Multimedia Contents

65. Domestic Robotics

Erwin Prassler, Mario E. Munich, Paolo Pirjanian, Kazuhiro Kosuge

When the first edition of this book was published domestic robots were spoken of as a dream that was slowly becoming reality. At that time, in 2008, we looked back on more than twenty years of research and development in domestic robotics, especially in cleaning robotics. Although everybody expected cleaning to be the killer app for domestic robotics in the first half of these twenty years nothing big really happened. About ten years before the first edition of this book appeared, all of a sudden things started moving. Several small, but also some larger enterprises announced that they would soon launch domestic cleaning robots. The robotics community was anxiously awaiting these first cleaning robots and so were consumers. The big burst, however, was yet to come. The price tag of those cleaning robots was far beyond what people were willing to pay for a vacuum cleaner. It took another four years until, in 2002, a small and inexpensive device, which was not even called a cleaning robot, brought the first breakthrough: *Roomba*. Sales of the Roomba quickly passed the first million robots and increased rapidly. While for the first years after Roomba's release, the big players remained on the sidelines, possibly to revise their own designs and, in particular their business models and price tags, some other small players followed quickly and came out with their own products. We reported about theses devices and their creators in the first edition. Since then the momentum in the field of domestics robotics has steadily increased. Nowadays most big appliance manufacturers have domestic cleaning robots in their portfolio. We are not only seeing more and more domestic cleaning robots and lawn mowers on the market, but we are also seeing new types of domestic robots, window cleaners, plant watering robots, tele-presence robots, domestic surveillance robots, and robotic sports devices. Some of these new types of domestic robots are still prototypes or concept studies. Others have already crossed the threshold to becoming commercial products.

For the second edition of this chapter, we have decided to not only enumerate the devices that have emerged and survived in the past five years, but also to take a look back at how it all began, contrasting this retrospection with the burst of progress in the past five years in domestic cleaning robotics. We will not describe and discuss in detail every single cleaning robot that has seen the light of the day, but select those that are representative for the evolution of the technology as well as the market. We will also reserve some space for new types of mobile domestic robots, which will be the success stories or failures for the next edition of this chapter. Further we will look into nonmobile domestic robots, also called smart appliances, and examine their fate. Last but not least, we will look at the recent developments in the area of intelligent homes that surround and, at times, also control the mobile domestic robots and smart appliances described in the preceding sections.

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65.1 Mobile Domestic Robotics

The first mention of a domestic cleaning robot dates back to 1985. The device, nicknamed *Robby*, was developed by Hitachi starting in 1983 and officially carried the name HCR-00 (Fig. 65.1). Robby was equipped with a gyroscope to keep track of its position and a rotating sonar scanner for obstacle detection.

65.1.1 Domestic Floor Cleaning

Very similar to today's cleaning robots described further below, Robby already mapped its environment and used the map for path planning. HRC-00 remained a prototype like its successors HRC-01 to HRC-03.

First Generation of Domestic Cleaning Robotics (1985–1999)

Also in 1985, the Swedish appliance manufacturer Electrolux started the development of a concept vacuum cleaner *Stardust*. The device was equipped with eight fixed sonar sensors and one rotating sensors for obstacle detection. To maintain its orientation Stardust used an infrared sensor that tracked an infrared light bulb mounted to the ceiling. In 1988 Stardust was presented to the public at Domotechnica in Cologne, Germany, one of the largest fairs worldwide for domestic appliances [65.1].

Fig. 65.1 First generation of domestic floor cleaning robots (1985–1999)

About five years later, between 1989 and 1991, Panasonic undertook an effort to develop a domestic cleaning robot that led to two prototypes, one of them, *Brownie*, is shown in Fig. 65.1. Brownie was a battery-powered vacuum cleaner with a diameter of 40 cm, and at 18 kg, a super heavy weight compared to today's domestic cleaning robots. It was equipped with a gyroscope, a ring of sonar sensors, and a dust sensor. Likely, it was limitations in battery technology for driving such a heavy robot, as well as the total cost, which prevented Brownie from become anything more than a prototype.

Six more years went by before Minolta presented its *Minolta Cleaning Robot* and the first European player, Electrolux, its Robot Vacuum Cleaner, later called Trilobite, which was presented to the public in BBC's TV show *Tomorrows World* in 1996.

The devices had already become significantly smaller and lighter in these six years. The Minolta robot had dimensions of 321 mm × 320 mm × 170 mm and weighted about 8 kg. It was powered by nickel metal hybrid battery and used sonar and tactile sensors for obstacle detection, a cliff-sensor to discover staircases, and a gyroscope to track its position and orientation. Electrolux' robot also had a sophisticated sonar system, which let it follow contours and even return to a homing position. It already had the size and shape of later floor cleaning robots.

Five more domestic cleaning robots made their first appearance during this time, which we call the infancy of domestic cleaning robotics. Two of them only reached the proof of concept level: *AutoCleaner* from InMach Intelligent Machines – the German startup later developed low-cost navigation systems for the professional cleaning robot Robo40, which became commercially available in 2007 – and Koala form EPFL-Lami. AutoCleaner was the first domestic wet-cleaner proof of concept, which cleaned the floor using a rotating microfiber towel that was pulled through a water tank. Koala used a suction spout to reach corners. Two more robots reached at least the status of industrial prototypes, but were never commercialized: Dyson's *DC06* and Cye from *Probotics*. DC06 was a unique domestic

Fig. 65.2 Second generation of domestic floor cleaning robots (2000–2008)

cleaning robot. It differed not only in terms of the announced list price of approximately US$ 4000, but also in many other aspects: Dyson claimed that it had three onboard CPUs, more than 50 sensors for obstacle avoidance, cliff-detection, localization and more. On top of that came the unique Dual Cyclone cleaning technology. The DC06 never made it to the market. Neither did Cye. Cye was a small mobile robot that could pull and push a (semi-)regular vacuum cleaner. It was announced as the *first personal robot* which could not only vacuum the floor but also serve coffee or deliver mail. It is unclear if Cye ever delivered coffee or mail or vacuumed a real living room. It disappeared as quickly as it appeared. The last out of the nine first robots that we call first generation was the Kärcher RoboCleaner. Its successor RC3000 was amongst the first cleaning robots that had a docking station at which the robot could not only recharge its battery but also unload the dust, which it had collected. We will come back to the Kärcher RC3000 in the next section.

The first generation domestic floor cleaning robots shown in Fig. 65.1 were the ones presented to the public. However, they were by far not the only ones that were developed in the period between 1985 and 1999. By browsing over the patents in the field of cleaning robots during that period it becomes obvious that many of the big appliance and electronic device manufacturers worldwide performed research and development on domestic cleaning robots. Besides the ones mentioned above, one can find such big names as Nintendo, Matsushita, Sanyo, Samsung, Honda, Procter & Gamble, Electrolux, Philips, Henkel and more. So, although only a few players dared to go public, domestic cleaning was already on the radar of many international enterprises. What kept them away from taking the next steps is not hard to guess. It was the risk of getting into a rather conservative and tight market – the cleaning business is extremely conservative – with a semimature technology carrying a price tag that looked quite differently than the one on well-established technology, such as traditional vacuum cleaners.

The Second Generation of Domestic Cleaning Robotics (2000–2008)

Figure 65.2 shows the second generation of domestic cleaning robots. What made the difference between the first and the second generation? The amount of experimentation regarding the overall design decreased, with the majority of manufacturers settling on the disc shape. The number of sensors decreased, as well as their level of sophistication. Sophisticated and expensive sensors such as sonar largely disappeared. Most designs were limited to very few, simple, and inexpensive sensors such as bumpers, simple one-dimensional range sensors, typically based on infrared (IR), and cliff sensors. This was most likely a rather painful lesson learned from the designs in the first generation. What roboticists considered the state of the art in mobile robotics: environmental sensing, map building, range sensors with high quality angular and range resolution, and combined localization and mapping, were far too expensive to be built into a domestic cleaning robot. Those robots had to compete with regular vacuum cleaners in a price range of a few hundred dollars. This competition imposed very harsh cost limits for the robotic components that could be built into a domestic cleaning robot: 50 to 100 USD and often less. These cost constraints had a significant impact on a very fundamental expectation of what cleaning robots should achieve: systematic coverage of the area to be cleaned. Cleaning was understood to be synonymous with covering an area with a systematic and intuitive motion while applying some type of cleaning operation. Most of the patents filed for the first generation of domestic cleaning robots mentioned above described cleaning robots that were supposed to cover their workspace in a systematic fashion.

Systematic coverage, however, is impossible without absolute positioning and without decent knowledge of the environment. The second generation of domestic cleaning robots had to provide a solution for this dilemma of systematic coverage with cheap and simple sensors, which must not cost more than several tens of dollars.

The solution to this dilemma was already proposed in some early prototypes. The idea was to waive the requirement of systematic coverage, which would also involve intuitive motion patterns, and instead produce *semisystematic* coverage and *semi-intuitive* motion patterns. This semisystematic coverage was achieved by a combination of random motion, hard-coded motion patterns such as spiral- or meander-shaped motions, which – considered alone – reflects some systematic coverage, and some other systematic and intuitive motion patterns, for example, following contours of walls or other objects in the workspace. The theory of stochastic process states that the mean squared distance of a particle that performs a random walk with respect to the origin of its motion increases proportionally with time. That implies that the particle moving in confined space will cover that space in a finite amount of time.

First-generation domestic cleaning robots like the Electrolux Robotics Vacuum Cleaner (later Trilobite) or the Kärcher Robot Cleaner (later Kärcher RC 3000) already used random motion combined with hard-coded motion patterns to achieve a certain degree of coverage. But apparently the insight that the attribute *robotic* in front of *vacuum cleaner* was not enough of a sales argument to justify a price three to five times higher than that of a regular vacuum cleaner was not so easy to digest. Some of the second-generation cleaning robots were offered for a price on the order of 1500 USD or even more. In the end these robots shared the same fate: they become shelf warmers.

This is also due to the fact that in 2002 a robot was launched which was to herald a breakthrough in domestic cleaning robotics: Roomba. Its creator, iRobot Inc., had learned the lesson that others were still struggling with: if you want to sell a domestic appliance, better sell it for a price that is known for domestic appliances. For the sake of fairness one has to mention that the traditional vacuum cleaner manufacturers had to design the robots so they matched the quality and performance level that could be expected from the brand name. They could not take the risk of making their product too poor. Therefore it easily became over specified compared to what the market required at the time. New manufacturers such as iRobot in contrast had no brand name to defend [65.1].

If it is a totally new device, which may not only cause excitement but also concerns and reservations, sell it for less and not for more. When Roomba entered the market it was sold for 199 USD. That was a price, which did not cause customers to think about whether they really needed it, whether the quality was good enough, or whether the device would get into every corner of a room or underneath every couch or bed. The creators of Roomba were also smart enough not to call it a robot. This that prevented many customers from developing wrong expectation of what robots could or should do.

The robot technology that was built into the Roomba was everything but new or revolutionary. Roomba used a suspended front-shield for contact-sensing, a low-cost infrared range-sensor for contour-following, a cliff-sensor to prevent it from falling down stair-cases, and it could detect photoelectric barriers, so-called *virtual walls*, which kept it from leaving a room or a certain part of its workspace. Roomba further used the combination of random motion and hardcoded area-covering motion patterns to achieve a certain level of coverage. All this technology was known before Roomba.

Still Roomba can be seen as a milestone not only in domestic robotics but also in robotics at large. Why is that? It was the first time in robotics history that robotics was no longer synonymous with high-tech, high-price. Roomba showed that automation of everyday service tasks, such as domestic cleaning, could be achieved with a moderate effort in terms of hardware and at a decent price, given that one accepts some graceful degradation in the overall performance. There is no such thing as a free lunch, not even in robotics and this degradation in the performance is the price to be paid. What turned Roomba into a milestone was the cost-effective design, where the limitations of low-cost hardware – in Roomba's case the sensors – were balanced out by smart heuristics for problem-solving. This

Table 65.1 Technical specification of a selection of second-generation domestic cleaning robots

					
Manufacturer	iRobot	Sharper Image	Electrolux	Kärcher	Yujin
Model	Roomba	eVac	Trilobite 2.0	RC 3000	iclebo
Drive	Differential	Differential	Differential	Differential	Differential
Sensors	Suspended front shield as contact sensor, IR range sensor, four IR cliff sensors, dust sensor	Touch sensor, cliff sensor, IR for wall-following	180° sonar sensors (1 transmitter, 8 receivers), infrared cliff sensor, magnetic stripe detector, suspended front shield as contact sensor	Suspended front shield as contact sensor, four IR cliff sensor	Main brush, side brush anti-bacterial filter
Mapping and localization	n/a	n/a	n/a	n/a	n/a
Navigation/coverage	Random motion with bang and bounce, contour following, spiral motion	Random motion with bang and bounce, spot cleaning with star pattern	Wall-following, random motion with obstacle avoidance	Random motion with bang and bounce, spot cleaning with see-saw motion pattern	Heuristic pat-terns: random, circular, zig-zag, wall following
Cleaning technology	Side brush, two counter-rotating brushes, suction pump	Rotating brushes, vacuum pump	Rotating brush, suction pump	Rotating brush, suction pump	Main brush, side brush
Run time (min)	60–90	15–45	60	20–60	150
Performance	–	–	28 m^2/h	15 m^2/h	–
Docking/recharging station	Yes	No	Yes	Yes	no
Size (Ø/h) (cm)/(cm)	35/8,25	32/14	35/13	28/10	35/9
Weight (kg)	2,7	3	5	2	4
Year of launch	2002	2004	2004	2003	2005
Price range	250 USD	100 USD	1300 EUR	1350 EUR	530 USD

design of a commercially viable product, at a price point competitive with nonrobotized solutions, turned Roomba into the first successful domestic cleaning robot, and the most frequently sold robot in the past 50 years.

In Table 65.1 we give an overview of the technical specifications of some of these second generation robots. A more complete overview is included in 065-bib43

The idea to develop and commercialize a domestic cleaning robot at a price level of 199 USD, comparable to the price of traditional domestic appliances, was very appealing to consumers. However, it was not an overly profitable business model, even if Roomba was manufactured in a low-wage country at a cost of significantly less than 100 USD. Extreme cost pressure, however, often compromises the quality of a product. So a decision to adhere to this low price of below 200 USD may also have been a decision against the quality of the product. Today nearly a dozen models of Roomba are on the market, which differ mostly in terms of their cleaning technology and extra features. Their prices are in a range from 250 to 900 USD.

The Third Generation of Domestic Cleaning Robotics (2009–2012)

The second generation of domestic cleaning robots also provided their developers and distributors with a number of painful and partly contradictory insights:

- A domestic cleaning robot sold at a price that is significantly beyond the price of comparable nonrobotic devices, runs a high risk of failing, because many customers may not be willing to pay extra money for a cleaning robot just because it is a robot.
- A domestic cleaning robot sold at the same price level as an inexpensive comparable appliance, runs a high risk of failing, because the low price may

compromise the quality and functionality of the product, and many customers may not be willing to pay even a rather low price for a product that is known to be of poor quality.

- For most customers – traditional, as well as technophiles – efficient cleaning requires systematic and efficient coverage of the workspace. A domestic cleaning robot that uses sophisticated sensors to achieve systematic and efficient coverage may easily end up with a price tag that is significantly above the price of a comparable nonrobotic device and hence runs a high risk of failure.
- A domestic cleaning robot, which refrains from using expensive sensors to achieve systematic coverage but instead uses low-cost sensors for collision avoidance, fall protection, and confinement as well as using random motion combined with some hard-coded motion patterns to achieve a certain level of coverage, runs a risk of not satisfying those customers who expect systematic cleaning and coverage.

From a developers point of view these lessons sound as if customers expect not less than to square the circle. The truth is that customers do not care about squares and circles. They expect value for money.

With the insights above one could classify potential customers of domestic cleaning robots into three categories:

- Customers who only care about the price and not so much about quality and functionality. The criterion for this class of customers was obvious: reduce the price as much as possible without ignoring that there may be a bottom line for what customers might expect in terms of quality and functionality.
- Customers who care about the price and quality, but are willing to adjust their expectations of functionality and efficiency. The criterion for such customers was to reduce the price but only to a certain extent, which does not compromise the quality of the product too much. Expectations of such customers in terms of efficiency (i. e., systematic coverage) can be compensated by auxiliary equipment such as automatic charging stations.
- Customers, who care about price, quality, and efficiency. Apparently these customers are the most demanding. None of the second-generation domestic cleaning robots has really managed to satisfy them. The criterion to serve them would be to develop a low-cost navigation system based on low-cost sensors that provides systematic coverage.

As satisfying the last group of customers, which is also likely the largest of the three groups, seemed nearly impossible, the third generation of domestic cleaning robots have diverged somewhat. Some manufacturers have focused on products that serve the first category of customers, some serve the second group and some even made an effort to square the circle.

May they be successful in the end or not, what cannot be overlooked is the explosion of the number of manufacturers and distributors of domestic cleaning robots in the past five years. At the end of the 2012, twenty-seven years after the first mention of a domestic cleaning robot to the public, Amazon alone listed more than 131 results under the key word *robot vacuum cleaner*, with 14 manufacturers and suppliers. The business to business (B2B) portal www.made-in-china.com lists more than 71 companies for *robot vacuum cleaner* and a total of 875 products. Some of these 875 robot vacuum cleaners look surprisingly similar to the products sold over B2C platforms under very-well known brand names.

In Fig. 65.3 we show some of the products, which primarily intend to serve customers of the first category and therefore stayed under a price of 200 EUR. Figure 65.3a shows a model series of six cleaning robots made by XRobot of the Chinese manufacturer Shenzhen Silver Star Intelligent Electronics Ltd. In B2B trading these robots cost between 64 and 102 USD per piece at a minimum order of 500 pieces. Most models of this series are also sold under the brand name of European and American enterprises. Figure 65.3b shows another series of still rather cheap robotic vacuum cleaners. The attentive reader may notice that the robots in the left and the right figure are not totally unique. Some just have different names and different prices. This is not entirely unintended. It just illustrates that in domestic cleaning robotics the value creation chain is no longer limited to the developers and manufacturers, just as in every other business.

Apart from a few minor details, all robots in Fig. 65.3 use very similar, though not to say the same, technology. They use very few and very cheap (contact, cliff, sometimes dirt) sensors and random motion combined with preprogrammed motion patterns. The vacuum technology consists of a rotating brush, sometimes combined with a small fan. Not surprisingly, robotic vacuum cleaners like the ones in Fig. 65.3 are often called Roomba-clones. The collection of robots in Fig. 65.3 is neither representative nor comprehensive.

Roomba has undoubtedly written robot history. It is the merit of Roomba and its developers that domestic cleaning robots are no longer considered as gadgets but as real appliances. Roomba has opened the door for all

Fig. 65.3 Third generation of domestic floor cleaning robots: low-cost, low-tech

Fig. 65.4 The seventh generation of Roombas

the cleaning robots mentioned above, be they Roomba-clones or not. And Roomba is the by far the best-selling robot ever.

In Fig. 65.4 we show some of the grandchildren and great-grandchildren of the very first Roomba, which started in 2002. The Roomba has gone through several facelifts in these ten years. The latest series, the Roomba 700 is the sixth generation of Roombas. It has matured quite a bit in many respects. It has matured in terms of handling, cleaning technology, obstacle avoidance and navigation technology. At the same time Roomba is delivered in more than a dozen versions, ranging from 250 to 900 USD. These versions differ in the design, in the sophistication of the user interface, in the navigation and coverage strategies, and in the details of the cleaning technology.

According to iRobot more than 6 million units have been sold in the ten years of its existence. Roomba has certainly satisfied quite a number of customers. It is built with good quality, and comes with a self-charging home base and other auxiliary equipment. What has not changed, however, is the basic strategy for covering the workspace. The sixth generation just like the first uses random motion with some precoded motion patterns and heuristics.

This raises one rather fundamental question. Will Roomba's success story continue? Will it maintain its market position? Or has Roomba possibly reached or even passed its summit? These questions will not be answered before the third edition of this book, as any statement in this direction would be pure speculation.

In any case, there are a few recent domestic cleaning robots, which demonstrate that covering a work space in a systematic fashion does not necessarily require expensive sensing, that would push the price for a domestic cleaning robot to a level which customers would not be willing to pay.

Four different key technologies enable the devices shown in Table 65.2 to localize themselves and navigate

Table 65.2 Systematic cleaning at low-cost. The information in this table was partly collected from the websites and the technical documentation of the manufactures and partly from public websites such as www.botroom.com, staubsaugerroboter-test.org, www.robotreviews.com, www.geek.com, gizmodo.com, www.engadget.com

					
Manufacturer	LG	Samsung	Neato Robotics	Iclebo	Evolution Robotics/iRobot
Distributor			Vorwerk	Philips	Dirt Devil EVO/iRobot
Model	Hom-Bot 3.0	Navibot SR 8895 Silencio	Neato XV-21	Philips FC9910/01 HomeRun/ iclebo smart	Mint 4200
CPU	32 bit	2 CPUs			ARM7
Drive	Differential	Differential	Differential	Differential	Differential
Sensors	Camera (ceiling), camera (floor), sonar & infrared for collision avoidance cliff sensors, gyroscope, acceleration	Range sensors camera, cliff sensors, collision sensors, gyro	1-D laser range finder, cliff sensor, gyroscope, acceleration,	Camera (ceiling), cliff sensor, infra red for collision detection, gyroscope,	Northstar Indoor GPS, cliff sensors, bumper, gyro
Mapping and localization	SLAM	SLAM based on ceiling pictures at 30 fps (Visionary Mapping System)	SLAM based on laser range finder (onboard Room Positioning System (RPS))	SLAM based on ceiling pictures	SLAM with Northstar, map-building
Navigation/coverage	Systematic	Systematic	Systematic	Systematic	Systematic
Cleaning technology	Brush roller, 2 side brushes	Brush roller, 2 side brushes	Bristled brush	Brush roller, 2 side brushes, micro-fiber mop	Dry or wet (or premoistened) microfiber cloths
Run time (min)	75	90	90	70	180
Performance	–	$80\,m^2/h$	–	$40\,m^2/h$	–
Docking/recharging station	Yes	Yes	Yes	Yes	No
Size (Ø/h) (cm)/(cm)	36/9	35/8	34× 34/10	35/10	31× 11/ 29
Weight (kg)	3,2	3,2	5	4	2
Year of launch	2011	2011	2012	2011	2010
Price range	US$ 799.00 (Amazon.com)	EUR 349.00 (Amazon.de)	US$ 350.00 (Amazon.com)	EUR 499.00 (Amazon.de)	US$ 174.00 (Amazon.com)

in an unknown domestic workspace and systematically cover that space:

- Visual odometry, with a camera pointing to the ceiling, combined with simultaneous localization and mapping (SLAM) used by LG Homebot, Samsung Navibot SR 8xxx, iclebo smart and Philips Homerun,
- Localization, using infra read patterns projected to the ceiling, and mapping based on contact information used by Mint,
- Proprioceptive motion estimation, using inexpensive inertial measurement units (including inexpensive gyroscopes and accelerometers)
- Simultaneous localization and mapping (SLAM), using, for example a one-dimensional laser rangefinder like Neato XV-xx.

These technologies by themselves are not entirely new. As a matter of fact methods such as simultaneous localization and mapping, visual odometry, and virtual landmark based navigation are not state of the technologies form a scientific point of view.

The true achievement of the developers of the above systems, which cannot be assessed high enough, is that they managed to reduce the cost of these technologies and at the same time make them robust enough for 24/7 operation. These key technologies will be described in more detail in Sect. 65.1.2 Enabling Technologies. A review of domestic vacuum cleaning robots and some criteria to evaluate their performance are presented in VIDEO 727 and VIDEO 729.

65.1.2 Domestic Window Cleaning

Window cleaning does not seem to be significantly more pleasant housework as floor cleaning. Notwithstanding, robotic window cleaners have not experienced similar attention or progress as floor cleaners. As a matter of fact, today there are only three commercial robotic window cleaners on the market, shown in Fig. 65.5. www.made-in-china.com does not even list one entry for *window cleaning robot*, although two of the three commercial products are Chinese brands. Why is that so, given the fact that domestic floor cleaning has become a billion-dollar business? The answer to this question has two parts: an economic and a technical one.

The economic one is that windows in private homes are cleaned far less often than floors. Customers may hesitate to buy expensive equipment for a task that needs to be done once a month or even less. So the market for domestic window cleaners is presumably much smaller than that for floor cleaners.

The technical one refers to the technical hurdles that have to be overcome. The technical problems that robotic window cleaners have to face are:

- Adhesion to a vertical, fragile surface, which possibly needs to be moistened in order to be cleaned, and related, the power supply necessary to produce that adhesion.
- Requirements for cleaning performance; people may tolerate if the floor is not 100% clean, but nobody would buy a window cleaner that leaves streaks on the window.

While floor cleaners do not bother about gravity and falling down unless they are near staircases or ledges, gravity is an essential problem for window-cleaning robots, and the solutions are usually not very cheap. Special mechanisms have to be designed for secure motion. Typically special tether mechanisms prevent the robots from falling. Special locomotion mechanisms have to create enough adhesion force to hold a robot attached to a flat, vertical, damageable surface such as glass and at the same time move the body up and down and sideways. These mechanisms have to be small and light and create enough adhesion forces as well as low energy and resource consumption.

The two robotic window cleaners shown in Fig. 65.6, RACOON and QUIRL, are research prototypes, which were developed by Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) in Germany. In these prototypes the adhesion problem was solved by means of suction cups. RACOON used caterpillar drives that were equipped with passive suction cups. Passive means that the system does not actively create a vacuum in the cup. Rather a small valve aerates or seals the suction cup depending on the position of the cup along the drive. Drives with passive suction cups have the advantage of moderate energy consumption. They have, however, one severe disadvantage. They tend to lose their adhesion after a while. The reason for this is the torque that acts on the center of gravity of the system. Due to this torque there is a traction force acting on the upper cups while at the same time pressure is exerted on the lower cups. Without any attractive force acting on the upper cups the adhesion there gets weaker and eventually the system falls. Therefore passive suction cups are rarely practical.

An apparent solution to this problem is the use of active suction pumps, which generate a vacuum under the upper suction cups. This solution prevents the system from falling. However, supplying the vacuum to the cups makes the system significantly more complex, heavier, and larger. Researchers at Fraunhofer IPA [65.2] have therefore invented a smart solution, which gets by with passive cups, but gets around the problem of decreasing adhesion. The solution uses a spacer at the rear of the vehicle. This spacer neutralizes the torque around the center of gravity which is typical for a systems with passive suctions cups. The spacer causes a traction force which acts on the lower suction cups. This traction force creates a torque around the spacer, which counteracts the torque around the center of gravity and also causes a pressure on the upper suction cubs. RACOON was presented at the Hannover Fair in 2002 and got quite some attention. But it never became a product. Neither became its successor QUIRL.

In QUIRL, the number of components, the weight, and the size of the system were significantly optimized. The main functions *cleaning*, *holding*, and *moving* were unified in one single component. QUIRL consisted of

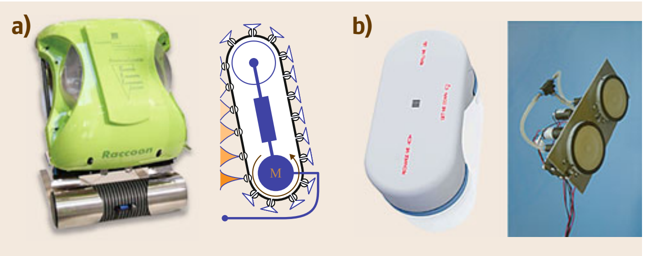

Fig. 65.6 **(a)** RACOON and **(b)** QUIRL, two early research prototypes of domestic window cleaning robots

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Fig. 65.5a–c Commercial robotics window cleaners **(a)** Windoro, **(b)** Winbot, **(c)** Hobot

two vacuum cups that were attached to a common frame which were driven by two separate motors, which rotated independently of each other. The overall motion of QUIRL could be controlled by selecting the velocities and rotational directions of the vacuum cups. If the motor of one vacuum cup was turned off and the cup did not rotate, QUIRL rotated around this fixed cup. If both motors and cups rotated in the same direction this led to an overall rotation of QUIRL about its vertical axis. If both drives rotated in the opposite direction at exactly the same velocity then QUIRL made a linear motion. If both drives rotated in the opposite direction but their velocities were not identical then the translational motion was superimposed by a rotational motion and QUIRL moved along a curved trajectory. In order to clean the surface some cleaning mechanism or tool needed to be fixed to the vacuum cups. By attaching, for example, specific cleaning towels in the cups the abrasion effect was increased and a very good cleaning performance could be achieved.

The field of robotic window cleaning has not made as much progress as domestic floor cleaning, but it has still made progress. In Fig. 65.5 we show three commercially available window cleaners – Windoro WCR I001, Winbot 7, and Hobot 168 – available today.

In 2010 the South-Korean enterprise Ilshim Global Co. Ltd. introduced its commercial window cleaner Windoro (WCR). Windoro consists of two modules, a navigator module and a cleaning module that are held together by two strong neodymium permanent magnets, whose distance can be adjusted. The navigator module and the cleaning module are placed on the inner and outer side of the window, respectively, like a sandwich with the glass pane in between. The two modules operate as a tandem. The navigator module has a differential drive system with two wide-based rubber wheels. Also the cleaning unit moves on two rubber wheels, which serve as spacers for the four spinning cleaning pads. When the navigator module moves, the cleaning module on the other side of the window moves with it. The linkage by permanent magnets obviously has one rather fundamental advantage. As long as the window does not exceed a certain thickness, namely 28 mm, the permanent magnets hold the robot safely attached to the window. Windoro cannot fall, even if its battery runs out of power. For that reason Windoro does not need any safety mechanism like a safety rope. Unfortunately there is a price to pay for this: it is very difficult and unhandy if not impossible to use Windoro if you cannot open the window that you want to clean.

Windoro first explores the width and height of the window before it then starts to clean the window from the top to the bottom in a zig-zag motion, with a velocity of 8 cm/s. While the robot moves over the window the cleaning module sprays a cleaning solution onto the window surface. With four spinning microfiber pads the cleaning module removes dirt and sprayed solution from the surface.

The second commercial window-cleaning robot is Winbot, a product of the Chinese company Ecovacs, which has established its own brand. Winbot was first introduced in 2011. The most recent version Winbot 7 was presented at the electronics fair CES (Consumer Electronics Show) 2013 in Las Vegas. Ecovacs also manufactures and distributes the robotic vacuum cleaner family Deebot.

Winbot uses two suction rings and a vacuum pump for the adhesion at the window. The outer ring also serves as a safety mechanism. If the air pressure in the ring increases, that means Winbot has reached the edge of a window plane, it backs up, turns around and moves in a different direction. A second suction cup serves as a safety anchor for Winbot while it moves. It is connected to Winbot by a safety rope and catches the robot if it falls. Winbot can move at a velocity of approximately 15 cm/s. Its drive system consists of two differentially driven anti-slip rubber tracks.

After it has been turned on, Winbot, like Windoro, first explores the height and width of the window, then calculates a zig-zag path that covers the window area and finally executes this path. Winbot has no *active* cleaning technology such as spinning pads. It uses two micro-fiber towels that are attached to two plates at the front and at the rear of the robot. The micro-fiber towel in the front has to be moistened before Winbot starts moving. It resolves and removes the dirt. A rubber blade behind the front towel removes the remaining moisture.

Aquabot turbo, Aquabot — TigerShark, Hayward — Dolphin Dynamic Plus, Maytronic — Dirt Devil, Rampage Robotic pool cleaner

Aquabot Alpha Aqutron robotic systems — Vero pool cleaner, iRobot — SwimBot Pro Pool Cleaning Robot, Swimob — Polaris 9400, Zodiac Pool Systems

Fig. 65.7 Robotics pool cleaners

The micro-fiber towel in the rear of the robot finally dries the window.

The third, and most recent, system, Hobot 168, is a product of the Taiwanese company Hobot Technology Inc. It was first presented at IFA 2012 (Internationale Funk Ausstellung) in Berlin and launched in summer 2013. It looks surprisingly similar to Quirl in Fig. 65.5 and apparently uses a similar adhesion and locomotion mechanism, namely two rotating vacuum cubs, to move across the window.

The preceding paragraphs read as if the times are over where windows had to be cleaned by hand. Regrettably this is not the case. Although all three devices reasonably solved the adhesion problem their overall performance is modest. Several tests by housewives and magazines came to the same sobering conclusion: There is a lot of noise and very little cleaning. As a matter of fact, although the navigation problem on a vertical rectangular surface, which is free of obstacles apart from the window frame, seems to be a solvable one, Hobot 168 and Winbot showed a rather poor performance in terms of systematic coverage. After a semisuccessful effort to explore the width and height of the window, Winbot, in one of the tests, moved more or less erratically for several minutes, before it gave up somewhere along the road. Several of the currently available commercial window cleaning robots are reviewed in VIDEO 734, VIDEO 735, VIDEO 736, and VIDEO 737.

65.1.3 Pool Cleaning

While robotic floor cleaner and window cleaner were still struggling to get rid of the image of only being the crazy ideas of engineers and researchers at the beginning of the millennium, pool-cleaning robots were already well-established products. This may be due to the fact that the challenge of cleaning a rectangular pool is rather modest and so is the *robotic technology* used in robotic pool cleaners. It may also be due to the fact that pool owners belong to a class of customers who did not create the same price pressure as the ordinary housewife.

First patents on self-propelled pool cleaning devices date back to 1965, three years after the first industrial robot was installed. Ferdinand Chauvier, a South African engineer, could possibly be considered the father of automated pool cleaning. He developed several generations of devices for pool cleaning before he finally marketed *Kreepy Krauly*, the first automated pool cleaner in 1974. Kreepy Krauly was not only the first one of its kind but also the very first domestic service robot ever, 15 years before Joe Engelberg published his book *Robots in Service* at MIT Press in 1989 and coined the term *service robot*. Since then the technology of pool cleaning robots hasn't changed much.

As one can see in Fig. 65.7, most pool cleaners have track drives, which are operated differentially. Typically the motors that drive the tracks are also connected to the front and rear scrubbing brushes, which clean the pool surface, while the robot moves. While tracked drive system were rather common for the early generations of pool cleaners, newer pool cleaners also use wheel drives, for example, the Polaris 9400 from Zodiac Pool Systems. A wheel drive can be advantageous because the space between the bottom of the robot and the ground allows a better water flow and a higher throughput. Also Zodic claims that Polaris 9400 has higher maneuverability.

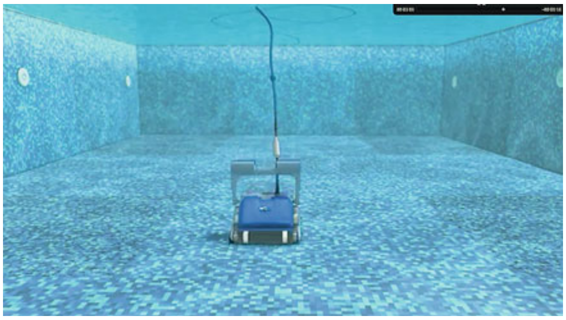


Fig. 65.8 Example of the navigation and cleaning strategy of a robotic pool cleaner

Since most sensors, which are used in mobile robots or in aerial robots do not work under water, the sensor modalities that are used by pool cleaners are manageable. Unfortunately the manufacturers do not disclose much about the sensor technology and technology in general used in their system. So we need to speculate a bit about how the behaviors shown in the commercials are internally implemented.

Most pool cleaners claim to be capable of avoiding obstacles. When they sense a collision, the back up for a certain distance, reverse the direction of motion and then continue, possibly on a track parallel to the one the led to the obstacle. They can *recognize* the walls of a pool, which form the borders of their workspace. They can even climb up the walls of a pool, float along the perimeter and then submerge again. They can *explore* the length and width of a pool. They can drive a certain distance before they change direction.

All these behaviors require a combination of several of the following sensors: *odometry* to measure traveled distance, an *inclinometer* to sense if the robot starts moving upward, e.g., when it keeps pushing against a wall and the front wheels start moving in a vertical direction, *contact sensors* to detect when the robot collides with an obstacle – be it a wall of the pool or a real obstacle on the ground of the pool – *sensor to measure the motor current*, which can be used in addition or instead of a collision sensor to detect if the robot pushes against an object, and possibly an *inertial measurement unit* to correct the heading when driving. Polaris and possibly other systems as well use an accelerometer to constantly determine its position in the pool. A sensor modality, which might be used underwater for obstacle detection and avoidance is laser, with wavelengths in the lower nano-meter range (e.g., 405 nm blue laser). But it is unknown if this principle has been considered for pool-cleaners.

In terms of *navigation and coverage* pool cleaners follow similar strategies to those floor cleaners, which we roughly classified as Roomba-clones. Earlier pool cleaners used random motion pattern. The newer ones shown in Fig. 65.7 use certain heuristics and strategies to perform some form of localization and exploration of the pool. The Maytronic's Dolphin, for example, first explores the length and the width of a pool. After being dropped into the pool and floating to the bottom of the floor it crosses the pool until it hits the first wall. With the support of a thruster it climbs up the wall until it reaches the surface. There it hovers to the side before it submerges again and moves back to the ground of the pool. Next it moves to the opposite side of the pool, climbs up the wall, hovers to the side and glides back to the ground. While moving on the ground from one wall to the other Dolphin measures the distance from wall to wall. Once it glides back from the second wall it moves halfway back toward the other wall. It then makes a 90° turn and repeats the exploration for the second set of opposite walls. After the exploration is completed, Dolphin knows the length and width of the pool and plans a pattern of parallel and orthogonal tracks as shown in Fig. 65.8 that in the end covers the entire pool.

Removing dirt and debris from the ground and the walls of a pool, requires loosening the dirt – if it is not loose already – and to soak it into a container, otherwise the dirt would only be circulated in the pool. The container is typically a jet pipe with a filter at one end that holds the dirt back while the water flows through the pipe back into the pool. Soaking in water and debris from the floor into a filter and pumping it back into the pool requires significant suction power. This is the reason why pool cleaners typically have an external power supply. This motor serves as a pump and as a thruster at the same time. Both effects together allow pool cleaners to easily climb up vertical walls. Using inflation at the bottom of the robot, and a water jet ejected at the top, enough traction power is created that both tracked and wheeled pool cleaners can drive up vertical surfaces.

As mentioned earlier, the cleaning technology, besides the water pump and the filter to keep back the debris, consists of a system of counter-rotating rubber brushes which brush the debris underneath the pool cleaner, where it ends up in the intake socket of the water pump. VIDEO 739 and VIDEO 740 compare a selection of home pool cleaning robots.

65.1.4 Lawn Mowing

Together with robotic pool cleaners and domestic floor cleaners, robotic lawnmowers today count as regular everyday products. People no longer consider them mystical pieces of technology, which have their own life and which at times become so autonomous that the user no longer knows what they are after.

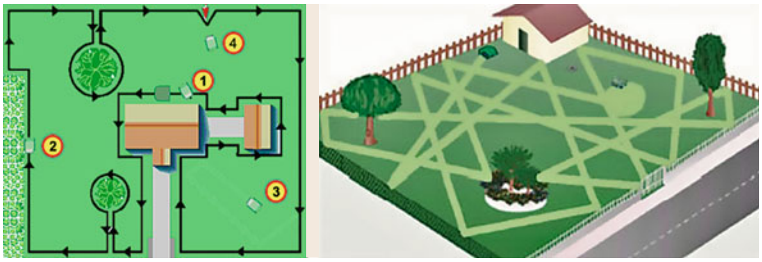


Fig. 65.9 Example for virtual fence and coverage strategy (random motion) of robotics lawnmowers

It is not surprising that robotic lawnmowers have a lot in common with domestic floor cleaners. They have to cover a workspace of a certain size with as little interaction with the owner as possible. They have to perform a certain operation to the surface such as cleaning the floor or mowing the lawn. They must not collide with any obstacles and if they do, they should at least not cause any damage. They must not get stuck anywhere in the environment and they should not leave the workspace without authorization.

The challenge for lawnmowers, much the same for domestic floor cleaners, is the systematic coverage of the workspace, which in turn requires precise positioning and mapping of the workspace. Given the fact that the price pressure is not as back-breaking as for robotic floor cleaners – there are not that many robotic lawnmowers which costs less than 1000 EUR – why not invest a little more in sensing and especially in position sensing and obtain a decent solution for the localization and coverage problem?

The answer to this question is: things are not that simple. Lawnmowers operate outdoors and none of the solution developed for the floor-cleaners in Fig. 65.2 will work. Regular GPS (global positioning system) has an accuracy of several meters and has a tendency to deliver erratic readings, which would lead to equally erratic motions of the lawnmowers. As a matter of fact Automower 220 from Husquana uses GPS, but only as an antitheft protection device. Differential GPS, which would provide accuracy below one meter, would be too expensive for an affordable robotics lawnmower. In a nutshell, absolute positioning or SLAM, which would be necessary to cover a large outdoor area like a garden in a systematic fashion, is not practical.

In order to cover their workspace robotics lawnmowers use similar strategies to the Roomba-like floor cleaners. They refer to heuristics, which do not provide an optimal performance but still show a decent result. Using sensors such as gyroscopes, digital compasses, or inertial measurement units, robotic lawnmowers follow a certain heading and cover the workspace as much as possible by parallel tracks. They move along a straight line until they hit an obstacle or reach the border of the workspace. There they back up to become clear from the obstacle, make a U-turn by 180° and drive back the way they came. Another heuristic that is frequently applied by robotic lawnmowers is the random motion shown also in Fig. 65.9. The mower moves along a straight line until it hits an obstacle or reaches the border of the workspace but then it does not just reverse but chooses a new direction randomly.

Since robotic lawnmowers move in open space, there is a danger that they leave their workspace and travel to areas where they are not supposed to be. For floor cleaners so-called virtual walls or fences solve this problem. Virtual walls are realized by infra read light beams emitted by some projectors, which can be placed in the workspace. The robots can sense these infrared light beams and consider them as obstacles, which evoke the typical obstacle avoidance behaviors. Lawnmowers use a similar technique, which is based on induction rather than light. To mark the border of the robot's workspace the owner has to place a wire around the area, which the robot must not leave (Fig. 65.9). This wire is connected to a low-voltage alternating current source. When the robot approaches the wire an inductivity sensor senses the current in the wire and causes the robot to reverse. Today most lawn mowers use a more sophisticated so-called *true in/out systems*, where the position is permanently tracked, not only when the robot approaches or passes the virtual fence [65.3].

The very first robotic lawnmowers had to be recharged manually. To avoid an all too frequent involvement of the human into the operation, Husqvarna – one of the pioneers in robotic lawn mowing – equipped its first mower with solar panels and called it *SolarMower*. SolarMower was released in 1995, and was one of the first robotics lawnmowers. Nowadays, all lawnmowers come with a base station where they can recharge their batteries without human intervention. Also solar panels are coming back as power source, however only as auxiliary power to increase the performance and runtime between two charges and not as main power supply.

Given the fact, that robotic lawnmowers do have poor positioning capabilities, it is somewhat tricky to guide them back to the docking station once the battery

Fig. 65.10 Robotic lawnmower

gets low and needs to be recharged. Some of the lawnmowers shown in Fig. 65.10 use special wires which radiate from the position of the docking station. This way a robot only needs to follow such a radiating wire to return to the docking station on the fastest way. Another strategy is to follow the wire at the workspace border. That will eventually lead the robot back to the docking station.

An exception is the Bosch Indego, which is equipped with mapping and localization capabilities. This allows Indego to plan a path that leads to a point close to the docking station. Then the robot can follow a wire for the docking maneuver [65.1].

To comply with the safety regulations and to avoid any injuries of humans or animals the cutting mechanism has to be very lightweight and designed such that it is guaranteed to stop if the device tilts or is lifted. The cutting mechanism of robotic lawnmowers typically consists of a rotating disc with three razor-like blades, which automatically retract into their mountings if the robot is stopped unscheduled, for example, if it hits an obstacle or is lifted.

Naturally the lightweight design limits the thickness of the grass that can be cut. Also it is important for the proper functioning of robotic lawnmowers that the lawn, which is to be cut, is not too high. This in turn requires a rather regular if not continuous operation of the lawnmowers. With regular use of the lawnmowers the grass cuttings are short enough to quickly decompose into nutritious compost, so there is no need to remove the cuttings after the lawn is mowed.

Figure 65.10 shows some of the better-known robotic lawnmowers on the market today. Besides the pioneers in robotic lawn mowing Husqvarna, Friendly Robotics and Zuchetti also a number of new players have entered the market, most noticeably the German automotive supplier Bosch and the Japanese car manufacturer Honda, which has set a milestone in non-industrial robotics with its humanoid robot Asimo.

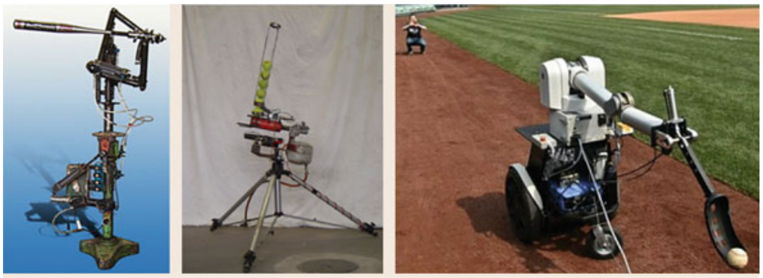
We certainly do not claim that the collection in Fig. 65.10 is complete. Like for domestic floor cleaning, Chinese B2B portals such as www.made-in-china.com or www.alibaba.com list around a hundred products under the category of robotic lawnmowers and 35 suppliers; the market development for robotic lawnmowers in the past five years was not quite as overwhelming as for domestic floor cleaners but was still remarkable. In Table 65.3 we show the technical specifications of a selection of lawnmowers from Fig. 65.10.

65.1.5 Sports Robotics

A subdomain of domestic robotics that was not included in the first edition of this handbook, because it virtually did not exist, or it was not visible at that time, is *sports robotics*. What is a sports robot? Since an official definition of this term does not yet exist – at least we haven't found one – we take the liberty and provide such a definition here. We define a sports robot as a *robotic device*, which either *supports* the human user in their physical exercises as a *coach or a companion*, or acts as an opponent in a game. An important aspect of this definition is the physical exercise of the human, which is supported or challenged.

We would like to emphasize that the above definition does not include any form of entertainment robots, which play games such as soccer against each other but do not involve any human activity other than watching.

In Fig. 65.11 we show three examples of *robotic baseball players*. As the name says the *Headless Batsman* can act as a batter at least for exercising. It rather successfully hits baseballs thrown at it in many ways. The kinematic structure consists of *two arms, one leg and no head*, as its developer, an industrial designer from Robocross, likes to call it, and is made from auto parts, steel pipes, and pneumatic hoses. The pneumatic hoses are parts of its pneumatic actuation by an air



Headless Batsman Pitching Machine PhillieBot – a robotic pitcher

Fig. 65.11 Robotic baseball players

Table 65.3 Technical specification of a selection of robotic lawnmowers

					
Manufacturer	Husqvarna	Friendly Robotics	Zuchetti	Bosch	Honda
Model	Automower 220 AC	Robomow RL1000	Ambroggio	Indego	Miimo
CPU				ARM9 (32 bit) + PowerPC (32 bit)	
Drive	Differential	Differential	Differential 4 driving wheels	Differential	Differential
Sensors	Lift sensor collision/contact sensor	Rain sensor, lift sensor, collision/contact sensor	Grass sensors, safety sensors on handles, lift sensor, sensor for collision sensor and rollover	Lift sensor, collision/contact sensor, gyro, tilt sensor	3×360 degree bump sensors, 2 lift sensors
Navigation/coverage	Random	Random		Logicut navigation system: parallel tracks in parcels; localization, mapping, path planning	Random, parallel or mixed
Cutting technology	3 pivoting razor blades	3 razor blades	Rotating disc	3 pivoting blades	3 blades, which bend on hitting hard objects
Virtual fence and guides	Dual guide wires to return to the base station	Boundary wire	Boundary wire	Boundary wire	Boundary wire
Performance (m^2)	1800 (m^2)	2000 (m^2)	400 (m^2)	1000 (m^2)	3000 (m^2)
Ground speed			18 m/min	27 m/min	
Motor power (W)		3×150		$2 \times 20 + 80$	$2 \times 25 + 56$
Battery type and capacity	NiMH 30 W		Li-Ion, 6.9Ah	32 V Li-Ion, 3Ah	Li-Ion
Run time	45 min	2 h 30 min	3 h 30 min	50 min	
Docking/recharging station	Automatic docking and recharging		No	Automatic docking and recharging	Automatic docking and recharging
Theft protection	Pin code lock	Personal password		Alarm & Pin code	Pin code lock
Size (L×W×H)	$71 \times 55 \times 30$	$87,5 \times 65 \times 31$			
Weight (kg)	10	25	7,9	11.1	
Year of launch				2012	
Price range	~$ 2400,00	$ 1900,00		~$ 1850,00	~$ 2600,00

compressor. The *Headless Batsman* is fully controlled by a human operator via a remote control, which has three buttons: one to control the robot's hip, a second one that actuates the arms and a third one to lift

JoggoBot – a jogging companion RUFUS – a robotic running coach

Fig. 65.12 **(a)** JoggoBot and **(b)** RUFUS two robotic sports companions

and drop the inside shoulder, changing the trajectory of its swing. Similar mechanisms like *Headless Batsman* were developed at Hiroshima University and Tokyo University.

The counterpart of *Headless Batsman* is a pitching machine, which is operated with the same remote control. The barrel of the machine is sawn-off fire extinguisher whose other end is directly connected to a one-inch port poppet valve, which in turn is connected to an 8 bar air pressure tank. The air pressure tank is supplied from a screw compressor. The charging mechanism consists of a double rod actuator with a ring welded horizontally on to the end. Mounted above the ring is a magazine that holds up to 10 balls, which directly drop into the ring. For a pitch the actuator moves the ring with the ball over the edge of the barrel, where it falls on to a small guide. From there the balls rolls backward into the barrel. The actuated ring is covered by a steel strip, which holds back the other balls in the magazine until the actuated ring returns to its initial position. Since both mechanisms are remotely controlled, the human, who controls them, can actually sit in a chair next to the playground and let the robots play against each other. Such a use would clearly violate the above definition of a sports robot but does not seem to be the one that is primarily intended.

Another robot that can throw baseballs is Philliebot (VIDEO 748) developed in University of Pennsylvania's GRASP laboratory. Philliebot was developed in a couple of weeks using only spare parts in the GRASP lab. It uses a Segway as mobile base, a Barret arm, and pneumatically actuated wrist to create the necessary dynamics for the pitch. When the button is pressed the arm moves to the back of the robot and then accelerates its motion toward the target of its pitch. When the arm reaches the highest point of motion the pneumatic wrist cylinder delivers a burst of compressed carbon dioxide to snap the wrist forward and release the ball. What remains is the question of why use robotic equipment worth several tens of thousands of dollars to throw a baseball, given that pitching machines have existed for many years. According to the developers, the fact that Philliebot is mobile and its software can be tweaked to vary pitch velocity and trajectory was enough to justify the experimentation.

The two sports robots shown in Fig. 65.12 do not really seduce their users to sit in a chair and relax. They both serve as so-called *robotic running coaches* or *running companions*.

Researchers at the Royal Melbourne Institute of Technology in Australia have redesigned a commercially available Parrot AR Drone quadrocopter and turned it into an autonomous, flying running partner for joggers, called Joggobot [65.4]. Joggobot uses an integrated, front-mounted camera to detect and track a special patter printed on the T-shirt worn by the jogger. Joggobot takes off when the camera registers the pattern and rises to about the same height as the pattern on the t-shirt. An internal sensor determines Joggobot's altitude. Joggobot can be set into a *companion mode*, in which at flies at a steady pace at a relative distance of about three meters to the jogger or in a *coach mode* in which it flies at a slightly more challenging speed.

There are two features of Joggobot that make the device somewhat limited: first the capacity of the battery limits the flight time to 20 min, which in turns limits the time for exercise; for a short run, this is certainly ok, but for serious training this is insufficient. Second, Joggobot can only fly in a straight line, to let Joggobot follow an arbitrary path the jogger needs to remotely control Joggobot's flight path.

A slightly different concept of a jogging companion is pursued in RUFUS (VIDEO 747), which is developed by runfun (www.runfun.com), a German startup company. RUFUS is an electrically driven, automatically guided, ground vehicle that supports and guides a runner during his/her training. RUFUS plays the role of a *personal running coach*. It fulfills a similar function to a treadmill, which exposes its user to a varying strain by varying its velocity and inclination and thereby improves the fitness, endurance, and resilience of the cardio-vascular system of the user. Unlike a treadmill, RUFUS is not a stationary device, however. It drives ahead of the runner like a pace maker in a marathon or a fake rabbit in a dog race, and sets the runner's speed. RUFUS's velocity is set either manually or automatically via a training program.

If operated in *manual mode* the velocity is either set directly as a velocity set point or indirectly as a heartbeat set point. If the training guidance is based on the heartbeat, then RUFUS controls its velocity such that the runner exercises optimally and continuously within a certain heartbeat interval under a moderate stain of the cardiovascular system.

Fig. 65.13 Tele-presence robots and robotic avatars

This has a twofold use: on the one hand this prevents users from overstressing themselves through overambitious and intensive training modules, possibly from even injuring him or herself. Such a protection function is beneficial for unfit or untrained runners. On the other hand RUFUS facilitates optimal training effect and progress through a careful guidance of the training.

The training effect can be further improved if RUFUS is operated in the *program mode* instead of the manual mode. In this mode RUFUS executes complete training modules, for example pyramid speed interval workouts, which are customized to the user. Such training modules are typically elaborated on by physiotherapists or sports physicians. They can be downloaded to the RUFUS embedded PC like an app from an app store.

RUFUS has a major advantage over JoggoBot. It has a battery capacity that allows it driving for about six hours on a flat road without recharging.

65.1.6 Tele-Presence

In a world in which not only large, but even small and medium-sized enterprises operate globally, in which families are scattered over continents, in which ubiquitous presence seems to become an essential requirement for professional progress, and in which professional services are more and more delivered over the internet, tele-presence has become a fast growing market in the past years.

Robotics adds a very important aspect to plain *tele-vision* by turning it into *tele-presence*: embodiment and remotely controlled motion. As tele-presence is nothing but the combination of tele-vision and tele-operation using a robotic device, which are often called *tele-presence robots* or *robotic avatars*.

Tele-presence robots offer a whole spectrum of services and applications ranging from plain mobile video-conferencing systems to tele-surveillance, tele-diagnosing, and tele-care, to tele-teaching and tele-commuting. The term *tele-commuting* was coined by Scott Hassan, a Google developer of the early days, nowadays entrepreneur and investor, and founder of WillowGarage and Suitable Technologies, the manufacturer of Beam-RPD (see also Table 65.4).

A *tele-presence robot* typically consists of a mobile robotic platform that:

- Can be tele-operated through some user-interface,
- Carries a camera, which often can be actuated separately (via a pan-tilt unit) and allow the operator to actively explore the remote environment, and
- Carries a display, which allows those at the remote site to see the operator of the tele-presence system and communicate and interact with it.

Figure 65.13 shows a collection of such tele-presence robots. The devices range from a price of

Table 65.4 Technical specification of a selection of tele-presence robots

				
Manufacturer	Double Robotics	Vgo Communications	Gostai	Suitable Technologies
Model	Double	VGo	Jazz Connect	Beam RPD
Height	120–150 cm	120 cm	100.5 cm	5 feet, 2 inch
Weight	7 kg	9 kg	8 kg	45 kg
Screen size	9, 7″ (iPad)	6″	5″	17″
Camera/field of view			High resolution/ wide angle, up to 640×480 pixels at 25 fps	Two wide-angle HD cameras
Video conferencing	Open-tok	VGo video conf.	2-way audio and video for remote discussions	–
Network	WiFi	WiFi / 4G / LTE	WiFi	WiFi (two dual-band radios) / 4G
Remote Control	iPad App	VGo App	Intuitive control interface on internet browser	Beam software client, mouse, keyboard, or Xbox controller
Navigation	Tele-operated	Tele-operated	Tele-operated with obstacle detection	Tele-operated
Sensors	Gyroscope, accelerometer	Obstacle and cliff detection sensors	12 ultrasonic sensors, 4 IR receivers (for base docking), telemetric laser for autonomous navigation	–
Drive	Differential (10″ wheels)	Differential	Differential	Differential
Battery	Lithium ion	–	–	–
Run time (h)	8	12	5	8
Docking station	–	Yes auto-docking	Yes auto-docking	Yes

some US$ 1500 for TeleMe from MantaroBot to more than ten-fold that amount for Beam RPD from Suitable Technologies. The system RP-VITA (Remote Presence Virtual + Independent Telemedicine Assistant) emerging from a cooperation between InTouch Health and iRobot is available only for lease, at a monthly fee of $ 4700. Giraff is the result of a European research project lead by Giraff Technologies funded by the European Commission and is not commercially available yet.

Not all tele-presence systems shown in Fig. 65.13 can be classified as domestic robots. A system that clearly stands out and is by no means a domestic robot is *RP-VITA* by InTouch Health and iRobot. RP-VITA is a remote healthcare system. RP-VITA shall enable doctors to command any clinical, patient or care team management process remotely. RP-VITA has a full-fledged autonomous navigation system that allows the personnel to focus on the patient care task rather than on remote navigation. This feature has been awarded clearance by the US Food and Drug Association (FDA). RP-VITA further provides access to important clinical data to support physicians, nurses and other care personnel in their diagnosis and other medical workflow. For example RP-VITA connects with diagnostic devices such as ultrasound and comes equipped with the latest electronic stethoscope. So RP-VITA is in a class of its own, which may also justify the higher price.

Apart from RP-VITA, the tele-presence robots shown in Fig. 65.13, can all be classified as semiprofessional or domestic service robots. The functionalities and services they offer do not necessarily vary on the same scale as their prices. This can be seen by a comparison of two of the above systems: Double and Beam RPD (see also Table 65.4).

Double is not much more than a mobile iPad equipped with the video-conferencing system Opentok. The mobile base uses a Segway-like dual-wheeled drive system that can balance a pole, which holds the iPad. When Double stands still, two retractable kickstands are deployed and allow the system to put the control system in an idle mode and save energy. Double can be remotely controlled and driven around a remote site through an app installed on a second iPad that enables communication with all known Doubles over the web. The height of the iPad holder can be remotely adjusted to enable communication at eye-level. Double Robotics list a number of potential services and applications for which Double could be used: Companies with sites at various locations can us Double to improve communication and collaboration between remote teams. Families can use Double to communicate with family members living abroad. Museums and art galleries can use Doubles to offer remote tours through their exhibitions.

Beam RPD uses two HD cameras with custom wide-angle lenses instead of the plain iPad camera. This gives Beam RPD peripheral vision that is comparable to a human's field of view. A digital zoom lets the operator further focus on details in the remote site. Beam uses an array of six microphones and audio processing algorithms, background noise reduction and echo cancellation. This equipment gives Beam an audio-quality, which obviously goes far beyond that of an iPad. Beam uses a 17-inch screen mounted at a height of 1.58 m that allows the display of a human face at its natural size and height. Another feature that goes beyond iPad standards is the WiFi connectivity. To provide reliable and seamless WiFi connectivity, Beam uses two dual-band radios and proprietary roaming algorithms. Altogether it is obvious that Beam RPD is far more than a movable iPad. It is left to the customers to decide whether this is worth a price which is an order of magnitude higher. VIDEO 741, VIDEO 742, VIDEO 744, and VIDEO 745 introduce several of the tele-presence robots available on the market today.

65.2 Enabling Technologies

The mass consumer market is very price-sensitive, so the price of the robot is key for the success of the product among consumers. Certain guidelines used in the consumer electronics market are relevant for the domestic robot market to provide a rough estimate of cost of the robot. Let's say that you want to develop a floor-care robot that would retail at $ 300, the *rule of thumb* is that your bill of materials (BOM) should be between 1/3–1/5 of the retail price. In other words, your BOM should be within $ 60–$ 100! And the BOM must include all mechanical parts, electrical parts, battery, processor, memory, motors, assembly, packaging, user manuals, etc.

Given the extreme cost constraints outlined above, this chapter focuses on enabling technologies that are viable, from the cost point of view, to be included in a mobile domestic robot with a price lower than $ 1000 (or ideally below $ 500). These technologies are required to have a reliability level in line with the expected life time (and warranty) of the product; otherwise, no matter how good the technology is, if it stops working in an unreasonable period of time, the robot will be returned to the retailer. Special emphasis should be placed in the ease of manufacture of the technology. Difficult to manufacture components create delays in the production line, decreasing the yield of the product and eventually increasing the overall cost of production, leading to either eroding profit margins or a rise in the retail price.

Mobile robots need to sense and understand the environment in which they operate. The first key enabler is the capability of detecting obstacles and hazards to safely and accurate navigate around them. Section 65.2.1 describes the different available technologies for obstacle and hazard detection. The second key enabler is the ability to localize and create a map of the environment to intelligently plan actions and motions that allow the robot achieve its goal. Section 65.2.2 presents the technologies available for localization and mapping using a number of low-cost, yet powerful sensors. Section 65.2.3 discusses alternative approaches to coverage of the space implemented in commercial products.

65.2.1 Sensing and Obstacle Avoidance

Domestic robots aim to take care of tedious chores, interacting with a household that includes owners, children, babies, pets, and stationary objects such chairs, tables, walls, etc. Domestic robots must be safe in order to gain acceptance in our daily life: it is not tolerable to have a robot falling down the stairs or hurting a household member. Thus, robots must be equipped with drop/cliff sensors and proximity sensor that ensure proper operation while still satisfying the mentioned cost constraints.

Cliff Sensors

A number of solutions are present in current robots in the market. Off-the-shelf solutions are IR sensors from Sharp that consists of an emitter (light emitting diode LED) and a receiver (photodetector or position-sensitive-device PSD) that provides an output proportional to the distance to the object. The Roomba uses

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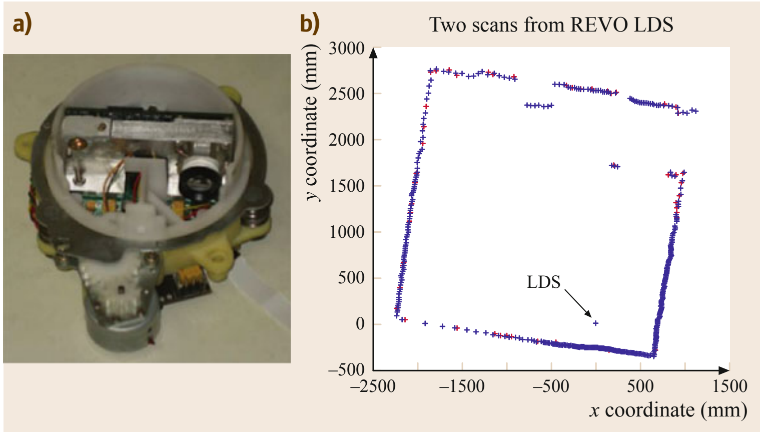

Fig.65.14a,b Laser Distance Sensor. **(a)** Prototype and **(b)** occupancy map generated with the sensor

a custom IR cliff sensor based on a similar principle that trades generic distance measurement with sensor cost. The Mint robot from Evolution Robotics employs a factory-calibrated mechanical hammer that triggers upon cliff detection. Solid-state sensors are usually more reliable that mechanical sensors, since they do not have moving parts, but have the drawback of a response dependent on the reflectivity of the surface in the IR spectrum and a dead-band in the response.

Contact and Proximity Sensors

Mechanical switches, called *bump sensors*, are commonly used for detecting when the robot gets in contact with obstacles. Bump sensors are cost-effective solutions providing the ability to stop the robot without damaging the obstacle. Touching obstacles is not desired unless performed very gently to ensure that the robot goes under curtains and bed skirts. IR and sonar sensors are frequently employed as touchless alternatives to the bump sensors by measuring the distance to obstacles. Both types of sensors are composed of an emitter and a receptor with an output proportional to the measured distance. IR sensors are usually more focused than sonars and less sensitive to multiple reflections on walls and other obstacles, but might lose thin obstacles such as chair legs. This type of sensors provides a point-wise measurement of distance to obstacles, so a robot needs a number of these sensors to obtain a dense representation of the obstacles in the environment. The information on obstacles and hazards (cliffs) is collected in occupancy grid maps and used for decision-making in systematic cleaning robots. A number of cost-effective dense distance measuring sensors have recently appeared in the market and will be discussed in the next sections. These dense distance measuring sensors have a cost on the order of tens of dollars, while the point distance measuring sensors have cost only a few dollars, so most of the domestic robots currently available on the market have yet to incorporate dense distance measuring sensors. The only exception is the Neato XV-21 that uses a low-cost laser distance measuring system.

Laser Distance Sensor

A low-cost Laser Distance Sensor was developed by Konolige and colleagues [65.5] using a laser point beam and a global shutter CMOS imaging sensor separated by a small baseline. The system operates by triangulation and achieves full 360 planar scan by rotating the optical assembly on a full circle. The sensor has a range of 0.2 to 6 m with an error < 3 cm at 6 m and an angular resolution of 1 degree, providing 4000 readings per second (up to 10 Hz) with a small size (approximate width of 10 cm shown in Fig. 65.14a) and low power (< 2 W). The sensor is eye safe and provides measurements that enable laser-based SLAM as shown by Fig. 65.14b.

Structured-Light Distance Sensors

Structured-light distance sensors consist of an emitter that projects a known pattern on the environment and a receptor that computes depth based on the deformation of the received pattern. The Kinect [65.6] interface to the Xbox game system uses a structured-light sensor from PrimeSense [65.7] thus showcasing the readiness of this sensor for consumer applications. The emitter consists of a laser with optics that projects a known pattern (Speckles [65.8, 9]) in near-IR light and a complementary metal-oxide-semiconductor (CMOS) IR camera that observes the pattern to estimate depth using triangulation. The emitter and the camera are calibrated during manufacturing assuming a rigid configuration. The speckles can be further shaped into ellipsis using optics with different focal lengths in x and y so that the orientation of the observed ellipsis is proportional to depth. Speckles of different sizes are used to obtain different depth accuracy depending on size. Figure 65.15a shows the speckles pattern projected by the sensor and an image taken in the dark by photographer Audrey Penven showing the IR speckles. Figure 65.15b shows the components of the Kinect sensor and the corresponding RGB and depth images of a scene.

Time of Flight (TOF) Distance Sensors

Time of flight (TOF) sensors consist of a light source (usually a laser) that emits a continuous waveform and a special imaging sensor that measures the phase shift of the received signal in each pixel. The depth at each pixel is proportional to the phase shift. TOF sensors have been in the market for quite some time, but the need for allocating a large portion of the sensor to the decoding electronics has made it challenging to produce low-cost sensors at reasonable resolution. Some of the companies offering TOF sensor have been Mesa Imaging AG that produces the SwissRanger [65.10] sensors, Softkinetics [65.11], PMDVision.

Stereo Vision

Stereo vision is a well-known computer vision solution to the extraction of three-dimensional (3-D) depth maps in areas with sufficient texture to find image correspondences. As opposed to structured light or TOF sensors, stereo vision systems are totally passive, but require a calibrated stereo rig, and their performance depends on the level of external illumination and on the amount of texture present in images.

The selection of the optimal dense mapping sensor depends on the application. The laser distance sensor provides reasonable information for laser-based SLAM and obstacle detection and avoidance; however, it only provides range information on a plane as opposed to the dense 3-D range offered by the structured light, TOF, or stereo systems. The structured light sensor uses a simple imaging sensor but requires additional computation to estimate depth in each pixel while the TOF sensor computes depth in each pixel at the expense of a sensor with lower fill factor. The stereo system does not require additional lighting, but requires an additional camera and a computation module to extract depth. Other parameters to consider are the maximum and minimum range that the sensor provides to ensure that it fits the requirements of the application in terms of mapping and obstacle detection.

65.2.2 Localization and Mapping

A robot that knows its location and understands its surroundings is able to plan intelligent maneuvers to achieve its goals. Localization and mapping are basic primitives that enable smart and efficient behavior. Early successful robots like the Roomba chose to sacrifice localization and mapping in order to achieve an appealing retail price since the localization and mapping technology was either too expensive or not existent at the time (many of the dense sensors presented in the previous section were developed after the Roomba). In recent years, a number of low-cost, yet powerful simultaneous localization and mapping (SLAM) technologies have been developed and integrated in floor-care products. These technologies are described in the following sections.

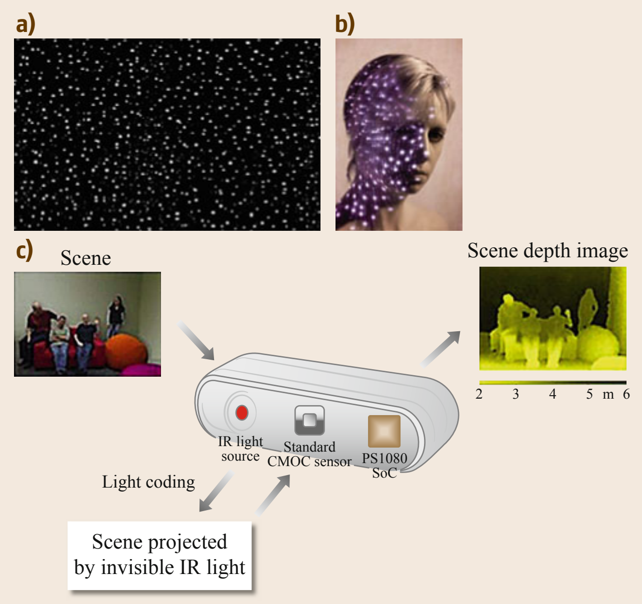

Fig.65.15a–c Primesense sensor: **(a,b)** Speckles pattern projected by the laser emitter. **(c)** Block diagram of the Kinect sensor

Vector Field SLAM

The Mint robot by Evolution Robotics uses active beacons for localization. The Northstar beacon projects two IR spots onto the ceiling that are modulated to simplify the detection of the spots with the sensor. The spots are invisible to the human eye and thus do not produce visual clutter. While placing the beacon can still be regarded as a modification to the environment, surveys among our customers suggest that the vast majority largely accepts setting up the beacon prior to running the robot [65.12]. The Northstar sensor uses 3 photodiodes to compute the direction to the spots from the measured current through the photodiodes. The photodiodes can be sampled at high frequency to detect the modulated spot frequencies for data association. The sensor is quite inexpensive and suitable for cost-sensitive applications. However, the sensor suffers from multipath since light not only reaches the sensor directly but also through reflections from walls and other furniture, making the position computed by the sensor inadequate to be directly used for localization and mapping. The sensor is augmented with a localization method that learns the light distribution in the room through a simultaneous localization and mapping (SLAM) approach [65.13]. Figure 65.16 shows the Mint robot cleaning the environment depicting the operation of the Northstar localization system and the problem of multipath. The figure also shows the Mint robot and the Northstar cube and the Northstar sensor.

In vector field SLAM the spatial variation of continuous signals is learned and simultaneously used for localizing the robot by fusing information from dead-reckoning (odometry and gyro) and Northstar. In the following, this method is introduced and tailored toward measurements obtained from Northstar. The signal field is represented as a regular grid of fixed node positions $b_i = (b_{i,x}, b_{i,y})^{\mathrm{T}}$, $i = 1 \ldots N$, where each node $m_i \in R^4$ holds the expected Northstar positions of both spots when placing the robot at b_i and pointing it in a fixed orientation $\theta_0 = 0$. Vector field and robot pose are then estimated through the application of SLAM.

Let the robot path be a time series of poses $x_0 \ldots x_{\mathrm{T}}$, $x_t \in \mathrm{SE}(2)$, i. e., the set of rigid transformations in the horizontal plane, and let $x_0 = (0, 0, 0)^{\mathrm{T}}$. At each time step $t = 1 \ldots T$ the robot receives a motion input u_{t} with covariance R_{t} and a measurement $z_t = (z_{x1}, z_{y1}, z_{x2}, z_{y2})^{\mathrm{T}}$ of the two Northstar spot positions with covariance Q_t. The spot positions are also each affected by the rotational variability denoted $c = (c_x, c_y)^{\mathrm{T}}$. The rotational variability models errors in measuring the direction to the spots caused by not having the sensor perfectly level.

The SLAM problem is solved with the ESEIF-SLAM that is constant time and requires memory linear in the size of the area explored by the robot. The method has been implemented in the processor of Mint, an ARM 7 processor with 64 kByte RAM [65.13]. Vector field SLAM has been extended to address covering larger areas by using more Northstar beacons [65.15] and to provide a solution for the re-localization of the robot after it has been kidnapped or paused and resumed [65.16].

Figure 65.18 presents the map obtained by the robot after a cleaning run in a home environment of 125 m^2 covered by three Northstar beacons marked with the pink and green disks (units are in meters). The robot navigated in the home by following a cleaning strategy based on systematically covering sectors of the environment. As long as at least one beacon is visible to the robot, the strategy moves the robot onto a neighboring region until no space is left to clean. At the end the robot follows along the perimeter of detected obsta-

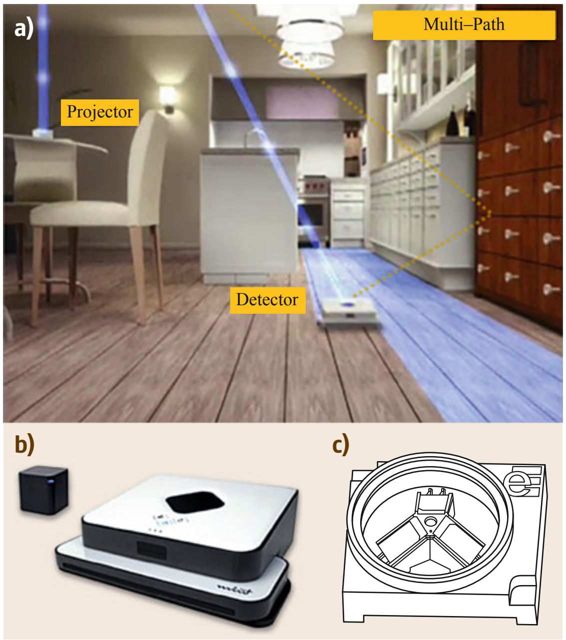

Fig. 65.16a–c Mint robot. **(a)** Normal operation of the Mint robot using Northstar (the *yellow path* indicates multipath). **(b)** Mint robot and Northstar cube. **(c)** Northstar sensor

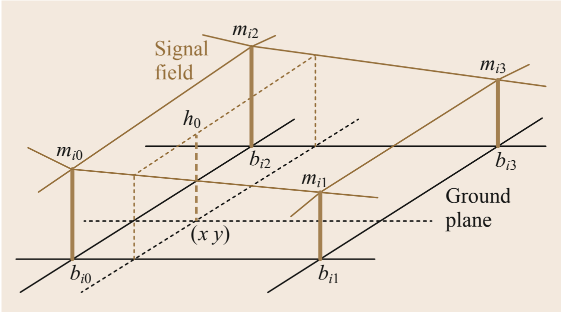

Fig. 65.17 Vector field SLAM with Northstar

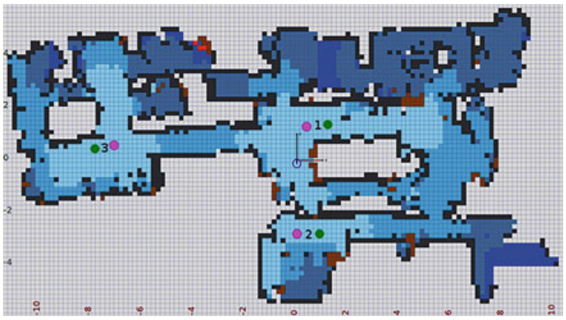

Fig. 65.18 Robot map obtained with vector field SLAM in a 125 m^2 home environment

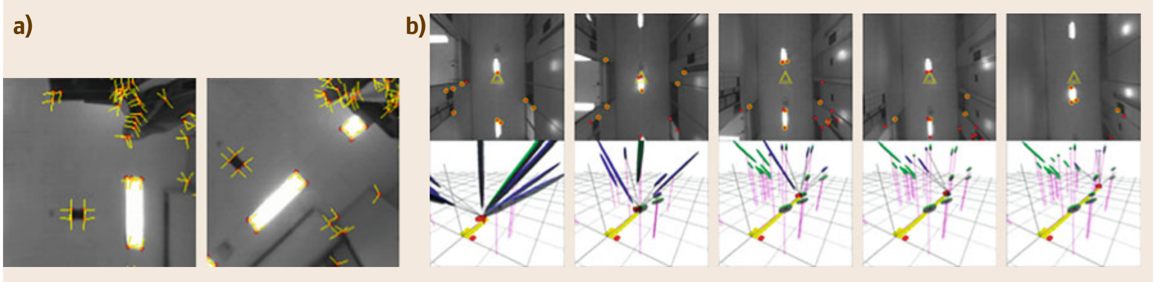

Fig. 65.19 (a) cv-SLAM (after [65.14]). **(b)** Features extracted by the vision front-end. Map obtained with the EKF

cles for a thorough cleaning around walls and furniture. As the robot moves through the environment it creates an occupancy grid map using the position information from localization. Each visited cell is classified into one of the following categories: obstacles (drawn in black), floor changes (drawn in brown), hazards (drawn in red), and free space (drawn in shades of blue that indicate visibility of the spots, the lighter the blue, the better the visibility).

Visual SLAM

Visual localization and mapping is attractive for a variety of applications due to the rich input and the low cost and footprint of visual sensors. The difficulties lie in robustly extracting a critical subset of information from the high-rate visual data stream and processing it efficiently to yield useful output. Despite steady increases in the computational power of most platforms, such challenges are nonetheless exacerbated by the limited processing and storage provided by low-cost, embedded systems appropriate for low-power applications or consumer products. Many state-of-the-art approaches to visual SLAM depend on a per-frame processing rate sufficiently high, relative to the speed of camera motion, to permit strong temporal assumptions on the image sequence. This section reviews two approaches to visual SLAM focused on domestic robots. Ceiling vision similar to the work of *Jeong* and *Lee* [65.14] can be found in the Navibot from Samsung, the Roboking from LG, and the Iclebo/Homerun from Yujin Robotics/Philips. Furthermore, visual SLAM systems have been developed for low-cost and embedded systems [65.17, 18].

cv-SLAM

The ceiling vision SLAM [65.14] system is composed of a camera facing upward, looking toward the ceiling. The system extracts corner features using a Harris detector and matches features using correlation. Feature matching achieves invariance to view point changes by training a set of multiview descriptors of the features as matching proceeds during the run. The main orientation(s) of the feature are further used as descriptors of the feature to ensure a two-dimensional (2-D) rotation invariant feature matching that can be used for relocalization. The localization and mapping backend of the system is based on an extended Kalman filter (EKF) that fuses visual and dead-reckoning information (odometry and gyro) and that tracks the pose of the robot in a two-and-a-half-dimensional (2.5-D) (x, y, θ) and the 3-D position of the features (landmarks of the map). The orientation(s) of the features are also represented in 3-D and tracked with the EKF to predict changes in the feature patch due to motion of the robot (as the robot moves, features on the ceiling will undergo a rotation while features on the walls will experience a shearing transformation in addition to rotation).

Figure 65.19a shows corner points and their estimated orientations in views with rotation only. Figure 65.19b presents snapshots from a sequential map-building experiment on a corridor.

vSLAM

The vSLAM [65.17, 18] system from Evolution Robotics is designed for a low-cost robotic platform equipped with simple odometry and a single camera. Figure 65.20 shows the block diagram of the system. Operating primarily as a view recognition engine, the visual measurement front-end requires only occasional, weak assumptions on processing rate, and intrinsically provides robust loop closing when previously mapped areas are revisited. The visual measurements and odometry are fused in the back-end in a graph representation and optimized incrementally. The SLAM graph complexity is bounded during operation using variable elimination and constraint pruning, with heuristic schedules in order to keep optimization and storage costs commensurate with explored area, rather than with time of exploration, all while causing minimal loss in mapping and localization accuracy. The system has been evaluated on real datasets with planar ground-truth reference, showing that the system operates successfully even at frame rates below 2 Hz, running on an ARM9 processor with 64 MB of RAM [65.18].

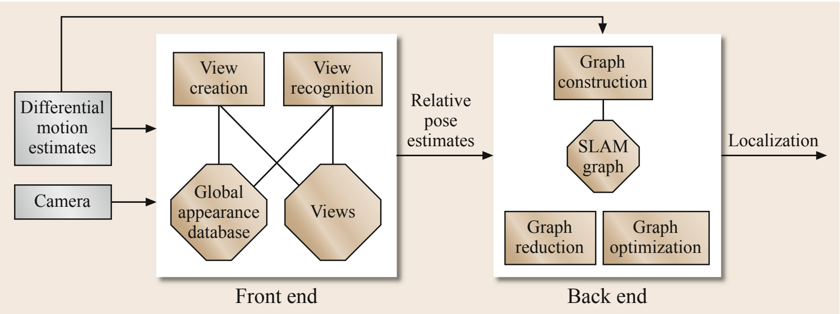

Fig. 65.20 vSLAM block diagram

View recognition engines [65.17–22] have proven attractive components for SLAM systems because they permit robust and flexible loop closing. Instead of making correspondences between individual features or measurements as in the cv-SLAM system, view recognition engines typically match constellations of features or entire images, without requiring tracking. vSLAM [65.17] creates views by first matching SIFT [65.23] features on pairs of incoming images, and second computing structure and motions estimates using bundle adjustment. The SIFT features are stored in a local database for each view and on a global database for the complete map. View recognition is performed by a feature lookup in the global database that provides a set of candidate view matches. Feature lookup in the local view database followed by robust outlier rejection and a local bundle adjustment completes the view recognition and visual pose estimation process.

Commonly used graph SLAM methods for agglomerating sensor information often incur computation and storage costs that grow with time, rather than with space explored. For a robot operating for extended periods within a limited spatial area – typical of practical applications – this is an undesirable trade-off. vSLAM [65.18] instead applies probabilistically sound graph reduction methods that limit the complexity of the graph to a linear factor of the complexity of the explored space. Past poses of the robot that are not used for view recognition can be marginalized out of the estimation, and their incident constraints are collapsed back into the graph.

Figure 65.21 presents the results of running the vSLAM system in two sequences, one collected in a regular household (*right*) (same house as the one shown in Fig. 65.18 for vector field SLAM) and the other collected in a large warehouse environment (*left*). The first set of plots show the ground truth path of

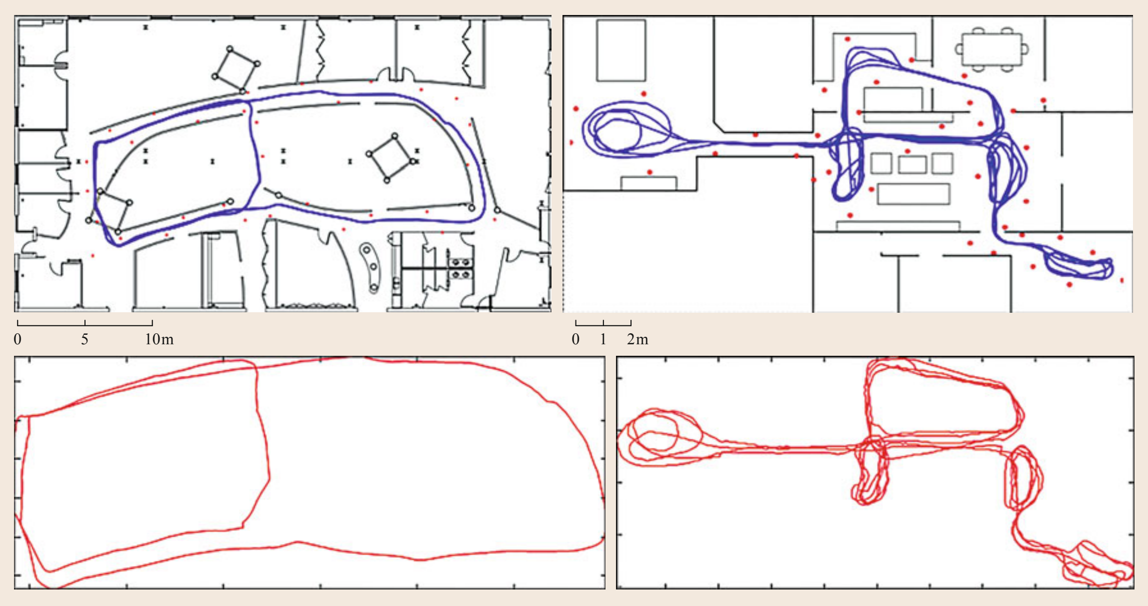

Fig. 65.21 vSLAM results on a warehouse environment and in a household environment

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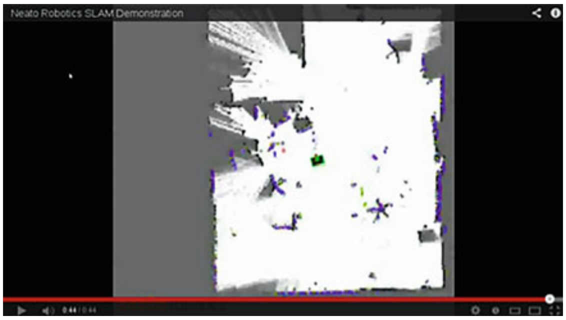

Fig. 65.22 Map created with the Neato XV-11 robot (www.youtube.com/watch?v=zodC8EFvh7g)

the robot and the floor plan of the environments. The second set of plots shows the trajectory of the robot estimated with vSLAM. The warehouse environment extends over an area of 24×12 m and the house over an area of 20×9 m. The estimated trajectory has a root mean square (RMS) error of 44 cm in the warehouse case and of 28 cm in the household case.

Laser-Based SLAM

The previous sections presented a number of low-cost solutions to the SLAM problem in which the data association was (almost) perfect. In the case of Vector-Field SLAM, the modulation of the spots of the Northstar cube ensures a unique identification of the spot. In the case of visual SLAM, the visual front-end incorporates a number of checks to ensure that misrecognitions are very rare. Laser-based SLAM has the characteristic that the measurements acquired with the laser are not unique since it is possible to obtain similar measurements in a variety of places in a household (just aiming the laser to a wall will provide measurements that are indistinguishable from a measurement to a different wall). In addition to the data association problem, laser distance measurement sensors, such as the one presented in Sect. 65.2.1, provide both range and bearing to the landmarks. Both Northstar and cameras give only bearing measurements to the spots or features.

The laser-based SLAM literature is quite extensive [65.25]. The estimation back-end could be an extended Kalman filter (EKF), a Particle Filter, or a GraphSLAM system. Several data association algorithms are available, some of them are proactive (or even greedy) [65.26, 27] and some are lazy [65.28] in assigning correspondences between measurements and landmarks. The selection of the algorithm to implement in the domestic robot would be guided by the trade-off between computational resources and the performance requirements. Figure 65.22 presents a map obtained with the Neato XV-11 robot.

65.2.3 Navigation and Coverage

The Trilobite robot vacuum cleaner by Electrolux was one of the pioneer robots to be commercialized. The trilobite was equipped with a sophisticated custom sonar sensor system that allowed the robot to navigate without touching obstacles (or touching them very gently). The coverage strategy consisted of two stages: first, explore the perimeter of the room to estimate the area to clean and second, cover the room with wall-to-wall diagonal passes. The perimeter exploration stage assumes that the robot would eventually traverse through the complete boundary of the area to clean and return to the charging station (Fig. 65.23a).

As mentioned previously, the cost constraints forced early robots like the Roomba to eschew advanced features like localization and mapping in order to offer a product at a price point accepted by consumers. Nevertheless, the navigation strategy implemented in the Roomba was quite effective in covering the space, especially when running in single rooms or in presence of large amount of clutter. The Roomba uses a spiral pattern in open area to optimally cover the space without localization until it hits an obstacle (Fig. 65.23b). Then it selects random orientation and continues moving in straight line until reaching the next obstacle where it selects another random orientation to continue with the same behavior. The spiral can be triggered when the robot travels for a certain distance without having found any obstacles. Many of the other random robots present in the market have a strategy that follows similar principles to the Roomba one.

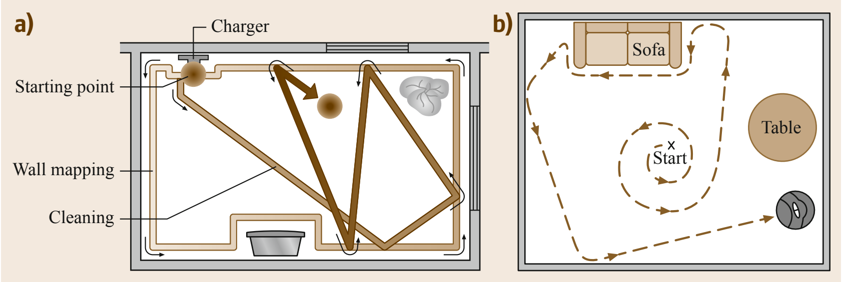

Fig. 65.23a,b Coverage strategies. Trilobite strategy. Roomba strategy [65.24]

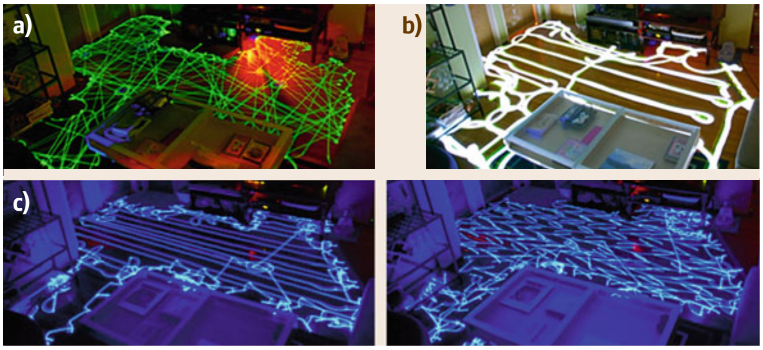

Fig. 65.24a–c Long exposure images [65.29] showing the coverage strategies of the **(a)** Roomba, **(b)** Neato, and **(c)** Mint

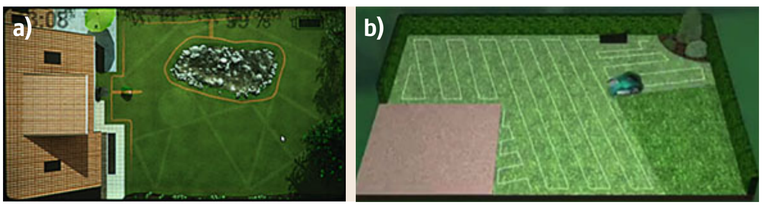

Fig. 65.25a,b Coverage strategies for lawnmowers. **(a)** Tango [65.30] by John Deere and **(b)** Indego [65.31] by Bosch

The systematic robots on the other hand take advantage of the localization system to plan efficient cleaning paths to maximize coverage in the least amount of time, pause for charging on the docking station and resume cleaning from the last cleaned spot, and intelligently navigate from room to room. Mint takes the strategy of focusing first on open area cleaning, covering the space in parallel straight passes to traverse as much open space as fast as possible, and then performing a final cleaning on the perimeter and around the obstacles. This perimeter cleaning step enables Mint to uncover portals to new areas that were not encountered during open area cleaning. Other robots like the Navibot from Samsung, the Roboking from LG and the iClebo from Yujin/Philips use a similar strategy without the final perimeter cleaning. The Neato XV-11, on the other hand, performs first an exploration and cleaning of the perimeter of the environment in order to create a good localization map and then completes the coverage of the open area. Figure 65.24 shows long exposure pictures of different robots: Roomba, Neato, Mint sweeping and Mint mopping. These long exposure pictures show the trajectory of the robots during normal cleaning operation.

The lawnmower robots use similar coverage strategies to the ones of vacuum cleaner robots. One element common to all lawnmower robots is the usage of an embedded wire to define the perimeter of the lawn. Within the boundaries defined by the wire, some robots like the Automower from Husqvarna or the Robomow from Friendly Robotics use a complete random coverage strategy. The Tango from John Deere combines straight motions in random directions with spiral motions (a-la-Roomba). The Indego from Bosch is the only robot that attempts to systematically cover the space by first exploring the perimeter to estimate the size of the lawn and then traversing the interior with parallel straight passes. Systematic coverage is enabled by fusing sensory information from wheel odometry and an inertial measurement unit (IMU) by means of probabilistic reasoning with prior knowledge. Figure 65.25 depicts the coverage strategies of the Tango and the Indego.

65.3 Smart Homes

Several attempts have been made in the literature to define the term smart home, for example, in [65.32] the term is defined as the *the latest expression of the various ways in which technology in the home has developed*. In [65.33], the notion of a smart home is defined more explicitly as:

> *a residence equipped with computing and information technology which anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through management of technology within the home and connections to the world beyond.*

Smart homes typically comprise elements such as network of sensors and actuators, and also entire robotic systems.

In 1999, a company called e2 Home was established by Ericsson and Electrolux to explore the possibilities of smart homes [65.34]. E2 Home built several houses with smart home devices using IT technologies. Through the exploration, several issues relating to smart homes from business point of view have been unveiled, which include the difficulties relating to the complexity of the system, starting up the new business model, handling of intellectual property rights (IPR) for the third parties contents, and the consumer's needs. The company was liquidated in 2004.

Current smart home technology includes video monitoring, motion detectors, fall detectors, pressure mats, environment control, health monitoring such as blood pressure, pulse rate, body temperature, weight, and human computer interaction (HCI) technology, for example, to recognize gestures. Smart homes also often refer to houses connected to a smart grid, which is defined as [65.35]:

> *a developing network of new technologies, equipment, and controls working together to respond immediately to our 21st century demand for electricity.*

In this case, the smart home is defined as [65.35]:

> *a residence with the capability of efficiently controlling generated solar energy and power consumption making it ideal for vehicle power supply and management.*

The development of smart homes requires a number of technical questions and challenges to be addressed [65.32]: how to convert current home structures and architectures into smart homes, how to standardize smart home components, for example, sensor networks, how to keep the equipment cost at a reasonable level, and how to deal with security and privacy issues.

In the following sections we will describe a number of prominent smart home developments, the Aware Home at Georgia Institute of Technology, the Gator Tech Smart House at the University of Florida, and the sensorized environment for life (SELF) at AIST (the Japan National Institute of Advanced Industrial Science and Technology) (Figs. 65.26, 65.27). These developments show that current smart home technology goes significantly beyond existing home automation. Accounting for the significant increase in the elderly population in the near future, many of today's smart home developments pay special attention to improving the quality of life of elderly people. The descriptions below will also address the question on how to integrate robotics systems into smart home concepts.

65.3.1 Gator Tech Smart House

The Gator Tech Smart House (Fig. 65.26) was built at the University of Florida [65.36]. It addresses the needs of elderly people to live independently and maintain dignity and quality of life at older ages. The house is equipped with many smart devices such as smart floors, tracking the motion of the occupants of the house, smart blinds, automatically adjusting ambient light, smart display, smart cameras, smart phones that can act as a remote control to other appliances, location tracking, smart leak detectors, and smart beds. The exterior of the house has a smart mailbox which alerts residence if mail is delivered and a smart front door which can sense home owners using an radio frequency identification (RFID) tag, allowing keyless entry to home owners.

The kitchen of the Gator Tech Smart House includes a smart microwave, which uses RFID on food packages. This allows the microwave to adjust the settings for cooking the meal. It also informs the resident about the readiness of the meal. The kitchen further comprises a smart refrigerator that monitors food availability and consumption, and detects expired food items. The smart refrigerator can create shopping lists automatically and has an integrated meal preparation advisor based on items in the refrigerator and pantry.

The implementation of such a complex system has raised a number of technical issues and questions, including the development of the smart devices, data handling of networks of sensors, and interconnecting smart devices to other devices in the environment. These questions led to some new research tracks on smart houses, primarily grouped into pervasive computing and mobile computing network research.

Fig. 65.26 Georgia Institute of Technology: Aware Home

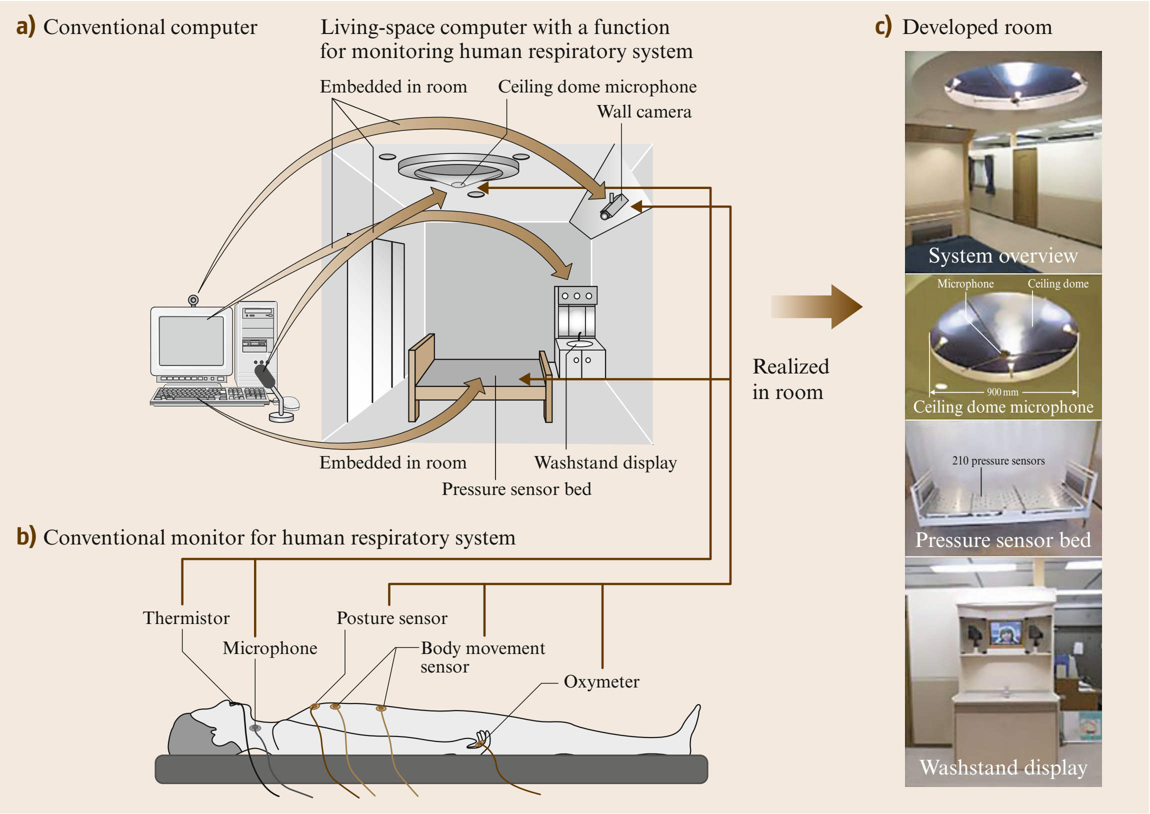

Fig. 65.27 AIST, the sensorized environment for life

65.3.2 Aware Home

Aware Home is a living laboratory for research in ubiquitous computing for everyday activities. This project is conducted at Georgia Institute of Technology [65.37]. The major objective of the Aware Home project is to build an environment that is capable of being aware and keeping track of the states and activities of its inhabitants. Aware Home creates a partnership between the resident and the surrounding sensing and computing technologies. This opens several fields of research, not only from the technology point of view, but also in terms of the social aspects of the inhabitants. The main research agenda of Aware Home spans human-centered and technology-centered research, software engineering, and social implications.

Technology and application-centered research focuses on sensor networks, distributed computing, context awareness and ubiquitous sensing, individual interaction with the home, smart floors, and finding lost objects. Research on context awareness is inspired by the fact that humans communicate with each other very success-fully by referring to what is called shared context. For communication between humans and computer systems, this shared context must be made explicitly. Sensor systems, which facilitate the extraction of context, need to be developed.

This human-centered research focuses on support for the elderly and other social issues. A key concept in sup-porting the elderly is *aging in place*. Aware Home is designed to support the elderly and allow them to be independent instead of moving to elderly care facilities. Supporting the elderly leads to the study on cognitive support such as reminding them when to take medication, guiding them when they lose their way, and locating lost items.

65.3.3 SELF – Sensorized Environment for LiFe

SELF stands for Sensorized Environment for LiFe [65.1]. The objectives of SELF are to develop a network of sensors which are embedded in the environment, information gathering using the networked sensors, storing and analyzing the information, and the reporting of useful information to assist and maintain good health. The basic advantages of SELF, due to the embedded nature of the sensors are:

1. No limit on size, weight, or power source,
2. It does not disturb the human,
3. It does not impose physical restrictions, and
4. Sensors are rarely broken since they are fixed to the environment.

SELF can be viewed as a system that monitors a person's behavior or activity and represents the data objectively in an approach known as self-externalization. SELF is motivated by the fact that humans sometimes cannot notice a change in their condition which affects their health without a medical doctor. Therefore, the use of network sensors to monitor human behavior and report useful information that greatly affects the health status will further improve quality of life.

The SELF study considers behavior as a means of communication, and sensors embedded into the environment as one way to observer a person's behavior. The SELF implementation consists of a bed with a sensor, a ceiling with microphones, a washstand with a display, etc. The bed with sensors can determine the time the subject sleeps and wakes up, their posture during sleeping, and their breathing pattern. The microphones attached to the ceiling can detect snoring or normal breathing sounds. Based on the monitored data, the washstand display is used as an output device to provide the subject's health status and thus create feedback to the subject.

Video-References

VIDEO 727 Robotic Vacuum Cleaners Reviewed by Click – Spring 2014
available from http://handbookofrobotics.org/view-chapter/65/videodetails/727
VIDEO 729 How would you choose the best Robotic Vacuum Cleaner?
available from http://handbookofrobotics.org/view-chapter/65/videodetails/729
VIDEO 731 Husqvarna Automower versus competitors
available from http://handbookofrobotics.org/view-chapter/65/videodetails/731
VIDEO 734 Windoro window cleaning robot review
available from http://handbookofrobotics.org/view-chapter/65/videodetails/734
VIDEO 735 WINBOT W710 versus HOBOT 168
available from http://handbookofrobotics.org/view-chapter/65/videodetails/735
VIDEO 736 Winbot window cleaning robot
available from http://handbookofrobotics.org/view-chapter/65/videodetails/736
VIDEO 737 Serbot Robot Clean Ant Profi
available from http://handbookofrobotics.org/view-chapter/65/videodetails/737
VIDEO 739 Home Pool Cleaner Review – 5 types of robotic cleaners
available from http://handbookofrobotics.org/view-chapter/65/videodetails/739
VIDEO 740 Automatic pool cleaner reviews
available from http://handbookofrobotics.org/view-chapter/65/videodetails/740
VIDEO 741 Telepresence robot in action
available from http://handbookofrobotics.org/view-chapter/65/videodetails/741
VIDEO 742 Double robotics – overview
available from http://handbookofrobotics.org/view-chapter/65/videodetails/742
VIDEO 744 Test-Driving Beam, the telepresence robot
available from http://handbookofrobotics.org/view-chapter/65/videodetails/744
VIDEO 745 Beam's new Palo Alto store lets telepresence robots sell themselves. Literally
available from http://handbookofrobotics.org/view-chapter/65/videodetails/745
VIDEO 746 This robot is your running coach – Joggobot
available from http://handbookofrobotics.org/view-chapter/65/videodetails/746
VIDEO 747 RUFUS – your personal running coach
available from http://handbookofrobotics.org/view-chapter/65/videodetails/747
VIDEO 748 PhillieBot robot gives first pitch at a Phillies game
available from http://handbookofrobotics.org/view-chapter/65/videodetails/748

References

65.1 P. Ljunggren: Intelligent machines, Personal Communication
65.2 R.D. Schraft, M. Hägele, K. Wegener: *Service-Roboter-Visionen* (Hanser, Munich 2004)
65.3 A. Albert: Robert-Bosch GmbH, Personal Communication
65.4 Howstuffworks: http://electronics.howstuffworks.com/gadgets/home/robotic-vacuum2.htm

65.5 K. Konolige, J. Augenbraun, N. Donaldson, C. Fiebig, P. Shah: A low-cost laser distance sensor, Proc. Int. Conf. Robotics Autom. (ICRA), Pasadena (2008)
65.6 Gearfuse: http://www.gearfuse.com/robotic-vacuum-paths-mapped-and-compared-with-long-exposure-pictures/
65.7 P. Ridden: Joggobot turns a quadrocopter into a running companion, Gizmag, June 11 http://www.gizmag.com/joggobot-autonomous-quadrocopter-running-partner/22899/ (2012)
65.8 B. Freedman, A. Shpunt, J. Arieli: Distance-varying illumination and imaging techniques for depth mapping, US Patent 29 0698 (2010)
65.9 A. Shpunt, A. Zlesky: Depth-varying light fields for three dimensional sensing, US Patent 2008/10 6746 (2008)
65.10 Microsoft (Xbox): http://www.xbox.com/en-US/KINECT
65.11 Apple (Primesense): http://www.primesense.com/
65.12 J.-S. Gutmann, K. Culp, M. Munich, P. Pirjanian: The social impact of a systematic floor cleaner, ARSO Munich (2012)
65.13 J.-S. Gutmann, E. Eade, P. Fong, M. Munich: Vector field SLAM – localization by learning the spatial variation of continuous signals, Trans. Robotics **28**(3), 650–667 (2012)
65.14 W. Jeong, K. Lee: CV-SLAM: A new ceiling vision-based SLAM technique, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (2005)
65.15 J.-S. Gutmann, D. Goel, M. Munich: Scaling vector field SLAM to large environments, Proc. IAS, Jeju (2012)
65.16 J.-S. Gutmann, P. Fong, M. Munich: Localization in a vector field map, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (2012)
65.17 N. Karlsson, E.D. Bernardo, J. Ostrowski, L. Goncalves, P. Pirjanian, M.E. Munich: The vSLAM algorithm for robust localization and mapping, Proc. Int. Conf. Robotics Autom. (ICRA) (2005)
65.18 E. Eade, P. Fong, M. Munich: Monocular graph SLAM with complexity reduction, IROS (2010)
65.19 M. Cummins, P. Newman: Accelerated appearance-only SLAM, Proc. Int. Conf. Robotics Autom. (ICRA), Pasadena (2008)
65.20 E. Eade, T. Drummond: Monocular slam as a graph of coalesced observations, Proc. 11th IEEE Int. Conf. Comput. Vis. (ICCV'07), Rio de Janeiro (2007)
65.21 E. Eade, T. Drummond: Unified loop closing and recovery for real time monocular slam, Proc. Br. Mach. Vis. Conf. (BMVC'08) Leeds (2008) pp. 53–62
65.22 K. Konolige, J. Bowman, J.D. Chen, P. Mihelich, M. Calonder, V. Lepetit, P. Fua: View-based maps, Proc. Robotics Sci. Syst. Seattle (2009)
65.23 D.G. Lowe: Distinctive image features from scale-invariant keypoints, Proceedings IJCV (2004)
65.24 Pmdtechnologies GmbH: http://www.pmdtec.com/
65.25 S. Thrun, W. Burgard, D. Fox: *Probabilistic Robotics* (MIT Press, Cambridge 2005)
65.26 J. Neira, J. D. Tard os: Data association in stochastic mapping using the joint compatibility test, IEEE Trans. Robotics Autom. **17**(6), 890–897 (2001)
65.27 S. Thrun, D. Fox, W. Burgard: A probabilistic approach to concurrent mapping and localization for mobile robots, Mach. Learn. **31**, 29–53 (1998)
65.28 D. Hähnel, S. Thrun, B. Wegbreit, W. Burgard: Towards lazy data association in SLAM, Proc. 11th Int. Symp. Robotics Res. (ISRR), Sienna (2003) pp. 421–431
65.29 John Deere: http://www.deere.com/wps/dcom/en_INT/products/equipment/autonomous_mower/autonomous_mower.page
65.30 Robert Bosch GmbH: http://www.bosch-indego.com/
65.31 E. Prassler, K. Kosuge: Domestic robotics. In: *Springer Handbook of Robotics*, ed. by B. Siciliano, O. Khatib (Springer, Berlin, Heidelberg 2008) pp. 1253–1281
65.32 D. Gann, J. Barlow, T. Venables: *Digital Futures: Making Homes Smarter. Report published by Chartered Institute of Housing* (Chartered Institute of Housing, Coventry 1999)
65.33 R. Harper: *Inside the Smart Home* (Springer, London 2003)
65.34 Japan Electronics and Information Technology Industries Association: http://www.eclipse-jp.com/jeita/
65.35 Gator Tech Smart House: http://www.icta.ufl.edu/gt.htm
65.36 Aware Home Research Initiative: http://www.awarehome.gatech.edu/
65.37 T. Hori, Y. Nishida, T. Suehiro, S. Hirai: SELF-Network: Design and implementation of network for distributed embedded sensors, IEEE/RSJ Int. Conf. Intell. Robots Syst. IROS (2000)