DOMESTIC ROBOTICS – A TECHNICAL SURVEY

M. Mugilvalavan [1], R. Nandhakumar [2]

Department of Mechatronics Engineering, Agni College of Technology, Chennai.

ABSTRACT

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.

INTRODUCTION

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.

CLEANING ROBOTS

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 multi robot 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 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.

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. 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-andbounce 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.

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 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 whichmust not cost more than say 300 USD, a sensor which costs 20USD 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. Avery 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 allowbut 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 multi robot 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 subwork spaces, 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 30–60min per charge. Professional cleaning robots often use regular 24V 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.

CONCLUSION

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. 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.

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