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A Short History of Cleaning Robots

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Abstract. The definition of the desired functions and the design of an ultimate versatile personal robot is an ongoing debate. Meanwhile, however, precursors of this yet to evolve species are well on their way to become commercial products. Cleaning robots for public environments as well as for private households seem to be able to provide the breakthrough which the designers of non-industrial robot systems have long awaited.

This survey describes a selection of 30 different cleaning robots, with the first developments reaching back more than 15 years. With a few exceptions we have focused on floor cleaning, in particular indoor floor cleaning. We describe a variety of scrubbing and vacuuming robots which were developed for this task. The described systems range from heavy, large, and expensive industrial cleaning vehicles to small-size, light-weight, low-cost household devices. The survey does not include, however, systems for cleaning facades of buildings, or windows, or production tools.

Although not all of the 30 cleaning robots abovementioned have yet reached the state of commercial products, their number alone certainly reflects the expectations regarding the economic value associated with the automation of cleaning tasks. In Europe only the estimates for the market for cleaning services range up to the order of US$ 100 billion per year. It is therefore not surprising that the cleaning industry and the manufacturers of cleaning devices are rather enthusiastic with respect to the automation of cleaning tasks using (semi-)autonomous mobile robot systems.

Keywords: cleaning robots, autonomous cleaning devices, automatic cleaning, autonomous vacuum cleaner, robotic floor scrubber, autonomous pool cleaner, robotic road sweeper

1. Introduction

Operating a robot system in a natural public environment in such a way that it provides a useful service like cleaning a floor, is totally different from operating an industrial robot in a work cell. This is particularly true if the robot is supposed to work autonomously over large periods of time.

An industrial robot, for example a welding robot, usually operates under rather controlled conditions. The robot executes a preprogrammed sequence of elementary operations, for example, moving from coordinates (x_n, y_n) to (x_{n+1}, y_{n+1}) in a loop that goes on until the system is stopped by the operator. Such a preprogrammed sequence of operations does not require the robot to observe the environment, build up internal models, or reason about the environment. It does not require the robot to adapt its behavior to changes of the environment which may occur during the robot's operation. Unknown or unpredicted changes in the environment of an industrial robot which may interfere with its programmed operation are simply not allowed; if they occur, this leads to an immediate shutdown of the robot. The robot is not required to reason about its task and to develop or plan a course of action which might solve to task. It is not necessary to reason about possible interference by and interactions with human workers since they usually have to stay outside the robot's workspace.

All these issues attain considerable relevance once a robot is exposed to a natural environment and requested to operate there without human control. Not many of these issues are solved in a general and satisfying way, which would vitiate any further research effort. This may be one explanation for the fact that robotic technology until today has been predominantly used in manufacturing. Notwithstanding the fact that quite an amazing number of non-manufacturing tasks and operations lend themselves to automation by so-called service robots (Engelberger, 1989; Hägele, 1994), only a very modest number of those service robots has ever reached a state of development which would allow regular operation. This is astonishing, since the predicted market potential of those non-industrial applications exceeds that of industrial robots by far.

There is at least one application, however, where the situation is definitely different: cleaning. The market figures for cleaning services are remarkable. For Europe only the estimates for the cleaning service market is on the order of US$ 100 billion per year (Schoffield, 1995). This figure seems to unhinge the otherwise conservative attitude of the industry with respect to the use of robotic technology for non-industrial applications.

More than 15 years ago, large companies in Asia, North-America, and Europe have already started developing mobile robot systems for various cleaning tasks. Although most of these early systems remained as prototypes, the idea of using robots for cleaning tasks has not lost anything of its attraction and faces an increasing interest. Meanwhile, the technology has reached a state that allows mass production of cleaning robots. Two major manufacturers of cleaning and household appliances in Europe have both announced for the end of the year 2000 a commercial robotic vacuum cleaner for private households.

In this paper we try to give a representative overview of these 15 years of development of cleaning robots. Altogether we describe a selection of 30 different cleaning robots. We suggest that this selection is representative, but do not claim that it is complete. To illustrate the chronology of the various system developments we attached a year to the system descriptions in Sections 3 and 4 whereever it was possible. This year normally stands for date of the first publication (in articles or press releases), presentation (at conferences or fairs), or public announcement. In a few cases it was not possible to locate the time of the first publication or presentation as can be seen from the missing date.

With few exceptions, we have focused on floor cleaning, in particular indoor floor cleaning. We describe a variety of scrubbing and vacuuming robots which were developed for this task. The described systems range from heavy, large, and expensive industrial cleaning vehicles to small-size, light-weight, low-cost household devices. The survey does not include, however, systems for cleaning facades of buildings or windows or production tools.

In the paper we refer only to information which was publicly accessible. In the case of commercial products, technical information often had to be extracted and inferred from product announcements, sales brochures or press releases. As detailed technical data are usually kept confidential for understandable reasons, providing a comprehensive system description was impossible in some cases.

It was even more difficult to get any reliable information on industrial prototypes. Quite often our information about those systems was limited only to a single fact, namely that of its existence. And even that in some cases was confirmed by not more than a single picture.

Ideally this overview would be accompanied by performance measures or system comparisons. Unfortunately this was not possible, since only in rare cases were the developers were willing to release any data on the performance of their systems.

2. A Taxonomy of Cleaning Robots

In order to structure the description of the 30 cleaning robots to be surveyed we suggest a "taxonomy" for cleaning robots. Setting up such a taxonomy involves arbitrary choices, of course, since there is a number of equally appropriate criteria along which these systems might be classified. These criteria range from technical aspects and the system development state, over system costs, to the specific facets of the application and the targeted work space.

At the top level we divided the universe of (floor) cleaning robots into two categories depending on their professional use: *home cleaning robots* and *industrial cleaning robots*. This distinction covers more aspects than it might appear at a first glance. Home cleaning robots are by magnitudes smaller, lighter, and cheaper than industrial cleaning robots. While the size and weight of home cleaning robots are comparable with those of regular home cleaning devices such as vacuum cleaners, industrial cleaning robots are considerably larger and can reach a weight of half a ton and more. The target price for a home cleaning robot is on the order of US$ 500 to US$ 1000. An industrial cleaning robot can easily cost between US$ 50,000 to US$ 100,000, which means a price difference of a factor of 100.

Naturally, this price does not come about randomly. Industrial cleaning robots often carry complex cleaning units, which allow the application of several cleaning procedures (e.g., spraying, brushing, vacuuming) at the same time. Industrial cleaning robots in the price range of several US$ 10k are commonly equipped with sophisticated navigation systems, including costly sensor systems for perceiving the surrounding work space, obstacle avoidance and positioning. An essential component of these navigation systems is the planning unit, which computes the cleaning trajectory that optimally covers the work space of the cleaning robot. Well-equipped cleaning robots also have some quality assurance capabilities. They are capable of measuring the pollution on the ground and the result of the cleaning procedure, and thus can intensify the cleaning effort in areas which are more substantially particularly polluted.

Cleaning robots which are designed for private use rarely carry such sophisticated equipment, particularly if they are not to cost more than a few hundred dollars. Their sensor systems often are not more than an array of cheap contact sensors or infrared sensors. In the absence of farther reaching range sensors and reliable position sensors, simple locomotion heuristics, for example following random motion patterns, replaces the computation of optimal cleaning trajectories.

Orthogonally to the distinction between home cleaning robots and industrial cleaning robots we have further introduced the three categories *commercial product*, *industrial prototype*, and *research prototype*. These categories are supposed to reflect the state of system development. From a technical point of view the difference between commercial products and industrial prototypes is often hard to see or literally nonexistent. Often the technology of industrial prototypes is as advanced as the technology of their commercial relatives. What makes the difference is not a matter of technical matureness, but is based on whether the supplier has decided to start to market the system as a product.

Finally we distinguish cleaning robots according to their specific application and the cleaning technology which they employ. We have subclasses, for example, for *robotic vacuum cleaners*, *sweepers*, *and floor scrubbers* or *pool cleaning robots* or *duct cleaning robots*.

Our final taxonomy of cleaning robots is shown in Table 1. It should be noted that this taxonomy reflects the set of systems which we describe in this paper. With more systems and more applications the taxonomy may have to be modified appropriately. It should be also mentioned that we refrained from

Table 1. A taxonomy of cleaning robots.

	Cleaning robots	
	Home	Industrial
Commercial products	Robotic vaccum cleaners, sweepers, and floor scrubbers Pool cleaning robots	Robotic vacuum cleaners and carpet cleaners Robotic floor scrubbers and sweepers Duct cleaning robots
Industrial prototypes	Robotic vaccum cleaners, sweepers, and floor scrubbers	Robotic floor scrubbers and sweepers
Research prototypes	Robotic vaccum cleaners, sweepers, and floor scrubbers	Robotic road sweepers

further subdividing classes, for example, *robotic vacuum cleaners*, *sweepers*, *and floor scrubbers* into subclasses *robotic vacuum cleaners*, *robotic sweepers*, and *robotic floor scrubbers*, if for each such subclass there were not at least two instances.

3. Home Cleaning Robots

3.1. Commercial Products

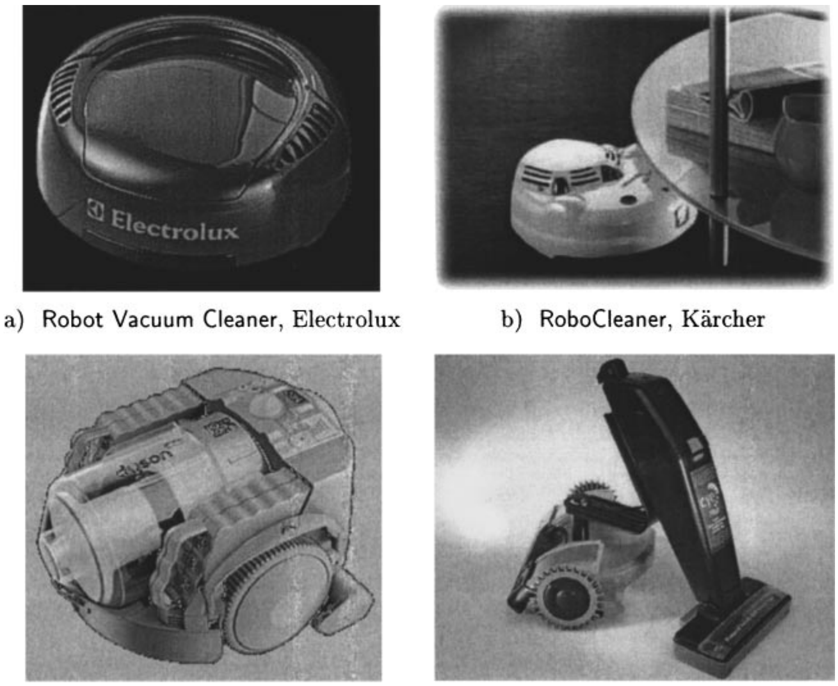
3.1.1. Robotic Vacuum Cleaners, Sweepers, and Floor Scrubbers. Probably the most promising and ubiquitous product idea for an autonomous cleaning robot is that of a robotic vacuum cleaner. Who would not buy one, provided the price were reasonable and would not exceed the price of a high quality, regular vacuum cleaner? The market potential seems to be enormous. First prototypes (Hitachi, Sanyo) were already presented around 1991. This suggested that the technology was there and one could have expected to see these prototypes as products on the market very rapidly. This did not happen, however; another decade had to pass before the first actual products were announced last year.

We collected information on five robotic vacuum cleaners which have reached the state of commercial products. It is worthwhile mentioning that no other system described in this paper has so far left the state of batch production.

Two of these five systems are commercially available already and were brought to the market by small enterprises, GeckoSystems (US) and Probotics (US). Whether these two systems are true household devices and ready for mass production or were designed more for entertainment and educational purposes is an open question.

The remaining three systems were announced to be released at the end of the year 2000 or for the beginning of 2001 by Electrolux (Sweden), Kärcher (Germany), and Dyson (UK). Of these, Electrolux and Kärcher are large enterprises with worldwide sales networks. The race for the first mass-produced robotic vacuum cleaner seems to be carried out by the two big players, Electrolux and Kärcher. According to unofficial announcements, both their systems will be available for approximately US$ 500.

Robot Vacuum Cleaner, Electrolux, Sweden, 1997
So far there is only little technical data available about the Electrolux Robot Vacuum Cleaner shown in Fig. 1(a). The device has a diameter of about 15 inch. It is powered by batteries which are recharged while



a) Robot Vacuum Cleaner, Electrolux

b) RoboCleaner, Kärcher

c) DC06, Dyson

d) Cye, Probotics

Figure 1. Commercial robotic vacuum cleaners.

the robot is stored on a charging stand. Robot Vacuum Cleaner can turn on the spot which suggests that the vehicle has a differential drive. For navigation and obstacle avoidance it uses a sonar based “radar”. To avoid damages in case of a contact the vacuum cleaner is equipped with a shock-absorbing bumper.

When Robot Vacuum Cleaner is started it first finds the closest wall. From there it follows the wall and the contour of the room and of any object it senses with its sonar system until it finally returns to this initial point near the wall. Electrolux does not describe, however, how this point is reliably discovered again. After the vacuum cleaner has covered the borders of the room it cleans the rest of the room by moving in random patterns.

Reference: http://www3.electrolux.se/robot/meny.html

RoboCleaner, Kärcher, Germany, 1999

Robot Vacuum Cleaner’s strongest competitor, the Kärcher RoboCleaner (see Fig. 1(b)), has been announced for Spring 2001. RoboCleaner has about the same size as the Electrolux system and weighs 1.4 kg. Like the Electrolux system RoboCleaner has a differential drive system. Approximately every twenty to thirty minutes the battery powered vehicle automatically returns to a base where it is recharged and its dust container is emptied. Altogether RoboCleaner has a power consumption of 20 W.

RoboCleaner cleans a room by following a random motion pattern. Doing so 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.

Reference: http://www.karcher.com/

DC06, Dyson, UK, 1999

The Dyson vacuum cleaner DC06 (see Fig. 1(c)), which was announced for the beginning of the year 2000, differs from the Electrolux and Kärcher systems not only with respect to the price. A DC06 costs approximately US$ 4000. This price, however, is related to the system design of the DC06 vacuum cleaner. While Robot Vacuum Cleaner and RoboCleaner are both equipped with single microcontrollers, a DC06 is controlled by three on-board computers. The DC06 system has more than 50 sensory devices, which enable the vehicle to locate itself in a room to detect and avoid obstacles and to stay away from staircases.

Due to its generous sensor and computer outfit, a DC06 can map its working space and distinguish between places where it has been already and where not. This allows a DC06 to vacuum a room in a systematic fashion by following a preplanned cleaning trajectory.

Reference: http://www.dyson.com

Cye, Probotics Inc., US, 1999

While the devices described above were developed for the specific application *vacuum cleaning*, Cye is sold for US$ 845 as a general purpose robot for a variety of applications, such as serving coffee, delivering mail, and vacuum cleaning. Quite ambitiously, Probotics Inc., the creator of the device, claims Cye to be the first personal robot. Cye is configurable for specific applications. In the cleaning configuration shown in Fig. 1(d) Cye is connected with a regular vacuum cleaner by a mounting. In operation Cye pulls or pushes the vacuum cleaner.

In terms of the navigation system, the developers of Cye also followed a slightly different philosophy than the developers of DC06, for example. While DC06 has more than 50 sensors, Cye only has a few, to measure the motor current and the wheel revolution. The motor current and wheel deceleration values are measured to discover collisions with objects. With the wheel encoders, Cye can monitor the distance which it has travelled and its orientation. With this limited sensor equipment Cye naturally has to operate more or less blindfolded. Cye’s peg wheels, however, allow it to keep track of its position along a planned path with reasonable accuracy. This reduces the need for sophisticated sensors and extensive sensing. Furthermore, while DC06 is equipped with three onboard computers, Cye (like RoboCleaner and Robot Vacuum Cleaner) uses only a single microcontroller as on-board computer. It is remotely controlled by a PC. The operating console on the PC allows the user to enter a map of Cye’s workspace and to define cleaning paths.

Notwithstanding the above claim of Cye being the first personal robot in its current state of development, Cye certainly has more characteristics of a professionally designed experimental mobile robot platform than of a versatile household device.

Reference: http://www.probotics.com

CareBot™ PCR, Gecko Systems, US, 1998

Another device, which is commercialized as a “personal computer robot” is CareBot PCR. Configured as a robotic vacuum cleaner CareBot PCR is offered at a price of US$ 2,995. Like Cye, CareBot PCR is

more an experimental platform for roboticists than a true household device. It is equipped with a navigation system which runs on a multiprocessor architecture and enables CareBot PCR to explore and map its environment, avoid obstacles, monitor its position, and control the integrated vacuum cleaner.
Reference: http://www.geckosystems.com/carebot/

3.1.2. Pool Cleaning Robots. Two other commercially available automatic cleaning robots were designed for the special application of cleaning pools. The apparent feature that distinguishes these pool cleaning robots from those described above is that they have to operate under water. This imposes some constraints on the design of the vehicle and its drive system, mostly tractor drives, as well as to the sensory equipment. On the other side, the navigation problem is somewhat easier, since the bottom of a pool usually has a quite simple geometric structure (rectangular) with no obstacles. Unfortunately there is little technical data available on both systems.

Dolphin DIAGNOSTIC 2001, Maytronics Ltd., Israel
Dolphin DIAGNOSTIC 2001 (see Fig. 2(a)) is a microprocessor controlled vehicle with a tractor drive. It is able to calculate a cleaning pattern for an arbitrarily shaped and sized pool. We do not have any information on the vehicle' sensory equipment and on the cleaning strategy. The Dolphin DIAGNOSTIC 2001 pool cleaner is available for US$ 999.
Reference: http://www.maytronics.com/

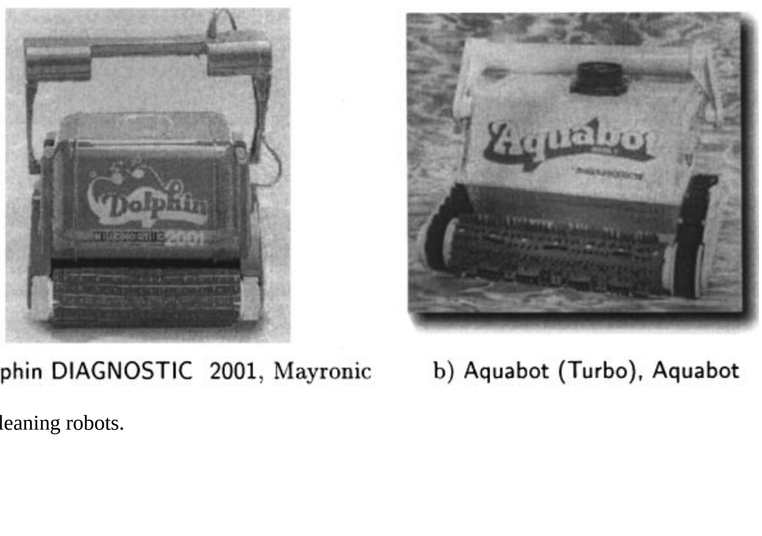
Aquabot Turbo, Aqua Products Inc., US
The competing system is Aquabot (Turbo) by Aqua Products. The design of Aquabot (Turbo) is very similar to that of a Dolphin DIAGNOSTIC 2001. It is based on a tractor drive and it has an external power supply through a floating power cord. Aquabot (Turbo) has a cleaning performance of 6500 square feet per hour. The price for aa Aquabot Turbo is US$ 999.
Reference: http://www.aquaproducts.com/

3.2. *Industrial Prototypes*

Although the development of at least two of the systems described in this section reaches back to the beginning of the nineties and earlier (Hitachi, 1986; Panasonic, 1991), they all remained in the state of industrial prototypes. It is unknown whether one of these systems has been announced or introduced as a product.

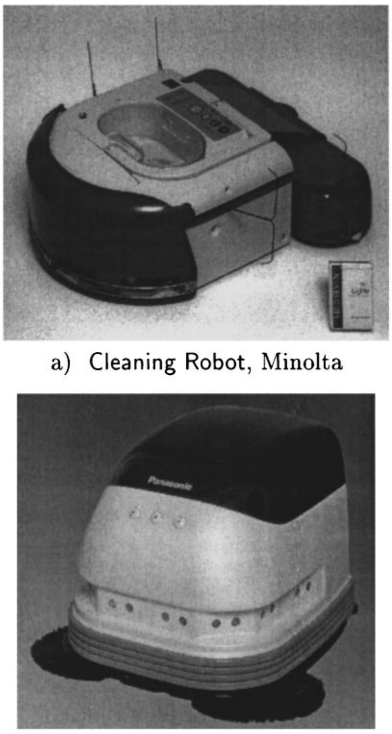
Cleaning Robot, Minolta, Japan, 1997
The Minolta Cleaning Robot, a more recent prototype, has a size of 321 mm $\times$ 320 mm $\times$ 170 mm and weighs about 8 kg. It has a two-wheel differential drive system, is powered by a Nickel Metal Hydrid battery, and uses a scrubber mechanism for cleaning the floor covering. Due to its small size and its rounded shape (see Fig. 3(a)), it can even get into tight corners. Cleaning Robot's sensory equipment includes sonar and tactile sensors, level sensors to discover stair cases, elevations and transitions between different floor coverings, and a gyroscope for maintaining position and orientation. Cleaning Robot's has a teach-in modus for programming cleaning trajectories.
Reference:
Schraft, R.D. and Schmierer, G. 1998. *Serviceroboter*, Springer-Verlag: Berlin.
Minolta 1997. *Science & Technology in Japan*, 16 (62):64.

Robby, Hitachi, Japan, 1986
Robby is the first known prototype of a robotic vacuum cleaner. First information about this system dates back to 1986. For its navigation Robby uses a gyroscope,



a) Dolphin DIAGNOSTIC 2001, Mayronic   b) Aquabot (Turbo), Aquabot

Figure 2. Commercial pool cleaning robots.



a) Cleaning Robot, Minolta

b) Brownie, Panasonic

Figure 3. Industrial prototypes of robotic vacuum cleaners.

infrared sensors, and a rotating sonar scanner.

Reference:
Schraft, R.D. and Schmierer, G. 1998. *Serviceroboter*, Springer-Verlag: Berlin.

Brownie, Panasonic, Japan, 1991

Panasonic developed two prototypes of home cleaning robots in 1989 and 1991, respectively. The second model, Brownie (see Fig. 3(b)), was presented in 1992 at Domotechnica in Cologne. Brownie is a cordless vacuum cleaner, has a diameter of approx. 40 cm and weighs 18 kg. It is equipped with a gyroscope, sonar sensors, and a dust sensor. The sensor data are fed to a microcontroller which computes a collision-free path. Once Brownie's batteries are low, it returns to a charging station.

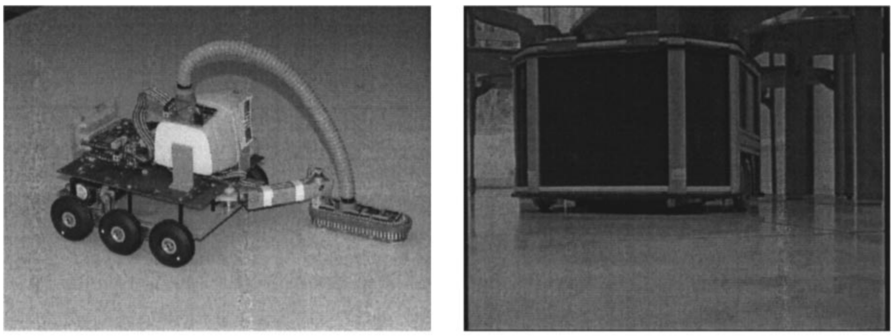
Reference:
Schraft, R.D. and Schmierer, G. 1998. *Serviceroboter*, Springer-Verlag: Berlin.
Data sheet, Panasonic/Matushita Electric Industrial Co., Ltd., 1991.

3.3. Research Prototypes

In this section we describe two research prototypes of cleaning robots (see Fig. 4). Koala is an autonomous vacuum cleaner, AutoCleaner is an autonomous floor scrubber for cleaning non-textile floor coverages.

Koala, LAMI, Swiss, 1997

A design study for an autonomous vacuum cleaner was conducted by the Laboratory of Microcomputing (LAMI), Swiss Institute of Technology. The study includes an investigation of possible shapes of a robotic vacuum cleaner, what sensors it should be equipped with, whether or not it should have a manipulator, and the requirements for the navigation system. The study lead to the development of Koala, a functional model of a robotic vacuum cleaner. Koala is based on a six wheel drive actuated by two DC motors, where each motor controls three wheels. It has a 2 DOF arm, where the second link of the arm is the actual *cleaning head*. This manipulator extends Koala's operational range considerably, since it can reach areas which are not accessible for the whole body. The arm, however, adds considerable complexity to the overall design, which would turn into cost when Koala ever became a product.



a) Koala, LAMI b) AutoCleaner, P+S Automation

Figure 4. Functional models of home cleaning robots.

Koala's sensor system consists of a tactile sensor system (tactile skin) for the cleaning head, a compass, and a dust sensor. It is controlled by four microcontrollers, two MC68331 and two MC68HC11, respectively, which are arranged in a master-slave configuration.

Reference:
Ulrich, I., Mondada, F., and Nicoud, J.-D. 1997. Autonomous vacuum cleaner. *Robotics and Autonomous Systems*, 19:233–245.
http://diwww.epfl.ch/lami/robots/K-family/vacuum.html

AutoCleaner, P+S Automation, Germany, 1999
AutoCleaner, developed by P+S Automation, is an autonomous wet cleaning floor scrubber for non-textile floor coverings such as parquet or wooden floors, stone floors or tiles, marble or concrete floors. The vehicle is based on a differential drive system with two castor wheels and carries a removable wet cleaning unit with an endless cloth and a container for collecting the slop and detergent. Both, the vehicle and the cleaning unit are powered by a two 12 V batteries. AutoCleaner uses tactile sensors (bumpers) for collision detection and avoidance and wheel encoders to monitor its own locomotion. Its navigation software runs on a 68HC11 microcontroller. AutoCleaner employs an optimized "blind cleaning" strategy, which combines a random walk with programmed trajectory patterns such as spirals and serpentines.

Reference: http://www.psautomation.de

4. Industrial Cleaning Robots

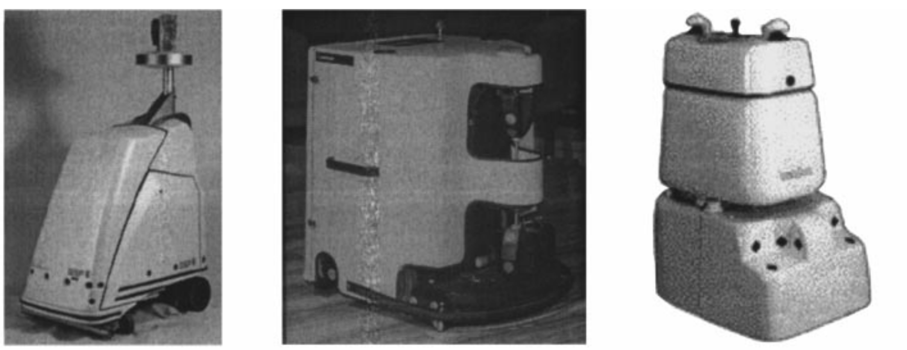
Although automatic cleaning by means of robot systems and the economic potential associated with this service is not limited to private households, it will undoubtedly be one of the target applications and environments for mass products. The number of commercially available systems which are described in this section suggests that the economic potential is even higher in the area of professional cleaning. Although the price of the systems below is in the range of several US$ 10K—due to the fact that the systems are produced in small series only—there seems to be an acceptable return on investment.

4.1. Commercial Products

4.1.1. Industrial Robotic Vacuum Cleaners and Carpet Cleaners. Figure 5 shows the robotic vacuum cleaners AutoVacC 6 and Cybervac II, and the robotic carpet cleaner DOLPHIN, which are described in this section.

AutoVacC 6, RoboSoft, France, 1996
AutoVacC 6 is an industrial robotic vacuum cleaner developed by Robosoft. It weighs about 300 kg, has a size of 115 cm $\times$ 65 cm $\times$ 130 cm and is powered by four 12 V sealed batteries with 60 Ah. Its propulsion consists of two 300 Watts DC Motors with 48 V input voltage which differentially drive the two main wheels. AutoVacC 6 is equipped with an array of ultrasonic sensors for obstacle detection and avoidance. For monitoring its position during operation it uses a laser range finder and an odometry systems with optical shaft encoders. AutoVacC 6 is controlled by two 68040 processors linked by a VME bus. It has three operation modes: it can be controlled remotely by a human operator, operate by repeating a taught cleaning trajectory, or work completely autonomously.

Reference: http://www.robosoft.fr



a) AutoVacC 6, RoboSoft b) Cybervac II, Cyberworks c) DOLPHIN, vonSchrader

Figure 5. Industrial robotic vacuum cleaners and carpet cleaners.

Cybervac II, Cyberworks Inc., Canada, 1991

A system which no longer seems to be on the market is Cybervac II. Like many other cleaning robots, Cybervac II was based on a differential drive system. It was powered by two 12 V batteries with 165 Ah and could reach a maximum speed of 40 cm/sec. It had a size of 90 cm $\times$ 75 cm $\times$ 95 cm and weighs 185 kg. Cybervac II had a cleaning performance of 800 m^2/h. The Cybervac II sensor system consisted primarily of a rotating sonar array of 12 ultrasonic transducers. The system could be further equipped with a vision system for tracking natural environmental features and an infrared ranging system. It was controlled by a Motorola 680X0 compatible 16/32 bit processor and an 8 bit I/O processor (Z80180).

Cybervac II was able to clean an unknown area by moving back and forth along parallel tracks between the boundaries (walls) of the workspace. When Cybervac II hit an obstacle it used a rather simple strategy to continue its operation and still cover the entire area. It did not try to get around the object. Instead it just turned around like at a regular boundary and continued its motion along the regular cleaning pattern. Cybervac II memorized such an event and stored the location of the obstacle to return later on and clean the area behind the obstacle.

Worth mentioning is Cybervac II's mechanical safety system. Cybervac II was equipped with a free-floating 2-axis shroud which acted as an omni-directional safety bumper for the robot chassis.

Reference: Data sheet, Cyberworks Inc., 1990.

DOLPHIN, VonSchrader, US

DOLPHIN, manufactured by VonSchrader is a mobile robot for carpet cleaning. With a size of of 70 cm $\times$ 55 cm $\times$ 105 cm it is somewhat smaller, for example, than AutoVacC 6. DOLPHIN does not have an independent power supply by batteries but needs a 110–120 Volt AC supply (50 ft. self-winding power supply cord). Accordingly it has a considerably smaller weight (approx. 75 kg). DOLPHIN has two gear motors with approx. 125 Watts. DOLPHIN's cleaning principle is as follows: air and detergent are mixed under pressure to generate a low moisture cleaning solution. This solution is discharged ahead of a cylindrical brush. The brush applies the solution to the carpet fibers. Loosened dirt is immediately extracted. DOLPHIN's has two operation modes: manual control by a joystick, autonomous locomotion along a preprogrammed cleaning trajectory.

Reference: http://www.vonschrader.com

4.1.2. Robotic Floor Scrubbers and Sweepers. Another group of industrial cleaning robots is formed by robotic floor scrubbers and sweepers (shown in Fig. 6). This distinction only refers to the cleaning principle and cleaning systems used by the various robots. It should be mentioned, though, that the difference between the employed cleaning principle is often far less significant in the classification of a cleaning robot than other system features such as sensory equipment or the control and guidance system.

ST82 R VARIOTECH®, Hefter Cleantech/Siemens, Germany, 1996

The ST82 R VARIOTECH® cleaning robot was developed in a collaboration between Hefter Cleantech and Siemens AG and is now manufactured and sold by Hefter. Several systems are installed in Albert Heijn supermarkets in the Netherlands and have been commercially used to clean natural crowded supermarket environments for more than two years during regular business hours.

Meanwhile more systems have been installed at the airport of Manchester, UK, in supermarkets in Germany and Austria, and in an exhibition hall at EXPO 2000.

The cleaning robot is based on a Hefter floor scrubber and is equipped with the commercially available Siemens navigation system SINAS. This navigation system comprises a 2D laser scanner, an array of sonar sensors, a gyroscope and an odometry system. The robot is programmed in a *teach-in mode*, where the robot is steered manually through its workspace along the desired cleaning trajectory. In this mode the robot also builds up an internal map of the environment which is later used for autonomous navigation through the supermarket. The map is further updated during regular operation. The robot can thus cope with unknown objects.

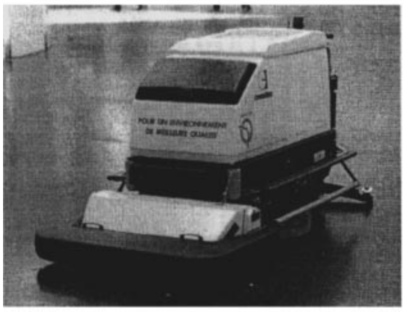
Reference:
http://www.hefter.de/cleantech/
Lawitzky, G. 2000. A navigation system for cleaning robots. *Autonomous Robots* (same issue).

RoboKent (ScrubberVac, SweeperVac), ServusRobots, US, 1989

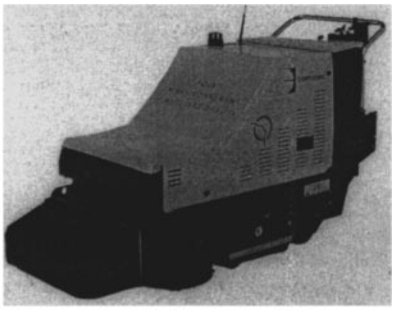
With over 300 units sold, a true old-timer amongst cleaning robots is the Servus Robots ScrubberVac and SweeperVac formally, RoboKent. It was developed and introduced to the market by The Kent Company a subsidiary of AB Electrolux of Sweden more then ten years ago. The Kent Company—after having changed

a) ST32 R VARIOTECH®, Hefter Cleantech

b) ScrubberVac, Servus Robots



c) Auror, Cybernetix (ROL)



c) Baror, Cybernetix (ROL)

e) CAB-X, Cybernetix (ROL)

f) Abilix 500, Midi Robots

Figure 6. Robotic floor scrubbers and sweepers.

hands several times—was bought up by Servus Robots in 1999.

Servus Robots has two versions, ScrubberVac and SweeperVac. As the name indicates, the ScrubberVac carries a 26 inch wide scrubbing unit. The cleaning solution used by this unit is recycled through a system of filters. The SweeperVac is equipped instead with a vacuum cleaning unit and a 22″ broom.

The ScrubberVac (and SweeperVac) does not need to be pre-programmed. It is rather able to plan its cleaning trajectory autonomously. It does not require any modifications of the environment such as installation of special navigational landmarks. The ScrubberVac (and SweeperVac) can detect and avoid obstacles. When it discovers an unknown object along its path it first stops and waits. If the obstacle does not move away within a few seconds, The ScrubberVac (and SweeperVac) moves around the obstacle and continues its mission.

Reference:
http://www.servusrobots.com
Engelberger, J.F. 1989. *Robotics in Service,* Kogan Page Ltd.

Auror and Baror, Cybernetix (ROL), France, 1994/1996
Auror and Baror are two cleaning robots which mechanically look quite different—Auror is a robotic scrubber, Baror a robotic sweeper. Auror and Baror share the same navigation system. Both machines can be operated in a manual and in an autonomous mode. In the automatic mode, Auror and Baror follow a trajectory defined by magnetic beacons set in the ground. These beacons form a system of artificial landmarks which allow the robots to keep track of their position. Each beacon encodes information on the trajectory leading to neighboring beacons (straight, turn right, turn left) and on its own precise position. Auror and Baror carry a sensor which allows them to read this information, which then is used to follow a certain trajectory and to precisely determine the robots position during their locomotion.

For obstacle detection and avoidance Auror and Baror are equipped with a system of ultrasonic and infrared sensors. Contact bumpers at the front and on both sides can trigger an emergency stop. An offspring of Auror, which shares Auror's control and navigation system, is the robotic floor scrubber Hakomatic B 90 R distributed by Hako, Germany.

Reference:
AUROR-BAROR, 1996. *Robotized Cleaning Machines*, Data sheet, Cybernetix.

CAB-X, Cybernetix (ROL), France, 1989
CAB-X differs form other known cleaning robots with respect to its drive system. While most cleaning robots are wheeled, CAB-X uses a differential caterpillar drive. This enables the vehicle to get over curbs and to even cope with staircases. Such a caterpillar drive is apparently advantageous in an environment such as the Parisian metro, in which CAB-X has to operate. Like the Auror and Baror systems described above, CAB-X uses a system of multi-pole magnetic markers and a dead-reckoning system for its navigation. CAB-X is controlled by seven Intel microprocessors 8031 and 8088.

Reference: Fraunhofer IPA database and archive on service robots.

Abilix 500, Midi Robots, France, 1993
The last example of a cleaning robot in the category robotic scrubber and sweeper is the system Abilix 500, which was developed by Midi Robots, a subsidiary of Thomson-CSF. Like Auror and Baror Abilix 500 uses a network of artificial landmarks and a dead-reckoning system for navigation and an array of sonar sensors for obstacle detection and avoidance. Abilix 500 follows a pre-programmed cleaning trajectory.

Reference: Data sheet, Midi Robots.

4.1.3. Duct Cleaning Robots. On a different scale not only in terms of their size and weight, but also in terms of cost and overall market potential are so called *duct cleaning robots* (see Fig. 7). They have to be light and small to fit in a duct.

Deluxe Cleaning Robot, Indoor Environmental Solutions, Inc., US, 1998
A robot that serves for duct cleaning as well as for inspection is the Deluxe Cleaning Robot. It is 46 cm long and 28 cm wide and has a weight of 17 kg. The Deluxe Cleaning Robot comes with a differential track drive. It carries two cameras: a high resolution wide-angle color forward camera, and a black and white adjustable rear camera. The Deluxe Cleaning Robot can be equipped with an air wand, spray wand or a rotary brush as tool. The system does not move autonomously but is remotely controlled.

Reference: http://www.cleanducts.com/deluxe.htm

XPW-x01, Hanlim Mechatronics Co, Ltd, Korea
The XPW-x01 is a wheeled duct cleaning robot with four or six solid rubber tires. It is distributed in several variants, which differ in the size and the number

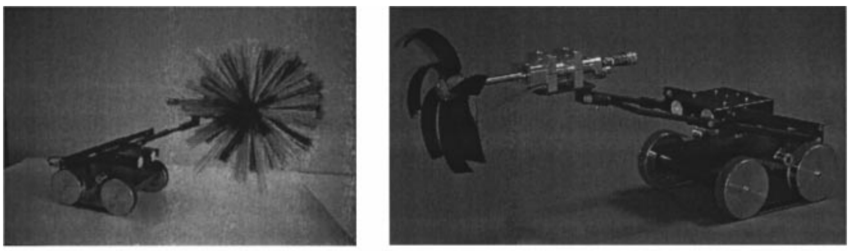


Figure 7. Duct cleaning robots.

of wheels. All system variations carry a high resolution CCD camera and are remotely controlled. Similar to the Deluxe Cleaning Robot the XPW-x01 system carries a rotating brush at the front side of the robot.

Reference: http://www.ductrobot.com/

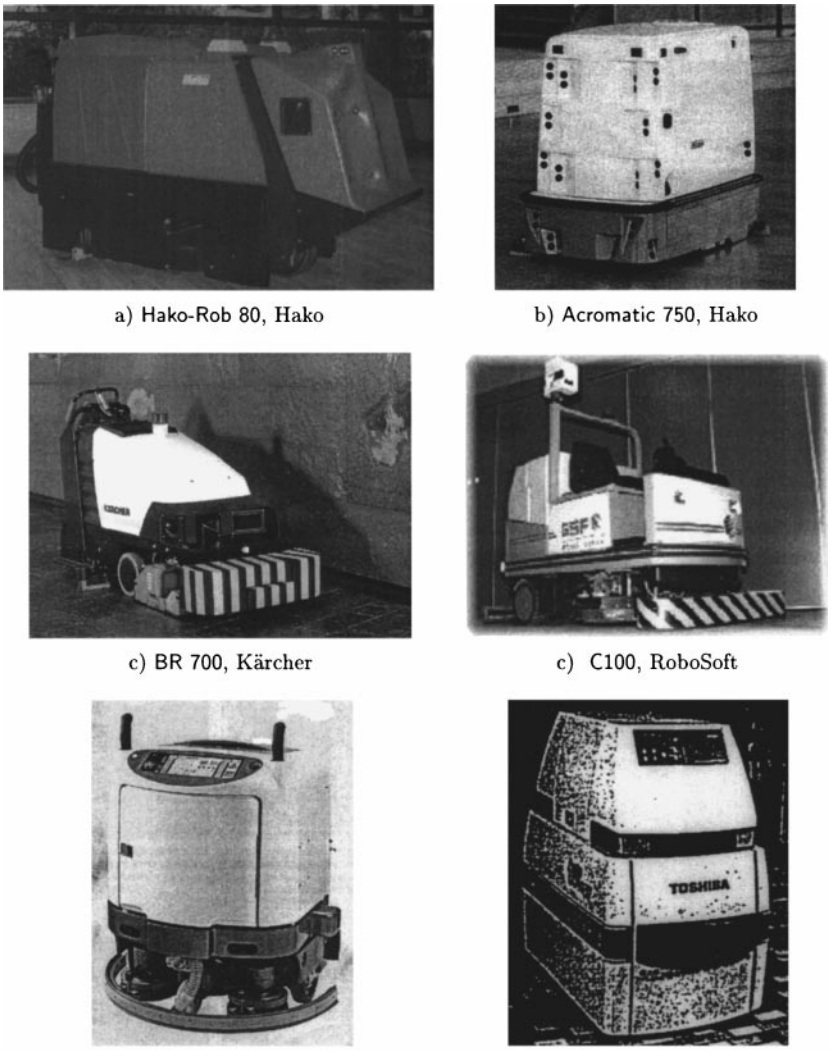
4.2. Industrial Prototypes

In this section we describe six industrial prototypes of robotic scrubbers and sweepers (see Fig. 8). As mentioned above the difference between these prototypes and commercial products is often not a matter of technical matureness but of an economic decision whether or not to bring the developed system to the market.

4.2.1. Robotic Floor Scrubbers and Sweepers

Hako-Robomatic 80, Hako/Anschütz, Germany, 1992

The Hako-Robomatic 80 cleaning robot carries a cleaning unit, which combines wet scrubbing and vacuuming in one operation. The cleaning robot is equipped with a set of sonar sensors to observe the surrounding environment and discover obstacles along its path. The sonar sensors are used to discover edges and discontinuities in the ground over which the robot might fall.



a) Hako-Rob 80, Hako

b) Acromatic 750, Hako

c) BR 700, Kärcher

c) C100, RoboSoft

e) AV-31, Fuji Industries

f) AutoSweepy, Toshiba

Figure 8. Industrial prototypes of robotic floor scrubbers and sweepers.

To keep track of its position during locomotion, the robot uses a dead-reckoning system and measures its distance to the closest wall by its sonar sensors.

The Hako-Robomatic has three modes of operation selected by a simple key switch: in manual mode it is operated as a normal hand pushed floor scrubber: in program mode the robot is taught its automatic path which is then executed when the switch is turned to automatic mode. The robot has three programming modes: start-point programming, line programming and thirdly contour mode. In the contour mode, for example, the robot is driven round an outside contour and then it repeats in automatic mode a meander path inside the boundaries of this contour. Should an obstacle hinder the robot's forward motion it makes a U-turn and continues to clean in parallel tracks.

Reference:

Vollautomatischer Reinigungsroboter Hako-Robomatic 80, data sheet, Hako.

Schofield, M. and Grünke, H. 1994. Cleaning robots from concept to product—the users point of view. In *Proc. of 25th Int. Symp. on Industrial Robots ISIR*, pp. 233–243.

Acromatic 750, Hako, Germany, 1996

The Hako-Robomatic 80's successor was the Acromatic 750. Drawing on experiences of testing the Hako Robomatic 80, the Acromatic 750 was a radical departure from other developments at the time in that a completely new mechanical design was made optimized for automatic control. Previously virtually all cleaning robots were based on adapting existing standard manual cleaning machines which always meant a lot of compromise. The new mechanical design was made highly compact so that the robot was highly manoeuvrable and had a high "pay load" in order to obtain the maximum running time without having to re-fill with water or change batteries, for example. A significant enhancement to the functionality was made in that the robot was equipped with software and sensors to allow model based navigation.

More recently the prototype has once again undergone a re-design with the sonar navigation sensors being replaced by a SICK laser scanner and the sonar anti-collision sensors being replaced by the Microsonic SonarSchutz system which is approved by German safety authorities as a contactless anti-collision safety system.

Reference:

Schofield M. 1999. "Neither Master nor Slave..." A practical case study in the development and employment of cleaning robots. In *Proc. IEEE 7th Int. Conf. on Emerging Technologies and Factory Automation ETFA'99*, Barcelona pp. 1427–1434.

BR 700, Alfred Kärcher GmbH & Co., Germany, 1996

BR 700 is a prototype of a robotic scrubber that was designed to clean the platforms of subway stations. BR 700 has a dead-reckoning system consisting of shaft-encoders and a gyroscope to monitor its position and motion, and a sonar system to perceive the environment while it is moving. The BR 700's safety system consists of a large soft bumper at the front side of the vehicle.

Cleaning trajectories are programmed in a *teach-in mode*. During this mode the system does not only record its position and its motion but also its perceptions of the environment through its sonar sensors while it is being steered along the desired trajectory. In the regular operation mode the BR 700 floor scrubber then follows these preprogrammed trajectories. If the BR 700 discovers an unknown object along its cleaning path it leaves this trajectory, drives around the obstacle and returns to the cleaning once it has passed the obstacle. Such a maneuver is executed only if there is enough room available. The BR 700 system can store three different cleaning paths.

Reference:

BR 700 Robot: *der Schrubbautomat zur bedienerlosen Bodenreinigung*, data sheet, Kärcher.

Per Roboter reinigen. *Lebensmitteltechnik* 12/1996.

Clean 100, RoboSoft, France, 1994

Clean 100 is a floor cleaning robot for supermarkets. It was developed by a consortium of European companies in the context of an European R&D project EUREKA EU No. 1094 CLEAN lead by RoboSoft France. It is based on C-100 floor scrubber manufactured by the Italian cleaning machine manufacturer Comac.

The Clean 100 is controlled by a navigation system including an onboard 68040 25 MHz microcontroller, a set of infrared and sonar sensor for collision avoidance, a dead-reckoning system and a laser scanner sensing reflector markers in the workspace both for position estimation. Like the BR 700 system, the Clean 100 has a *teach-in mode* during which it records the desired cleaning trajectory created by manually steering the vehicle through its workspace. Once put in an automatic mode, Clean 100 follows this recorded cleaning trajectory. When it discovers an unknown obstacle it stops until the obstacle disappears.

Reference: http://www.robosoft.fr/FRAMES/03Service/30Service.html

AV-31 (AV-71), Fuji Heavy Industries Ltd, Japan, 1993

The AV-31 cleaning robot was developed for sweeping and washing the floor in public areas such as train stations or office buildings. An AV-31 system was actually operated in the central station of Tokyo. Like the Hako cleaning robots, the AV-31 follows a meandering cleaning paths. Whenever it hits an obstacle it turns around and moves away in the opposite direction with a certain lateral offset until it hits the boundary of its workspace or another obstacle. It keeps traveling along those short cut meandering patterns until it can pass the obstacle and get around it. From there it continues moving along its initial path. The AV-31 cleaning robot is equipped with a fiber-optic gyroscope, an odometry system, and ultrasonic and tactile sensors. The AV-31 communicates with people through a speech synthesizer and plays music to entertain them and to attract peoples' attention.

Reference:
Yaguchi, H. 1996. Robot introduction to cleaning work in the East Japan Railway Company. *Advanced Robotics*, 10(4): 403–414.

AutoSweepy, Toshiba, Japan, 1986
The automatic floor scrubber and sweeper AutoSweepy was developed by Toshiba. AutoSweepy uses a gyroscope and an odometry system for positioning and a sonar system for obstacle detection and avoidance.
Reference: Fraunhofer IPA database and archive on service robots.

4.3. Research Prototypes

4.3.1 Robotic Road Sweepers.

Road Sweeper, TESS2 consortium (Kärcher, Fraunhofer IPA, FAW Ulm), Germany, 2000
Road Sweeper (see Fig. 9) is a cleaning robot designed to sweep large outdoor areas such as parking places of supermarkets or airports or factory yards. It is based on the commercial road sweeper KMR 1200 manufactured by Alfred Kärcher GmbH, Germany. Road Sweeper's navigation system includes an industrial controller Motorola 68332 25MHz for low level tasks such as velocity control, control of the cleaning unit and an industrial PC with a Pentium 166MHz as the main onboard computer for high level control tasks such sensor data processing, environmental mapping and motion planning. The sensor system of Road Sweeper consists of a SICK laser scanner LMS200, a set of Bosch ultrasonic sensors, a fiber optic gyroscope, and a Novatel differential GPS system.

The automatic guidance system of the road sweeper implements cleaning strategies which are similar to those used by the human driver. Border areas delimiting the workspace have to be cleaned first. This includes areas along curbs, fences or walls. The system then proceeds by moving along concentric overlapping trajectories towards the inner areas of the workspace. The system plans its optimal cleaning trajectories based on an internal map of the workspace. If the road sweeper discovers an unknown obstacle in its workspace it will be registered in a temporary copy of the permanent map, which is then used to plan an appropriate behavior.

Reference:
Prassler, E., Schwammkrug, D., Rohrmoser, B., and Schmidl, G. 2000. A robotic road sweeper. In *Proc. of IEEE Int. Conf. on Robotics and Automation ICRA 2000*, San Francisco, CA.

Road Sweeper, TESS2 consortium

Figure 9. Research prototype of a robotic road sweeper.

5. Summary

In this paper we described a variety of 30 different cleaning robots. These 30 systems constitute a representative selection of robotic cleaning devices developed over the passed 10–15 years, but is not a complete list. In particular, we included only a small number of research prototypes. The true number of research prototypes of cleaning robots is certainly much higher. Also the overview is limited to floor cleaning robots and does not include robots for cleaning windows or facades of buildings or production tools.

The variety of robotic cleaning systems ranges from low-cost, light-weight, "low-tech" devices for the private household, for example, robotic vacuum cleaners, to heavy, expensive industrial cleaning robots equipped with sophisticated cleaning units and navigation systems (see Table 1).

As we pointed out in the beginning this survey ideally would have been accompanied by some performance measures and/or by an evaluation and comparison of the presented systems. Due to the lack of accessible data such an evaluation or comparison was not possible. So this paper had to be confined to a mere presentation of systems. In other words the overview has more the flavor of a short history of cleaning robots.

Table 2. Technology utilized in robotic cleaning devices.

Drive systems
Differential (two/four/six wheels with castor wheels)
Tricycle (powered front wheels, powered rear wheels)
Caterpillar (differential)
Cleaning technology/modalities
Scrubbing (wet/dry)
Brushing
Sweeping
Vacuuming/sucking
Sensor equipment
Gyroscope, wheelencoders
Tactile sensing (bumper, suspended case)
Ultrasonic sensors (array/scanner)
Infrared
Laser scanner (natural landmarks/reflector markers)
(Vision)
Pollution sensors
Computer equipment
Micro-controller
Industrial PC
Multiprocessor system
Cleaning/navigation strategies
Random motion (with obstacle avoidance)
Contour following (with obstacle avoidance)
Hard-coded motion patterns (combined with random walk)
Following recorded (teach-in) cleaning trajectories
Following meandering paths (straight motion until a contact occurs, turn, continue on parallel track)
Online planning based on grid representation
Positioning strategies
Dead-reckoning
Absolute positioning with magnetic beacons or reflector markers
Aligning sensor readings with pre-programmed/generated map

Table 2 shows a summary of the technical key components (mechanical, electronic, and software) utilized in the described systems and gives a final impression of the scope of the employed technology.

The majority of the cleaning robots above are industrial and research prototypes. Some of these prototypes were presented years ago and seem no longer to exist. Still, the interest in developing robotic cleaning devices has by no means decreased. Rather the industrial effort, particularly in the development of commercial mass products, has been considerably increased. By the end of the year 2000 the first cleaning robots are supposed to appear on the shelves of warehouses, right in time for the christmas market.

We can only hope that this development opens the door to a new area in which robot systems outside of manufacturing environments are no longer seen as toys or academic proofs of concepts and in which service robots for various kinds of application penetrate our everyday life as inconspicuous and appreciated helpers giving its user more comfort, independence, leisure, and last but not least entertainment.

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Erwin Prassler received a master's degree in Computer Science from the Technical University of Munich in 1985 and a Ph.D. in Computer Science from the University of Ulm in March 1996. Between 1986 and 1989, he held positions as a member of the scientific staff at the Technical University of Munich and as a guest researcher in the Computer Science Department at the University of Toronto. In fall 1989, Dr. Prassler joined the Research Institute for Applied Knowledge Processing (FAW) in Ulm, Germany, as an associate researcher. Since 1994, Dr. Prassler has been heading a research group working in the field of mobile robots and service robots. He has published more than 50 papers, articles and reports in the fields of path planning and motion planning, robot navigation, service and rehabilitation robotics, and robotics in computer integrated manufacturing. He is the editor of a German research guide for robotics and automation. Erwin Prassler is a member of the Institute of Electrical and Electronic Engineers (IEEE), the Association for Computing (ACM), the German Association for Computer Science (GI), and the Association of German Engineers (VDI/VDE). He is the chair of the IEEE Technical Committee for Service Robots and a co-chair of the GI Committee for Robot Systems.

Arno Ritter received the degree as a Dipl.-Ing. for Electrical Engineering at the university of Kaiserslautern in 1996. Since 1997,

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Christoph Schaeffer received his master's degree (Dial.-Ing.) in Electrical Engineering/Computer Science from the University RWTH Aachen, Germany, in 1986. In 1987 he started as scientific R&D engineer at Fraunhofer-Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, Germany, in the fields of mobile robots. He has been a project leader for prototype developments in material flow and sevice robotics, since 1988. Christoph Schaeffer was successful proposer and Project Manager of European Research Project ESPRIT 5292 MOSAIC—Modular Motion Control System with unified Interfaces, 1990–1992. Furthermore he is co-proposer and International Working Group Leader of the Material Flow Group within the international IMS project Holonic Control Systems (HMS), 1993–2000. Since 1992 he has been Group Leader at Fraunhofer IPA in the department "Robot Systems", responsible for a group of ten full-time scientific engineers. Christoph Schaeffer is personal expert for motion control and sensor guidance of robot systems with application to industrial handling, material flow and service robotics. He has special expertise in control system architectures, program generation, motion planning, task scheduling and operator interfaces.

Paolo Fiorini holds a Laurea Degree in Electrical Engineering from the University of Padua (Italy), and MSEE from UCI, and Ph.D. in ME from UCLA. Since 1985 he has been a Staff Member in the Robotics and Teleoperation groups at NASA Jet Propulsion Laboratory of the California Institute of Technology, where he is active in the areas of Telerobotics, Intelligent Control and Operator Interfaces. Prior to his employment at JPL, he held several industrial positions in Italy and in the US. Dr. Fiorini has published more than sixty papers in scientific journals, conferences proceedings and technical reports, and organised several workshops in robotics. He was scientific secretary of the 1997 International Conference on Advanced Robotics. His experience also includes teaching as Visiting Professor at the National Univerisity of San Juan (Argentina) in 1995, at the University of Padova (Italy) in 1993. Currently, he is an Adjunct Professor of Control Systems at the University of Verona (Italy).