proposed performed recognition rates competitive with the state of the art. A similar hierarchical system based on visual cortex, but without center-surround interactions, was proposed by [48] to treat the action recognition problem in real video sequences. Using several layers emulating simple and complex neurons of the visual system for temporal and spatial invariance, plus SVM as a final classifier, the system extracted a vector representation of the input video to be used for recognition. A different model for biological motion (point-light stimuli) recognition, and including both dorsal and ventral modeling, was also proposed by [38].

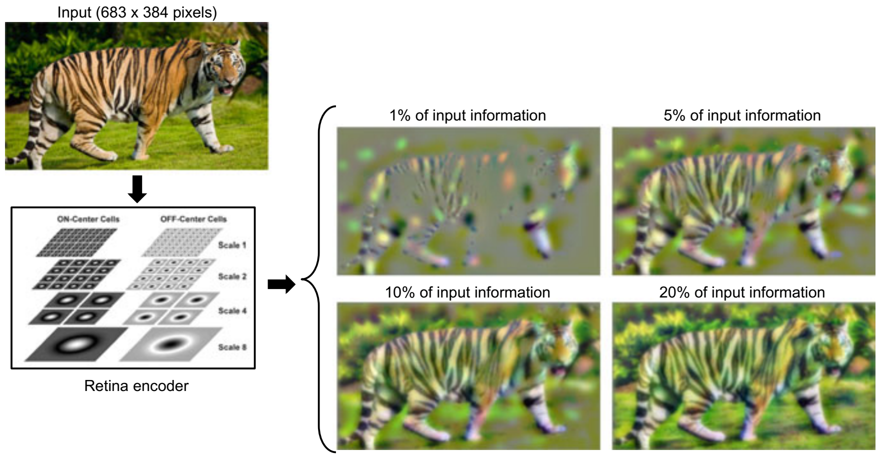


Fig. 8 Rank-order coding mechanism to extract the relevant information of the input image. Relevant information is computed as the output of a filtering stage containing several DoGs with combined polarity and spatial extent. It is then possible to reconstruct the input image considering only the responses of a small percentage of encoder cells

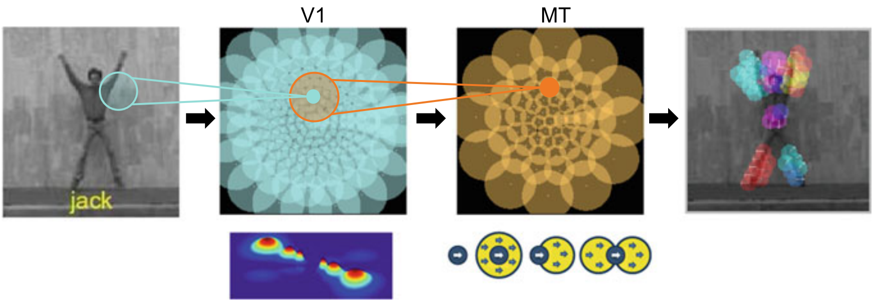


Fig. 9 Bio-inspired action recognition system proposed by [29, 30], based on the motion processing in the mammalian visual system. Input videos are processed by a V1 layer with several neurons encoding different motion directions. The activity generated by V1 neurons is gathered by the next MT layer, which additionally computes complex motion patterns through center-surround interactions. Finally, the activity of MT neurons is considered as a feature map for the recognition task

Regarding object recognition and the modeling of the ventral visual pathway, the authors in [91, 92] proposed a hierarchical model for V1 up to V4 visual areas (see Fig. 10). Each layer of the model extracts a certain feature which combines some temporal and spatial invariance given by the implementation of complex cells at different scales. The system learns features from different object categories making the system perform better and adapt to new objects. The response to these features is then evaluated by a SVM classifier in order to do the recognition.

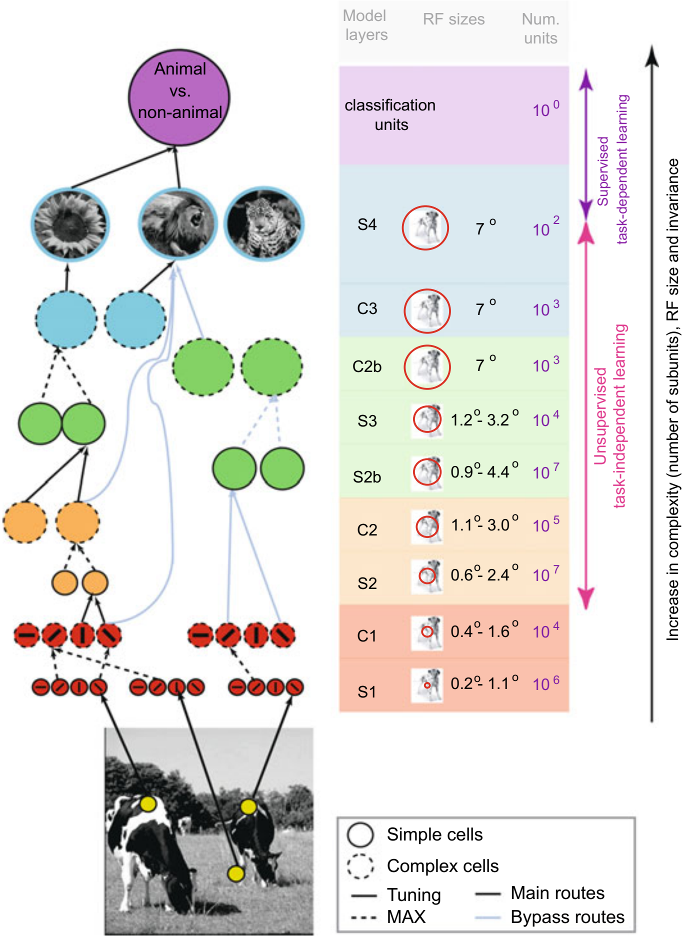
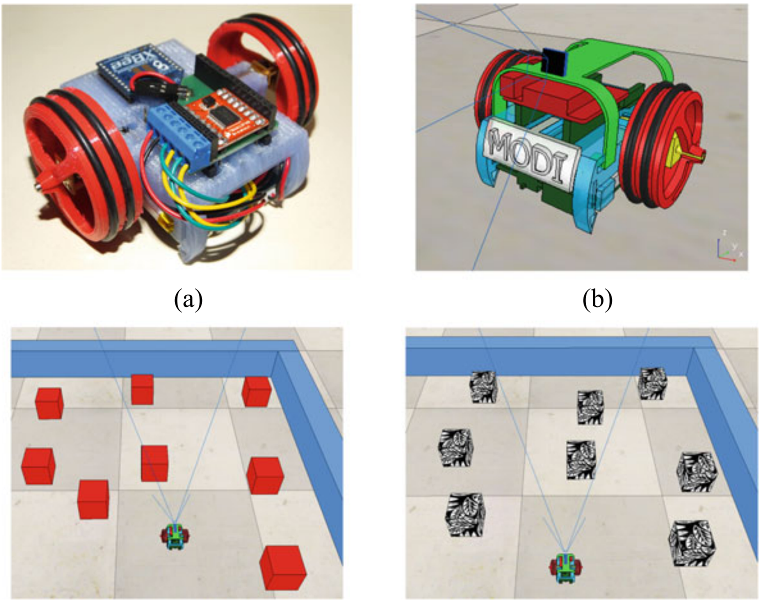


Fig. 10 Bio-inspired object recognition system based on the processing of the visual ventral stream (Image reprinted with permission from [91])

4 Building a Bio-inspired Robot Controller

Several authors have developed bio-inspired robot controllers, and more specifically, Brain-Based Robots [55]. To be considered and named as a brain-based robot, part of the robot-controller must be inspired or mimicking some brain processing. This robot definition conjugates the enactivism concept, where the designed controller is in accordance with the physical body of the robot, and this physical body is part of the environment (see Sect. 2.1).

Following the idea that brain properties are a result of how the robot body interacts with its environment, here we present an example of a brain-based robot as a case



(a) (b) (c) (d)

Fig. 11 MODI robot used to implement the bio-inspired robot controller. **a** Image of the real MODI robot. **b** MODI robot imported in the V-REP simulator with a camera mounted on the top. **c–d** Simulated V-REP environments where the obstacles, cubes, are randomly placed in the scenario. The image texture covering the cubes varies in order to enhance the advantages of a bio-inspired visual processing system

study. Using the MODI platform [81], a retina-based visual sensor and an adaptive artificial neural network (AANN) as robot controller, we develop a system where the brain controller emerges as a consequence of the commended task and the way the robot behaves in its inserted environment.

4.1 MODI Platform

For the study case presented in this chapter, we used the MODular Intelligence (MODI)[2] platform, shown in Fig. 11a, which is a small two-wheeled sensorless robot easy to build, to program and to replicate. It is Arduino-based containing only Open-Hardware components, it has no screws and its chassis and wheels are fully built in a 3D printer [84].

MODI is built in four pieces made in PLA as it can be seen in Fig. 12. Each of the four pieces was designed to be built in a fast prototyping machine such as fused

[2] https://github.com/mjescobar/MODI.

Fig. 12 Four pieces forming the mechanical hardware of MODI: **a** chassis, **b** logo, **c** extension and **d** the two wheels. Once everything is assembled, MODI has a diameter of 96 mm and a height of 50 mm

deposition modeling machine, in our case MakerBot Replicator 2. The detail of each piece is described as follows:

1. **Chasis (Fig. 12a):** This is the core of MODI design and it is conformed in a single piece which contains all the electronic parts (see Fig. 13).
2. **Logo (Fig. 12b):** Together with the chasis, it holds part of the electronic components. Its design also contains two RGB leds.
3. **Extension (Fig. 12c):** This extension is thought to be used to add sensors or cases in order to custom each robot.
4. **Wheels (Fig. 12d):** They are designed with two grooves on the side to mount a couple of o-ring, and thus avoid sliding.

MODI dimensions are 95 cm in diameter and 50 mm in height. Using an inner density of 30–40%, the fabrication time is around 300 min. The entire assembly procedure of the mechanical hardware together with the electronic components is represented in Fig. 13.

The results shown in this chapter were simulated in the Virtual Robot Experimentation Platform, or V-REP, developed by [80]. This platform allowed us to simulate an environment and also connect the input and outputs of the robot with an external robot-controller. The robot has a mounted camera (see Fig. 11b) which recorded

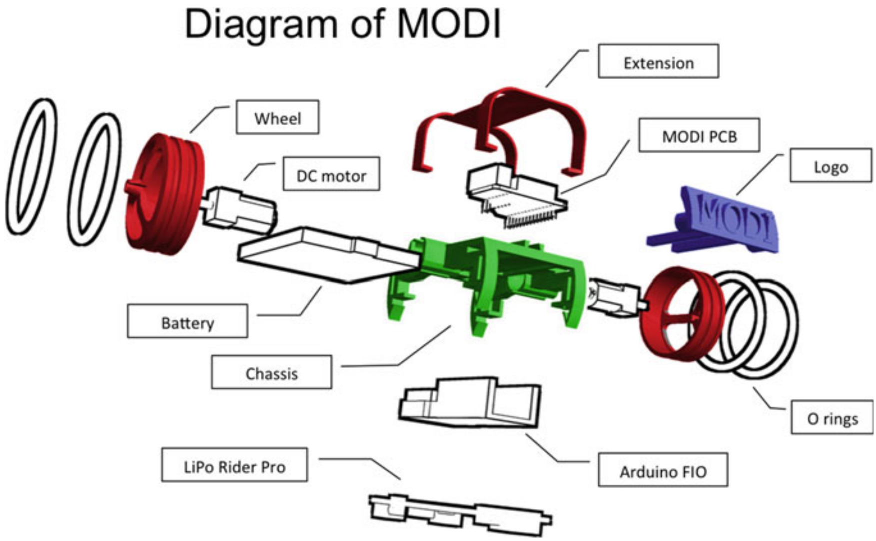


Fig. 13 Diagram of the assembly procedure of all the parts conforming MODI. The parts Logo and Extension are intended to facilitate a custom design of each robot, and also, to incorporate additional hardware as sensors

image is used as input of the robot controller. An image of the simulator is shown in Fig. 11c and d for two variations of the tested environments.

4.2 Retina-Based Visual Sensor

For this bio-implementation, we incorporate in our robot a visual processing mechanism based on the mammalian retina similar to the one described by [82, 109]. For this implementation, the response of a modeled retinal ganglion cell $A(t)$ is the convolution of its receptive fields (RF, modeled as DoG) and the luminosity profile of the input image $I(t)$

$$A(t) = \int_0^t \int_{RF} I(x - x_0, y - y_0, t - u) K(x, y, u) dx dy du = (I * K)(x_0, y_0, t). \tag{1}$$

Considering only spatial convolution, we define the cell receptive field K_{spat} as

$$K_{spat}(x, y) = w_{spat} G_{\sigma_c}(x, y) - G_{\sigma_s}(x, y), \tag{2}$$

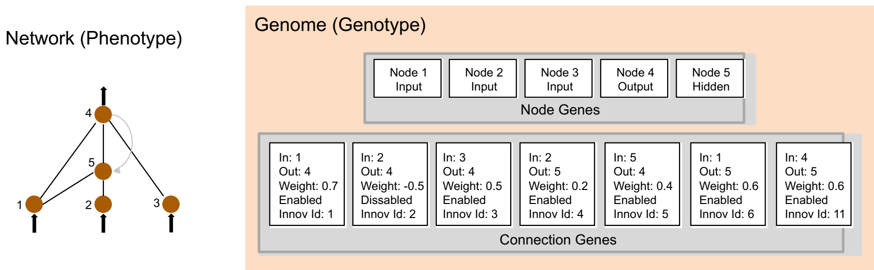
where w_{spat} is a constant defining the ration between the center and surround influence. $G_\sigma(x, y)$ is a normalized, two-dimensional Gaussian function of standard deviation σ. The subindices c and s represent the center and surround component, respectively.

Similar to [82], we used layers of ON and OFF ganglion cells with varying RF sizes. The bigger RF, the fewer number of ganglion cells are needed to cover the input image. For this experiment, we considered $w_{spat} = 1$ and $\sigma_s/\sigma_c = 3.$, making the DoG filter act as an edge detector. The higher output activity contains the most relevant information of the input image (the sharpest edges). Thus, if we consider only a given percentage of the neurons with the highest activity (the ones that fire first in terms of spikes), we can reconstruct a simplified version of the image rich enough to categorize its content (see Fig. 8).

4.3 Adaptive NN: NeuroEvolution of Augmenting Topologies (NEAT)

NeuroEvolution of Augmenting Topologies (NEAT) [100] is a supervised algorithm to create adaptive neural networks, where the network topology and connectivity is learned by genetic algorithms. This adaptive property reveals one of the main advantages of this algorithm: the initial network structure (topology) is not needed and the simplest one is used as starting point. Each network topology is encoded in a genome as it is shown in Fig. 14 defining an individual. Individuals with similar topologies define a species. The survival capacity of each individual along the different algorithm generations will depend on a fitness function. Individuals with a high fitness value not only have a higher probability of survival, but also to be combined to generate a new generation, and thus preserve the species.

The neural network topology shown in Fig. 14a is encoded by the Genome shown in Fig. 14b. Node Genes represent the nodes and the Connection Genes the connections between them. Each node receives a unique Innovation Id number, which is preserved along the learning process allowing the system to recover it if in one generation it was removed (as a result of the evolution). A more recent adaptation of this algorithm aiming to recover symmetries of the input data, inspired by the so-called



(a) (b)

Fig. 14 Example of a neural network shown in (**a**) and its encoded Genome used by NEAT (**b**) (Image adapted from [100])

Compositional Pattern Producing Network (CPPN) [99], allows the learning of the nonlinear function associated with each node to vary the output function of each node (normally a sigmoid). The functions available are: sigmoid, Gaussian, and periodic functions (e.g., sine, cosine). The choice of the output function of each node is not encoded in the Genome, but it can only be modified by Genome mutations.

The evolution of the genome forming the NEAT networks is driven by its performance for a given fitness function. The fitness function determines the reproduction probability of a certain genome. The child generated by the reproduction mechanism will conserve the parents nodes and connections and randomly change the connection weights. If a connection only belongs to one parent, it is inherited instantaneously. Networks belonging to the same specie, have a higher probability to become parents of a new population of neural networks. Mutations are also used to add variability to the reproduction process. Mutations can either create a new node, eliminate a node or randomly modify the connection weight between two nodes.

4.4 Experimental Results

Putting all the elements previously described together, we attempt to make MODI interact with its simulated environment, and through its perceptual input (based on retina processing) let it learn to avoid obstacles. We built the schema shown in Fig. 15, where the whole system is implemented in V-REP simulator. MODI robot receives as input visual images obtained from a camera module sensor located on the robot's front head. The recorded image is down-sampled to 32×32 pixels and then processed by the retina-based encoder, which follows the rank-order encoding strategy. The output of retina-based processing, which is a sparse representation of the input image, is then processed by an Adaptive Artificial Neural Network (AANN) which maps the retina output to a motor action in the simulated environment.

The embodiment of the MODI robot, given by the AANN, is evaluated as the total distance crossed within a fixed time window (in our case 20s). The AANN evolves over time using the NEAT algorithm following a custom fitness function. The fitness function $\mathbb{F}$ is based on the concept that when an obstacle collision occurs, the robot will traverse less distance than avoiding them. Therefore, according to the distance d crossed by the robot, the value of $\mathbb{F}$ is defined as

$$\mathbb{F} = 1/(1 + \exp(3 * (2 - d))), \tag{3}$$

where the value of 2 is the mean distance crossed within the time window of fitness evaluation (20s) and the value of 3 was defined experimentally.

In order to find the AANN, we ran NEAT algorithm for 20 generations with 50 individuals in each of them. We tried two different scenarios, one of them being more "naturalistic" as it is shown in Fig. 16a, and two different systems: having or not a retina-based encoder (retina and raw input, respectively). The evolution of the fitness value along the generations is shown in Fig. 16b, with mean and standard

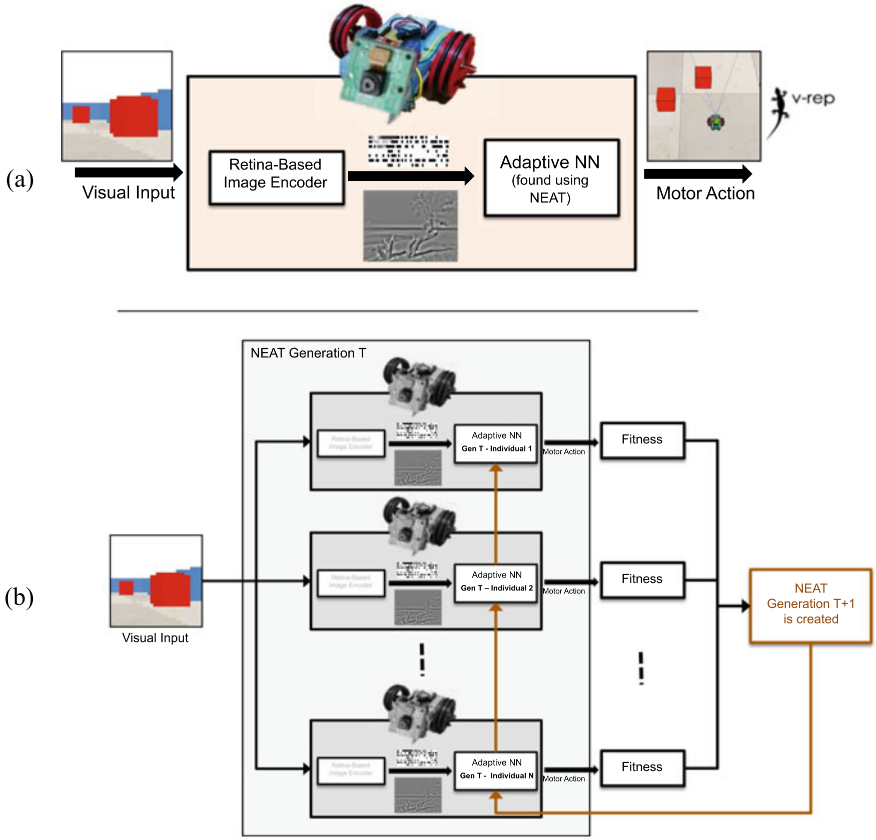


Fig. 15 Schema used to evaluate the enactive capabilities of our bio-inspired robot controller. **a** Using a simulated environment given by V-REP, the input image captured by the camera sensor is processed by a retina-based encoder system. The processing of the retina encoder is used as an input of the Adaptive Artificial Neural Network (AANN) found using NEAT algorithm. The AANN generates a motor action in the environment evoking a new visual image as input stimulus. **b** Learning process of the AANN. Using NEAT algorithm a total of N individuals are generated. Each of them is a neural network converting retina encoder output to a motor action. The performance of each individual is evaluated using a Fitness function over a period of 20 seconds. The individuals with the best performance are then used to generate the next generation of AANNs

deviation values computed from the performance of all the individuals forming the respective generation. In both scenarios, no significant differences were observed in the fitness evolution but differences in the correct learning can be appreciated in the resulting videos of the champions in each case.[3] In the scenario with color filled blocks the fitness in the system without retina-based processing performed better, but

[3] **Scenario with color cubes:** raw visual input (https://youtu.be/dLpcimLrfkA); retina-based visual input (https://youtu.be/I9dhgVhbiVs). **Scenario with textured cubes:** raw visual input (https://youtu.be/xlW1cIa42ls); retina-based visual input (https://youtu.be/Y6eHLBWxPfg).

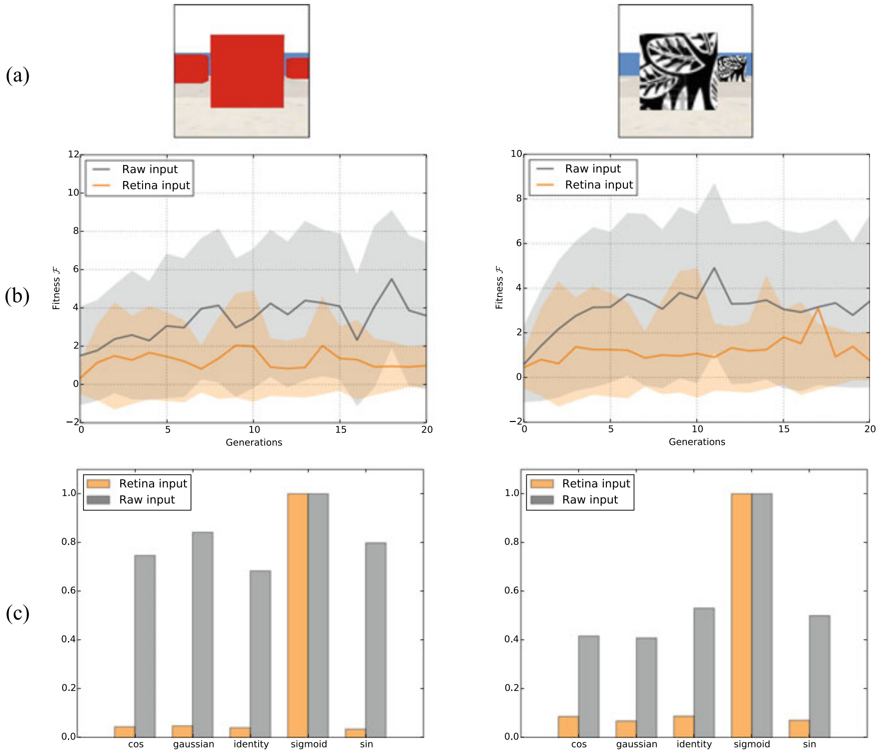


Fig. 16 Results obtained with the bio-inspired robot controller here designed for two different simulated scenarios implemented in V-REP. Both scenarios are generated by placing obstacles randomly inside an environment of fixed size. **a** The obstacles were simulated by color filled cubes (*left*) or natural textured cubes (*right*). A view from the MODI robot is shown here. **b** Evolution of the fitness value along the learning stage for 20 generations of 50 individuals each. Orange data represent the fitness value of a system with a retina-based encoder feeding the AANN, while the gray data considers values coming directly from the camera module. **c** Histograms of the output node functions of the champion networks with (orange) and without (gray) a retina-based encoder system. In both scenarios, the same effect is observed: most of the nodes use a bio-inspired function (Sigmoid) as output activity conversion

no significant differences were observed in the real behavior shown in the videos. By the contrary, in the scenario where the cubes were filled with a more naturalistic image, the fitness was not able to capture the real performance of the learned AANN. Even if the performance of the system without retina processing was better, the behavior of the system with retina-based system overperformed the simple architecture.

Analyzing the structure of the ANNNs selected as champions in the two scenarios for the two systems configuration, a common pattern emerged. As we previously mentioned, each node of the network has the capability to modify its output function through the mutation mechanism. If we explore the distribution of the functions used by each system we observed, in both scenarios, that the AANN using a retina-based encoder is mainly driven by Sigmoid functions and very rarely using other types of nonlinearities, such as, Gaussian or periodic functions. This result is consequent with basic neuron models, where the output activity of a neuron (firing rate) is obtained using a sigmoid of its membrane potential [26].

5 Conclusion

In this chapter, we have explained how embodied AI and enactive cognitive science has enriched robotics with principles, generally specified in so-called bio-inspired robotics. These principles apply on each component of a robotic system (sensors, actuators and controllers) and also on more abstract properties like autonomy, emergence, and ecological design. This view has been exemplified with a variety of recently developed systems, particularly considering sensory processing and controller design. Even if these examples report interesting results and propose future avenues of research, the domain of bio-inspired robotics is far from an established and stable domain and many questions remain open to endow it with well-mastered technologies.

Particularly, it is clear that the most satisfactory and faithful bio-inspired robots are inspired from primitive animals (e.g., insects) and a long road remains to be done toward a full spectrum of human capabilities. This is clearly linked to the corresponding lack of knowledge in cognitive science where ambitious research program should be launched, particularly concerning what is called Artificial General Intelligence [1], not dedicated to specific intelligent processes but rather to general-purpose adaptation. To quote an example given in that paper, the most interesting challenge to approach human intelligence is not to design a robot playing chess, but able to enter an unknown house and to make coffee.

Though its interest for autonomy has been augmented above, putting motivation and needs in robots is also at a preliminary stage, also for the reason that biological data are still missing in this domain. The limbic system (including some regions of the prefrontal cortex, the basal ganglia, the amygdala, and other subcortical structures) and particularly its oldest parts and their relation to the body remains very poorly known (but see [22]). We will elaborate more on this aspect as an important perspective just below.

Having mentioned the need for more accurate information from the biological and cognitive sides, we can finally evoke another relevant topic of debate here. For the moment, we have mainly discussed about principles and techniques to design efficient artificial systems, but it is also more and more acknowledged that bio-inspired robotics is also a very good methodology to better understand cognition and its biological foundations. This is undoubtedly another excellent reason to promote research in this domain!

5.1 Perspective

A step further, beyond sensorimotor interaction discussed in this chapter, to which extent would more sophisticated biological cognitive behaviors fruitfully inspire robotics? As a perspective of the present work, let us very briefly discuss this last point.

Through phylogenetic evolution, the main—when not unique—goal of the animal is: Survive. To this end, sensorimotor interaction is not sufficient, and the biological system has to be able to perceive what is "good" or "bad" regarding this vital goal [75]. Furthermore, such a system has to be able to select, among all possible actions, the one that will optimize both exploitation of resources (in the sense to benefit from positive resources and avoid negative ones) and exploration of the environment in order to avoid any (bad) surprise regarding future situations. As reviewed in this paper, robot-controllers based on basal-ganglia modeling have already been considered, taking this idea into account. As far as the role of the prefrontal cortex is concerned, bio-inspired robotics may go further in depth taking more sophisticated results into account as review in [74]. These authors hypothesize that goal-driven cognition is primary, and organized into two discrete phases: goal selection and goal engaged, with distinct value functions. This not only allows neuroscientists to better explain high-level brain functions, but likely provide very fruitful inspiration for autonomous robotics. The amygdala is in a sense an ancestral basic structure related to motivated behavior [57], while modeling of Pavlovian behavior might be a starting point to build more complex goal-driven behavior as illustrated in Fig. 17.

A step further, children seem intrinsically motivated to manipulate and explore in order to actively learn and generate situations that provide such learning opportunities. This capability has been transposed to robots [70] showing that it is a crucial step towards machines capable of acting in open-ended [49].

Yet another step further, a great challenge would be to be able to explain the whole complex ground behavior of "survival" of a biological or robotic system by a unifying general "fundamental law". This huge challenge has been taken up by [50], including for the modeling of goal-oriented behavior [35] involving the basal-ganglia [36]. The key idea is to state that a system survives if it is able to maintain its vital variables within certain bounds, which in a non-deterministic environment means to minimize the probabilistic surprise with respect to the system observable. What makes this idea quite fruitful is the fact that such "surprise" is bounded by the system information free-energy (as stated by Feynman and revisited by Friston in neuroscience), which is an observable quantity. Up to now, in neuroscience, this principle has been set as compatible with the main notions related to cognition and active inference, whereas its application to robotics is still to be done.

Though non exhaustive, these glimpses of ongoing neuroscience researches yielding effective systemic modeling of cognitive behaviors really indicate that bio-inspired robots still have a lot to learn from neuroscience.

Acknowledgements This work was partially supported by ANR-CONICYT KEOPS (ANR-47); ECOS-CONICYT C13E06; FONDECYT Nro. 1140403, Nro. 1150638; AFOSR Grant Nro.

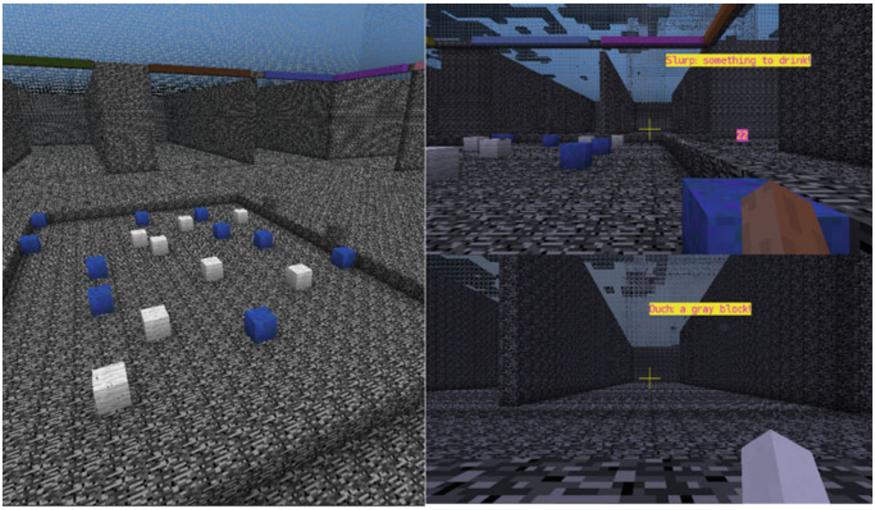


Fig. 17 A Platform for Systemic Neuroscience Simulation [27]. Using the MineCraft survival game environment, a simple survival behavior is simulated in which the human player has been replaced by a bot, that implements Pavlovian mechanism related to the role of the amygdala. This simulation is an unpublished ongoing work following the modeling proposed by [18] and considering mechanism of reinforcement learning [10]

FA9550-19-1-0002; UTFSM DGIP-Grant 231358; Millennium Institute ICM-P09-022-F; Basal Project FB0008. We would also like to thank Patricio Cerda for the simulations performed using MODI and V-REP platform described in Sect. 4.

References

1. Adams S, Arel I, Bach J, Coop R, Furlan R, Goertzel B, Hall JS, Samsonovich AV, Scheutz M, Schlesinger M, Shapiro SC, Sowa JF (2012) Mapping the landscape of human-level artificial general intelligence. AI Mag 33(1)
2. Alexandre F (2009) Cortical basis of communication: local computation, coordination, attention. Neural Netw 22(2):126–133
3. Alexandre F, Guyot F, Haton JP, Burnod Y (1991) The cortical column: a new processing unit for multilayered networks. Neural Netw 4(1):15–25
4. Arkin RC (1998) Behavior-based robotics. MIT Press, Cambridge
5. Attneave F (1954) Some informational aspects of visual perception. Psychol Rev 183–193
6. Aubert G, Kornprobst P (2006) Mathematics of image processing. In: Françoise JP, Naber G, Tsou S (eds) Encyclopedia of mathematical physics, vol 3. Elsevier, Oxford, pp 1–9. ftp://ftp-sop.inria.fr/odyssee/Publications/2006/aubert-kornprobst:06.pdf
7. Barlow H (2001) Redundancy reduction revisited. Network 12(3):241–253
8. Barlow HB (1961) Possible principles underlying the transformation of sensory messages. Sens Commun 217–234
9. Baudot P (2006) Natural computation, much ado about nothing? PhD thesis, University Pierre et Marie Curie, Paris. http://tel.archives-ouvertes.fr/docs/00/20/37/12/PDF/These_

piero_nature_is_the_code.pdf http://tel.archives-ouvertes.fr/docs/00/20/37/12/PDF/These_piero_nature_is_the_code.pdf
10. Beati T, Carrere M, Alexandre F (2013) Which reinforcing signals in autonomous systems? In: Third international symposium on biology of decision making, Paris, France. https://hal.inria.fr/hal-00826603
11. Bobick A, Richards W (2006) Classifying objects from visual information. Technical report AIM-879, M.I.T. http://dspace.mit.edu/handle/1721.1/6443
12. Bongard J, Lipson H (2005) Active coevolutionary learning of deterministic finite automata. J Mach Learn Res 6:1651–1678
13. Bongard J, Zykov V, Lipson H (2006) Resilient machines through continuous self-modeling. Science 314(5802):1118–1121
14. Brivanlou IH, Warland DK, Meister M (1998) Mechanisms of concerted firing among retinal ganglion cells. Neuron 20:527–529
15. Brooks R (1986) A robust layered control system for a mobile robot. IEEE J Robot Autom 2(1):14–23
16. Brooks RA (1991) Intelligence without representation. Artif Intell 47(1–3):139–159
17. Brown C, Coombs D, Soong J (1993) Real-time smooth pursuit tracking. In: Blake A, Yuille A (eds) Active vision, chap VIII. The MIT Press, pp 123–136
18. Carrere M, Alexandre F (2015) A pavlovian model of the amygdala and its influence within the medial temporal lobe. Front Syst Neurosci 14. https://doi.org/10.3389/fnsys.2015.00041. https://hal.inria.fr/hal-01145790
19. Carvajal C (2014) Dynamic interplay between standard and non-standard retinal pathways in the early thalamocortical visual system: a modeling study. PhD thesis, Université de Lorraine
20. Cessac B, Viéville T (2008) On dynamics of integrate-and-fire neural networks with adaptive conductances. Front Neurosci 2(2)
21. Comon P, Jutten C, Herault J (1991) Blind separation of sources, part II: problems statement. Signal Process 24:11–20. http://portal.acm.org/citation.cfm?id=119708
22. Craig A (2009) How do you feel - now? The anterior insula and human awareness. Nat Rev Neurosci 10:59–70
23. Dacey D (1999) Primate retina: cell types, circuits and color opponency. Prog Retin Eye Res 18(6):737–763
24. Damasio A, Carvalho GB (2013) The nature of feelings: evolutionary and neurobiological origins. Nat Rev Neurosci 14(2):143–152
25. Davis DN (2002) Computational architectures for intelligence and motivation. In: Proceedings of the 2002 IEEE international symposium on intelligent control. IEEE, pp 520–525
26. Dayan P, Abbott LF (2005) Theoretical neuroscience: computational and mathematical modeling of neural systems. The MIT Press, Cambridge
27. Denoyelle N, Pouget F, Viéville T, Alexandre F (2014) VirtualEnaction: a platform for systemic neuroscience simulation. In: International congress on neurotechnology, electronics and informatics, Rome, Italy. https://hal.inria.fr/hal-01063054
28. DeVries S (1999) Correlated firing in rabbit retinal ganglion cells. J Neurophysiol 81(2):908–920
29. Escobar MJ, Kornprobst P (2012) Action recognition via bio-inspired features: the richness of center-surround interactions. Comput Vis Image Underst 116:593–605
30. Escobar MJ, Masson GS, Vieville T, Kornprobst P (2009) Action recognition using a bio-inspired feedforward spiking network. Int J Comput Vision 82(3):284
31. Farabet C, Couprie C, Najman L, LeCun Y (2013) Learning hierarchical features for scene labeling. IEEE Trans Pattern Anal Mach Intell 35(8):1915–1929. http://doi.ieeecomputersociety.org/10.1109/TPAMI.2012.231
32. Faugeras O, Luong Q, Papadopoulo T (2001) The geometry of multiple images. MIT Press, Cambridge
33. Field G, Chichilnisky E (2007) Information processing in the primate retina: circuitry and coding. Annu Rev Neurosci 30:1–30

34. Floreano D, Suzuki M (2006) Active vision and neural development in animals and robots. In: Proceedings of the seventh international conference on cognitive modeling, pp 10–11. http://iccm2006.units.it/
35. Friston K, Rigoli F, Ognibene D, Mathys C, Fitzgerald T, Pezzulo G (2015) Active inference and epistemic value. Cogn Neurosci 1–28. http://view.ncbi.nlm.nih.gov/pubmed/25689102
36. Friston K, Schwartenbeck P, Fitzgerald T, Moutoussis M, Behrens T, Dolan RJ (2013) The anatomy of choice: active inference and agency. Front Human Neurosci 7. https://doi.org/10.3389/fnhum.2013.00598. http://dx.doi.org/10.3389/fnhum.2013.00598
37. Geisler W (2008) Visual perception and the statistical properties of natural scenes. Annu Rev Psychol 59:167–192
38. Giese M, Poggio T (2003) Neural mechanisms for the recognition of biological movements and actions. Nat Rev Neurosci 4:179–192
39. Girard B, Cuzin V, Guillot A, Gurney K, Prescott T (2003) A basal-ganglia inspired model of action selection evaluated in a robotic survival task. J Integr Neurosci 2(2):179–200
40. Gollisch T, Meister M (2008) Rapid neural coding in the retina with relative spike latencies. Science 319:1108–1111. https://doi.org/10.1126/science.1149639
41. Gurney K, Prescott T, Wickens J, Redgrave P (2004) Computational models of the basal ganglia: from robots to membranes. Trends Neurosci 27(8):453–459
42. ter Haar Romeny BM (2003) Front-end vision and multi-scale image analysis - multi-scale computer vision theory and applications, written in mathematics. Comput Imaging Vis vol 27. Springer, Berlin
43. Harnard S (1990) The symbol grounding problem. Physica D 42:335–346
44. Henderson TC (1992) Object identification in context: the visual processing of natural scenes. Can J Psychol: Special Issue Object Scene Process 46:319–342
45. Hubel D, Wiesel T (1962) Receptive fields, binocular interaction and functional architecture in the cat visual cortex. J Physiol 160:106–154
46. Hyvärinen (2009) Natural image statistics. Springer, Berlin. http://www.cs.helsinki.fi/u/ahyvarin/papers/viscor.shtml
47. Iocchi L, Nardi D, Salerno M (2001) Reactivity and deliberation: a survey on multi-robot systems. In: Balancing reactivity and social deliberation in multi-agent systems. Springer, Berlin, pp 9–32
48. Jhuang H, Serre T, Wolf L, Poggio T (2007) A biologically inspired system for action recognition. In: ICCV, pp 1–8
49. Kaplan F, Oudeyer PY (2008) Intrinsically motivated machines. In: Lungarella M, Iida F, Bongard J, Pfeifer R (eds) 50 Years of AI, p. n/a. Lungarella M, Iida F, Bongard J, Pfeifer R. https://hal.inria.fr/inria-00420223
50. Karl F (2012) A free energy principle for biological systems. Entropy 14(11):2100–2121. https://doi.org/10.3390/e14112100. http://dx.doi.org/10.3390/e14112100
51. Kassab R, Alexandre F (2009) Incremental data-driven learning of a novelty detection model for one-class classification with application to high-dimensional noisy data. Mach Learn 74(2):191–234
52. Knill DC, Richards W (eds) (1996) Perception as bayesian inference. Cambridge University Press, New York
53. Kornprobst P, Vieville T, Chemla S, Rochel O (2006) Modeling cortical maps with feed-backs. In: 29th European conference on visual perception, p 53
54. Krichmar JL (2013) A neurorobotic platform to test the influence of neuromodulatory signaling on anxious and curious behavior. Front Neurorobot 7
55. Krichmar JL, Wagatsuma H (2011) Neuromorphic and brain-based robots. Cambridge University Press, Cambridge
56. Kurzweil R (2012) How to create a mind: the secret of human thought revealed. Penguin, London
57. LeDoux J (2007) The amygdala. Curr Biol 17(20):R868–R874
58. Marr D (1982) Vision: A computational investigation into the human representation and processing of visual information. W.H. Freeman, New York

59. Masland R (2001) The fundamental plan of the retina. Nature Neurosci 4(9)
60. Masland R (2001) Neuronal diversity in the retina. Curr Opin Neurobiol 11(4):431–436
61. Masland RH, Martin PR (2007) The unsolved mystery of vision. Current Biol 17(15):R577–R582. https://doi.org/10.1016/j.cub.2007.05.040. http://dx.doi.org/10.1016/j.cub.2007.05.040
62. Mastronarde D (1983) Correlated firing of cat retinal ganglion cells. I. Spontaneously active inputs to X-and Y-cells. J Neurophysiol 49(2):303–324
63. Maunsell J, Newsome W (1987) Visual processing in monkey extrastriate cortex. Ann Rev Neurosci 10:363–401
64. Medioni G, Kang S (2004) Emerging topics in computer vision. Prentice Hall, Hoboken
65. Meister M, Pine J, Baylor DA (1994) Multi-neuronal signals from the retina: acquisition and analysis. J Neurosci Methods 51(1):95–106. http://view.ncbi.nlm.nih.gov/pubmed/8189755
66. Meyer JA, Guillot A, Girard B, Khamassi M, Pirim P, Berthoz A (2005) The psikharpax project: towards building an artificial rat. Robot Auton Syst 211–223
67. Milner AD, Goodale MA (2008) Two visual systems re-viewed. Neuropsychologia 46:774–785
68. Minsky M (1988) Society of mind. A touchstone book. Simon & Schuster, New York
69. Minsky M (2007) The emotion machine: commonsense thinking, artificial intelligence, and the future of the human mind. Simon & Schuster, New York
70. Moulin-Frier C, Nguyen SM, Oudeyer PY (2013) Self-organization of early vocal development in infants and machines: the role of intrinsic motivation. Front Psychol 4(1006). https://doi.org/10.3389/fpsyg.2013.01006. https://hal.inria.fr/hal-00927940
71. Neuenschwander S, Singer W (1996) Long-range synchronization of oscillatory light responses in the cat retina and lateral geniculate nucleus. Nature 379(6567):728–732
72. Nirenberg S, Latham P (1998) Population coding in the retina. Curr Opin Neurobiol 8:488–493
73. O'Regan K, Noe A (2001) A sensorimotor account of vision and visual consciousness. Behav Brain Sci 24:939–1031
74. O'Reilly R, Munakata Y, Frank MJ, Hazy TE (2014) Goal-driven cognition in the brain: a computational framework (2014). arXiv:1404.7591
75. Pezzulo G, Verschure PFMJ, Balkenius C, Pennartz CMA (2014) The principles of goal-directed decision-making: from neural mechanisms to computation and robotics. Philos Trans R Soc Lond B: Biolog Sci 369(1655):20130,470+. https://doi.org/10.1098/rstb.2013.0470
76. Pfeifer R, Bongard J, Grand S (2007) How the body shapes the way we think: a new view of intelligence, Bradford Books. MIT Press, Cambridge
77. Philipona D, O'Regan K, Nadal JP, Coenen OM (2004) Perception of the structure of the physical world using unknown sensors and effectors. In: Thrun S, Saul L, Scholkopf B (eds) Advances in neural information processing systems 16. MIT Press, Cambridge
78. Prescott TJ, Fernando, Gurney K, Humphries MD, Redgrave P (2006) A robot model of the basal ganglia: behavior and intrinsic processing. Neural Netw 19(1):31–61
79. Rao R, Sejnowski TJ (1991) Predictive sequence learning in recurrent neocortical circuits. Advances in neural information and processing systems, vol 12. MIT Press, Cambridge
80. Rohmer E, Singh SP, Freese M (2013) V-rep: a versatile and scalable robot simulation framework. In: 2013 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE, pp 1321–1326
81. Rubilar F, Escobar MJ, Arredondo T (2014) Bio-inspired architecture for a reactive-deliberative robot controller. In: 2014 international joint conference on neural networks (IJCNN). IEEE, pp 2027–2035
82. Rullen RV, Thorpe S (2001) Rate coding versus temporal order coding: What the retina ganglion cells tell the visual cortex. Neural Comput 13(6):1255–1283
83. Russell S, Norvig P (2003) Artificial intelligence - a modern approach. Prentice-Hall, Upper Saddle River
84. Saez S (2013) Diseño y construcción de plataforma para estudio de enjambres de robots. PhD thesis, Professional Engineer's thesis, Department of Electronic Engineering. Universidad Técnica Federico Santa María

85. Samson C, Leborgne M, Espiau B (1991) Robot control. The task-function approach. In: Oxford Engineering Science Series, vol 22. Oxford University Press, Oxford
86. Schneidman E, Berry M, Segev R, Bialek W (2006) Weak pairwise correlations imply strongly correlated network states in a neural population. Nature 440(7087):1007–1012
87. Schwartz G, Berry MJ (2008) Sophisticated temporal pattern recognition in retinal ganglion cells. J Neurophysiol 99(4):1787–1798. https://doi.org/10.1152/jn.01025.2007
88. Schwartz G, Harris R, Shrom D, Berry MJ (2007) Detection and prediction of periodic patterns by the retina. Nature Neurosci 10(5):552–554. https://doi.org/10.1038/nn1887. http://dx.doi.org/10.1038/nn1887
89. Schwartz G, Taylor S, Fisher C, Harris R, Berry MJ (2007) Synchronized firing among retinal ganglion cells signals motion reversal. Neuron 55(6):958–969. https://doi.org/10.1016/j.neuron.2007.07.042. http://dx.doi.org/10.1016/j.neuron.2007.07.042
90. Searle JR (1980) Minds, brains, and programs. Behav Brain Sci 3:417–457
91. Serre T (2006) Learning a dictionary of shape-components in visual cortex: comparison with neurons, humans and machines. PhD thesis, Massachusetts Institute of Technology, Cambridge, MA
92. Serre T, Wolf L, Poggio T (2005) Object recognition with features inspired by visual cortex. In: CVPR, pp 994–1000
93. Shannon C (1948) A mathematical theory of communication. Bell Syst Techn J 27:379–423, 623–656. http://cm.bell-labs.com/cm/ms/what/shannonday/shannon1948.pdf
94. Shlens J, Field G, Gauthier J, Grivich M, Petrusca D, Sher A, Litke A, Chichilnisky E (2006) The structure of multi-neuron firing patterns in primate retina. J Neurosci 26(32):8254
95. Simoncelli E, Olshausen B (2001) Natural image statistics and neural representation. Annu Rev Neurosci 24(1):1193–1216
96. Singh P, Minsky M (2003) An architecture for combining ways to think. In: International conference on integration of knowledge intensive multi-agent systems. IEEE, pp 669–674
97. Singh P, Minsky M (2005) An architecture for cognitive diversity. In: Visions of mind: architectures for cognition and affect. IGI Global, pp 312–331
98. Smith E, DeCoster J (2000) Dual-process models in social and cognitive psychol- ogy: conceptual integration and links to underlying memory systems. Pers Soc Psychol Rev 4(2):108–131
99. Stanley K (2007) Compositional pattern producing networks: A novel abstraction of development. Genet Program Evolvable Mach 8(2):131–162
100. Stanley K, Miikkulainen R (2002) Evolving neural networks through augmenting topologies. Evol Comput 10(2):99–127
101. Strack F, Deutsch R (2002) Reflective and impulsive determinants of social behavior. Pers Soc Psychol Rev 8(3):220–247
102. Suzuki M, Floreano D (2008) Enactive robot vision. Adapt Behav 16(2–3):122–128
103. Taouali W, Goffart L, Alexandre F, Rougier NP (2015) A parsimonious computational model of visual target position encoding in the superior colliculus. Biol Cybern. In Press
104. Teftef E, Escobar MJ, Astudillo A, Carvajal C, Cessac B, Palacios A, Viéville T, Alexandre F (2013) Modeling non-standard retinal in/out function using computer vision variational methods. Research Report RR-8217, INRIA. https://hal.inria.fr/hal-00783091
105. Thompson E, Palacios A, Varela F (1992) Ways of coloring: comparative color vision as a case study for cognitive science. Behav Brain Sci 15:1–26
106. Todorov E (2004) Optimally principles in sensorimotor control. Nature Neurosci 7(9):907–915
107. Torralba A, Oliva A (2003) Statistics of natural image categories. Netw: Comput Neural Syst 14:391–412. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.3.6355
108. Van Essen DC, Gallant JL (1994) Neural mechanisms of form and motion processing in the primate visual system. Neuron 13:1–10
109. VanRullen R, Thorpe SJ (2002) Surfing a spike wave down the ventral stream. Vision Res 42:2593–2615
110. Varela F, Thompson E, Rosh E (2001) The embodied mind: cognitive science and human experience. The MIT Press, Cambridge

111. Varela FJ (1979) Principles of biological autonomy. The North Holland series in general systems research. North Holland, New York
112. Vieville T (1997) A few steps towards 3D active vision. Springer, Berlin
113. Vieville T, Crahay S (2004) Using an hebbian learning rule for multi-class svm classifiers. J Comput Neurosci 17(3):271–287
114. Wang Y, Li S, Chen Q, Hu W (2007) Biology inspired robot behavior selection mechanism: Using genetic algorithm. In: Li K, Fei M, Irwin G, Ma S (eds) Bio-inspired computational intelligence and applications, vol 4688. Lecture notes in computer science. Springer, Berlin, pp 777–786
115. Wassle H (2004) Parallel processing in the mammalian retina. Nat Rev Neurosci 5(10):747–57
116. Wohrer A, Kornprobst P (2009) Virtual retina?: a biological retina model and simulator, with contrast gain control. J Comput Neurosci 26(2):219
117. Zagal J, Lipson H (2011) Towards self-reflecting machines: two-minds in one robot. In: Kampis G, Karsai I, Szathmáry E (eds) Advances in artificial life, vol 5777. Darwin meets von neumann, Lecture notes in computer science. Springer, Berlin, pp 156–164
118. Zagal JC, Lipson H (2009) Self-reflection in evolutionary robotics: resilient adaptation with a minimum of physical exploration. In: Proceedings of the 11th annual conference companion on genetic and evolutionary computation conference: Late Breaking Papers. ACM, pp 2179–2188

Biomedical Devices: Materials, Fabrication and Control

Sheila Lascano and Danilo Estay

Abstract In this chapter, we present an overview of materials used in rapid prototyping of biomedical devices, with their pros and cons, which are later used for implants of robotic prosthetic devices. Materials used in medical devices must meet strict performance requirements through all their life cycle, design, manufacturing, packaging, shipping, use and end use. The selection of materials in the biomedical field is strongly influenced by the application. In implants, the used materials must be corrosion resistant, biocompatible, bioactive, non-toxic and osseointegrated, with good mechanical strength and wear resistance, because this material will be in contact with body fluids. A material with those characteristics is considered a biomaterial. In the case of prosthesis, the selection of structural materials is focused on maximizing the strength/weight ratio of the overall prosthesis. Another aspect is manufacturability because the implant or prosthesis has to be cost-effective. There is a big number of materials to choose from, and each individual has particular needs. According to their chemical composition, the materials used in medical applications could be classified as metals, polymers, ceramics and composite materials.

1 Materials Used in Medicine

Materials used in medical devices must meet strict performance requirements through all their life cycle, design, manufacturing, packaging, shipping, use and end use. The selection of materials in the biomedical field is strongly influenced by the application. In implants, the used materials must be corrosion resistant, biocompatible, bioactive, non-toxic and osseointegrated, with good mechanical strength and wear resistance, because this material will be in contact with body fluids. A material with

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_9

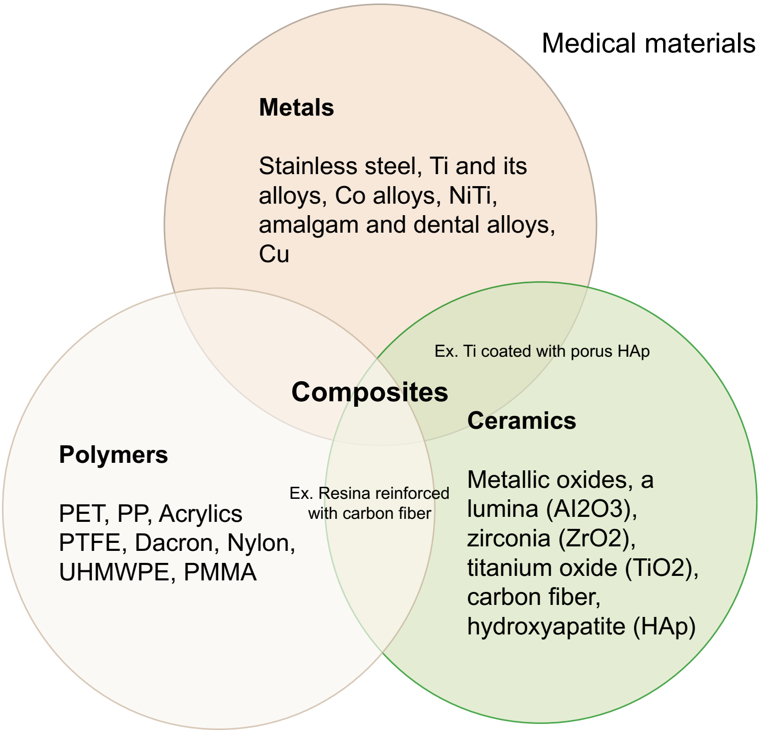


Fig. 1 Classification of materials used in biomedical devices according to their chemical composition and some examples

those characteristics is considered a biomaterial. In the case of prosthesis, the selection of structural materials is focused on maximizing the strength/weight ratio of the overall prosthesis. Another aspect is manufacturability, because the implant or prosthesis has to be cost-effective. There is a big amount of materials to choose from, and each individual has particular needs. According to their chemical composition, the materials used in medical applications could be classified as metals, polymers, ceramics and composite materials. Figure 1 shows some examples of materials used in prostheses and implants.

Metallic materials are widely used in biomedical and orthopedic applications. The metallic alloys used to substitute damaged biological tissues, reestablish functions or in contact with body fluids are known as metallic biomaterials. Metallic materials are used to replace defective or damaged tissues to recover the functionality. Two aspects have to be considered in materials selection for biomedical applications: (i) biocompatibility (defined as its ability to stay in harmony with host tissues) [1, 2] and (ii) good corrosion resistance (in the human body at 37 °C). Some metals are beyond these problems such as precious metals, and other metals spontaneously form a thin,

Table 1 Comparison of the mechanical properties of implant materials [8]

Material	E (GPa)	sy (MPa)
FeCrNiMo (316 L)	210	450
CoCr (as cast)	200	500
CoNiCr (as wrought)	220	850
Ti6Al4V	105	900
TiAl5Fe2.5	105	900
Cp-Ti	100	300
Cp-Ta	200	300
Cp-Nb	120	250
Magnesium alloys	41	60–100
Human bone	ene-20	130–180

protective oxide film which limits the potential for further corrosion by passivation, for example, titanium.

The main categories of metals for orthopedic implants are stainless steels, cobalt-chromium alloys, titanium alloys and porous metallic materials. Among these metallic materials, Ti and its alloys are the best candidates for substitute bone tissue because of their excellent in vivo and in vitro behavior [3]. The benefits of titanium are its high strength-to-weight ratio and corrosion resistance, in addition, it is non-toxic, biocompatible (non-toxic and not rejected by the body), long-lasting, non-ferromagnetic, and osseointegrated (the joining of bone with artificial implant), and their long-range availability. Furthermore, Ti and its alloys present a low stiffness compared to other metallic alloys, such as Co-based alloys and stainless steels. However, the mismatch between the Young modulus of titanium alloys and bone persists, promoting stress shielding, which causes bone resorption. This fact is the reason for the research in new alloys with the Young modulus similar to bone and improved corrosion resistance and the development of a porous structure to replicate the bone architecture [4–7] or improve the adhesion of cells to the implant. Table 1 summarizes the properties of some metallic biomaterials.

Moreover, it should be noted that the metallic materials employed in medical, surgical and dental instruments, as well as external prostheses, are not considered as metallic biomaterials because they are not exposed to physiological body fluids, for example, when metallic materials are used in the structure of external prostheses to provide better mechanical strength in external orthopedic applications. For example, Fig. 2 presents an orthopedic robot hand design using aluminum alloys as structural support [9].

In general, ceramics exhibit some advantages such as high wear resistance and generally, they act as electrical and thermal insulators. Recently, the use of ceramic materials in biomedical applications has earned significant attention as candidates for the fabrication of implants, because they are characterized by their excellent chemical stability before oxygen, water, acidic, alkaline, saline environments and organic

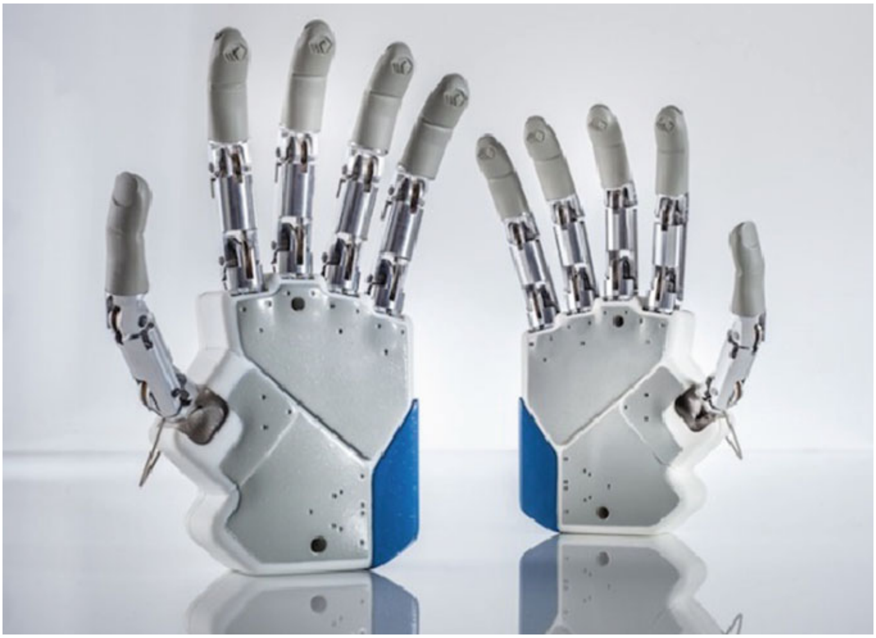


Fig. 2 Anthropomorphic robot hands for research ©Prensilia SRL (www.prensilia.com)

solvents. The most used materials are alumina (aluminum oxide monocrystal), zirconia oxidized, pyrolytic carbon, hydroxyapatite (calcium hydrated phosphate) and vitroceramics based on SiO2-CaO-Na2O-P2O5 and some others such as MgO and K2O. Actually, the zirconia is used in hip implants, knee replacement and dental implants as a substitute for metallic materials [7].

The newest generation of ceramics are much better performing composites which incorporate tetragonal, nanosized, yttria-stabilized zirconia particles (close to 25%) into an alumina matrix (close to 75%) improving the composite's mechanical properties by preventing initiation and propagation of cracks [10]. In addition, a small amount ($<1\%$) of chromium oxide further strengthens the composite ceramic [10]. As a consequence, the wear rates of the new composite ceramic bearings are significantly less than older alumina bearings [11, 12].

Another ceramic used in implants is hydroxyapatite which (HA, Ca10(PO4) 6(OH)2) is the main mineral constituent of teeth and bones. Theoretically, it exists as the hydroxyl end-member of apatite. Synthetic HA is widely used as a substitute for the hard tissues of the human body because it shows excellent biocompatibility with hard tissues and even through skin and muscle tissues [13]. As an implant, the HA can bond and promote natural tissue ingrowth because of its similarity to bone mineral [14–16]. However, HA has low mechanical properties, limiting its use in load-bearing applications. Another use of HA is as a coating to improve the bioactivity of Ti and its alloys, but poor ceramic/metal bonding may cause the surgery to fail [17, 18].

Some applications of ceramics as biomedical materials include hip prostheses, knee implants and dentistry. As aforementioned, polymeric materials are used in hip prostheses to reduce the friction between the acetabular cup and femoral head. However, the polymers are present in these implants for reducing the friction between the acetabular cup and femoral head. Nowadays, polymers are widely used because of their great potentialities, both the facility to obtain different compositions as well as the feasibility to process by different methods, with well-defined characteristics and the capability to be processed in fibers, fabrics, films and blocks. These materials can be both natural and synthetics; in any case, biostable[1] and biodegradable[2] formulations can be found. The low density is the major advantage of polymer materials, in addition to their manufacturability and good surface finishing. Actually, the boom in the development of biopolymers is tissue engineering [19, 20]. In the tissue engineering method, a three-dimensional scaffold is fabricated as the template for neo-tissue development. Then, appropriate cells are seeded to the matrix in vitro [21]. Because of the manufacturability of polymer materials, the in vitro fabrication of more complex biological structures is becoming a reality [22].

The polymers most used for biomedical and pharmacologic applications are

- Low Density Poly Ethylene (LDPE),
- Polyvinyl Chloride (PVC),
- Polystyrene (PS),
- High-Density Poly Ethylene (HDPE),
- Polypropylene (PP),
- Thermostable polyesters,
- Polyurethane (PU),
- Acrylics,
- Nylon (polyacetate),
- Epoxies,
- Others: polyacetals, cellulosics, thermoplastic polyesters, polycarbonates, polysulfones, silicones and urea-formaldehyde resins (UFR).

Figure 3 presents the statistics on the most used polymers in biomedical and pharmacologic applications.

Plastic polymer laminates are widely used for the fabrication of prosthetic devices, including upper and lower limbs. As mentioned before, materials selection for the fabrication of orthopedic devices is an important issue because this affects the efficacy of treatment and rehabilitation of the patient and has repercussions in its style of life. With advances in textile and material sciences in recent years, new fabrics and composite materials have been developed to enhance the practical use and the rate of

[1] Permanent character, capable to substitute in partial or total form organs and tissue damaged or destroyed.

[2] Temporal or provisional character with an adequate functionality during a limited time, necessary to solve the problem.

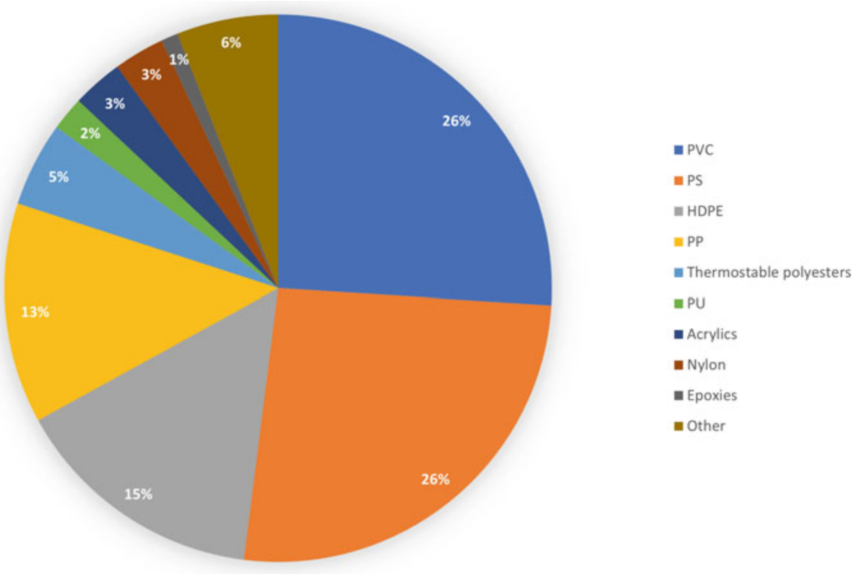


Fig. 3 Polymers most used for biomedical and pharmacologic applications

patient compliance during the course of the treatment [23]. The general properties required of a reinforced composite are high strength-to-weight ratio, capacity to absorb torque, bending and shear stresses, being able to resist fracture under impact, capable of resisting stress in all planes, cost-effectiveness and easy to apply.

Three composite materials are widely used: Fiberglass, Kevlar® (Aramid®) and Carbon composites. Fiberglass is by far the most commonly used and economical. In addition, the composite materials reinforced with fiberglass are also characterized by a high density (compared with Kevlar and Carbon composites) and have a good wettability (positive aspect in the lay-up of different geometries). Kevlar is exceptionally lightweight and most expensive. Kevlar composites are tough and present good resistance under high loads of torque. Kevlar fabrics are resistant to chemicals; for this reason, they are difficult to infiltrate with resins. However, the longitudinal compressive strength of aligned unidirectional laminae made from Kevlar is only 20% of the tensile strength; in contrast, the data observed for glass and carbon fibers show that they have similar tension and compression strengths [24]. Until now, carbon composites are the most valuable to orthopedic applications because they are of high strength-to-weight ratio, are stiff and capable to maintain the form and structure under loads. For example, Amputee sports performance has greatly improved over the past 20 years along with the development of carbon fiber prostheses [25].

Table 2 shows the physical and mechanical properties of glass, Kevlar and carbon fibers used as reinforcement in composite materials. The Type I carbon fibers have been graphitized to give maximum stiffness but have relatively low strength, whereas Type II have been graphitized to produce maximum strength [24].

Table 2 Properties of glass, Kevlar and carbon fibers at 20 °C [24]

Property	E glass	Kevlar 49	Carbon Type I	Carbon Type II
Diameter (μm)	8–14	11.9	7.0–9.7	7.6–8.6
Density (Mg m-3)	2.56	1.45	1.95	1.75
Young's modulus (GN m-2)	76	125	390	250
Tensile strength (MN m-2)	1.4–2.5	2.8–3.6	2.2	2.7
Elongation to fracture (%)	1.8–3.2	2.2–2.8	0.5	1.0
Coefficient of thermal expansion (10-6 °C-1)	4.9	−2 (p) 59 (r)	−0.5−1.2 (p) 7–12 (r)	−0.1−0.5 (p) 7–12 (r)
Thermal conductivity, parallel to fiber axis (W m-1 °C-1)	1.04	0.04	105	24
Specific Young's modulus modulus/density, (GN m-2)	30	86	200	143
Specific tensile strength Tensile strength/density(MN m-2)	1.4	2.2	1.1	1.5
Flexibility ratio, Type I carbon fiber = 1	1.44	0.59	1.00	1.56
Fracture strength (GN m-2)	3.5	–	2.2	2.7
Minimum radius of curvature (mm)	0.12	–	0.71	0.37

Finally, an attempt to summarize the general properties and applications of some materials used in medical devices is presented in Table 3.

2 Rapid Processing Applied to Biomedical Devices and Tissue Engineering

There are different processing techniques to produce implants and prostheses. However, this chapter emphasizes rapid processing applied to the manufacturing of biomedical devices. Modern techniques, such as computer-aided design/computer-aided manufacturing (CAD-CAM) and rapid prototyping (RP) technologies offer new routes toward the planning of reconstructive surgery, allowing aesthetic outcomes to be optimized, and ensuring ultimate prosthetic and functional rehabilitation [7, 26–28].

In medicine, the use of RP has been to create physically solid models to better describe, understand and diagnose the condition of individual patients. The key is the use of medical imaging technology such as computed tomography (CT) or MRI to produce a solid model directly from 3D data output and to obtain a 3D CAD model. CT and MRI combine software slices to create a 3D model, and RP takes

Table 3 Materials used in medical devices and their properties and applications [24]

Material		Properties	Applications
Metals	Stainless steel, titanium and its alloys, Co alloys, NiTi	High density, good mechanical response under different load conditions: wear, impact, tension and compression. Low biocompatibility and poor corrosion resistance	Implants, maxillofacial prostheses, screws, pins and side plates for the internal fixation of implants, screws, bars, rods, wires, posts, hip implants, dental implants, expandable rib cages, finger and toe replacements
	Copper (Cu)	It corrodes in the uterus	Contraceptive devices
	Amalgam and dental alloys	Biocompatible with saliva	Dental implants and dental repairs
	Stents	Biocompatible with blood	Repair of the arteries and veins
Ceramics	Metallic oxides, alumina (Al_2O_3), zirconia (ZrO_2), titanium oxide (TiO_2), carbon fiber, artificial apatite	High wear resistance Good biocompatibility, corrosion resistance, bioinerts, high compression strength, high density and hardness, low machinability and poor manufacturability	Hip prostheses, ceramic teeth, cements and coatings
Polymers	PET, PP, Acrylics, PTFE	Low density and poor mechanical strength, manufacturability, biofilm formation	Stitches, substitution of veins and arteries, maxillofacial surgeon: nose, ear, jaw, teeth, artificial tendon Cosmetic plastic surgery
	Dacron, Nylon (polyester)	Lightweight	Suture threads
	Ultra-high-molecular-weight polyethylene (UHMWPE)	Brittle, Low tension strength, poor fatigue resistance	Knee prostheses
	PMMA	Low tension strength, poor fatigue resistance, brittle	Bone cement
Composites	Metals coated with ceramic: Titanium with porous hydroxyapatite Material covered with carbon or diamond. Acrylic, polyester and epoxy resins reinforced with fabrics (dacron, nylon, fiberglass, carbon and kevlar)	Good biocompatibility, corrosion resistance, bioinerts, good mechanical strength under tension loads	Orthopedic implants reinforced with carbon fibers, heart artificial valve, catering of joints

a 3D model and reproduces it in a solid form by combining layers together [29]. Applications include dentistry, neurosurgery, implant design and development, maxillofacial surgery, orthopedics, separation of conjoined twins and tissue engineering [29]. Recently, the use of intraoral digital scanners to create digital impressions has been reported by Lee and coworkers [7]. This approach would make it possible to eliminate the use of impression materials, identify preparation margins, evaluate inter-occlusal clearance and design prostheses [30]. The accuracy of the digital impression is similar to that of the conventional impression [31–33] and patients and clinicians prefer the digital impression approach [34–36]. Although the most frequent application of RP techniques in medicine is the fabrication of physic models, the manufacturing of implants and prostheses is not a distant prospect. A summary of the applications of RP techniques in the manufacturing of prostheses and implants is featured below.

3 Total Hip Arthroplasty

Total hip arthroplasty (THA) is one of the most cost-effective surgical procedures performed today showing over 95% and 80% implant survivorship [37] with more than 1 million of THA performed worldwide annually and increasing [38]. The increasing demand for THA has generated great interest in the cost-effectiveness of new technologies. However, the probability of infection is high, and the procedure can have devastating complications, whose treatment includes a re-operation called “revision surgery” followed by a 6-week course of intravenous antibiotics and a second re-implantation. Zhang, et al. [39] study a solution to reduce revision surgeries. They proposed a novel biphasic spacer module, constituted by a bone defect geometry-specific calcium phosphate (CaP) sheath, which is fabricated preoperatively by patient-customized CT/CAD and low-temperature 3DP, and an axial bone cement pillar carrying antibiotics. The objective is to produce a bone repair effect in the infected arthroplasty cases combined with a critical bone defect. The external surface of the sheath is designed to be micro-porous for improving the bone ingrowth, and the internal surface is smooth for easy removal of the cement pillar, and reduces the damage of the newly formed bone tissue in the revision surgery. The process steps are similar to those applied in 3DP, however in this case, the use of low-temperature 3DP process [40] allows the incorporation of bioactive molecules and drugs during the printing process. Another important challenge is performing THA in cases of osteoarthritis secondary to developmental dysplasia of the hip (DDP) because the acetabular deficiency makes the positioning of the acetabular component difficult. Xu et al. [41] describe the process of generating solid anatomical models of pelvis structures applying RP technologies. These models could be used to facilitate preoperative planning.

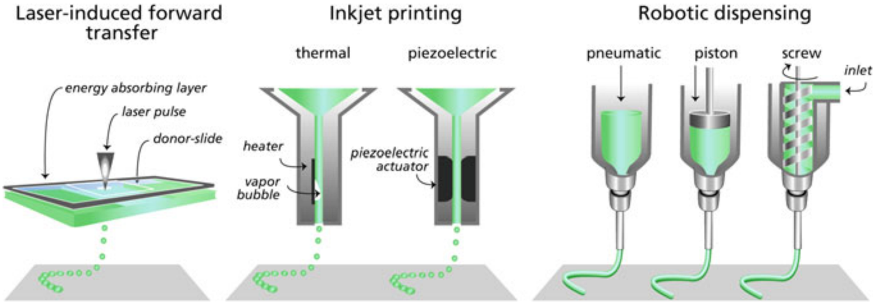
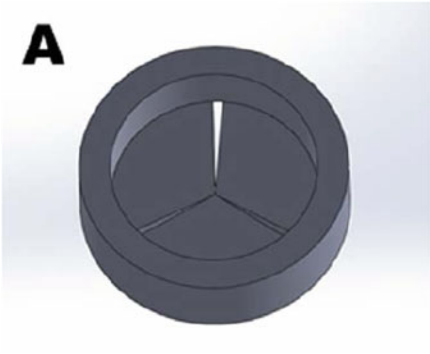


Fig. 4 Components of inkjet, microextrusion and laser-assisted bioprinters [45]

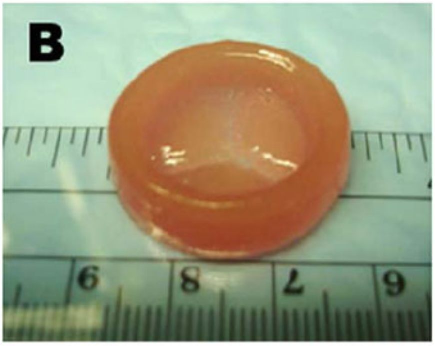
4 Tissue Engineering

In addition to the aforementioned applications, the advances in RP technologies have enabled the 3D printing of biocompatible materials, cells and supporting components into complex 3D functional living tissues [42]. Recent review [42] describes the 3D bioprinting of tissues and organs. According to this investigation, the following 3D bioprinting approaches exist: Biomimicry, autonomous self-assembly and mini-tissue building blocks. In Biomimicry, the application of 3D printing is orientated to the manufacturing of identical reproductions of the cellular and extracellular components of a tissue organ [43]. Autonomous self-assembly is another approach to replicating biological tissues using embryonic organ development as a guide. Mini-tissues are relevant to both of the above technologies because the organs and tissues are comprised of smaller, functional building blocks [44] or mini-tissues. The main technologies used for deposition and patterning of biological materials are inkjet 3D printing, microextrusion and Laser-Assisted Printing (Fig. 4). Thermal inkjet bioprinter is a modification of the conventional process [45], where the ink in the carriage is replaced with a biological material, and the paper was changed by an elevator stage to provide movement in X-Y axes. Microextrusion printers use pneumatic or mechanical (piston or screw) dispensing systems to extrude continuous beads of material and/or cells. Laser-assisted printers use lasers focused on an absorbing substrate to generate pressures that propel cell-containing materials onto a collector substrate [44].

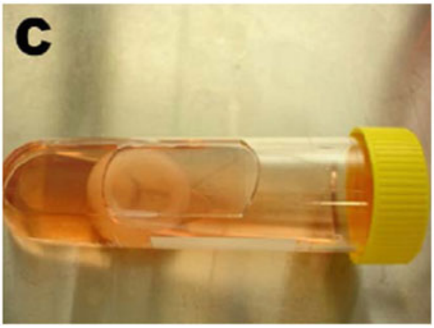
Jana et al. [46] compare different types of bioprinters. Four processes are mentioned: Inkjet, Laser-Based, Stereolithography and Bioplotting. The working principles are similar to RP technologies, however, 3DP technologies are designed for non-biological applications, such as deposition of metals, ceramics and thermoplastics, and generally involved the use of inorganic solvents, high temperatures or crosslinking agents that are not compatible with living cells and biological materials. Materials used in the regenerative of tissues for repairing regeneration are based on natural polymers (biocompatible and bioactive), including alginate, gelatin, chitosan, fibrin and hyaluronic acid. Synthetic polymers including polyethylene glycol, PEG



(a) heart valve model designed by Solidworks



(b) as-printed valve conduit



(c) the bioprinted valve conduit kept intact after 7-day static culture in culture tube

Fig. 5 Bioprinting of heart valve conduit with encapsulation of HAVIC within the leaflets [51]

[47]. The advantage of synthetic polymers is that they can be tailored with specific properties [42].

Cardiovascular diseases are a major health concern causing substantial illness and death of population [48, 49]. One of the most common forms of cardiovascular health problems is valvular heart disease [46]. Tissue engineering of heart valves might be an attractive solution. Conventional manufacturing techniques such as freeze-drying, salt leaching, gas foaming and fiber deposition cannot produce a scaffold structure of a heart valve [50]. 3D bioprinting is presented as an alternative to design and print heart valve [46]. Figure 5 shows a 3D bioprinting of living heart valve conduits based on photocrosslinkable Methacrylated hyaluronic acid (4%) and Methacrylated Gelatine (10%) hybrid hydrogels [51].

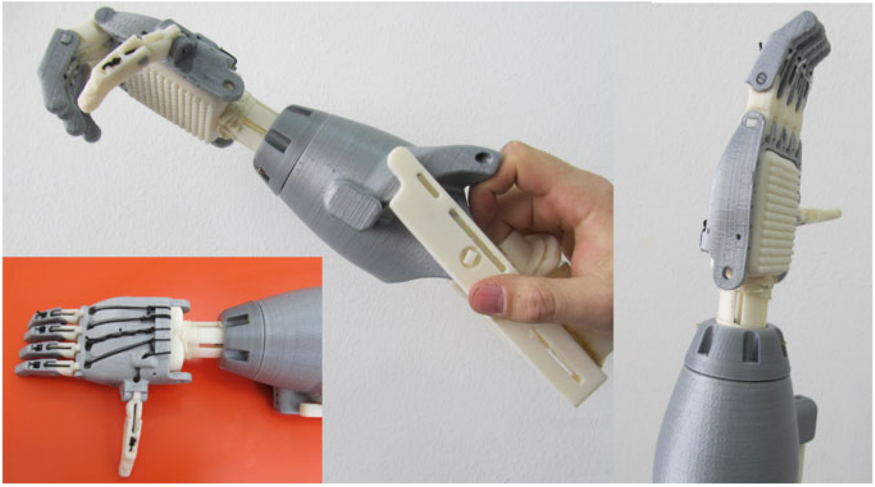


Fig. 6 Upper limb printed by using RP technologies

5 Orthopedics

One of most attractive applications of RP technologies is the external orthopedic devices. In Fig. 6, a printed prosthetic upper limb is presented. The versatility and good accuracy of some RP technologies have made possible the development of prostheses at a lower cost than those fabricated with conventional manufacturing techniques. An important advantage is the possibility to incorporate electronics and mechanical parts easily, which reduces considerably the complexity of these devices.

6 Anthropomorphic Prosthetics Kinematics

Prosthetic devices can be subdivided into two groups according to limb amputation: Upper and Lower limb prosthetics. Lower extremity prosthetics have evolved to the point at which a bilateral below-the-knee amputee may be competitive with the best runners in the world. On the other hand, little progress has been made in commercially upper limb devices; according to Kamen [52], *Prosthetic legs are in the 21st century, with prosthetic arms, we are in the Flintstones*. Nowadays, with the advances in electronics, it is possible to read body signals and actuate mechanical devices accordingly. Although great advances exist in upper limb, state of the art and devices lack the characteristic combination necessary for daily activities [53]; research devices are usually developed to accomplish a specific function but usually cosmetic appearance and affordability are not considered.

6.1 Lower Limb Prosthetics: Ankle Case Study

Conventional feet (CF) is an early design with the goal of restoring walking for daily activities; higher performance activities such as running and jumping require higher capabilities in prosthetics design. To understand prosthetic requirements, it is necessary to describe a concept of human walking, the gait cycle:

- Stance phase accounts for 60% of gait cycle, which is the phase where the foot is in contact with ground; it can be subdivided into initial contact, loading response, mid stance, terminal stance and toe off.
- Swing phase is when the foot is not in contact with the ground; its subphases are initial, mid and terminal swing.

6.1.1 Transtibial Limb Prosthetics

Toe dorsiflexion occurs twice during walking; it allows for different leverage ratios and efficient propulsion; it is essential for foot function [54]. Ankle articulation allows for three rotational DoFs, usually, only dorsiflexion/plantarflexion is considered in prosthetic devices [55, 56]. A transtibial prosthetic with 3 DoFs in the ankle is presented by Madusanka et al. [57]; its design also includes a passive regenerative system to reduce the energy consumption of dorsiflexion/plantarflexion.

When walking, the ankle produces 540% more work than other limbs [58]. Energy-storing-and-returning (ESR) feet is a prosthetic device with the capability of deforming during the stance phase, thus storing energy which is released in the terminal stance. According to energy release efficiency, a prosthetic foot can be used for different activities [59] (walking, running, etc.). ESRs can be subdivided into early, advanced and articulated and, although articulated ESRs use electronics and small motors to lock and unlock the articulation, they are passive devices.

Bionic Feet is an active prosthetics device; its main difference is the external power supply for stabilizing and impulse during the gait cycle [60]; this robotic prosthesis is able to reduce energy requirements in the user, and thus avoid fatigue. Versluys [61] indicates that an 80 [kg.] user requires a 136 [Nm] ankle torque. Main actuators used in bionic feet must be capable to provide a high torque and return the ankle position during the swing phase for the next step. According to Cherelle [60], actuators can be classified into stiff and compliant, the difference is that the latter has the capacity to store energy. If pneumatic actuators are used, energy storing is easily achieved; when using electric actuators as DC motors, an elastic media is needed and can be subdivided into the series elastic actuator (SEA), series elastic actuator with parallel spring (SEAPS), variable stiffness actuator (VSA) and variable stiffness actuator with parallel spring.

Zhu et al. [62] studied the effect of an additional toe articulation; simulation studies demonstrate that ankle energy consumption is 20% greater when toe articulation is not considered, but active toe implies additional weight and a more complex structure (Fig. 7).

(a) Conventional foot

(b) Energy storing and restoring feet

(c) Bionic feet

Fig. 7 Lower limb passive and active prosthetics [51]

6.2 Upper Limb Prosthetics: Shoulder Case Study

Mean rejection rates in electric powered prosthetics for upper limb is 35% in pediatric population and 20% in adults; reasons for this are low functionality, weight and lack of tactile feedback. Mechatronic devices in this area are far away to restore original limb features, nevertheless, Razak [63] made a comparative study and established an improved ability when comparing biomechatronics with body-powered devices.

The force exerted by the human arm depends on the specific joint; the maximum force is generated at the most proximal joint (shoulder), and it decreases when advancing to the most distal joint, the distal interphalangeal joint (DIP) in the fingers.

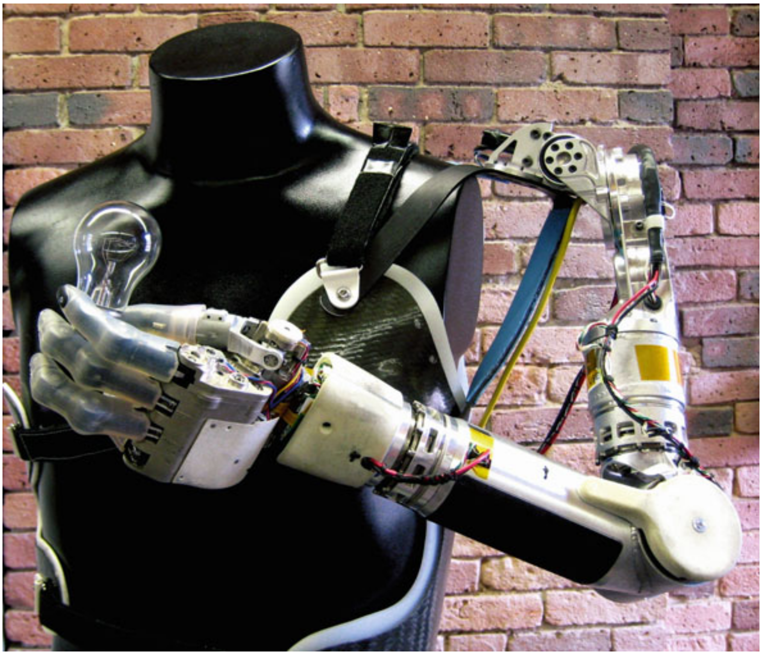


Fig. 8 Shoulder disarticulation DEKA arm configuration

When considering joint precision in terms of the angle, the most accurate joint is the shoulder, and precision diminishes when moving to the distal joints. However, if precision is defined in terms of position, the distal joints are the most accurate [64].

6.2.1 Shoulder Disarticulation Prosthetics

The shoulder consists of three bones: clavicle, scapula and humerus. The shoulder can be modeled as a ball-and-socket joint. The main motions of the shoulder joint are flexion/extension, abduction/adduction and internal/external rotation.

To the authors' knowledge, the most advanced prosthetic in this area is the DEKAs arm (Fig. 8) built by the Defense Advanced Research Projects Agency (DARPA). The project began in 2006 and three prototypes have been built since. The third generation arm was developed after the Department of Veteran Affairs (VA) feedback; Table 4 shows its powered DoFs. It is available in three different configurations according to amputation level: transradial, transhumeral and shoulder disarticulation; a full description is given by Resnik [65]. The arm is the first prosthetic device controlled by electromyogram electrodes (EMG) approved by the Food and Drug Administration (FDA).

Table 4 Powered DoFs of DEK Arm [66]

Joint	Movement
Shoulder	Flexion, extension, abduction, adduction
Humeral rotator*	Internal rotation, external rotation
Elbow	Flexion, extension
Forearm	Pronation, supination
Wrist	Flexion**, extension**
Thumb	Flexion, extension, abduction, adduction
Index finger	Flexion, extension
Fingers 3-5	Flexion, extension

*Humeral rotation occurs proximal to elbow joint
**Third-generation DEKA Arm wrist has compound movement

7 Sensors

Sensors used in bionic prosthetic devices can be classified into two categories:

- Mechanical signal sensor used to provide information about the device state such as environmental reaction forces; position, velocity and acceleration sensors; and joint angle and torque applied.
- Body signal sensors used to measure user intention of motion.

Mechanical sensors are widely known; here, a brief description of body sensors' main transducers and their applications on prosthetic devices is given. Robotic prosthetics use signals originated in the body to control the kinematics of artificial limbs; sensors acquire these signals by monitoring muscle contractions. According to Ortiz-Catalan [67], they can be classified in two categories:

- Superficial electrodes located in the skin;
- Implantable electrodes located inside the body.

7.1 Surface Electrodes

Surface electrodes are the most used in commercially available prosthetics; the main advantage of this kind of electrode is that they are easily installed and replaced; implantable electrodes require percutaneous implantation or surgical procedures. On the other hand, surface electrodes are more sensitive to environmental conditions such as sweat/dry skin, electrode shift and user fatigue [68], and it is difficult for them to record information from inner muscles. Implantable Electrodes are closer to signal source and a better signal-to-noise ratio can be achieved; this is why it is assumed that more specific information can be extracted. Hargrove [69] established no significant difference in classification accuracy when intramuscular MES is compared to the surface MES.

Although muscle- and nerve-based transducers may achieve similar accuracy, their use in prosthetic devices must take into account that muscles may not be available due to amputations while nerves are still present.

8 Control of Prosthetics

8.1 Lower Limb Prosthetics

According to Tucker [70], the control for lower limb prosthetic devices involves three stages:

- *High-level*: Estimation of motion intention. This means understanding the desires of the amputee to generate a physical action. The goal is to predict the optimal control strategy to apply according to the activity in progress, i.e., walking and running.
- *Mid-level*: This stage involves the translation of user desires into an appropriate output state of the prosthetic device (position, speed, force).
- *Low-level*: How to control the actuators to achieve the output state determined at mid-level. At this level, the controller determines the error for the actual state compared with the desired state and executes a control action to minimize the error.

8.1.1 High-Level

Different activities involve distinct requirements for muscles, and prosthetic devices must be able to act accordingly. Walking upstairs requires a high level of energy introduction, while level walking does not. To determine the activity and action desires of the amputee, it is crucial to establish an adequate control system (force, position, velocity, etc.) to apply; misinterpretation of the next action may trigger a loss of balance.

Any decision regarding estimation of motion intention involves analyzing available information from a variety of sources, including previous state, applied forces and external environmental conditions. An excessive time to analyze this data and switch the control system may be as dangerous as misinterpretation.

A wide variety of activity recognition algorithms can be applied; only a short description is given here. The appropriate algorithm depends on the first instance of the number of activities the prosthetic must be able to recognize; when it is designed for a low number of activities, a heuristic approach is possible; here, transition rules for switching between the gait modes can be manually or analytically selected accordingly for a particular user. The number of rules increases with the number of modes to be recognized (i.e., it is not practical for a large number of activities). When the number of modes to recognize increases, an automatic pattern recognition approach is necessary; in this case, techniques such as Artificial Neural Network, Linear Discriminant Analysis and Dynamic Bayesian Network are used. The main advantage is the wide variety of input signals that can be analyzed to establish when to switch modes, on the other hand, the disadvantage is that the device must be individually trained for each user.

8.1.2 Mid-Level

This control translates user desires and determines the necessary device state to achieve; the main control strategies used are summarized in Table 5.

8.1.3 Low-Level

While at low-level stage the controls use the reference mid-level output and try to reach it, two strategies are used:

- Feed-forward control requires a mathematical model in order to predict the state of the devices based on the current state and current input.
- Feedback control does not require a model, instead it measures the current state of the device and tries to minimize the error.

8.2 Upper Limb Prosthetics

Lower limb control algorithms are designed to identify a specific set of activities and generate a control strategy accordingly. Most recognizable activity patterns are based on gait cycle or typical activities such as standing up and sitting; upper limb control algorithms do not have that advantage, as the human arm is characterized by the ability to perform different activities with dexterity.

Although control by muscle contraction is considered intuitive, a transhumeral amputee does not count with the appropriate muscles to control wrist flexion/extension and another muscle must be used. Furthermore, a shoulder disarticulation amputee must control the hand, wrist, elbow and shoulder with the remaining muscles/nerves; one strategy used is mode switching to select the limb to control. This is slow and not intuitive; thus, it is necessary to evaluate nerve signals to improve control.

For higher levels of amputation, the complexity of control increases and pattern recognition techniques are more appropriate. In pattern recognition algorithms, a machine goes through a learning process; its goal is to provide an answer for every possible combination of input signals of the user and perform the most likely

Table 5 Types of mid-level control used in lower limb prosthetic devices

	Controller type	Characteristics
Phase-based	Time-based	Actions are programmed according to a delay in identifiable actions such as heel strike or toe-off. Easy to implement. Heavily depends on gait cycle regularity
	Normalized trajectory control	Uses previously recorded gait data and scales it according to pace and user size. Identification of appropriate trajectory to scale to speed and weight at the same time
	Echo control	Trajectory of the unassisted limb is recorded and replayed in the assisted limb with a phase delay. Gait cycle must start with unassisted limb. Undesired movement can be replayed
	Virtual constrain control	Center of pressure in the prosthetic foot is used as input. Implements walking patterns similar literature available parameters. A different controller must be implemented in swing phase
	Finite state controller	Is the most popular mid-level control strategy identifies the gait cycle phase with a series of laws. A different controller is needed for each activity identified by the high-level controller
Non-phase based	Complementary Limb Motion Estimation	Inferes the motion intention of the residual limb by measurement of other limbs, arm motion is highly correlated with motion of lower limbs and can be used to control. It is not possible yet to correlate the method to different activities
	Force-feedback control	measures the reaction force between the user and the device and tries to minimize it. It is used for task when force amplification is needed such as in exoskeleton, and also as a performance metric of how well the device can be controlled

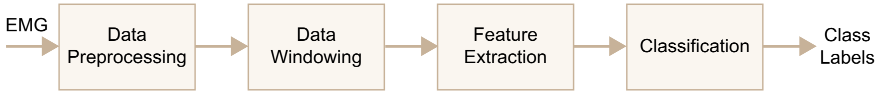


Fig. 9 Pattern recognition stages [71]

movement; in other words, it intends to understand user's desire and effectuate the movement.

The machine is given a set of inputs and learns to associate them with the desired action; this process is called supervised training; with enough training data, the machine learns to associate a combination of inputs with a specific output. When an input combination is different from the training set, its output is the best guess of the user's intention of movement.

As input signal may contain lots of unuseful information, preprocessing is needed; according to Scheme [71], the fundamental stages for their application in electromyogram control of upper limb powered prosthetics are depicted in Fig. 9.

- Data prepossessing: removing unwanted signals or signal conditioning.
- Data windowing: the signal is multiplied by a function which is non-zero only in specific intervals; its main application is spectral analysis and filtering.
- Feature extraction: it is used to increase the useful information density.
- Classification: stage at which the user's intention of motion is interpreted.

As stated previously, the first myoelectric arm approved by FDA is the DEKA arm third generation, which is a major challenge to control due to its 10 DoFs (see Table 4). Most signal inputs come from electrodes attached to residual muscles, and others come from a combination of methods such as pressure switches and foot control.

9 Conclusions

9.1 Biomedical Devices: Rapid Manufacturing and Control

The use of rapid processing and rapid roboting applied to the manufacturing and control of biomedical devices is an amazing field, which uses the knowledge of engineering and medicine to design, modeling, produce and control medical devices. Recently, the design and manufacturing of medical devices have been assisted by modern techniques, such as computer-aided design/computer-aided manufacturing (CAD-CAM) and rapid prototyping (RP) technologies. The use of these techniques suggests new paths toward the optimization of aesthetic outcomes in reconstructive surgery, and warranting prosthetic and functional rehabilitation.

The advances in this field are promoted by the use of rapid prototyping (RP) techniques to create physically solid models to improve the comprehension and diagnosis of the conditions in the patient and to facilitate preoperative planning. In this sense, from imaging technologies such as computed tomography, it is possible to produce a 3D CAD file and, as a result, a 3D printing model. Different industries such as dentistry, neurosurgery, implant design and development, maxillofacial surgery, orthopedics and tissue engineering are implementing 3D bioprinting.

Although the most frequent application of RP techniques in medicine is the fabrication of physic models, the manufacturing of implants and prostheses is not a pipe dream. Tissue engineering is a fast-growing field of investigation and reveals some real advances: the use of the low-temperature 3DP process allows the incorporation of bioactive molecules and drugs during the printing process. Actually, three 3D bioprinting additive techniques are available, Thermal Inkjet Bioprinter, Microextrusion and Laser-Assisted Printing. The main principle is the deposition or extrusion of continuous beads of material and/or cells. This is a big challenge, because 3DP technologies are designed for non-biological applications, and generally involved high temperatures to stabilize the solvents used in the process that are not compatible with living cells. However, an increasing trend is observed in the design and prototyping of living organs and tissues.

9.2 Prosthetic Devices: Design and Control

To restore the functionality of an amputated limb is a challenging task; advances in the area are heavily divided according to limb amputation: lower and upper limbs. People with lower limb amputation are able to walk, run or even go upstairs/downstairs, on the other hand, it is more difficult to restore the functionality in upper limb amputation; the characteristic dexterity of the human arm generates an countless movements variety when considering grasping objects of different shapes, and gestures used in nonverbal communication. The control complexity of any prosthetic device increases with the number of activities which is able to recognize or perform; in lower limbs, most movements are related to the gait cycle, but if trying to *sit a child in the lap and "move him up/down"* with a prosthetic device, the child will probably fall, as it is an uncommon function to recognize.

Human limbs have a high number of joints, and some of them are capable of conducting slight movements, such as the knee, which besides its flexion/extension main movement, can perform medial and lateral rotation. These slight movements are not as important for the gait cycle as the flexion/extension, thereby it is common to diminish the DoFs in a limb mechanical counterpart. Another reason to diminish DoFs is mechanical complexity: more DoFs lead to more actuators, increased weight, higher failure points and eventual additional energy storage requirements. Additionally, there is no need for extra DoFs if they cannot be controlled separately; with more DoFs, the controller complexity increases because of a larger quantity of motion intentions to be recognized; any failure in this process may end up in an accident.

To understand the motion intention of the user, a variety of sensors has been employed. The main focus is on reading the signals naturally used by the body to generate the limb motion such as muscle contraction, and its nerve signals. Natural control of the artificial limb has not been possible; users must generate specific muscle contractions or signal patterns to execute a motion. The complexity of this signal pattern increases as the number of user motion intentions to recognize by the controller increases.

References

1. Albrektsson T, Johansson C (2001) Osteoinduction, osteoconduction and osseointegration. Eur Spine J 10(2):S96–S101
2. Ryan G, Pandit A, Apatsidis DP (2006) Fabrication methods of porous metals for use in orthopaedic applications. Biomaterials 27(13):2651–2670
3. Geetha Ma, Singh AK, Asokamani Ra, Gogia AK (2009) Ti based biomaterials, the ultimate choice for orthopaedic implants–a review. Prog Mater Sci 54(3):397–425
4. Aguilar C, Guerra C, Lascano S, Guzman D, Rojas PA, Thirumurugan M, Bejar L, Medina A (2016) Synthesis and characterization of ti-ta-nb-mn foams. Mater Sci Eng C 58:420–431
5. Boutin P (2014) Arthroplastie totale de la hanche par prothese en alumine frittée. etude expérimentale et premieres applications cliniques. Revue de Chirurgie Orthopédique et Traumatologique, 100(1):14–21
6. Garino JP (2011) Ceramic hip replacement history. In: Seminars in arthroplasty, vol 22. WB Saunders, pp 214–217
7. Lee J-H (2014) Accelerated techniques for a post and core and a crown restoration with intraoral digital scanners and CAD/CAM and rapid prototyping. J Prosthet Dent 112(5):1024–1029
8. Niinomi M, Hattori T, Kasuga T, Fukui H (2005) Titanium and its alloys
9. Cipriani C, Controzzi M, Chiara Carrozza M (2011) The smarthand transradial prosthesis. J Neuroeng Rehabil 8(1):29
10. Kumar N, Arora NC, Datta B (2014) Bearing surfaces in hip replacement-evolution and likely future. Med J Armed Forces India 70(4):371–376
11. D'Antonio JA, Sutton K (2009) Ceramic materials as bearing surfaces for total hip arthroplasty. J Am Acad Orthop Surg 17(2):63–68
12. Tateiwa T, Clarke IC, Williams PA, Garino J, Manaka M, Shishido T, Yamamoto K, Imakiire A (2008) Ceramic total hip arthroplasty in the united states: safety and risk issues revisited. Am J Orthop 37(2):E26–E31
13. Chenglin C, Jingchuan Z, Zhongda Y, Shidong W (1999) Hydroxyapatite-ti functionally graded biomaterial fabricated by powder metallurgy. Mater Sci Eng A 271(1):95–100
14. Ruys AJ, Wei M, Sorrell CC, Dickson MR, Brandwood A, Milthorpe BK (1995) Sintering effects on the strength of hydroxyapatite. Biomaterials 16(5):409–415
15. Tampieri A, Celotti G, Sprio S, Mingazzini C (2000) Characteristics of synthetic hydroxyapatites and attempts to improve their thermal stability. Mater Chem Phys 64(1):54–61
16. Chang B-S, Hong K-S, Youn H-J, Ryu H-S, Chung S-S, Park K-W et al (2000) Osteoconduction at porous hydroxyapatite with various pore configurations. Biomaterials 21(12):1291–1298
17. Brossa F, Cigada A, Chiesa R, Paracchini L, Consonni C (1994) Post-deposition treatment effects on hydroxyapatite vacuum plasma spray coatings. J Mater Sci Mater Med 5(12):855–857
18. Yang CY, Wang BC, Chang E, Wu JD (1995) The influences of plasma spraying parameters on the characteristics of hydroxyapatite coatings: a quantitative study. J Mater Sci Mater Med 6(5):249–257

19. Mottaghitalab F, Hosseinkhani H, Ali Shokrgozar M, Mao C, Yang M, Farokhi M (2015) Silk as a potential candidate for bone tissue engineering. J Control Release
20. Nair LS, Laurencin CT (2006) Polymers as biomaterials for tissue engineering and controlled drug delivery. In: Tissue engineering I. Springer, pp 47–90
21. Fallahiarezoudar E, Ahmadipourroudposht M, Idris A, Mohd Yusof N (2015) A review of: application of synthetic scaffold in tissue engineering heart valves. Mater Sci Eng C 48:556–565
22. Ilagan R, Rapoport S, Shepherd B, Presnell S (2016) Chapter 41 - tissue engineering through additive manufacturing: hope for a bioengineered kidney? In: Little MH (ed) Kidney development, disease, repair and regeneration. Academic Press, San Diego, pp 555–568
23. Luximon A (2013) Handbook of footwear design and manufacture. Elsevier
24. Hull D, Clyne TW (1996) An introduction to composite materials. Cambridge university press
25. Nolan L (2008) Carbon fibre prostheses and running in amputees: a review. Foot Ankle Surg 14(3):125–129
26. Ciocca L, Marchetti C, Mazzoni S, Baldissara P, Gatto MRA, Cipriani R, Scotti R, Tarsitano A (2015) Accuracy of fibular sectioning and insertion into a rapid-prototyped bone plate, for mandibular reconstruction using cad-cam technology. J Cranio-Maxillofac Surg 43(1):28–33
27. Tarsitano A, Mazzoni S, Cipriani R, Scotti R, Marchetti C, Ciocca L (2014) The cad-cam technique for mandibular reconstruction: an 18 patients oncological case-series. J Cranio-Maxillofac Surg 42(7):1460–1464
28. Jin-Song Hou M, Chen C-BP, Wang M, Wang J-G, Zhang B, Tao Q, Wang C, Huang H-Z (2012) Application of cad/cam-assisted technique with surgical treatment in reconstruction of the mandible. J Cranio-Maxillofac Surg 40(8):e432–e437
29. Gibson I (2006) Advanced manufacturing technology for medical applications: reverse engineering, software conversion and rapid prototyping. Wiley
30. Ng J, Ruse D, Wyatt C (2014) A comparison of the marginal fit of crowns fabricated with digital and conventional methods. J Prosthet Dent 112(3):555–560
31. Ender A, Mehl A (2010) Full arch scans: conventional versus digital impressions-an in-vitro study. Int J Comput Dent 14(1):11–21
32. Seelbach P, Brueckel C, Wöstmann B (2013) Accuracy of digital and conventional impression techniques and workflow. Clin Oral Investig 17(7):1759–1764
33. Tidehag P, Ottosson K, Sjögren G (2014) Accuracy of ceramic restorations made using an in-office optical scanning technique: an in vitro study. Oper Dent 39(3):308–316
34. Wismeijer D, Mans R, Genuchten M, Reijers HA (2014) Patients' preferences when comparing analogue implant impressions using a polyether impression material versus digital impressions (intraoral scan) of dental implants. Clin Oral Implants Res 25(10):1113–1118
35. Lee SJ, Gallucci GO (2013) Digital vs. conventional implant impressions: efficiency outcomes. Clin Oral Implants Res 24(1):111–115
36. van Noort R (2012) The future of dental devices is digital. Dent Mater 28(1):3–12
37. Pivec R, Johnson AJ, Mears SC, Mont MA (2012) Hip arthroplasty. The Lancet 380(9855):1768–1777
38. Berstock JR, Blom AW, Beswick AD (2014) A systematic review and meta-analysis of the standard versus mini-incision posterior approach to total hip arthroplasty. J Arthroplast 29(10):1970–1982
39. Zhang Y, Zhu J, Wang Z, Zhou Y, Zhang X (2015) Constructing a 3d-printable, bioceramic sheathed articular spacer assembly for infected hip arthroplasty. J Med Hypotheses Ideas 9(1):13–19
40. Inzana JA, Olvera D, Fuller SM, Kelly JP, Graeve OA, Schwarz EM, Kates SL, Awad HA (2014) 3d printing of composite calcium phosphate and collagen scaffolds for bone regeneration. Biomaterials 35(13):4026–4034
41. Xu J, Li D, Ma R-f, Barden B, Ding Y (2015) Application of rapid prototyping pelvic model for patients with ddh to facilitate arthroplasty planning: a pilot study. J Arthroplast
42. Murphy SV, Atala A (2014) 3d bioprinting of tissues and organs. Nat Biotechnol 32(8):773–785

43. Ingber DE, Mow VC, Butler D, Niklason L, Huard J, Mao J, Yannas I, Kaplan D, Vunjak-Novakovic G (2006) Tissue engineering and developmental biology: going biomimetic. Tissue Eng 12(12):3265–3283
44. Mironov V, Visconti RP, Kasyanov V, Forgacs G, Drake CJ, Markwald RR (2009) Organ printing: tissue spheroids as building blocks. Biomaterials 30(12):2164–2174
45. Malda J, Visser J, Melchels FP, Jüngst T, Hennink WE, Dhert WJA, Groll J, Hutmacher DW (2013) 25th anniversary article: engineering hydrogels for biofabrication. Adv Mater 25(36):5011–5028
46. Jana S, Lerman A (2015) Bioprinting a cardiac valve. In: Biotechnology advances
47. Li Z, Kawashita M (2011) Current progress in inorganic artificial biomaterials. J Artif Organs 14(3):163–170
48. Gonçalves A, Marcos-Alberca P, Almeria C, Feltes G, Ana Hernández-Antolín R, Rodríguez E, Luis Rodrigo J, Cobiella J, Maroto L, Silva Cardoso JC et al (2013) Quality of life improvement at midterm follow-up after transcatheter aortic valve implantation. Int J Cardiol 162(2):117–122
49. Padala M, Brent Keeling W, Guyton RA, Thourani VH (2011) Innovations in therapies for heart valve disease. Circ J 75(5):1028–1041
50. Wüst S, Müller R, Hofmann S (2011) Controlled positioning of cells in biomaterials-approaches towards 3d tissue printing. J Funct Biomater 2(3):119–154
51. Duan B, Kapetanovic E, Hockaday LA, Butcher JT (2014) Three-dimensional printed trileaflet valve conduits using biological hydrogels and human valve interstitial cells. Acta Biomater 10(5):1836–1846
52. Kamen D (2008) Dean kamen's luke arm prosthesis readies for clinical trials
53. Belter JT, Segil JL, Dollar AM, Weir RF (2013) Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review. J Rehabil Res Dev 50(5):599–618
54. Bojsen-Møller F, Lamoreux L (1979) Significance of free dorsiflexion of the toes in walking. Acta Orthop 50(4):471–479
55. Zheng H, Shen X (2015) Design and control of a pneumatically actuated transtibial prosthesis. J Bionic Eng 12(2):217–226
56. Cherelle P, Grosu V, Matthys A, Vanderborght B, Lefeber D (2014) Design and validation of the ankle mimicking prosthetic (amp-) foot 2.0. IEEE Trans Neural Syst Rehabil Eng 22(1):138–148
57. Madusanka DGK, Wijayasingha LNS, Sanjeevan K, Ahamed MAR, Edirisooriya JCW, Gopura RARC (2014) A 3dof transtibial robotic prosthetic limb. In: 2014 7th international conference on information and automation for sustainability (ICIAfS). IEEE, pp 1–6
58. Winter DA (1991) Biomechanics and motor control of human gait: normal, elderly and pathological. Waterloo Biomechanics
59. Hafner BJ, Sanders JE, Czerniecki JM, Fergason J (2002) Transtibial energy-storage-and-return prosthetic devices: a review of energy concepts and a proposed nomenclature. J Rehabil Res Dev 39(1):1–12
60. Cherelle P, Mathijssen G, Wang Q, Vanderborght B, Lefeber D (2014) Advances in propulsive bionic feet and their actuation principles. Adv Mech Eng 6:984046
61. cherelle2014 R, Desomer A, Lenaerts G, Beyl P, Van Damme M, Vanderborght B, Vanderniepen I, Van Der Perre G, Lefeber D (2008) From conventional prosthetic feet to bionic feet: a review study. In: 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, 2008. BioRob 2008. IEEE, pp 49–54
62. Zhu J, Wang Q, Wang L (2014) Effects of toe stiffness on ankle kinetics in a robotic transtibial prosthesis during level-ground walking. Mechatronics 24(8):1254–1261
63. Abd Razak NA, Abu Osman NA, Kamyab M, Wan Abas WAB, Gholizadeh H (2014) Satisfaction and problems experienced with wrist movements: comparison between a common body-powered prosthesis and a new biomechatronics prosthesis. Am J Phys Med Rehabil 93(5):437–444
64. Tan HZ, Srinivasan MA, Eberman B, Cheng B (1994) Human factors for the design of force-reflecting haptic interfaces. Dyn Syst Control 55(1):353–359

65. Resnik L, Klinger SL, Etter K (2014) The deka arm: its features, functionality, and evolution during the veterans affairs study to optimize the deka arm. Prosthet Orthot Int 38(6):492–504
66. Resnik L, Lieberman Klinger S, Etter K (2014) User and clinician perspectives on deka arm: results of va study to optimize deka arm. J Rehabil Res Dev 51(1):27–38
67. Ortiz-Catalan M, Brånemark R, Håkansson B, Delbeke J (2012) On the viability of implantable electrodes for the natural control of artificial limbs: review and discussion. BioMed Eng OnLine 11(1)
68. Young AJ, Kuiken TA, Hargrove LJ (2014) Analysis of using EMG and mechanical sensors to enhance intent recognition in powered lower limb prostheses. J Neural Eng 11(5):2244–2252
69. Hargrove LJ (2005) A Comparison of surface and intramuscular myoelectric signal classification. PhD thesis, University of New Brunswick
70. Tucker MR, Olivier J, Pagel A, Bleuler H, Bouri M, Lambercy O, Millán JdR, Riener R, Vallery H, Gassert R (2015) Control strategies for active lower extremity prosthetics and orthotics: a review. J Neuroeng Rehabil 12(1):1
71. Scheme E, Englehart K (2011) Electromyogram pattern recognition for control of powered upper-limb prostheses: state of the art and challenges for clinical use. J Rehabil Res Dev 48(6):643

Future Trends for Rapid Roboting

Fernando Auat and Pablo Prieto

Abstract The chapter presents final remarks and future challenges concerning the integration of 3D printing, electronics and computer science for producing specially customized robots to support the new Rapid Roboting concept.

1 Concluding and Remarks

Additive Manufacturing has been demonstrated as an essential tool for the fast development of robot parts. Examples of this can be found in chapters "Printing 3D electronics for robotics", "Rapid Prototyping for Bio-Inspired Robots", and "Soft Robotics", with the development parts integrating electronics, making a robot for testing a bio-inspired vision system and developing flexible features, respectively.

The chapter "Printing 3D electronics for robotics" introduces how utilising Additive Manufacturing to deposit conductive materials and make sensors or actuators is possible. Another remarkable technique is applying conductive and semiconducting inks in the AM process to create rigid or flexible electronics, creating sensors and actuators that provide sensing, motion collaborating to robot intelligence or autonomy. For example, by reading and interpreting the inner conductivity, monitoring forces applied to the piece is possible. A more straightforward approach is building complex geometries using Additive Manufacturing and embedding electronic components in the fabricating process. A handy example of this is embedding batteries and energy sources in 3D-printed parts, for example, building custom-shape lithium-ion batteries.

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F. Auat et al. (eds.), *Rapid Roboting*, Intelligent Systems, Control and Automation: Science and Engineering 82,
https://doi.org/10.1007/978-3-319-40003-7_10

Many manufacturing challenges remain, such as the need for additional materials, improved resolution, anisotropy behaviour and strength improvement. However, the exponentially increasing research focus on 3D printing processes ensures that the ongoing evolution of these manufacturing systems will overcome these concerns. However, building fully functional robots containing electronics using additive manufacturing is possible today. The chapter "Rapid Prototyping for Bio-Inspired Robots" presents "Modi", a robot for implementing algorithms for artificial bio-inspired vision. The little robot was built entirely by using low-cost Additive Manufacturing technology and Arduino open-source electronics. The chassis was constructed quickly, avoiding as much as possible external wires and connections. This project is an excellent example of the importance of developing basic robots rapidly, especially when the robots are used as a supporting tool for research, in this case, for neuroscience.

As shown in the chapter "Soft Robotics", additive manufacturing has become an essential technological tool for developing complex and flexible robot parts composed of different materials. Multi-material 3D printers, like the ones in the material jetting group, can produce high-quality, flexible and multi-material parts. However, they are still expensive for small companies or research groups. Instead of utilising 3D printing for the entire building process, a mixture between a traditional moulding and 3D printing process can be used and it can still speed up the development of the parts. It is expected that shortly new desktop multi-material 3D printers arrive on the market at competitive prices, but it depends on patent expirations and the arrival of new companies to further develop the technology for creating new devices.

Using Additive Manufacturing to produce final parts instead of testing or building prototypes is a common practice. Such trend has been fueled by developments in new materials and the increased reliability, production speed and low costs of Fused Deposition Modelling (FDM), Stereolithography (SLA) and Selective Laser Sintering (SLS) technologies. Functional end parts built with those technologies are already a reality. Fused Deposition Modelling (FDM) and Stereolithographic (SLA) machines at prices of as little as 200 USD are a reality. Selective Laser Sintering (SLS) technology also offers new desktop machines, but the prices are still high (in 2021), starting at 5,000 USD. As it happened with Material Extrusion and Vat Photo Polymerisation, it is expected that Powder Bed Fusion further enables the production of low-cost and high-quality machines in the following years, opening new opportunities to the Rapid Prototyping concept. The other technologies are still evolving, and some essential patents are still active, but in the meantime, all the Additive Manufacturing can potentially be available at reasonable prices for small companies.

But when talking about Rapid Roboting, as stated in chapter "Rapid Roboting: The New Approach for Quickly Development of Customized Robots", we should also focus on robotics programming. Therefore, the chapter "Prototyping the Brain of a Robot" presents an overview of what can be done and the robot programming limits. Although nowadays we can find a vast offer of programming frameworks, we should consider that some frameworks allow for rapid testing of our algorithms, but others allow us to include intelligence in our developments. As cases of study, we find chapters "Design of Mobile Robots" and "Autonomous Service Units", where we visit the application of rapid roboting techniques to design, build, programming and test several robotic solutions. Finally, the chapter "Biomedical Devices: Materials, Fabrication, and Control" shows how additive manufacturing, rapid prototyping and (lastly) rapid roboting can be extrapolated to biomedical disciplines.

The different chapters of this book are intended to show the reader the importance of the rapid roboting concept, covering hardware, programming and rapid prototyping, with the aim of facilitating the TRL improvement of our robotic solution: an idea in a lab that starts with TRL 1 or 2 can be easily pushed up to TRL 4 or 5, obtaining a proof, a concept and a prototype that under the right circumstances might become the solution to our problem.

2 New Challenges

Despite the excitement of Rapid Roboting, it is thought to enhance the TRL of an idea that comes not only from a lab at a University or Institution but also from industry or any practitioner. It is not thought to be of high specialisation, but to use the current informatic advantages to reach a working solution without specialised knowledge. But the latter does not mean that knowledge is not necessary, it is the opposite; we believe that the chapters covered in this book will guide the reader through the different topics of rapid roboting to, in the end, form an idea of what is necessary to start building low-cost working robotic solutions that can be later transformed into a commercial product. The rapid roboting concept is not conceived for implementing final part manufacturing lines. Therefore, we should not expect to have mass production of our ideas but can be implemented to consolidate and validate an idea that could be commercial.

Additive manufacturing processes, the continuous finding of new printable materials, the advances in electronics and the Internet of Things, and Robotics are becoming more and more important in areas such as agriculture, space exploration and biomedicine, among others, and we should be aware of the importance of keeping us up to date.