54. Domestic Robotics

Erwin Prassler, Kazuhiro Kosuge

Who would not want to have a robot at home that vacuums the house, cleans the kitchen or the bathroom, loads or unloads the dishwasher, or polishes the shoes? In spite of the hundreds of millions of potential customers and users surprisingly few such robots exist. In this chapter, we first look into what it means not only to develop but also to commercialize a domestic robot. Using domestic cleaning robots as a representative example we look into the task details and its context. We also discuss the economic context and the market situation, and the technical challenges which slow down the triumphal procession of domestic robots. We will then have a look at the latest developments of domestic floor cleaning robots, robotic pool cleaners, and window cleaning robots. The survey of domestic cleaning robotics concludes with an outlook to new technologies that might help to solve some of the problems discussed at the beginning. The subsequent section then gives an account on the state of the art in robotic lawn mowing. The Section *Smart appliances* briefly surveys the latest developments in ironing robotics, intelligent refrigerators, and digital wardrobes. The Section *Smart homes* looks into a selection of ongoing and completed research projects in the field of smart environments and smart homes.

The section *Domestic robotics: It is the business case that matters* finally concludes with a contemplation of the market situation for domestic robots, business models, and some crucial insights into the commercialization of service robots.

The dream of having a robot in everybody's home is as old as the word *robot* itself. In Karel Capek's famous play *Rossums Universal Robots* there was already a commercial (poster) advertising for a personal robot: " . . . Cheap labor. Rossum's Robots. Robots for the tropics. 150 dollars each. Everyone should buy his own robot. Do you want to cheapen your output? Order Rossum's Robots."

Vacuuming the house, cleaning the kitchen and the bathroom, cleaning up the chaos in the children's playroom, loading and unloading the dishwasher or the laundry machine, polishing the shoes, doing the ironing, stowing away the content of the shopping basket: the list of applications of robots in our homes seems endless. So the question seems appropriate: where are all these smart mechanical helpers that can take care of all these unpleasant tasks? Isn't there a huge market for such devices? Almost everybody would buy one.

There is good news and there is bad news regarding these questions. The good news is: domestic robots are coming. The bad news is: they are coming very slowly, some of them may be more expensive than many people would like, and most of them will not be the 100% substitute of a robot housemaid or butler, which everybody would like to have.

In this chapter, we will present the state of the art in domestic robotics. We will describe some of the most recent developments in domestic cleaning robotics and a number of other smart appliances, including robotic lawn mowing, ironing robots, and digital wardrobes. We also include a section on smart homes. This may be considered as a borderline area of domestic robotics. However, since smart homes often use sensor, actor, and communication technologies which are very similar to that in *regular* domestic robotics, it is certainly more appropriate to include this topic rather than to exclude it.

Ideally, we would not only present the latest developments in all of the applications and areas above, but also look deeper into the task context, the economic context and market situation, and the fundamental technical problems and challenges. Ideally, we would also identify the emerging key technologies for each of these areas. This may, however, get a bit out of hand and also lead to many redundancies. For example, the technical problems and challenges for domestic cleaning are not that different from the problems for robotic lawn-mowing. The same holds for the economic situation. So for the sake of a comprehensive treatment we provide a deeper investigation of these problems only for domestic cleaning robotics and confine ourselves to a report on the latest developments for the remaining applications.

Furthermore, since domestic cleaning robotics and robotics for professional cleaning are not entirely different subjects, we will try to provide a broader picture of the technical problems and the economic situation covering both areas. We will see that, especially for professional cleaning robots, the market analysis is somewhat easier to capture, since there are better statistics and more concise business models. Domestic cleaning and domestic robotics in general is still a bit of a gadget market, which is difficult to analyze and predict. So, the excursion to the professional application, while we are contemplating the more economic aspects of domestic and cleaning robotics, may be forgivable.

A discussion on the technology push, the market pull, and the pitfalls in which technology and business developers can easily be trapped concludes this chapter.

54.1 Cleaning Robots

54.1.1 The Task and Its Context

Task Analysis

On an abstract level, the task appears always the same: clean some workspace in the presence of obstacles. The instantiations of cleaning task, however, may differ significantly from environment to environment and from task context to task context. Assume, for example, the task is to clean a swimming pool. Most swimming pools have a rather simple geometric shape – most of them are rectangular – and hence the cleaning task is straightforward to automatize. Using odometry or some low-cost digital compass the pool cleaner should be able to sense and control its orientation and position. Area coverage is a matter of meandering between the walls at the bottom of the pool until the device is turned off or the battery is empty. Obstacle avoidance is mostly unnecessary in such a setting. Not surprisingly, automatically guided pool cleaners are well-established products, which have been on the market for many years. They are not always called robots though.

Now assume a large facility such as a shopping mall or a hospital or an airport with several floors, endless, narrow and cluttered hallways and with many people moving around. Cleaning such an environment is apparently a different story. The cleaning robot most likely has to face an arbitrarily structured and cluttered three-dimensional (3-D) environment extending over many rooms and possibly over many floors and levels. *Optimal* navigation and operation basically requires 3-D sensing and 3-D modeling. How else should the robot be able to account for 3-D obstacles and navigate in a collision-free manner. Also area coverage becomes significantly more difficult.

The operation and maintenance of large facilities such as airports, shopping malls, or hospitals often involves work flows with a very tight schedule. Often the facilities are large enough to employ a fleet of cleaning robots rather than just one. Fleet management and multirobot coordination are required for optimal execution of the cleaning task. This is even more so when time matters and cleaning has to take place within small time windows. So the use of cleaning robots in such facilities means more than just turning on an off the robots and charging the batteries. It requires a careful integration of the automated service into a sensitive set of work flows.

The above two instances clearly illustrate the variations between cleaning tasks, and at this point we have not even looked into the specific needs and requirements of the surface which needs to be cleaned. Carpet apparently needs to be treated in a different manner from hard floor coverings such as wood or stone. The former needs to be vacuumed or brushed while the latter often requires wet cleaning. Vacuuming requires a significant amount of energy, which makes autonomous vacuuming by battery-powered cleaning robots almost impossible for large areas, scrubbing requires less energy, however often entails heavier devices, since the robots may have to carry nonnegligible volumes of cleaning liquid and dirty water.

In the following we have tried to list some of the typical *dimensions* of a cleaning task:

- containment of work space (enclosed, open)
- *complexity* of work space (cluttered, uncluttered, narrow, wide, static, dynamic)
- scale of work space (small, medium, large)
- dimension (2-D, 3-D)
- surface structure and orientation (even, uneven, horizontal, vertical, slanted)
- cleaning requirements

Economic Context and Market Situation

According to a figure from 1995 [54.1] the professional cleaning services only in Europe total approximately USD 50 billion per year. It can be expected that this figure has further increased in the past 10 years. Of these USD 50 billion about 78%, or USD 39 billion, account for labor, while the remaining USD 11 billion cover equipment, material, and overheads. All in all professional cleaning is a huge market. If one could only automatize a small fraction of these services it would be a billion-dollar or billion-euro business. These figures do not include the domestic market. In Germany alone there are about 40 million households and each needs to be cleaned and in each there is a vacuum cleaner, which is replaced every 6–8 years. If only 15% of these vacuum cleaners would be replaced by a robotic vacuum cleaner there would be a market volume of 1 million units per year.

Engineers and business people realized this potential a long time ago and have been developing cleaning robots for almost 20 years now. Surprisingly we did not see many of those cleaning robots until recently. Apparently, there must have been some problems, which were not only of technical nature. We will discuss these in greater detail at the end of this chapter, after having presented what is out there already. It should be mentioned, though, that the situation changed significantly, when a little inexpensive device, more of a toy than a cleaning machine, named Roomba came onto the market in 2002.

54.1.2 Technical Challenges

Besides the economical challenge to identify meaningful business cases, the automation of cleaning by means of robots also poses a number of technical challenges. From a scientific point of view these challenges seem to be (almost) solved, but many solutions are not much more than proofs of concept. These theoretical solutions basically work under laboratory conditions but have not been subjected to industrial conditions or faced any extended field tests under real working conditions. Companies that want to develop products often have to reinvent those solutions and adapt them to industrial needs.

The following list gives a short overview of such technical challenges inherent in the design of cleaning robots for domestic as well as professional use. Since the majority of developments in cleaning robotics have been mobile robots for floor cleaning, the list below may be slightly biased towards this application.

- absolute positioning
- area coverage in unknown, dynamic environments
- sensor coverage for robust obstacle avoidance
- error recovery
- safety
- operation interface/human–robot interaction
- multirobot coordination
- power supply

Absolute Positioning. Knowing its current position is essential for the operation of a cleaning robot that needs to cover thousands of square meters of cluttered work space. A cleaning robot must recover its position at every location in its workspace with a reasonable accuracy no matter how far it has traveled already. A robot which loses its position will not be able to execute its task reliably. For the customer this means that the service cannot be delivered regularly and reliably, which is not acceptable. The same holds for other reliability issues (see below), which can easily become liability issues.

There are a number of solutions to the absolute positioning problem. Landmark-based position estimation using passive artificial or natural landmarks is one approach to solve the problem. Position estimation with active beacons (sonar, IR, radio) is another one. Both approaches are particularly suited for applications where the position has to be estimated sufficiently accurately over arbitrary distances.

Although positioning technology has matured sufficiently enough to enable reliable solutions not only for indoor but also for outdoor applications, one can find significantly more proofs of concepts than off-the-shelf solutions. This holds even more so for solutions with a reasonable price-to-performance ratio. In a later section we will briefly discuss some recent approaches based on smart sensor networks and radiofrequency identification (RFID) technology which may fill this need.

For a detailed discussion and comparison of the above and other approaches we refer to Chap. 37 *Simultaneous Localization and Mapping* or [54.2], where the latter is an excellent, but somewhat outdated state-of-the-art survey on robot positioning.

It is worth mentioning that existing domestic cleaning robots operate almost entirely without absolute position information. Without reliable position information, however, these robots cannot move in a deliberate manner. They can only move randomly in a *bang-and-bounce* mode and/or execute some hard-coded motion patterns. *Bang and bounce* means that the robot moves until it *bangs* into or sees an obstacle and then *bounces off* like a ball by turning around and moving on in an opposite direction. The area-covering performance of such an approach is rather poor (see the next paragraph).

Area Coverage. Motion planning for covering an unknown dynamic environment and absolute position estimation are key functions for systematically cleaning a workspace. The coverage problem – by nature a geometric problem – has been intensively studied in the literature (see [54.3] for a good overview) and quite a few interesting solutions have been proposed even for unknown environments. What is not straightforward at all is the transfer of theses solutions from 2-D simulation environments into 3-D real world environments. Particularly the assumptions regarding the perception of the environment and the sensing modalities are often far more ideal than what has to be faced in the real world.

Again it should be noted that available domestic cleaning robots do not provide any systematic coverage of their workspace. They combine random motion with hard-coded motion patterns to achieve some minimal coverage. Given the moderate cost of theses devices such a solution is acceptable for many private customers. For professional applications coverage by random motion has a far lower acceptance, or it may not be accepted by professionals at all. Professional cleaning has a strong association with a certain, guaranteed degree of coverage – it does not necessarily have to be 100% – and not with random motion.

Sensor Coverage. A comprehensive perception of the robot's surrounding is essential for safe, collision-free motion and also for the observation of unknown parts of the environment. So it is important for the safety of the robot and the surrounding objects or nearby animals or humans beings as well as for the successful completion of a mission or a task. Coverage means that the robot does not only perceive some small limited portion of its workspace – e.g., a 2-D range image taken at a certain height above the ground – but has a perception which enables it to account for every known or unknown obstacle or hazard in its surrounding environment. From an academic point of view this is again an almost solved issue. Sensor coverage in 3-D can be achieved by means of stereo vision or 3-D laser range finders. There is an abundance of literature treating this issue.

What remains to be solved is sensor coverage under everyday conditions including changing and adversarial lighting conditions, surfaces with little or no reflection or with little or no texture, and other unfavorable conditions.

The above holds primarily for cleaning robots for professional use. Cleaning robots for private homes have almost no sensors at all. For a device which must not cost more than say 300 USD, a sensor which costs 20 USD is a very expensive component. So adding more and more sensors to make the robot behave more intelligently is not necessarily a good solution as it may significantly increase the price of the robot.

Error Recovery. Every technical system is susceptible to errors. This seems to be a fundamental principle and no design can prevent this or account for every possible error. What is needed are mechanisms which either allow the robot to recover from possible or frequent failures or reach a failsafe position. A very frequent failure situation for a cleaning robot is being trapped in some obstacle structure. The control system must be able to recognize this and provide some escape mechanism or strategy. Other frequent errors are false sensor readings. The robot should be able to identify whether or not its sensors function properly. In the case of malfunction the faulty components should be switched off.

The ability to recover from errors is desirable for every robot, be it a cleaning robot or not. For a commercial device this ability is, however, not only a desirable system property but also has an important economic aspect. Every malfunction which the device cannot recover from will cause a call to the service hotline and a request for repair or maintenance.

Safety. To operate an automatically guided vehicle such as a cleaning robot in a public environment a variety of machinery directives must be obeyed. According to the standard EN954, for example, every automatically guided vehicle needs a front bumper as a personnel protection device in the main travel direction. If the vehicle can reverse its direction it also needs a rear bumper. There are numerous other directives such as ANSI/ASME B56.5-2004 or EN1525:1998 which have to be taken into consideration and obeyed. An interesting insight into this subject is given, for example, in [54.4].

Domestic cleaning robots, given their low weight and low power, hardly create any danger for themselves or the environment. If they get annoying they are often small and light enough to be even kicked away. So the safety requirements for domestic robots are commonly less demanding than they are for professional cleaning robots. Still, many if not all available domestic robots have safety precautions, which satisfy for example EN954. Many have precautions to prevent falling over a cliff or staircases or being picked up and turned upside down or carried away.

Operation Interface/Human–Robot Interaction. The complexity of the operation interface of a device has a strong influence on its acceptance. Given that cleaning devices are typically operated by nontechnical personnel, the operation interface of a cleaning robot which is supposed to replace an existing cleaning device has to account for the needs and expectations of those users or operators. If the use of a cleaning robot would require special education, its use and acceptance would be severely limited. This suggests that the operation interface, for domestic as well as for professional cleaning robots, should be intuitive and straightforward.

Such a conclusion is certainly not false but also not entirely true. The operation interface of any device should allow the user to advance his/her skills in using the device. It should allow but not urge the interested user or operator to also use advanced features, e.g., advanced control or programming of the device.

The design of the operation interface is also influenced by the operation mode in which the robot is used. A fully autonomous robot may only need an on/off switch and an emergency button, while a teleoperated device may have some sophisticated remote control including a sophisticated graphical user interface (GUI).

Multirobot Coordination. Cleaning a large workspace or large facility may easily exceed the capacity of a single robot in terms of onboard power, or cleaning liquid and other consumables, or time constraints imposed by the facility management. For cleaning large facilities the use of a multirobot system is self-suggesting. This raises a few questions, however.

The first one is task planning and coordination for multiple robots. For this central fleet management is required. The degree of automation provided by such a central fleet management may vary considerably. The fleet management might involve a sophisticated task planner, which autonomously decomposes the entire cleaning task and the workspace into subtasks and subworkspaces, which are then allocated to single robots. In such a setting the fleet management also needs to control the proper execution, i. e., by monitoring the position of the robots, and provide help in the case of errors. In a less automated solution, the fleet management is just a control center for a human operator. Task allocation and monitoring is then done by the human operator.

The fleet management can also be the *bridge* between the robots and the surrounding facility and the automated components therein, for example, the fleet management could open electric doors or call the elevators to allow the robots to move between several floors.

Another problem when using several robots is caused by active sensors such as sonar, infrared, or laser range finders. A robot might interpret a sensor signal which is actually emitted by another robot as the echo of its own sensors. Such false sensor readings severely affect position estimation, map building, and collision avoidance. Therefore the sensor signals of different robots either need to be synchronized or assigned a unique identifier so that the signals can be uniquely assigned to distinct robots.

Power Supply. Covering an area is not only an algorithmic problem. It requires traveling over considerable distances and therefore leads to a considerable power consumption. Since autonomous motion in a cluttered workspace rarely allows a power cord to be pulled behind the robot, power supply is typically provided by batteries and is typically limited. The limitations are due to the weight and the capacities of today's batteries. Domestic cleaning robots as described below claim to have an average operation period of 30–60 min per charge. Professional cleaning robots often use regular 24 V lead-acid batteries for cars. They achieve longer operation periods per charge accordingly. The price for that, however, is a significant increase of weight, which in turn increases the requirements for safety precautions.

The limited power which is provided today by common battery technology also has an effect on the cleaning technology which can be used for autonomous cleaning. For example, it is nearly meaningless to design a true robotic vacuum cleaner for professional cleaning of larger areas as the energy consumption of vacuum cleaning is prohibitive. The weight of the batteries and the short operation periods per charge make it almost impracticable to use true vacuuming in cleaning robots. Industrial vacuum cleaners are rarely battery driven but typically have power cords.

In the following section we provide an overview of commercial domestic cleaning robots. Not included in this overview are academic proofs of concepts or industrial prototypes. This is partially due to the fact that academic research in this area has almost disappeared since the release of commercial products. Exempted from this are domestic window-cleaning robots. Although the technology is also available this application is still in its infancy and there are no commercial products.

We have divided our overview of domestic cleaning robots into three major categories: *floor-cleaning robots*, *pool cleaners*, and *window cleaners*. We intend to provide a representative but not complete overview of existing systems.

54.1.3 Domestic Floor-Cleaning Robots

Since the year 2000, more than a dozen domestic floor-cleaning robots have been released and a few more have been announced. In the following, we will glance over a total of 13 domestic floor-cleaning robots which were or are commercially available. We have excluded those that have only been announced but do not seem to be available (yet).

Trilobite 2.0, AB Electrolux (Sweden). In 2001, AB Electrolux in Sweden launched the home cleaning robot Trilobite 1.0. This was a milestone in the history of cleaning robotics. After some first developments of domestic cleaning robots in the beginning of the 1990s and even more developments but not very successful market launches of professional cleaning robots, Trilobite was the first home cleaning robot that became commercially available as a *mass* product. Trilobite uses a very sophisticated sonar system for navigation. This sonar system allows Trilobite to sense nearby environment and thereby detect and avoid collisions with obstacles. This is a capability which many of the cheaper systems described below do not have. The sonar system also allows Trilobite to follow the contour of obstacles such as walls. After undocking from its charging station, Trilobite explores its workspace by following the delimiting walls until it returns to its starting point. While on its exploration tour Trilobite integrates its sensor information into a map of the workspace. Having information about its workspace allows Trilobite to show a significantly better coverage performance than can be achieved by a pure random motion. Trilobite is not able to determine its position reliably, however, so it is not capable of real systematic coverage of the workspace. Special magnetic strips can be used to lock Trilobite in a room. They act as a wall and can be placed in doorways and other openings. An infrared sensor allows Trilobite furthermore to discover cliffs and stair cases. The price of a Trilobite 2.0 has dropped form around 1900 EUR at the time of the market launch in June 2004 to 1000 EUR in summer 2006.

Fig. 54.1 Electrolux: Trilobite 2.0

Robocleaner RC3000, Kärcher GmbH (Germany). Four years after it was announced in 1999, Kärcher's Robocleaner RC3000 was launched in October 2003. RoboCleaner cleans a room by following a random motion pattern. By so doing it gradually covers the entire area which is to be cleaned. Through a sensor which monitors the pollution of the air sucked in it is even able to detect areas which are particularly polluted. When such an area is discovered RoboCleaner increases its suction power accordingly. It has an average cleaning performance of 15 m^2/h. Robocleaner RC3000 does not have a sophisticated sonar system like Trilobite 2.0 but uses only tactile sensors to discover collisions with obstacles. It even has tactile *cat-ear*-shaped

Table 54.1 Domestic cleaning robots in Europe

Manufacturer	**Electrolux**	**Karcher**	**Zucchetti**	**Friendly Robotics**	**RoboMop International**
System	Trilobite 2.0	RC3000	Orazio Plus	Friendly Vac	RoboMop
Market release	10/2004	10/2003	04/2004	05/2004	03/2005
Cleaning technology	Rotating brush, suction pump	Rotating brush, suction pump	Wet mop, dry mop, vacuuming fan	Rotating brush,	Disposable electostatic pad
Coverage strategy	Wall-following, random motion with obstacle avoidance	Random motion with bang and bounce, spot cleaning with see-saw motion pattern	Random motion with bang and bounce	Parallel and spiral motion patterns, contour following, bang and bounce	No software controlled motion strategy; works purely mechanically, random motion with bang and bounce
Performance	$28\,m^2/h$	$15\,m^2/h$	–	$100\,m^2/h$	$60\,m^2/h$
Sensors	180° ultrasound sensors (1 transmitter, 8 receivers), infrared cliff sensor, magntetic stripe detector, suspended front shield as contact sensor	Suspended front shield as contact sensor, four IR cliff sensor, pollution	360° contact sensor, stair avoidance sensor	Sonar sensors, touch sensor, cliff sensor	No sensing, no programmed works, purely mechanical
Drive system	Differential	Differential	Differential	Differential	Rolling sphere with eccentric weight
Velocity	0.4 m/sec	0.2 m/sec	–	–	0.3 m/sec
Battery	NiMH	NiMH	2×12 V7 A lead batteries	2×127 AH sealed lead acid	Mignon AA
Automatic recharging station	Yes	Yes	Yes	No	No
Run time	60 min	20–60 min	30–60 min	60 min	30–60 min
Size	$\varnothing = 35.0$ cm, $h = 13.0$ cm	$\varnothing = 28.0$ cm, $h = 10.5$ cm	$w = 37.5$ cm, $l = 50.8$ cm, $h = 19.2$ cm	$\varnothing = 43.0$ cm, $h = 33.0$ cm	$\varnothing = 28.5$ cm, $h = 8.5$ cm
Weight	5 kg	2 kg	13 kg	13.5 kg	175 g
Noise	75 dB	54 dB	–	–	–
Price	1300 EUR	1350 EUR	1750 EUR	1599 USD	10 EUR
Status (06/2007)	Available	Meanwhile sold as SIEMENS VSR 8000	Available	Available	Available

sensors at its top which prevent it from getting stuck under a bed or a couch. While it is in many respects similar to the low-cost systems described below Robocleaner RC3000 has a unique feature which seems to be appreciated by its users: robocleaner very reliably returns to its docking and charging station, once its battery gets low, which is typically after half an hour of operation. While Robocleaner recharges its batteries, its dust bin is emptied by the docking station which itself is a vacuum cleaner. So Robocleaner RC3000 can work unattended

Fig. 54.2 Kärcher: Robocleaner RC3000

for an extend period of time. With a price of about 1500 USD Robocleaner RC3000 is a rather high-priced device. The Robocleaner RC3000 was discontinued by Kärcher and is meanwhile distributed by Bosch-Siemens-Haushaltsgeräte under their own brand name.

Orazio, Zucchetti (Italy). Unlike Trilobite 2.0 and Robocleaner RC300, which are dry cleaners sweeping and vacuuming the floor, Orazio manufactured by Zuccetti, has an additional wet cleaning mode. Altogether it offers five cleaning modes: *continuous vacuuming*: vacuums continuously without use of detergents or cloths, carpets are recognized and get intensive care; *wet cloth*: floor surfaces are processed with a cleansing cloth dampened by detergent solutions, carpets are considered as obstacles and avoided; *dry cloth*: cleanses surfaces without the use of water or vacuuming, carpets are considered as obstacles and avoided; *wet cloth with vacuuming*: surfaces are processed with the cleansing cloth dampened by detergent solutions, when an obstacle is reached, Orazio backs off and vacuums accumulated particles for several seconds, carpets are considered as obstacles; *dry cloth with vacuuming*: cleanses surfaces without the use of water, when an obstacle is reached, Orazio backs off and vacuums accumulated particles, carpets can be considered as obstacles and be avoided or recognized for intensive treatment. Orazio uses only tactile sensing. If it bumps into an obstacle it bounces off and backs up for 5 cm, turns a random angle and then continues. Without any position and range sensing Orazio cannot achieve systematic coverage. Orazio's price ranges from 1299

Fig. 54.3 Zucchetti: Orazio

Fig. 54.4 Friendly Robotics: Friendly Vac

USD for single-floor apartments to 1799 USD for apartments with staircases (staircase detection is included in this case).

Friendly Vac, Friendly Robotics (Israel). Friendly Robotics released a robotic vacuum cleaner called Friendly Vac in 2004. Friendly Vac has a true vacuuming unit and hence claims to have a better cleaning performance than other home cleaning robots. It has an operation time of around 90 min per charge and can clean 100 m^2 during this time. Friendly Vac has range sensors which enable it to avoid collisions with obstacle and it can also sense stair cases and cliffs. Friendly Vac moves along parallel tracks to cover the cleaning area. If it encounters an obstacle it turns and moves in the opposite direction. With a hight of 33 cm Friendly Vac is taller than any other home cleaning robot. It therefore lacks the ability to get underneath most furniture in a home. Also Friendly Vac has no docking station and therefore needs to be recharged manually. Friendly Vac costs 1450 USD.

Roomba and Scooba, iRobot Inc. (USA). The by far most-sold service robot is Roomba developed by iRobot Inc. in Burlington USA. According to an official statement in July 2006, iRobot has sold more than two million units since the product was released in 2002. Both of these events, the market launch of the first version of Roomba in 2002, and record sales figures reached four years afterwards, can certainly be counted as milestones in the history of service robotics. This overwhelming success, however, has little do to with Roomba's performance as a cleaning device – which is not paramount. It exclusively has to do with Roomba's price. Depending on the version, *Roomba Red*, *Roomba Discovery*, *Roomba Discovery SE*, *Roomba Scheduler*, the price for a Roomba ranges between 150 and 330 USD (July

Table 54.2 Domestic cleaning robots in the USA

Manufacturer **System** **Market release**	**iRobot** Roomba 09/2002	**Sharper Image** eVac 06/2004	**Metapo** CleanMate QQ-2 03/2006	**Black & Decker** Zoombot RV501 04/2004
Cleaning technology	Spinning side brush, two counterrotating brushes, suction pump	Rotary brushes, vaccum pump	Vaccum fan, side brush	Vacuum fan, two side brushes
Coverage strategy	Random motion with bang and bounce, contour following, spiral motion	Random motion with bang and bounce, spot cleaning with *star* pattern	Random motion with bang and bounce, preprogrammed motion patterns	Random motion with bang and bounce, contour following, preprogrammed motion pattern
Performance	–	–	$30\,m^2/h$	–
Sensors	Suspended front shield as contact sensor, IR range sensor, four IR cliff sensors, dust sensor	Touch sensor, cliff sensor	Photosensor for cliff detection	Suspended front shield as contact sensor, cliff sensor
Drive system	Differential	Differential	Differential	Differential
Velocity	0.28 m/sec	–	–	–
Battery	NiMH	NiMH	3 V lithium battery (CR2032)	NiMH
Automatic recharging station	Yes	No	Yes	No
Run time	60–90 min	15–45 min	40–60 min	–
Size	$\varnothing = 35.0$ cm $h = 8.25$ cm	$\varnothing = 31.75$ cm $h = 14.0$ cm	$\varnothing = 35.5$ cm $h = 9.0$ cm	$w = 33.8$ cm $l = 33.8$ cm $h = 10.2$ cm
Weight	2.7 kg	3 kg	2.7 kg	4.5 kg
Noise	80 dB	–	80 dB	–
Price	350 EUR	100 USD	200 USD	100 USD
Status (06/2007)	Available	Available	Available	Available

2006). Regardless of its performance, Roomba was the first robotic appliance to have a price comparable to a manually operated device. The robotic technology of Roomba is very simple. Roomba has a differential drive with two rubber wheels and a caster wheel in the front, which give good maneuverability. Roomba's chassis is suspended. If it is lifted the motors are shut off to prevent damage or injures. The cleaning mechanism consists of a rotating cylindric brush at the underbody and a spinning side brush on the right. The cleaning mechanism is very sensitive to hairs, carpet tassel, and the like, which can block the mechanism. Roomba has four infrared cliff sensors, which protect it from following down staircases or other cliffs. It has further an infrared sensor which allows it to sense the distance to obstacles on its right and to follow the contour of walls or furniture. Roomba furthermore has a suspended front shield which is used as

Fig. 54.5 iRobot: Roomba

a tactile sensor to discover collisions with objects. More recent versions of Roomba have also a dust sensor to recognize areas which are more heavily polluted. Roomba combines several locomotion heuristics to cover a certain area: *following a wall or the contour* of an obstacle using its infrared sensor, a *hard-coded spiral motion*, and a *randomized (zig-zag) motion* which is also used to escape from collisions. Roomba comes with a number of accessories. Roomba's workspace can be confined through so-called virtual walls. These are infrared beams emitted from separate virtual wall units, which can be sensed by Roomba and treated like obstacles. More recent versions of Roomba also come which a charger station, to which the robot returns once its battery gets low. The latest version *Roomba Scheduler* allows the user to program operation intervals in which Roomba shall become active.

A more recent development of iRobot is Scooba, a floor washer. Scooba has a different design and apparently uses a different cleaning technology, but otherwise it uses the same technology. It has the same differential drive system, the same sensor equipment, and uses the same navigation strategies. The price for a Scooba ranges from 300 to 400 USD (July 2006).

eVac Robotic Vacuum, The Sharper Image Inc. (USA). One of the strongest competitors of Roomba is the eVac Robotics Vacuum by The Sharper Image Inc. released in June 2004. The eVac Robotic Vacuum has an eye-catching design which looks more like the latest design of a modern vacuum cleaner than the flying saucer design of many of its fellows. According to Sharper Image eVac is a true vacuum cleaner with a traditional vacuuming motor. It does not only sweep dirt particles into a dust bin like many other so-called robotic vacuum cleaners. It must be stated though that eVac's vacuuming performance is still far below that of regular AC-powered vacuum cleaners. Except from the 5 inch wheels the drive system is very similar to that of Roomba. Also the navigation system is comparable apart from some details. eVac does not have any range sensors but only relies on tactile sensing. eVac has touch sensors in its front bumper. When this bumper comes into contact with an obstacle such as a wall or a piece of furniture it backs up a little, makes a slight turn, and then continues. Using its bumper eVac can quasi feel its way around an obstacle or along a wall. Like Roomba, eVac combines this contour-following behavior with random motion and with a hard-coded motion pattern. The hard-coded motion pattern consists of parallel tracks along which eVac moves back and forth. Underneath its bumper eVac has two infrared

Fig. 54.6 The Sharper Image: eVac Robotic Vacuum

sensors to detect drops and edges. Unlike Roomba, eVac does not use virtual walls. Instead it comes with four traffic cones which can be used to block a possible escape from the cleaning area. Since the cones can only be sensed by touch they are far less effective than Roomba's virtual walls. The eVac Robotic Vacuum can operate autonomously but can also be controlled by an operator through a radiofrequency (RF) remote control.

While the systems described so far all had some unique features the following two robots seem to be more or less Roomba clones.

CleanMate, Metapo Inc. (USA). The cleaning robot CleanMate 365, released by Metapo in 2005, has five preprogrammed moving patterns: spiral, special bounce, along wall, s-shape, and polygonal spiral. It iterates through a fixed sequence of these patterns as long as it is in operation, moving at a speed of 35 cm/s. CleanMate 365 has a suspended front shield, which it uses as bumper, and photosensors that detect stairs and prevent CleanMate from falling down. Cleanmate 365's *uniqueness* comes from two minor features. It has a light sensor which enables it to show a helpful behavior. Once its battery gets low CleanMate 365 searches for more light. It moves from darker areas, e.g., from underneath a bed,

Fig. 54.7 Metapo: CleanMate 365

Fig. 54.8 Black & Decker: Zoombot Vacuum

to brighter areas. So, it can be easily found when it has run out of power. Also Cleanmate 365 has an ultraviolet tube attached which can generate ozone to provide disinfection. CleanMate 365 sells for around 200 USD.

Zoombot, Black & Decker Inc. (USA). Nearly unbeatable in terms of price is Black & Decker's Zoombot RV500, which sells for less than 100 USD. In spite of this low price, the robotic technology is basically the same as for a Roomba or for a Karcher Robocleaner RC 3000, which is more than ten times as expensive. Zoombot uses a touch sensor in its front shield for collision detection. After a collision it backs up, turns around, and continues cleaning. It uses motion patterns such as spirals, wall-following, zig-zagging and a random motion to cover the cleaning area. Zoombot has cliff sensors under the bumper to detect drops such as ledges and stairs. It seems, however, that the mechanical design and also the cleaning technology and hence the cleaning performance of Zoombot are clearly inferior to that of all other home cleaning robots discussed so far. It leaves dirt behind and moves considerably slower than its competitors. Zoombot, however, is not the cheapest cleaning robot, as we will see in the next paragraph, although this even cheaper fellow hardly deserves to be called a robot.

RoboMop, RoboMop International (Norway). RoboMop is not what we would consider a typical mobile robot. It merely consists of two parts: a self-propelled *robotic ball*, which pushes an aluminum *cleaning frame*. Attached to the underside of the cleaning frame is a disposable electrostatic pad, which picks up dust as RoboMop moves. RoboMop does not have any motion or coverage strategy or algorithm. It keeps rolling straight as long as nothing blocks its motion. Once it hits an object it physically bounces of the surface like a ball and then keeps moving again. So there is no robotic in-

Fig. 54.9 RoboMop International: RoboMop (RoboMaid in the US)

telligence whatsoever behind RoboMop. RoboMop is really just a self-propelled ball or sphere. There are no sensors which prevent RoboMop from falling down staircases or becoming hung by a cord. However, in spite of the obvious shortcomings of RoboMop it is still an amazing device. It shines in terms of the simplicity of its technology, and it sells for less than 30 EUR. For this amount, the price-to-performance ratio is almost unbeatable, even if it gets stuck every once in a while and cannot vacuum the carpet. The maintenance is manageable and so is the number of components which can break. One simply must not step upon it.

Ottoro, Hanool Robotics Inc. (South Korea). The Cadillac amongst the home cleaning robots is Ottoro made by Hanool Robotics and released in 2003. This comment holds in any respect, including its price of 3400 USD. Ottoro has the most luxurious sensor configuration of all the robots described in this chapter. It has two digital cameras onboard. One of them is specifically devoted to estimate Ottoro's position using a light pattern projected onto the ceiling by Ottoro's base and charge station.

Fig. 54.10 Hanool Robotics: Ottoro

Table 54.3 Domestic cleaning robots in Asia

Manufacturer System Market release	Hanool Robotics Ottoro 03/2002	LG Roboking 08/2005	Samsung/Hauzen VC-R560 07/2006	Yunjin Iclebo 07/2005
Cleaning technology	210 W vacuum pump with revolving suction tool in front	120 W vacuum pump		Main brush, side brush antibacterial filter
Coverage strategy	Systematic coverage by moving along parallel lines and wall following (using precise positioning)	Option: systematic coverage by moving in a lattice pattern, or random motion, or spiral motion pattern	Draws a 3-D map of the environment to identify its relative location, enabling faster and more efficient cleaning of a defined area	Heuristic patterns: random, circular, zig-zag, wall following
Performance	–	–	$25\,m^2/h$	–
Sensors	2 precision cameras (top and front) to sense location and surrounding environement; position estimation using laser projection of light pattern;12 pairs of ultrasonic; air bumper around chassis	Gyroscope, 7 infrared, 2 wheel sensors, 3 bump sensors, 1 wheel sinking sensor, 3 cliff sensors	–	7 infrared sensors, bump semsors, 3 cliff sensors; safety sensor (shut off when lifting)
Drive system	Synchro drive (3 aligned wheels with sychronized orientation change)	Differential	Differential	Heuristic patterns; random, circular, zig–zag, wall following
Velocity	0.3 m/sec	0.3 m/sec	0.4 m/sec	0.3 m/sec
Battery	Lithium polymer	Lithium polymer	–	Lithium ion
Automatic recharging station	Yes	No	Yes	No
Run time	60 min	70 min	–	150 min
Size	$w = 46.0$ cm $l = 60.0$ cm $h = 28.0$ cm	$\varnothing = 34.0$ cm $h = 13.5$ cm	$\varnothing = 36.0$ cm $h = 13.0$ cm	$\varnothing = 35.0$ cm $h = 9.0$ cm
Weight	15 kg	–	6 kg	4.1 kg
Noise	60 dB	–	–	59 dB
Price	3400 USD	900 USD	800 EUR	530 USD
Status (06/2007)	Available (only in Asia)	Available (only in Asia)	Available (only in Asia)	Available

With this, Ottoro is possibly the only domestic cleaning robot that can estimate its position with respect to the base's reference system. According to the product specifications Ottoro senses its position with an accuracy of ±3 cm. A problem of course arises if Ottoro leaves the area from which the light pattern on the ceiling is visible. Besides the two cameras Ottoro uses 12 pairs of ultrasonic sensors for safe navigation and obstacle avoidance. Furthermore *highly sensitive* air bumper sensors are wrapped around Ottoro's chassis. With the ability to estimate its position with a reasonable accuracy, Ottoro does not have to rely on random motion or other motion heuristics to cover the cleaning area. Based on a map of the work space Ottoro can plan a systematic cleaning path, monitor its execution by its location sensor, and also register the cleaned area to avoid multiple visits and inefficient coverage. Ottoro not only has a unique sensor configuration but also uses a unique drive system and a suction spout (*Ottoro's hand*). Its drive systems consists of three *moveable* wheels (three-wheel synchro-drive), which allows Ottoro to move instantly in any direction from any location. Its suction spout allows Ottoro to clean corners and spots which are out of reach for any other domestic cleaning robot.

In summary, Ottoro is a rather unique exemplar amongst existing domestic cleaning robots as it makes full use of the state-of-the-art technology in mobile robot navigation. Apparently this does not come for free. It is unknown how many units of Ottoro have been sold.

RoboKing V-R4000, LG (South Korea). The second out of the four South-Korean-made domestic cleaning robots is Roboking (model name: V-R 4000). Roboking's sensory equipment and design is not as luxurious as that of Ottoro and not as expensive, but is still impressive. Roboking is controlled by a 32 bit digital signal processor (DSP). It uses a gyro sensor to monitor its motion and control its position. This is a valuable extension to position control based purely on odometry, but it does not give absolute position like Ottoro's localization system. Besides the gyroscope Roboking has seven infrared sensors for obstacle avoidance, three cliff sensors, two shaft encoders, three bumper sensors, a wheel-sinking sensor, a dust amount and dust bag sensor, and two rotational brush driving sensors. Depending on the *cleaning circumstances* Roboking can switch between four cleaning patterns: *immaculate cleaning/gyro matrix moving*, in which the robot moves in a left-to-right lattice pattern followed by an up-and-down lattice pattern; *perfect cleaning/variable matrix moving*, in which the robot moves in a small lattice pattern and expands its motion pattern when reaching larger free space; *intensive cleaning/spiral moving*, in which the robot spirals around a specific space to clean it; *fast cleaning/random moving*, in which the robot moves randomly and not on a fixed pattern. LG further advertises the powerful

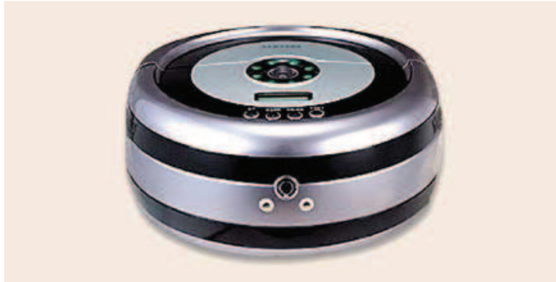

Fig. 54.12 Samsung: VC-RP30W Robotic Vacuum

brushless direct current (BLDC) suction motor (120 W) and the lithium polymer (Li–Po) batteries of Roboking. Roboking sells for around 900 USD.

VC-RS60 Robotic Vacuum, Samsung (South Korea). Not much information is available on the VC-RS60 Robotic Vacuum announced by Samsung in November 2003. It has a webcam which can even be accessed through the Internet, so that the user can control the operation while elsewhere. The VC-RS60 can be programmed to work at specific times like Roomba Scheduler. Is is said to create a 3-D map of the environment to identify its relative location, enabling faster and more efficient cleaning of a defined area. In July 2006, Samsung released a revised model, the VC-RS60, which even offers voice control. The new model, which seems to be available only for the Korean market at this time, sells for approximately 750 USD.

Iclebo, Yujin Robotics (South Korea). While its three compatriots were distinct enough in their technical design not to be put into one class with the Roomba family, the design of Iclebo and its upgrades is very similar to that of Roomba. It combines a number of heuristics such as bump and bounce, wall following, moving on parallel tracks or on a circular trajectory. It has a set of seven infrared sensors to monitor the surrounding workspace and uses three optical cliff sensors to keep it away from

Fig. 54.11 LG: RoboKing V-R4000

Fig. 54.13 Yujin Robotics: Iclebo

staircases and ledges. Iclebo has three filter systems: an antibacterial filter, an electrostatic filter, and a semi-high efficiency-particulate airfilter (HEPA). Iclebo was released by Yujin Robotics in summer 2005 and sells for around 500 USD.

54.1.4 Pool-Cleaning Robots

Domestic cleaning robots, in spite of promising sales figure, are still struggling to get rid of the reputation of being exotic devices or toys and to become regular appliances. Pool-cleaning robots never really had such problems. Robotic pool cleaners have been established products for years. 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. Given the liquid surrounding there is not much sensing other then motor encoders and measuring the motor current for obstacle detection. In the following we only describe the three cleaners which are the most established.

Aquabot, Aqua Products (USA). Aquabot is an automatic pool cleaner for residential pools. It uses two sealed high-quality motors. One motor causes the drive belts and drive tracks to move the unit. They also cause the front and rear scrubbing brushes to clean the pool surface, walls, and steps. The second motor is the pump motor, which generates extremely powerful suction so that Aquabot is not only able to filter the water but can also climb up the pool walls to the waterline. Aquabot has an external power supply through a floating power cord. Aquabot and Aquabot Turbo alternate between two cleaning patterns. One is a zigzag motion, where the wall is used as a navigational aid. Whenever Aquabot hits the wall of the pool it reverses its direction and moves towards the pool center at a certain angle. On each pass it covers roughly 60% of the pool area. The second pattern is a rectangular meander pattern, where again the wall is used as a navigational aid. Auqabot has a sensor to detect obstacles such as walls or heavier objects at the bottom of the pool appearing in front of it. Once it discovers a collision it reverses direction and continues moving in the opposite direction. Aquabot (Turbo) has a cleaning performance of 315 square meters per hour and sells for approximately 850 USD.

TigerShark Pool Cleaner, Aquavac (USA). TigerShark is the basic model of a product line of *xShark* robotic cleaners by Aquavac Systems. The basic design of TigerShark is very similar to that of Aquabot. It is equipped with two polyurethane drive tracks. TigerSharks motors – one for locomotion, one for the suction unit – are sealed in a motor unit. It has a *calculated* ground speed of 15 meters per minute and a work cycle of 5 h. TigerShark's cleaning unit consists of a suction pump with a suction rate of 300 liters per min and a removable, reusable, cartridge filter. Tigershark's suction power creates enough adhesion to let it climb up the walls of the pool. Very little information is available on TigerShark's control system and its coverage strategy. According to the user manual TigerShark is equipped with an adaptive seek control logic (ASCL) microprocessor which can sense the pool contour and calculate an efficient motion pattern to achieve coverage. Unfortunately, it remains a secret exactly how the contour is sensed and how the motion pattern is calculated. A reasonable guess is that both Aquabot and TigerShark measure the motor current to sense an obstacle in their way. Like Aquabot, TigerShark sells for around 850 USD.

Fig. 54.14 Aqua Products: Aquabot

Fig. 54.15 Aquavac: TigerShark Pool Cleaner

Fig. 54.16 Maytronics: Dolphin Diagnostic 2001

Dolphin Diagnostic 2001, Maytronics (Israel). Dolphin Diagnostic 2001 is the best-selling member of a whole family of Dolphin automatic pool cleaners manufactured by Maytronics in Israel. Dolphin Diagnostic 2001 seems to differ from TigerShark by Aquavac only in color. A careful look into the user manuals and into the technical drawings is required to identify differences in the mechanical design. Dolphin Diagnostic 2001 is slightly lighter than TigerShark and has slightly less suction power. It has a ground speed of 15 m/min and a coverage rate of 350 m^2/h. Dolphin Diagnostic 2001 is capable of exploring the size and shape of a pool and calculating an efficient cleaning pattern. As for the Tigershark it remains unclear how the exploration and calculation of a cleaning pattern work. The manufacturer, Maytronics, does not reveal any information on this. Dolphin Diagnostic 2001 has an integrated air sensor which will detect if the cleaner has left the water, turn itself around, and crawl back into the water to continue cleaning. Maytronics advertises Dolphin's diagnostic capabilities. The cleaner runs a constant self-diagnostic program and allows technicians to instantly download information about the operation of the unit for in-the-field diagnostics and on-site repair. Dolphin automatic pool cleaners range from 800 USD for residential cleaners to 5000 USD for professional cleaners used for public pools.

54.1.5 Window-Cleaning Robots

While robotic pool cleaners and also domestic floor-cleaning robots have become established and accepted products, the automation of another area of domestic cleaning is still in its infancy: window cleaning. The reasons for this are not too difficult to find. Windows in private homes are cleaned far less often than the floor. Who would buy a robot for automatizing a task which needs to be done every once in a while and how much would he or she pay for it? The answer is certainly frustrating for somebody who wants to develop window-cleaning robots for domestic applications. 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 mechanism have to be designed for secure motion. Typically special tether mechanism 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 sideward. These mechanisms have to be small and light and create enough adhesion forces and must have low energy and resource consumption. The cost for those mechanisms are typically far beyond the price even of expensive appliances. This may explain why there are no commercial domestic window-cleaning robots available at present.

Robots which have to climb up even vertical surfaces often use caterpillar drives which are equipped with passive of active 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 a torque which 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 practicable.

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 [54.5] 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 (see Fig. 54.17) 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,

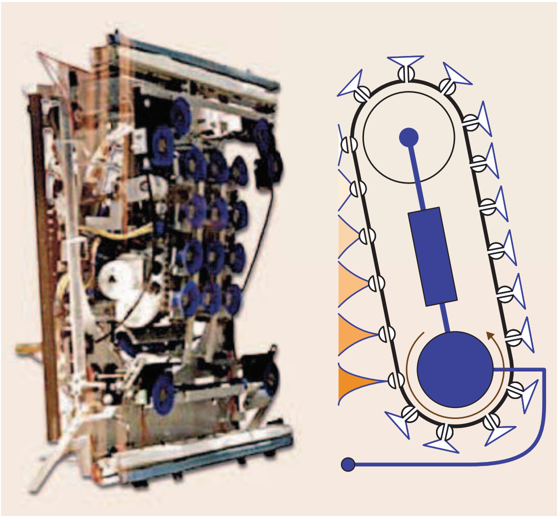

Fig. 54.17 Fraunhofer IPA: climbing robots with passive suction cups

which counteracts the torque around the center of gravity and also causes a pressure on the upper suction cups.

RACOON, Fraunhofer IPA/Procter & Gamble, (Germany). RACOON is a window-cleaning robot which was developed in a joint venture between Procter & Gamble and Fraunhofer IPA and was presented during the Hannover Fair 2002. RACOON uses passive suction cups with a spacer as described above. RACOON was developed as a demonstrator for automatic domestic window cleaning. Given its size and weight, the design shown in Fig. 54.18 below was not really intended to become a product.

Fig. 54.18 Fraunhofer IPA: the window cleaner Racoon

Fig. 54.19 Fraunhofer IPA: bottom view of QUIRL

Fig. 54.20 Fraunhofer IPA: QUIRL design study

QUIRL, Fraunhofer IPA, (Germany). With the window cleaner QUIRL Fraunhofer IPA presented a successor of RACOON with a totally revised design. In QUIRL, the number of components, the weight, and the size of the system were significantly optimized, as can be seen in the figures 54.19 and 54.20. The main functions *cleaning*, *holding*, and *moving* were unified in one single component. The prototype of QUIRL consists of two vacuum cups which are attached to a common frame and which are driven by two separate motors and rotate independently of each other. The overall motion of QUIRL can be controlled by selecting the velocities and rotational directions of the vacuum cups. If the motor of one vacuum cup is turned off and the cup does not rotate, QUIRL rotates around this fixed cup. If both motors and cups rotate in the same direction this leads to an overall rotation of QUIRL about its vertical axis. If both drives rotate in the opposite direction at exactly the same velocity then QUIRL makes a linear motion. If both drives rotate in the opposite direction but their velocities are not identical then the translational motion is superimposed by a rotational motion and QUIRL moves along a curved trajectory. In order to clean the surface some cleaning mechanism or tool needs to be fixed to the vacuum cups. By attaching, for example, specific cleaning towels in the cups the abrasion effect is increased and a very good cleaning performance can be achieved. In summary, by implementing the cleaning, holding, and moving function by one single mechanism the system complexity of QUIRL, its weight, its size, and not to forget its cost could be significantly reduced. QUIRL is described in more detail in [54.5]. There is only one problem: QUIRL is still waiting to become a product.

54.1.6 Old Problems, New Technologies

In this section we discuss some new technologies which seem to have the potential to solve some of the pressing technical issues discussed in Sect. 54.1.2. The following is a list of the most promising of such enabling technologies:

- low-cost (3-D) sensing (photonic mixer device (PMD) or other technology in mass manufacturing)
- low-cost absolute localization (local positioning systems), sensor networks
- new energy concepts such a fuel cells

Should the promises come true and the potential of these enabling technologies materialize then they might in fact lead to a considerable increase of the acceptance and use of cleaning robots in domestic as much as in professional environments.

3-D Sensing (at Low Cost). We have learned above that sensor coverage and a comprehensive perception of the workspace are fundamental for the safe operation of a cleaning robot. Sensor coverage at present is certainly possible but at a high price. This situation seems to be changing with the arrival of small 3-D time-of-flight range cameras such as the SwissRanger SR-3000 [54.6]. These cameras use highly sensitive, custom-made complementary metal–oxide–semiconductor (CMOS)/charge-coupled device (CCD) image sensors and measure the time of flight (TOF) of an emitted light wave in the near-infrared spectrum.

The development of this sensor technology was primarily driven by the automotive industry for safety applications. Hence the expectation is that there is a mass market and the sensor can be produced and distributed at a reasonable price. It was predicted that the price of these 3-D range cameras would come down to the level of an expensive webcam. At present the price for a single unit is still in the order of 5000 EUR, which means that its enabling features are somewhat hampered by the cost.

Absolute Localization (at Low Cost). A radical solution to the absolute positioning problem is to cast the workspace with a sufficiently large and dense network of artificial markers or beacons, which can be sensed by the robot nearly from everywhere in the workspace. An overview of such approaches and systems developed in the recent past is given in [54.7].

A very recent approach has been developed in a joint venture of two German companies: Vorwerk Teppichwerke, a carpet manufacturer, and InMach Intelligente Maschinen, a developer of robot control and navigation systems. This approach uses a so-called *smart floor* [54.8] to support robot position estimation and navigation over large distances. The core idea of the smart floor is to distribute and integrate RFID transponders in the floor in an area-covering manner and use the transponders for various purposes. Since integration into the floor covering itself would complicate the manufacturing and increase the price of the floor covering and would have to be implemented separately and specifically for every type of floor covering, Vorwerk Teppichwerke has developed a so-called *smart underlay* (see Fig. 54.21).

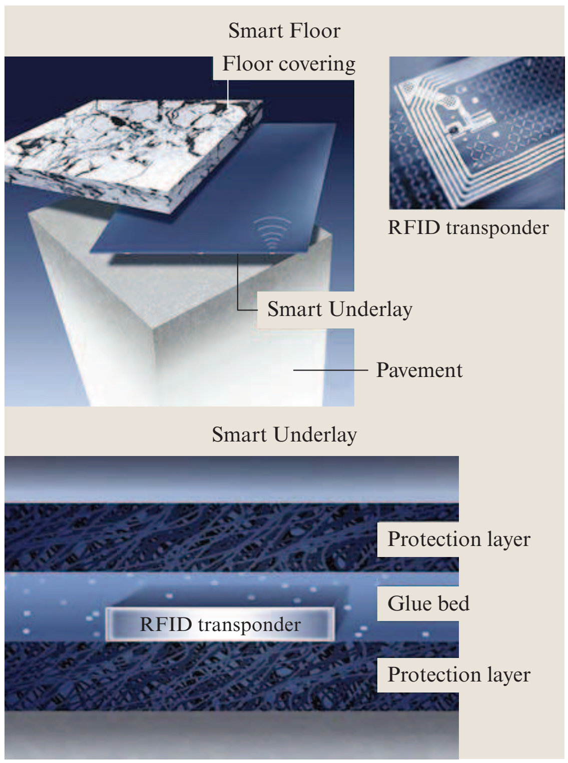

Fig. 54.21 The design of smart underlay and smart floor

Fig. 54.22 CeBIT 2006: smart underlay placed under carpet, laminate, tile, and PVC

Fig. 54.23 Professional cleaning robot Robo40 navigating on smart floor

The smart underlay is a separate mat-like textile, in which the RFID transponders are integrated, typically in a regular grid. This underlay can be placed nearly below every nonmetallic floor covering. During CeBIT 2006, the world's largest information technology (IT) fair, the smart underlay concept was demonstrated to the public. The smart underlay was placed under four different floor coverings: carpet, laminate, tile, polyvinyl chloride (PVC) (see Fig. 54.22). The Swiss–German cleaning robot Robo40, shown in Fig. 54.23, is the first one to operate and navigate on such a smart floor. It is equipped with RFID-based navigation system which uses the RFID tags integrated into the underlay to estimate the position and control the locomotion of the robot [54.9].

The above system is not per se low-cost or much cheaper than other ones involving expensive sensors and sensing. That is true even if the cost of a RFID tag, which is around 30 to 40 EUR cents at present, are dropping further. After all, several thousands of square meters may have to be equipped with RFID tags or other sensors or markers with additional costs of up to several euros/dollars per square meter. Whether or not such an investment pays off and whether the price-to-performance ratio is acceptable for the customer very much depends on the specific application. In many applications only the automation of cleaning and some logistic and transportation functions justify and pay-off the investment in a smart infrastructure or a smart floor. Often there is a range of additional services or functions facilitated by such a smart environment, e.g., location-based services and other ubiquitous computing functions, which yield an even better return on investment. A common feature of solutions such as those described is undoubtedly that they enable robust and reliable absolute position estimation over arbitrary distances.

An alternative solution to wide-area indoor localization is the NorthStar system developed by Evolution Robotics. The idea underlying NorthStar is to project infrared light patters onto the ceiling above the robot's workspace and use these patterns for position estimation very much like old sailors used the stars in the sky, including the north star, to determine their positions in the vastness of the seas. NorthStar consists of two types of components: one or more IR projectors, which emit a collimated IR beam with a unique signature which leaves a unique IR light pattern on the ceiling, and a detector which uses a triangulation algorithm to estimate the position and heading in relation to the IR light pattern on the ceiling. The basic setup of a NorthStar system is shown in Fig. 54.24. The distance between

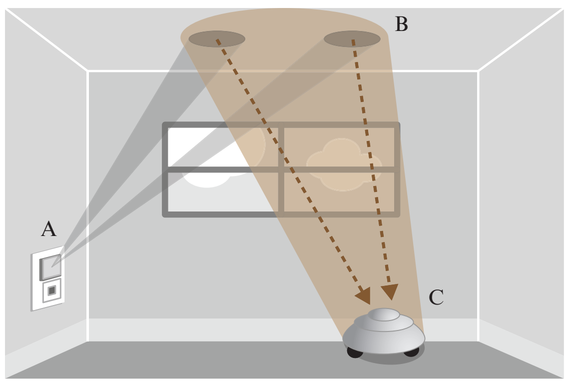

Fig. 54.24 Basic setup of a NorthStar system with an IR projector(s) mounted at fixed positions and a mobile detector carried, for example, by a robot

the detector plane and light plane must not exceed 6 m according to the product specification. Covering a larger workspace requires a rather dense network of projectors to be installed. Given that one projector sells for around 600 USD, this may become quite costly. It may be the case, however, that for a larger installation the price for one projector unit comes down significantly.

New Energy Concepts. In the preceding section it has become evident that energy consumption and power supply have a significant impact on the design and use of cleaning robots. A cleaning device which needs to be recharged every hour is useless for professional cleaning. Therefore better and more efficient power supply concepts are a burning issue in cleaning robotics.

A promising solution for the power supply problem, although not exhaustively investigated, may be fuel cells. A first practical application has been reported in [54.10]. The Tokyo-based company Sohgo Security has been developing a sentinel robot equipped with a fuel-cell battery that is supposed to work round the clock for one week without a recharge. The fuel-cell battery is to be supplied by Yuasa Corp., a Japanese battery manufacturer.

54.2 Lawn-Mowing Robots

As popular as domestic cleaning robots are robotic lawn-mowers. It may be somewhat surprising that the first commercial robotic lawn mower was released as early as 1995, long before any commercial domestic cleaning robot was in sight. This may be due to the fact that lawn-mowing is a domain where the performance requirements are not as critical and the customer expectations are not as high as in domestic cleaning.

Cleaning robots and lawn-mowing robot share a great deal of technical problems (see Sect. 54.1.2) and also solutions. Apart from the different services, cleaning versus mowing, and the different application-specific processing units, there are just minor differences in the basic system designs. Most lawn-mowing robots have differential drive systems with castor wheels. They use sensor equipment for navigation similar to that of cleaning robots and they use similar coverage strategies, mostly a bang-and-bounce strategy.

Since robotic lawn-mowers work outdoors, they can run away. To prevent this they are often kept enclosed by virtual fences. These are wires buried in the ground that emit an electromagnetic field which can be sensed by the robots and push them back. All robotic lawn-mowers have lift protection as an essential safety mechanism. The cutting mechanism is immediately shut off once the robot is lifted or falls upside down.

Given that the majority of humankind lives in cities, the market size for robotic lawn-mowers is certainly smaller than that for robotic cleaning devices. This may explain why the number of brands of robotic lawn-mowers that are available is also smaller than that of cleaning robots. In the following we describe the three most established commercial system and a fourth system which was introduced recently.

AutoMower, Husqvarna/Electrolux (Sweden). The father of all domestic robots, if not of all commercial service robots, is the predecessor of the AutoMower manufactured by Husqvarna, a subsidiary of the Electrolux group, Sweden. This predecessor, SolarMower, was released as early as 1995: earlier as any other known commercial domestic service robot. Unlike SolarMower, which was powered by a solar panel placed on top of the robot, AutoMower is powered by nickel–metal hydride batteries. When running out of power AutoMower returns to a charging station and recharges its batteries. A normal recharge takes approximately 1.5 h. Fully charged AutoMower can operate for up to 2 h. AutoMower is a lightweight amongst the robotic lawn mowers, weighing only 8.5 kg.

AutoMower's cutting mechanism consists of a rotating disc with three razor-like blades which automatically retract into their mountings if AutoMower is stopped unscheduled, for example, if it hit an obstacle or is lifted. It is important for the proper functioning of AutoMower that the lawn which is to be cut is not too high. This in turn requires a rather regular if not continuous operation of AutoMower. With regular use of AutoMower the

Fig. 54.25 Husqvarna/Electrolux: AutoMower

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.

AutoMower has no position or range sensors which would allow keeping track of its motion. It uses a random motion pattern to cover its work space and keep the lawn at an equal height. To prevent AutoMower from running away from its workspace a low-voltage induction cable is buried around the lawn. Once AutoMower senses this cable it stops, reverses its direction away from the cable, and then moves on towards the inner area of the workspace. Using this random motion and a bang-and-bounce strategy AutoMower can maintain an area of up to 1500 m^2. AutoMower is sold for approximately 2000 EUR.

RoboMower, FriendlyRobotics (Israel). Friendly Robotics (formerly Friendly Machines) also started developing a robotic lawnmower *Lawnkeeper* in 1995. Several product iterations finally led to the current product family RoboMower RL 850 and RoboMower RL 1000. With a weight of 22.5 kg without batteries RoboMower is significantly heavier then Automower. It is powered by two maintenance-free 2 × 17 AH sealed lead-acid batteries with a charging time of approximately 20 h.

RoboMower is equipped with touch sensors around its hull. If it collides with an obstacle it senses the contact, stops, turns around, and moves on in the opposite direction. RoboMower has furthermore sensors to detect the wire which is buried around RoboMower's work space. Although it has no position or range sensor RoboMower does not move entirely randomly. By using the buried wire as a reference and moving in a zigzag pattern in the confined area it can achieve a better coverage performance than a pure random motion would allow. To achieve good cutting performance RoboMower still needs to cover its workspace several

Fig. 54.26 Friendly Robotics: RoboMower 850

Fig. 54.27 Zucchetti: LawnBott Evolution

times. Using this strategy RoboMower RL 850 can mow and maintain an area of approx. 1000 m^2. RoboMower RL 850 without a docking station sells for USD 1000. RoboMower RL 1000 with a docking station sells for 1500 USD.

LawnBott, Zucchetti (Italy). A whole series of lawn-mowing robots have been developed by Zucchetti, Italy. LawnBotts (Professional, Deluxe, Evolution, Quattro) come with slightly different designs, features, and prices but do not substantially differ in their robotics technology. Also, the differences with respect to the previously described systems are minor.

LawnBott's workspace needs to be delineated by either an induction wire buried around the cutting area or by a fence which is at least 10 cm high. LawnBott uses a bang-and-bounce strategy to deal with obstacles. Coverage is achieved by random motion. LawnBott senses the height of the grass. If it discovers a spot with high grass, it stops moving randomly and enters a specific motion pattern. Starting at the spot with the higher grass it moves along a spiral until it reaches an area where the grass has nominal height again.

All LawnBott models are equipped with a wet grass sensor, which discovers when rain starts falling and sends the robot back to its base station. LawnBott's base and recharging station looks like a small garage and accommodates the robot entirely, so it is protected against rain and storms. All LawnBott models have a coverage performance of around 270 m^2/h and can cover an area of 3300 m^2 in total. The price of the LawnBott models ranges between USD 1850 and 2500.

RobotCut, Brill (Germany). A rather recent development with an eye-catching design is RobotCut, developed by the German companies Brill and InMach Intelligente Maschinen and commercialized by Brill. RobotCut was

Fig. 54.28 Brill: RobotCut

presented at GAFA 2006, an international fair for garden equipment, in Cologne, Germany. Unlike its competitors, which all use a rotating disc as cutting mechanisms, RobotCut uses a spindel cutting system, which claims to create a rather uniform cutting image. RobotCut has two rather large propelled front wheels which give the vehicle additional stability. RobotCut has a cutting width of 38 cm. The cutting height can easily be adjusted by screws at the rear castor wheels. RobotCut's brain is the so-called *optimized guidance system*, which enables the robot to move along parallel tracks and avoid random motions. RobotCut is designed to cover an area of 2500 m^2. RobotCut will be delivered in several versions, with a high-end version also being equipped with sonar for obstacle avoidance. RobotCut is announced for 1500 EUR.

54.3 Smart Appliances

The term *smart appliance*, although well established and widely used, seems to be everything but well defined. A Google search returned no fewer than 27 400 entries for *smart appliance* at the time when this text was written. Very often the term *smart* is used as a synonym for *networked*, referring to devices which are connected to and can communicate with the Internet. Smart appliances are often referred to in the context of home automation and ambient intelligence.

Our understanding of this term is somewhat narrower. What we have in mind when we talk about *smart appliances* are appliances which in one way or another use robotic technology (sensors, actors, smart control systems). Although it might seem to be more appropriate to then talk about *robotic appliances* we refrain from doing so, since we do not see a need to draw a clear line between *robotic appliances* and *smart appliance* at large.

One reason for this is that there are not that many *robotic appliances* other than the cleaning and lawn-mowing robots, which we have already described. In spite of the endless list of tasks which people might want to delegate to some kind of robot we found only two more applications which might be counted as *some kind of robot* in a colloquial sense. In both applications there is a degree of actuation and automation involved, which is enough reason for us to include them in a chapter on domestic robotics. The three applications described in the following three sections are: *ironing robots*, *intelligent refrigerators*, and so-called *digital* or *smart wardrobes*.

54.3.1 Ironing Robots

The plural in the title may raise wrong expectation. During our search we actually came only across a single device which was called as ironing robot even by its inventors: *Siemens Dressman* (also distributed as *Bosch ShirtMaster*).

Dressman, Siemens (Germany). The Siemens Dressman ironing robot complies with the definition of a robot

Fig. 54.29 Siemens: Ironing robot Dressman

only in the wider sense. It is a machine which automatizes a certain service, which is disliked by many people: ironing. More specifically, Dressman is designed to *iron* shirts. It does so by means of an inflatable torso made of parachute silk material. Once the shirt is stripped over the torso it is inflated with hot air in its interior. This hot air presses and dries the shirt. Creases are removed during this process. The hot air is created in a heater box in the underbody of the device. The torso adjusts perfectly to that of the garment, allowing the pressing of all kinds of shirts, including short-sleeved ones. When the ironing process has finished Dressman exhausts cold air for one minute in order to stabilize the cloth and prolong the ironing effect. The inflatable torso can accommodate shirts in European sizes of 35 to 50 (XS to XXXXL) and in US sizes of 38 to 52 (S to XXL). When fully set up Dressman measures 173 × 36.5 × 45 cm and weights 28 kg. During operation it consumes approximately 3300 W. Dressman was released in 2004 and sells for around 1000 EUR.

Fig. 54.30 Electrolux: intelligent refrigerator *ScreenFridge*

54.3.2 Intelligent Refrigerators

While the plural *ironing robots* in the headline of the preceding section was an overstatement, talking about intelligent refrigerators definitely is not. There are at least four so-called intelligent refrigerators out in the market: LG's *Internet Refrigerator*, Siemens' *CoolMedia fridge freezer*, Samsung's *HomePAD's Refrigerator*, and Electrolux' *ScreenFridge*. As indicated in the introduction to this section, *intelligent* in the context of refrigerators means *networked*. The share of robotic technology involved in an intelligent fridge is negligible. For this reason we only briefly discuss one representative of this class of smart appliances, namely the Electrolux ScreenFridge (see Fig. 54.30), which is one of the latest developments. ScreenFridge has a wireless connection to the Internet and to the TV. Its user interface is a 15-inch touch screen and pop-up keyboard. In addition to Internet, email, phone, radio, and MP3 player ScreenFridge also offers an advanced calendar and video messaging system. In spite of some visionary's expectations, there is currently no intelligent refrigerator on the market which can call the supermarket and order a six pack of beer when it notices that the beer stock gets low. There is no fundamental technical problem to implementing such a vision. What may be a barrier is the lack of an infrastructure to support such a service.

Although we do not want to further elaborate on this, it should be mentioned that large appliance manufactures such as LG and Samsung have apparently discovered the Internet for refining their appliances. Both companies do not only offer networked refrigerators but also other devices. LG and Samsung, for example, both offer an *Internet microwave oven*. LG even has an *Internet turbo drum washer* on the market. How big the market for such *intelligent* appliances currently is or in the future will be, is hard to predict. It may not be in everybody's budget to pay around USD 9000, for example, for a ScreenFridge.

54.3.3 Digital Wardrobes

The idea of fully automatizing not only the handling and maintenance of clothing but also to have support in the selection of the right dress for the right circumstances has led to the concept of *digital wardrobes*. Although this is a fascinating idea, which might especially be interesting for one or another bachelor who is in dire need of support in this respect or for those which have a significant collection of clothes and shoes, the implementation of the idea into products is still pending. We have come across only one design study for a digital wardrobe. This design study includes a business plan but otherwise awaits implementation. The design study uses little conventional robotics technology. The emphasis is more on the information technology side rather than on the physical handling.

EDWard – The Intelligent Wardrobe, Technical Univ. Darmstadt (Germany). The appearance of EDWard is not particularly unique. It does not differ from any regular wardrobe. What makes EDWard unique is what the inventors call *clothes awareness*. EDWard knows about evert piece of clothing which is stored in it. This includes shoes, as well as hats and ties. This clothes awareness is implemented by means of a database and a tracking system, which notices whenever an item is taken out of or put into EDWard. The database contains an entry for every piece of clothing stored in EDWard. It also contains information on how pieces of clothing can be combined to form an attractive outfit or for which temperatures or weather conditions they are suitable for. To keep track of what is going in and out of EDWard, every item needs to be marked by an RFID tag, which carries a unique identifier and other information which might be better stored directly on the item rather than in EDWards database. The computer which hosts the database is also connected to an RFID reader. Whenever a piece of clothing is taken out or put into EDWard it passes the reader and the antenna attached to it. In this way EDWard maintains a full record of what is stored in it.

Apart from the basic storage and retrieval function the inventors propose a range of additional functions such as search for clothing in the wardrobe, a *tie assistant*, a *shopping assistant*, which cares for compatibility and complementary in the dress and show collection, a *travel assistant*, which proposes the right dressing for the journey depending on the climate and weather conditions at the destination and the business to be done, a *washing assistant*, and many more.

Fig. 54.31 Technical University Darmstadt: the intelligent wardrobe EDWard

As already mentioned there is not too much robotic technology involved in EDWard at present. However, there are quite a few robotic function which could be added, for example a *robotic packing assistant*, which not only proposes clothing for the trip but also packs it into the suitcase.

54.4 Smart Homes

Several attempts have been made in the literature to define the term *smart home*, for example, in [54.11] the term is defined as the "the latest expression of the various ways in which technology in the home has developed". In [54.12], 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. 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 gesture.

The development of smart homes requires a number of technical questions and challenges to be addressed [54.11]: how to convert current home structures and architectures into a smart home, 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 Japan Electronics and Information Technology Industries Association (JEITA) house, the *Aware Home* at Georgia Institute of Technology, the *Gator Tech Smart House* at the University of Florida, the *Robotic Room* at the University of Tokyo, the sensorized environment for life (SELF) at AIST (the Japan National Institute of

Advanced Industrial Science and Technology). These developments show that current smart home technology goes significantly beyond existing home automation. Accounting for the significant increase in 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.

JEITA House (JEITA, Japan). The Japan Electronics and Information Technology Industries Association (JEITA) house project was carried out from 1999 to 2001 [54.13]. It was implemented in a two-storey Japanese house by several companies that participated in the project. The features of the JEITA house include a keyless system which unlocks the door with fingerprint scanners for personal identification. Based on the fingerprint data, a robot dog AIBO (SONY) would greet the persons entering the house. Functions such as opening curtains, turning on lights, or tuning on the air conditioner could be remotely controlled. The plants could be watered and pets could be fed using cellular phones as remote control devices. This would allow the residents to stay away from the house over longer periods. The components of the JEITA house had their own private IP addresses and were connected to a network.

The JEITA house was equipped with health monitoring sensors for elderly family members. For example, if the system detected something unusual, such as an irregular heartbeat, it sent a message to other members of the family through their cellular phones. Such health monitoring functions are extremely important when an elderly person lives independently. The house could also adapt to the habits of family members. This was an important and interesting novelty, since typically the situation is the other way around: the occupants have to adapt to the system. Lastly, the JEITA house also demonstrated the possibility of integrating robotic systems into homes.

Gator Tech Smart House (Univ. of Florida, USA). The Gator Tech Smart House was built at the University of Florida [54.14]. It addresses the needs of elderly people to live independently and maintain dignity and quality of life at a high age. 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 phone that can act as remote control to other appliances, location tracking, smart leak detectors, or 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 RFID tag, which allows 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, or 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.

Aware Home (Georgia Institute of Technology, USA). Aware Home is a living laboratory for research in ubiquitous computing for everyday activities. This project is conducted at Georgia Institute of Technology [54.15]. 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 human and 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

Fig. 54.32 Georgia Institute of Technology: Aware Home

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, or finding lost objects. Research on context awareness is inspired by the fact that humans communicate with each other very successfully by referring to what is called shared context. For communication between humans and computer system, this shared context must be made explicitly. Sensor systems which facilitate the extraction of context need to be developed.

The human-centered research focus on support for the elderly and other social issues. A key concept in supporting the elderly is *aging in place*. Aware Home is designed to support the elderly and allow them to be independent instead of moving them to elderly care facilities. Supporting the elderly leads to the study on cognitive support such as to remind elderly when to take their medicines, guide them whenever they are lost, and locate lost items.

Robotic Room (University of Tokyo, Japan). We have discussed some implementations of Smart Homes. So far, helping the elderly to improve their quality of life is a common goal and this was done in a partly passive way. The term passive implies that there is no physical contact to support the elderly. On the other hand, active support of the elderly requires systems that can physically interact with the elderly and can be augmented to a smart home. The system can also be controlled and can communicate with other smart home devices. With this system, the goal of independent living will be further enhanced. Examples of this system include a robotic partner, robotic walking support system, etc. The discussion below will focus on the goals of and research on such a system, which is an environment-type robot system and which has some elements of a robotic system that can physically interact with humans. This system is referred to as a *robotic room*.

The *Robotic Room* project is being conducted at the University of Tokyo [54.16]. The key concept of the Robotic Room is an environment-type robot system which will provide service to humans. In contrast to industrial robotic systems, which interact with objects, the robotic system in the Robotic Room interacts with humans. There are several target implementations of the Robotic Room, which are more user oriented. One illustration of the Robotic Room is shown in Fig. 54.33,

Fig. 54.33 University of Tokyo: the Robotic Room concept

which shows a robot arm mounted on the ceiling to serve a sick person.

This implementation of the Robotic Room has been considered for a robotic sickroom and one area of research that has been studied is behavior media research, which considers behavior as a communication media between human and robot system. The study of behavior media is further subdivided into behavior measurement and recognition, and behavior expression. An example of behavior measurement is the use of cameras to monitor breathing. This is an unconstrained behavior measurement. Behavior expression by robotic systems can be conveyed by motion, such as dancing to indicate joy.

The second target implementation of the Robotic Room is as a sensing room. As a robotic system, it can accumulate behavior and this leads to the study of behavior accumulation or behavior content. This accumulated behavior can be used for system decision making. This is motivated by the observation that older people are more experienced and can decide correctly based on a certain situation due to their accumulated experience.

The third Robotic Room implementation is as a distributed actuation room. In this robotic room, behavior adaptation research is studied. The robotic systems are designed to accumulate personal behavior information and behave based on the user's behavior. Behavior adaptation research can be subdivided into environment support and operational support. In environment support, the room contains a robotic kitchen which adjusts its height with respect to the user and a robotic lamp that adjust its position and brightness depending on the user's behavior.

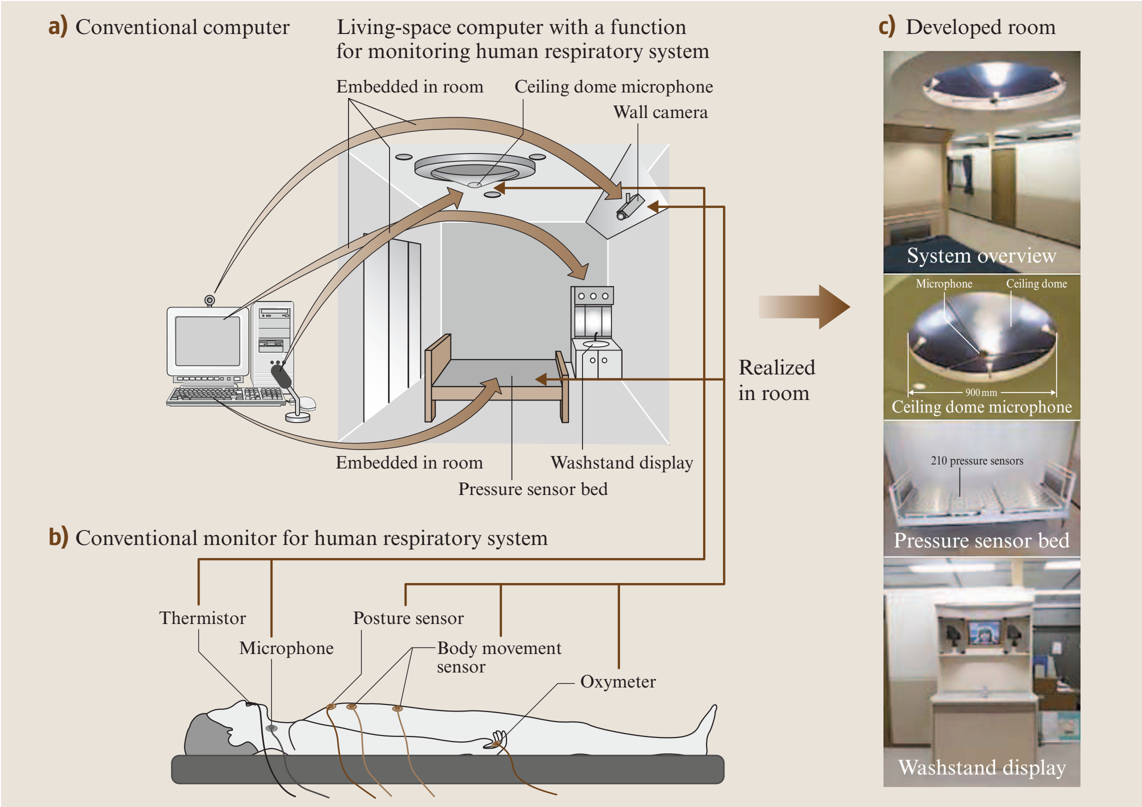

Fig. 54.34 AIST, the sensorized environment for life

SELF – Sensorized Environment for LiFe (AIST, Japan). SELF stands for Sensorized Environment for LiFe [54.17]. The objectives of SELF are to develop a network of sensors which are embedded in the environment, information gathering using the network sensors, storing and analyzing the information, and 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 size limit, weight, and 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. The motivation of SELF is that humans sometimes cannot notice a change in their condition which greatly affects their health status 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 is shown in Fig. 54.34, which shows 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.

54.5 Domestic Robotics: It Is the Business Case Which Matters

After having seen the plethora of domestic robots in the previous sections, we are tempted to say that domestic robotics are no longer a dream or a vision, they are a reality. More than two million domestic cleaning robots sold within four years appears to be a tremendous success story. Of course, as we stated earlier, this is certainly a milestone in the development of domestic robotics and service robotics in general. It is a success story since Roomba created a market. Compared to the sales figures for industrial robots, which are coarsely estimated to be around 100 000 units per year [54.18], the figures for domestic cleaning robots are five times as high.

However, the figures themselves present a naive fallacy. The estimated annual market volume for industrial robots totals around 3 billion EUR. The annual market volume for domestic cleaning robots, given the published figures, is estimated to be around 0.15 billion EUR, which is 20 times smaller. Furthermore, the market size for full-size household vacuum cleaners in the US was estimated to be close to 20 million units in 2003 [54.19]. So the ratio between domestic cleaning robots sold worldwide from 2002 to 2006 and regular vacuum cleaners sold only in the USA during the same time is 1:40. Conservatively estimated, this ratio may be around 1:400 or worse worldwide. Given these figures domestic cleaning robots still seem to be considered to be gadgets rather than appliances.

Is that a reason for joy? Of course, it is. The growth potential is enormous. If only 2% of all domestic vacuum cleaners sold per year were robots this would mean a growth of 800%. Having realized that, shall we now all invest in domestic cleaning robot manufacturers and then order a Ferrari? After all, a growth rate of 800% is an impressive target. As the reader might guess there is a problem here. Housewives (and househusband) are like companies and business people. They ask for a return on their investment. They invest in new equipment only if there is a return on investment and only if the new equipment has a competitive price-to-performance ratio. If it is cheaper to hire a cleaning person than to buy a cleaning robot, why should one buy a cleaning robot. The same holds if the device is cheap but does not do the job, as you still need to do the cleaning yourself.

Apparently, it all boils down to the question, how much is the average housewife or househusband ready to pay for a cleaning robot and what do they expect and how much are they ready to pay for a gadget? Are they ready to pay 3500 USD for a device which at least promises to systematically clean their living room or do they prefer to pay 100 USD for a toy which gets frequently trapped by cords and cables and breaks after a few month and create more noise than cleanliness?

Let us briefly look into professional cleaning and see whether the situation is different there. The professional cleaning of 1 m^2 floor costs on the order of 5–10 EUR cents if done manually with a mop (all figures are qualified estimates which are sufficient for a case study but do not claim to account for a specific application or business case). This includes the cost of labor and material. Now assume a 500 m^2 entry hall of a public building which is cleaned once a day, five days a week, 52 weeks a year. This totals approximately 6750 EUR per year.

Now assume that the cleaning is done by a robot which is deployed by a professional cleaner or housekeeper. Let us further assume that deploying and maintaining the cleaning robot takes the cleaner 20 min per day and that the cleaner has an hourly wage of 20 EUR. The labor for deploying and maintaining the cleaning robot accordingly costs approximately 1750 EUR per year.

What does this figure mean? Well it means that the cost for the cleaning robot must not exceed 5000 EUR per year, including consumables, repair, and purchase. Assuming a depreciation period of three years and assuming that consumables and repair make up 1000 EUR per year this means that the price for the robot must not exceed 12 000 EUR. Not a single one of the professional cleaning robot developed in the past 20 years has even gotten close to such a price. On average the price for a professional cleaning robot is around 50 000 EUR, four times the price that would satisfy our business case.

It should no longer be surprising that the number of professional cleaning robots installed over the past 20 years totals fewer than 500 units worldwide. What is even more disillusioning is the fact that, out of around 15 developments of robots for professional cleaning in the past 20 years, not a single one has survived and ever made it to a successful product [54.20].

What is the conclusion which we can draw from this? Well, launching a successful product does not only require a technology push but also a market pull. It is not the enthusiasm of the engineers which matters. It is the need of the customers and the business case.

54.6 Conclusions and Further Reading

In this chapter we have tried to give a survey of the state of the art in domestic robotics, smart appliances, and smart homes. We have tried to make this survey as comprehensive as possible, but do not claim that it is complete. In view of the huge market potential – we talk about hundreds of millions of customers – the field is developing rather dynamically. New products and new companies appear and disappear rather frequently.

We have discussed the technical challenges and open problems which have to be faced when developing a robot for a household task. Some of these challenges and problems require significantly more research to generate not only theoretical but also practical solutions; some are engineering problems, which are no less trivial. We have briefly looked into some new technologies which have the potential to boost the field and to make products more robust.

We have argued that wether or not a domestic robot makes its way onto the market is not only a matter of the engineers' ingenuity but also of the customers' needs and expectations and above all of the customers' wallet. There is a business case which needs to be met and not only technology to be developed.

We have given an overview of domestic cleaning robots for floors, windows, and pools and we have presented a selection of lawn-mowing robots. We have further looked into the latest developments in smart appliances such as ironing robots, intelligent refrigerators, and intelligent wardrobes. Some of these smart appliances are intelligent networked devices but are not service robots with motors, wheels, and sensors. We have finally looked at smart homes, in which domestic robots are or can be embedded.

Concluding this chapter one can say: some of the robots which Karel Capek and his brother Josef may have imagined in 1920 have become everyday reality 90 years later. Others, however, are still waiting to see the light of of day. And some may never see.

The publication that blazed the trail for service robotics as a whole and for robots for *household tasks* in particular is *Joe Engelberger*'s book *Robotics in Service* [54.21]. This book provides an amazing overview of potential applications of robotic technology for service tasks and, although it is nearly 20 years old, is still as inspiring as ever. A selective survey of the field of service robotics including domestic applications such as domestic cleaning and lawn mowing is given in [54.22]. A historical overview (until 2000) of the development of cleaning robotics from the very first prototypes to the very first products is presented in [54.23]. [54.24] reviews a selection of commercially available domestic robots and discusses open technical issues which have an impact on the development of domestic robots. The economic development of the field of service robotics as a whole branch and of domestic robots such as cleaning robots, robotic lawnmowers, entertainment robots, and assistive robots is documented in *World Robotics*, the annually published statistics of the Statistical Department of the International Federation of Robotics [54.18].

References

54.1 M. Schofield: Cleaning robots, Service Robots Int. J. **1**(3), 11–16 (1995)

54.2 J. Borenstein, H. Everett, L. Feng: *Where am I? Sensors and methods for mobile robot positioning*. University of Michigan. Tech. Report. (1996)

54.3 H. Choset: Coverage for robotics: a survey of recent results, Ann. Math. Artif. Intell. **31**, 113–126 (2001)

54.4 R.V. Bostelman, T.H. Hong, R. Madhavan: Towards AGV safety and navigation advancement obstacle detection using a TOF range camera, 12th Int. Conf. Adv. Robot., ICAR (2005)

54.5 R.D. Schraft, M. Hägele, K. Wegener: *Service-Roboter-Visionen* (Hanser Verlag, München 2004)

54.6 *SwissRanger SR-3000*. http://www.swissranger.ch/about.php

54.7 J. Hightower, G. Borriello: Location systems for ubiquitous computing, IEEE Comput. **34**(8), 57–66 (2001)

54.8 T. Weber: Smart floor: Neue Grundlagen für Robotersteuerung, CeBIT (2006)

54.9 E. Prassler, B. Kluge, T. Kämpke, M. Strobel: RFID navigation of service robots on smart floors, 3rd Int. Workshop Adv. Service Robots (2006)

54.10 Security firm develops fuel-cell robot. Press Release. http://www.fuelcellsworks.com/Supppage3152.html

54.11 D. Gann, J. Barlow, T. Venables: *Digital Futures: Making Homes Smarter*. Report published by Chartered Institute of Housing. (1999).

54.12 R. Harper: *Inside The Smart Home* (Springer, London 2003)

54.13 *JEITA*. http://www.eclipse-jp.com/jeita/
54.14 *Gator Tech Smart House*. http://www.icta.ufl.edu/gt.htm
54.15 *Aware Home Research Initiative*. http://www.awarehome.gatech.edu/
54.16 T. Sato, T. Harada, T. Mori: Environment-type robot system *Robotic Room* featured by behavior media, behavior contents, and behavior adaptation, IEEE/ASME Trans. Mechatron. **9**(3), 529–534 (2004)
54.17 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)
54.18 *World Robotics: Statistics, Market Analysis, Forecasts, Case Studies and Profitability of Robot Investment*. Int. Federation of Robotics. (annual)
54.19 R. Kirkpatrick: 2003 Association forecasts: vacuum cleaner manufacturers association, Appliance Magaz. (2003)
54.20 E. Prassler: Human friendly service robots: pitfalls, potentials, perspectives Invited talk, 15th German-Japanese Forum IT (2005)
54.21 J.F. Engelberger: *Robotics in Service* (Kogan Page, London 1989)
54.22 R.D. Schraft, G. Schmierer: *Service Robots: Products, Scenarios, Visions* (AK Peters, Natick 2000)
54.23 E. Prassler, A. Ritter, P. Fiorini, C. Schaeffer: A short history of cleaning robots, Auton. Robots **9**(16), 211–226 (2000)
54.24 H.I. Christenen: Intelligent home appliances, Proc. Robot. Res. Tenth Int. Symp. (2001)