1 Introduction

Industrial robots, which are among the most important elements for industrial automation, are the biggest commercial market for robotics. Since the 1970s more than one million units are in use in fields like car manufacturing or the chemical industry. These robots are operating in highly structured environments. The tasks performed by this type of robots are monotone and restricted due to a low flexibility. An economic growth of the robotics industry will only be achieved if the systems become mobile, adaptive to a dynamic environment and can be used for different tasks. The robots mentioned above belong to the class of service robots. A service robot can be defined as a system which operates semi- or fully autonomously to perform services useful to the well-being of humans and equipment, excluding manufacturing operations.[1]

Starting from autonomous guided vehicles, sewer inspection robots, cleaning robots or systems for entertainment, the number of service robots has increased tremendously during the last 15 years. It is expected that the service robot market will be growing by a factor of eight to about 50 billion USD in 2025. Most of these service robots belong to the class of autonomous mobile robots (AMR).

This book is an introduction to basic techniques and methods which allow the development of such machines. In the following, a short overview of the problem areas of AMRs, their applications and a historical survey are given.

1.1 Autonomous mobile robots

Autonomous mobile robots (AMR) can be defined as robots able to navigate through the environment in an autonomous way while performing goal-oriented tasks. They can be classified according to their operational environment into unmanned ground vehicles (UGV), unmanned water vehicles (UWVs), autonomous underwater vehicles (AUVs) and unmanned aerial vehicles (UAV). They can be used for different service tasks like autonomous inspection, surveillance or maintenance. Figure 1.1 demonstrates typical

[1] World Robotics 2003, United Nations and International Federation of Robotics

AMRs. The insect-type robot LAURON [GB01] developed at FZI, Karlsruhe (Germany) is designed for navigation in rough terrain. The autonomous helicopter H3 of the TU Berlin (Germany)[2] was built for search and transportation tasks while the RoboTuna project of MIT, Boston (USA)[3] examines biologically inspired underwater locomotion.

Figure 1.1 LAURON III (left), UAV H3 (middle), and RoboTuna II (right)

This textbook focuses on UGVs that make use of wheels for locomotion purposes. Most methods concerning localization, mapping and navigation can also be transferred to other types of AMRs. Common requirements for AMRs are autonomy and autarchy. Autonomy means that the system can decide self-dependently. One can separate between fully autonomous, in which the system decides totally by itself, and semi-autonomous, in which some decisions are made by a human operator. The decisions are normally based on incomplete knowledge about the environment and might be wrong considering the global task. The term autarchy signifies that the energy supply is carried along on the robot. It is clear that these are requirements essential for tasks in which a mobile robot is necessary.

To fulfill the requirements for autonomy of an AMR, the following features are essential:

Mobility This term describes the ability of the robot to move to specific positions in the operational environment. These positions could be in the local surrounding but also far away.

Adaptivity to unknown situations Because of a high dynamic of the environment the AMR will be confronted with situations which have not been specified before. Therefore, adaptivity is a key feature for AMRs.

Perception of environment For navigation and the ability to fulfill application tasks it is essential to retrieve information of the environment

[2] http://pdv.cs.tu-berlin.de/lfafr/index.html
[3] http://web.mit.edu/towtank/www/Tuna/Tuna2/tuna2.html

around the vehicle. The main problems arise from incomplete and noisy basic data.

Knowledge acquisition Because a complete model of the operational environment of the robot cannot be described a priori, the AMR must have the ability to acquire new knowledge while operating.

Interaction ability AMRs must also be able to get commands and new tasks from an operator. Very often speech and gesture are more suitable than standard techniques.

Safety The AMR must not destroy itself, damage any objects or hurt humans. An emergency stop is the simplest technique and should be avoided by using a prediction of critical situations.

Realtime processing Computer and software architecture able to deal with hard real-time requirements.

To implement the above mentioned features, different problem areas have to be handled. Given a mobile robotic platform, the first step towards a solution to a service robot problem is the modelling of its kinematics and dynamics. This includes e. g. the relation between wheel velocities and the robot movements or the influence of wheel slippage. Based on these models, simple navigation tasks can be described that do not consider obstacles in the environment. To avoid collisions, sensor systems are needed to detect different types of obstacles like stairs, furniture or vegetation. Based on the measurement principle, the extracted information is often noisy and incomplete. This makes it necessary to use different sensors and fusion algorithms for the measured values. The information is used by the collision avoidance strategies to decide whether an emergency stop or an evasion of obstacles is the best solution.

If the robot is supposed to be able to drive along a predefined path given as intermediate positions and orientations according to a fixed frame, it has to know where it is. This problem is called the localization problem. Because of disturbances from the environment (e. g. slippage of the wheel) it is not possible to solve this problem using solely kinematic or dynamic models in a precise way. Therefore, additional methods have to be taken into account.

For the execution of navigation tasks it is often helpful to describe the operational environment with maps. Therefore, one has to decide which features are extractable from the environment, and how to represent them. These maps can be used for navigation. This includes path planning under given quality criteria like time-optimum or length of the travelled path. Depending on the application, the AMR must recognize whole scenes or only specific objects that are to be manipulated. Problems are the extraction of features which lead to an unique identification and dynamic changes of the situation.

In the following, methods and techniques for the solution of the described problems will be introduced.

1.2 Applications of autonomous mobile robots

In general, all robotics applications can be classified according to the degree of unstructuredness of the environment and the degree of autonomy that is necessary for executing the task (see figure 1.2). Industrial robots are normally used in a well defined structured environment. For example, welding robots in car manufacturing get the exact position and orientation of where the segments of the chassis have to be welded together and where these parts are located. Therefore, the number of sensors that have to observe the manufacturing process is very low. The task execution is restricted to a fixed set of commands, which cannot cope with unforeseen conditions. Thus, the degree of autonomy of the task execution is also low.

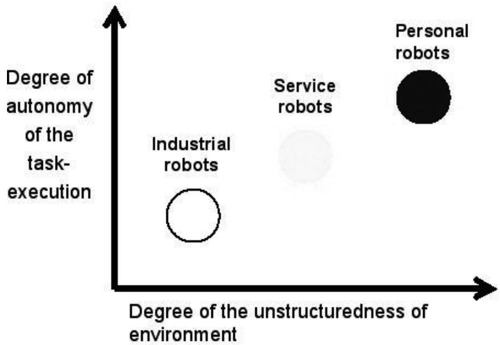

Figure 1.2 Classification of AMR systems with respect to the field of application

In contrast to that service robots have to operate within more unstructured environments. It is not possible to depict these environments completely. Consider for example an underwater robot that is intended to inspect a pipeline. In this case a model of the environment and its dynamic conditions like critical flows could not be given a priori. Furthermore, the use of specific sensor systems like camera systems will deliver a limited model of the environment because of e. g. the water turbidity. These disturbances cause a strong need to adapt to the current situation for he task execution.

Personal robots on the other hand are designed to be general purpose machines suitable for performing a huge amount of different tasks in arbitrary environments. A humanoid robot, for example, can be applied as a servant in a household. It should be able to clean dishes and windows or wash clothes. The operational environment is located both inside the house and in the garden. In the following only application areas and some examples in which specific service robots are used will be presented.

Service robots can be classified based on their application areas. A detailed description of these systems and its applications can be found in [SS04, Ich05].

Transportation Typical transportation systems are industrial automated guided vehicle (AGV), transportion systems for goods or support systems for handicapped persons. Because these vehicles operate mainly in the proximity of humans, the safety requirements are very high. The main focus lies on path planning under different environmental conditions and taking obstacles into account. A typical example of an AGV is TransCar of the company Telelift, Puchheim (Germany).[4] It moves routine and on-demand deliveries of medical supplies across multiple-floor facilities. Another transportation system is the autonomous truck Actros of the company UZIN, Ulm (Germany)[5], which carries production materials on the factory premises. The wheelchair Rolland of the University of Bremen (Germany)[6] is developed for the transport of elderly and handicapped people.

Surveillance Surveillance robots have the task of monitoring buildings and areas both in- and outdoor. Normally, a fixed path or waypoints are given, which are frequently visited. Besides the implementation of adequate navigation strategies, the detection of irregularities in structured and unstructured terrain has to be solved. In addition, the system has to distinguish between intruders and authorized persons. The robots Mosro and the Ofro of Robowatch, Berlin (Germany)[7] are representatives for this application.

Exploration Several robot systems for the application in environments that are either hazardous or non-accessible for humans were developed in the last years. These systems have to be immune to any disturbances

[4] http://www.swisslog.com/index/hcs-index/hcs-systems/hcs-agv/hcs-agv-transcar.htm
[5] http://www.goetting.de/de/multimedia/videos/fox_auf_vox.flv.html
[6] http://www.informatik.uni-bremen.de/rolland/
[7] http://www.robowatch.de/index.php

and unforeseen situations. They must be implemented in a way that an interaction of a human operator with the system via telecontrol is possible. The planetary rovers Spirit and Opportunity of the National Aeronautics and Space Administration (NASA, USA) landed on Mars in 2004 and are still operating.[8] The ROBOVOLC vehicle developed in the course of an EU project led by the University of Catania (Italy)[9] was used to explore the Etna volcano.

Inspection and maintenance Inspection and maintenance tasks represent one of the biggest application areas for service robots. They are used to analyze plants, buildings or large technical devices like ships. They can also be employed to clean or repair them. The operational environment could be subjected to extreme conditions like high and low temperatures or any kind of liquids. Besides methods for inspection and maintenance, the exact positioning is a great challenge. In sewer inspection, for instance, robots are used to detect broken pipes or other damages, which may lead to ground contamination. Kairo of the FZI, Karlsruhe (Germany) is a snake-like robot for the autonomous inspection of pipe networks [SKBD01]. The Robair system of the London South Bank University was developed to inspect rows of rivets for loose ones and cracks at the wings and fuselage of airplanes [SPCB06]. Other applications are underwater, like inspection and repairing of pipelines. The teleoperated vehicle Spider was designed by the company Cybernetix, Marseille (France) [SHW04] and visually analyses pipelines up to a depth of 1500 m.

Harvesting For forestry and agriculture, different service robots have been developed to reduce costs and to save resources. One problem area arises from the motion in uneven and unstructured terrain; another from the detection of the crop. The six-legged robot Harvester developed by the company Plustech, a Finnish John Deere subsidiary, is used for cutting trees in rough forests [SS00]. An autonomous fruit picking machine (AFPM) is a further example used for apple harvesting [BDB+07].

Housekeeping Housekeeping robots are an old dream presented in several science fiction stories. In the last years, several robots have been designed to vacuum-clean, to clean windows or to support people with their housework. Beside complex manipulation and navigation tasks,

[8] `http://marsrovers.nasa.gov/home/`
[9] `http://www.robovolc.dees.unict.it/activity/activity.htm`

these robot systems often have to interact with human operators verbally or based on gestures and mimic. Trilobite of the company Electrolux was one of the first vacuum cleaner products.[10] Equipped with ultrasonic sensors, Trilobite is able to avoid obstacles. When the battery load runs low, the robot drives back to the charging station. More sophisticated research robots for housekeeping are the humanoid robots ARMAR of the University of Karlsruhe (Germany)[11] and Care-O-bot[12] of the Fraunhofer Institute IPA, Stuttgart (Germany). Both machines are able to perform manipulation tasks, like dish washing, or fetch and carry operations.

Edutainment Edutainment robots combine education and entertainment. The idea to motivate learning with the help of interesting robot systems can be found on all education levels. For pupils, Lego Mindstorms[13] is often used to introduce them to mechatronics as well as programming robotic systems. The RoboCup competition[14] inspires students worldwide to delve into robotics methods and technologies. Research areas are multi-agent systems, object tracking and game strategies. Other projects for edutainment are museum guides like TOURBOT.[15] This robot can be used as an interactive tour guide, providing individual access to museums' exhibits and cultural heritage over the Internet, or as a flexible, on-site museum guide.

1.3 Historical overview

Among the first AMRs to be mentioned in the literature is a machine called ELSIE (Electro-light-sensitive Internal-External)[16], designed by W. Grey Walter in the 1940s and 50s in England. It is a rather simple device equipped with very basic sensors and actors in order to enable ELSIE to localize a light source in its environment and approach the source's position. A simple collision avoidance mechanism was available. ELSIE could be regarded as the first autonomous mobile robot able to react by itself to specific stimuli of the operation environment. The control was based on analog circuits.

[10] http://trilobite.electrolux.de/
[11] http://www.sfb588.uni-karlsruhe.de/
[12] http://www.care-o-bot.de/
[13] http://mindstorms.lego.com/
[14] http://www.robocup.org/
[15] http://www.ics.forth.gr/tourbot/
[16] See http://www.extremenxt.com/walter.htm

It took until the late 1960s for the first more serious AMR to be developed. The new robot developed by the Stanford Research Institute (SRI) was named Shakey, see figure 1.3.[17] It was equipped with a TV camera, a triangulating range finder, and bump sensors and made use of programs for perception, world-modeling, and acting. Due to the increased need for computation performance, it consisted of both an on-board and an off-board computer (PDP-10) connected via a radio link. Vision and planning were performed off-board, while all other functions were performed by the on-board unit. The revolutionary new approach introduced with this platform, however, was hierarchical control, still a common principle used in modern robots.

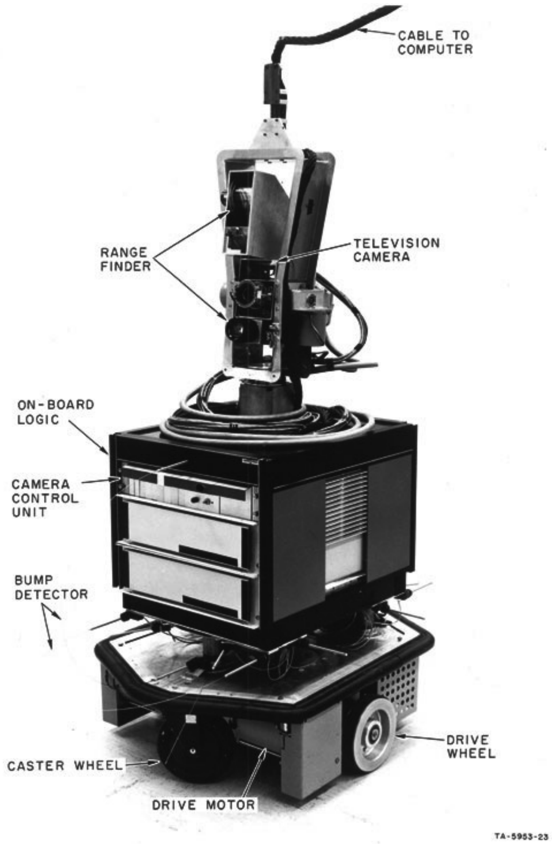

Figure 1.3 Shakey, the forefather of autonomous mobile indoor robots

[17] http://www.ai.sri.com/shakey/images.php

Shakey's control architecture consists of three levels: Low-level routines take care of simple tasks like moving, turning, or route planning. Intermediate-level routines combine the low-levels ones in order to be able to perform more complex tasks. On the highest hierarchy level routines to make and execute plans are found. Shakey can therefore be seen as the first cognitive robot which was able to solve complex task planning problems. Shakey had the task, for example, to move an object located on a platform in its operational environment. Because it was unable to move on the platform, Shakey first plans how to reach it. The solution was to move a ramp to the platform first and then drive over the ramp to the object. Therefore, the general problem solver STRIPS was used. The control programs are implemented with the programming languages Fortran and Lisp.

A few years later, in the early 1970s, the NASA in cooperation with Jet Propulsion Laboratory (JPL) at Pasadena (USA), launched a program intended to provide real-time control, reduce support requirements, and enhance performance and reliability. One result of this program was the Mars rover. Unfortunately, its degree of autonomy wasn't significantly higher than the one of other platforms developed in those early days of AMR research. However, it was equipped with a modified Stanford arm as manipulator and a variety of sensors like laser range-finders, or stereo TV cameras, as well as tactile and proximity sensors.

Its navigation system was based on a gyroscopic compass and optical wheel encoders employed for dead-reckoning. Again the need for the computational performance made an off-board computer inevitable as an addition to the 32 K memory on-board system to construct a "world model" and perform planning. The robot's basic ability was to analyze a simple environment with a limited number of objects, plan a path and follow it to a goal.

The representation of the world used for this purpose was a segmented terrain model consisting of map sectors of reasonable size. Each sector was assigned an attribute representing the accessibility for the robot: Hence, a certain sector was either not traversable or unknown. All other sectors were assumed to be traversable.

The Stanford Cart was developed by Hans Moravec of AI Lab, Stanford (1973–1981). This semi-autonomous controlled robot was equipped with a stereo-camera system, in order to generate 3D images. Since image processing on board was not possible, the image was sent to an external computer. After the image was processed, the distance information of the objects was sent back. The objects were described in polar-coordinates.

For the determination of an optimal path, a tree-search approach was used. The CMU mobile Robot (1981–1984) continued the Moravec research. This cylindrically shaped vehicle with a height of 1 m and a diameter of 30 cm had 12 on-board processors. As control architecture, a three level task-based approach was used, consiting of a planner, initiator, sensor processing and the motor control. Until now, several mobile robots apply such a control architecture.

Meldog was a remarkable approach to develop a autonomous robot. Meldog, which was built as a kind of motor cycle, was developed at the Mechanical Engineering Lab in Japan (1979–1983). It was a mobility aide to blind people and acted as a kind of robotic seeing-eye dog. The vehicle was able to detect obstacles in the nearby environment with ultrasonic sensors. Based on this information collision avoidance was performed. Furthermore, the speed adjustment to keep a distance of 1 m to the operator was triggered by ultrasonic measurements. With the help of a wired link, the operator was able to control the machine (left, right, straight, stop). Maps were also used to support path planning.

In Europe the development of AMRs was pushed forward by EUROMICRO, organizing micromouse contests from 1980 on at their annual meetings. The competition was to let a vehicle find the middle of a maze, made up of small walls of 10 mm thickness and 50 mm height in tiles of 17 cm side length. In 1981 a first Micromouse, as sketched in figure 1.4 [GHvP81], with a diameter of 15 cm, equipped with two coupled microprocessors, was brought to the meeting at Kopenhagen by the researchers of the University of Kaiserslautern. One of the microcontrollers was used to control the vehicle, the other one to solve the maze. Afterwards, a new design was developed for a much smaller vehicle. This was the micro mouse Speedy Gonzales (dimensions 130 mm×100 mm) [HK88] which managed to solve the maze successfully. Figure 1.5 shows a sketch of the robot and a picture of the vehicle in a maze.

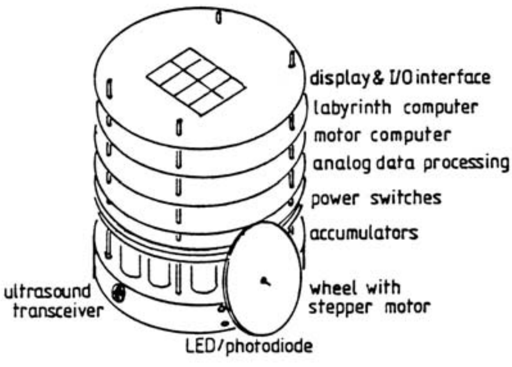

Figure 1.4 Concept of the Micromouse

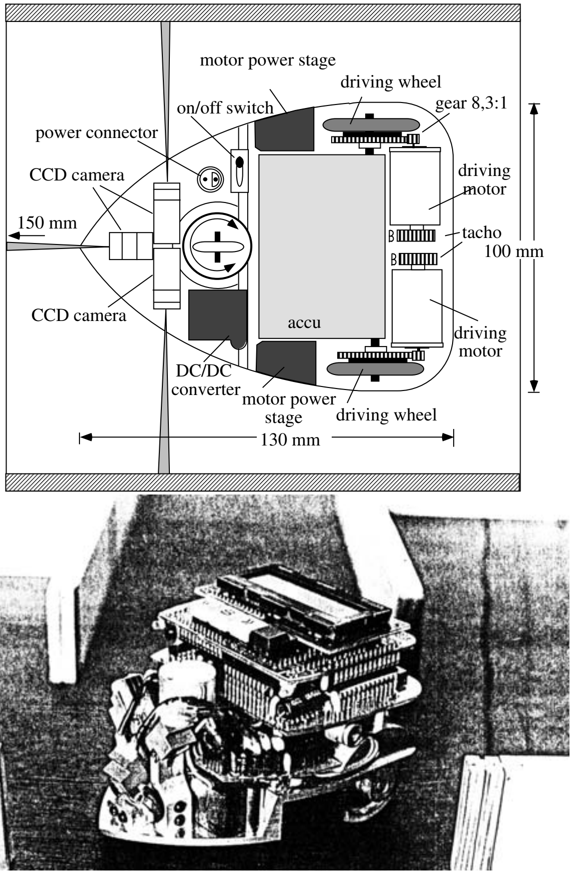

Figure 1.5 Micro mouse Speedy Gonzales

Besides this, several other activities were started in Germany in the 1980s. Several groups in Munich, Darmstadt, Berlin and Aachen developed mobile robots. At the TH Karlsruhe Prof. Rembold and his group started the KAMRO project (Karlsruhe Autonomous Mobile Robot, 1985–1995). The autonomous mobile robot KAMRO (see figure 1.6) was one of the first robots to perform assembly tasks autonomously. It was equipped with two arms (Puma 260 manipulators) with a gripper and an integrated camera, a mobile platform with an omnidirectional drive system, and different sensors for navigation, docking and manipulation. The tasks could be described on different levels: assembly precedence graphs, implicit elementary operations (pick, place) and explicit elementary operations (grasp, transfer, fine motion, join, exchange, etc.). KAMRO provided the basis of a whole series of autonomous vehicles at the University of Kaiserslautern.

In the 1990s, a lot of wheel-driven robots have been developed all over the world. Several companies started to build wheel-driven robots which were mainly sold to the research market. Besides this, service robots like vacuum cleaners, sewer inspection robots or autonomous transport vehicles have been used.

From the research point of view, Sojourner (see figure 1.7), developed at the JPL (1994–1997), was certainly one of the robotic highlights of the 1990s. This small robot driven by 6 wheels was the first machine on Mars. The machine was controlled by teleoperation from Earth. Path planning, for example, was done with the help of a simulation system. When an optimal path was selected, its parameters were transferred to Sojourner on Mars. Obstacle detection and avoidance was directly performed on the machine. Sojourner was equipped with a gripper able to collect samples. A first analysis of the collected material was also done on the machine.

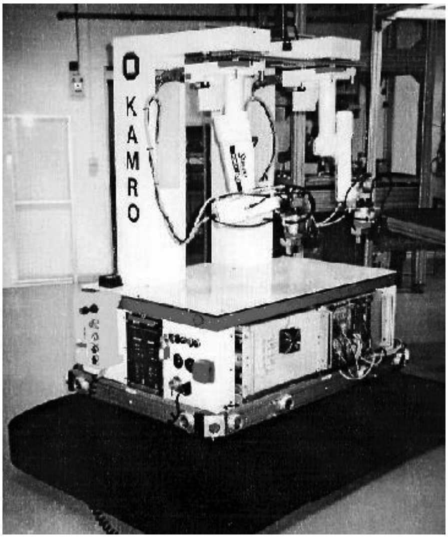

Figure 1.6 KAMRO of the University of Karlsruhe (Germany) designed for a flexible production (courtesy of Prof. Dillmann, TH Karlsruhe)

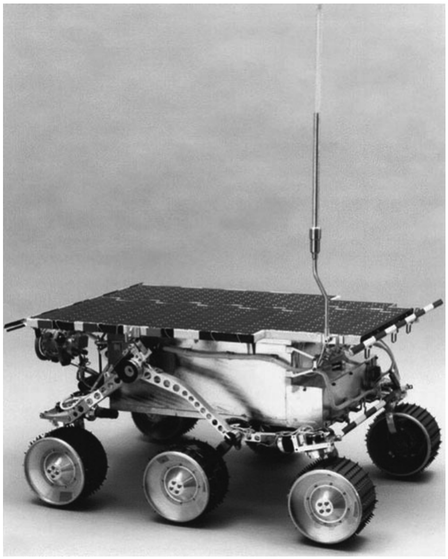

Figure 1.7 The Mars exploration rover Sojourner developed by NASA and JPL (from `http://www-robotics.jpl.nasa.gov/roboticImages/img811-67-browse.jpg`)

This short historical survey is certainly not complete. In the 1970s and 80s there have been further autonomous mobile robot research projects mainly in the US, Japan and Europe. During this period, the first AGV were used in factories to automatize production. Starting in the 1990s, service robots have been developed for all the above mentioned application areas. Most of the systems did not get beyond a prototype stage. Besides technical problems, the high cost was the main reason that these robot systems have not been placed on the market.

1.4 Book overview

After the above overview of the AMR topics, problems and applications, a short historical survey is given. Chapter 2 focuses on the kinematics of wheel-driven AMRs. Based on the rotational speed of typical wheel types, a kinematic model for the computation of the vehicle's linear and angular velocities is derived. For specific drive systems it is easier to apply a geometrical solution to the kinematic problem. Some examples of this are given.

The kinematic model is a foundation for several topics presented in the book. The description of the robot's state and the detection of objects in its environment are essential for tasks like localization and navigation. In chapter 3, the most important sensors and sensor systems for this purpose are introduced. Starting from tactile and pose[18] measurement sensors, different types of ranging and vision sensors are presented. Distance sensors are often the main source of information because they can be used in manifold ways e. g. for safety, 3D reconstruction or collision avoidance.

Despite sophisticated sensor systems like GPS, precise localization is still an open research problem. In chapter 4, the problem of localization is introduced and different techniques are presented. This includes dead-reckoning, localization based on optical flow, feature based methods and approaches using landmarks.

Complex AMR applications need an adequate map for the representation of the environment and for planning. In chapter 5, a classification of the different map types is given. Later, the concept for building different types of maps like metrical, grid, sector, topological and hybrid maps is discussed.

A precise determination of the position and orientation of the robot is required for map building. On the other hand, if a map exists and features of the environment can be correlated with it, one can derive the robot pose. SLAM methods generate new maps and estimate the pose of the robot in a simultaneous way. Chapter 6 gives a short overview of SLAM and presents solutions to some subproblems like the merging of maps.

[18] The pose describes the position and the orientation.

Strategies for moving from one location to another one in known or unknown environments are summarized under the term navigation. In chapter 7, algorithms for local and global path planning as well as path control are described. Local path planning covers both algorithms for planning based on different map types and methods of basic navigation abilities like collision avoidance.

The structuring of all control components according to functional and non functional requirements is done using control architecture. Chapter 8 introduces different standard architectures for AMRs. The main focus of the chapter is behavior based control architectures. The iB2C architecture is presented as an example and applied to specific control problems.

The book ends with an survey of software frameworks for robotic applications (chapter 9). Robotic frameworks support the development process. The implementation of control algorithms for complex AMRs is not possible without a suitable framework. In this chapter different features of frameworks are discussed and a comparison of well known examples from literature is given.