Robotics in the home, office, and playing field

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Abstract

Robots are gradually entering into diverse application domains such as home, office, and playing field. This article presents advanced research activities related to these domains. First is RoboCup which is an attempt to promote AI and robotics research by providing a common task for evaluation of various performance, theories, algorithms, and robot architectures. In order for robots (both physical robots and soft agents) to play a soccer game reasonably well, a wide range of technologies need to be integrated and a number of technical breakthrough must be accomplished. The recent results from the last two RoboCups are reviewed and future leagues are introduced. Second, the richer domain of service robotics has also received significant interest recently. The task here is to serve as a human assistant in an office or domestic environment, for tasks like cleaning and delivery. The human-robot interaction is a key issue to success, which poses new challenges in terms of integration of spoken dialogue, gestures, body language, etc. In addition mobile manipulation and safe navigation around humans is essential to success. These two areas integrates many different disciplines including control, perception, natural language processing, hybrid systems and handling of uncertainty, and applied to tour guiding, mail delivery, domestic services, and rescue activities.

1 Introduction

Robotics offers a fertile ground for demonstration of artificial intelligence techniques. The domain provides a basis for real-world evaluation of techniques under realistic assumptions. Construction of robotic systems requires at the same time integration of a diverse range of expertise in order to provide operational systems. Traditionally robot systems have been used in manufacturing, in particular in the car industry. The majority of robots sold today are still deployed for spot-welding and car painting. Mobile robots have so far not gained the expected wide-spread use. This is primarily due to two problems: i) adequate perception to enable deployment of systems is natural environments, and ii) lack of adaptive techniques for planning and error recovery in the context of rich environments.

Recently a number of new application areas have received significant interest. Already in 1989 the farther of robotics, Joseph Engelberger, predicted that service robotics will be a major new business area for robotics [Engelberger, 1989]. Service robotics involves assistance to elderly, commercial and domestic cleaning, tour guides, and delivery services (medicine, mail, printer output, etc). In parallel the area of entertainment has begun to attract significant attention. Excellent examples of entertainment robots include the MindStorm system sold by LEGO (an interactive toy for children) and the SonyDogs, developed by SONY (see next section). These applications clearly demonstrate that mobile robots gradually are becoming a part of our everyday life.

In terms of entertainment a well-structured effort of Robot Soccer has been initiated (term RoboCup). We will here introduce the overall aim of RoboCup, review results from recent competitions and point to its utility to artificial intelligence research. In parallel we will review recent new results in the area of service robotics and illustrate how this field brings together a range of different methodologies to allow deployment of mobile robots in our regular life.

2 RoboCup - Integrating AI and Robotics

RoboCup (The Robot World Cup Initiative) is an attempt to promote intelligent robotics research by providing a common task for evaluation of various theories, algorithms, and agent architectures [Kitano *et al.*, 1997]. RoboCup has currently chosen soccer as its standard task. In order for a robot (a physical robot or a software agent) to play a soccer game reasonably well, many technologies need to be integrated and a number of technical breakthroughs must be accomplished. The range of technologies spans the gamut of intelligent roboticsresearch, including design principles for autonomous agents, multi-agent collaboration, strategy acquisition, real-time reasoning and planning, robot learning, and sensor-fusion.

The First Robot World Cup Soccer Games and Conferences (RoboCup-97) was held during the International Joint Conference on Artificial Intelligence (UCAI-97) at Nagoya, Japan with 37 teams around the world, and the Second Robot World Cup Soccer Games and Conferences (RoboCup-98) was held on July 2-9,1998 at La Cite des Sciences et de l'Industrie (La Cite) in Paris with 61 teams. RoboCup-99 Stockholm will be held in conjunction with IJCAI-99 participated in by over 120 teams. A series of technical workshops and competitions have been planned for the future. While the competition part of RoboCup is highlighted in the media, other important RoboCup activities include technical workshops, the RoboCup Challenge program (which defines a series of benchmark problems), education, and infrastructure development. As of April 1999, RoboCup activity involves thousands of researchers from over 36 countries. Further information is available from the web site: http://ww.robocup•org/

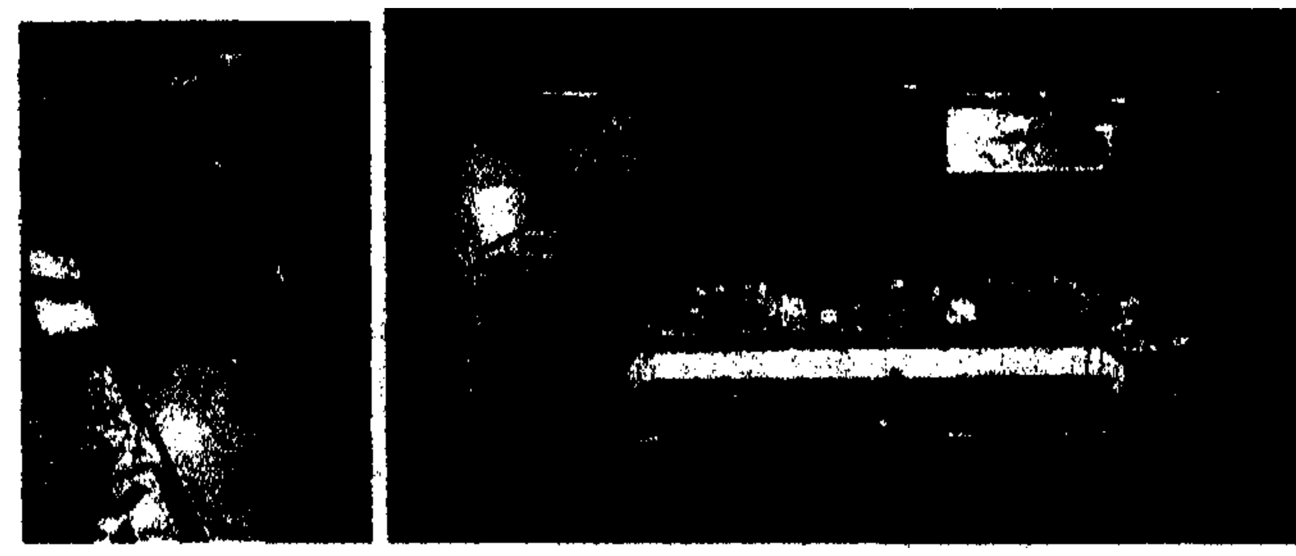
2.1 What's RoboCup?

RoboCup has a series of activities such as competitions, conferences, RoboCup challenges, education, infrastructure, and secondary domain. Among them, however, competition remains the most well-known component. We think competition has unique value in testing robots and software teams in environments outside of the laboratory. It also forces participants to build robot platforms which reliably perform the task, instead of showing superb performance once in a hundred times. And of course, competition is fun. It motivates students and appeals to spectators.

Currently, RoboCup consists of three competition tracks:

1. Simulation league: Each team consists of eleven programs, each controlling separately each of eleven team members. The simulation is run using the Soccer Server developed by Noda et al. Each player has distributed sensing capabilities (vision and auditory) and motion energy both of which are resource bounded. Communication is available between players and strict rules of the soccer game are enforced (e.g. off-sides). This league is mainly for researchers who may not have the resources for building real robots, but are highly interested in complex multi-agent reasoning and learning issues.

2. Small-size real robot league: The field is of the size and color of a ping-pong table (See Figure 1(a)), and up to five robots per team play a match with an orange golf ball. The robot size is limited to approximately $15cm^3$. Typically robots are built by the participating teams and move at speeds of up to 2m/8. Global vision is allowed, offering the challenge of real-time vision-based tracking of five fast moving robots in each team and the ball.



(a) the small size (b) the middle size

Figure 1: Competition sites

3. Middle-size real robot league: The field size is of the size and color of three by three ping-pong tables (See Figure 1(b)), and up to five robots per team play a match with a Futsal-4 ball. The size of the base of the robot is limited to approximately 50cm diameter. Global vision is not allowed. Goals are colored and the field is surrounded by walls to allow for possible distributed localization through robot sensing.

Aside from the winner of each league, RoboCup awards the Scientific Challenge Award and Engineering Challenge Award for the team which made a major challenge with some success. These awards were established to foster challenging scientific and engineering research in RoboCup. In general, the safest approach to winning the competition is to use conventional and reliable technologies well-tuned for the specific domain. The RoboCup domain is challenging enough so that any successful team must use some challenging technologies. However, these awards are given for truly high-risk and high impact design.

In RoboCup-97, the Scientific Challenge Award was given to Sean Luke of the University of Maryland for demonstrating the utility of evolutionary computation by co-evolving soccer teams. Two engineering challenge awards were given to Uttori-United (a joint team consisting of Ustunomiya Univ., Toyo Univ., and RIKEN, Japan) and RMIT Raiders (Royal Melbourne Institute of Technology, Australia) , for designing novel omnidirectional driving mechanisms.

In RoboCup-98, the Scientific Challenge Award was given to three research groups (Electrotechnical Laboratory (ETL), Japan, Sony Computer Science Laboratories, Inc., Japan, and German Research Center for Artificial Intelligence GmbH (DFKI)) for their simultaneous development of fully automatic commentator systems for RoboCup simulator league.

Technical details of teams represented in RoboCup-97 as well as related research results was published as the official publication [Kitano, 1998], and those in RoboCup-98 will appear (Asada and Kitano, 1999}, AI journal special issue on RoboCup features excellent works on RoboCup research issues about multiagent reinforcement learning, teamwork formation, and so on [Kitano and Asada, 1999] For the details of the results of all matches in RoboCup-97 and RoboCup-98, please visit the site: http://ww.robocup.org/

2.2 Research Issues and Approaches

In this section, we discuss several research issues involved in the development of real robots and software agents for RoboCup. One of the major reasons why RoboCup attracts so many researchers is that it requires the integration of a broad range of technologies into a team of complete agents, as opposed to a task-specific functional module.

Currently, each league has its own architectural constraints, and therefore research issues are slightly different from each other. We have published proposal papers about research issues in RoboCup initiative. For the synthetic agent in the simulation league, the following issues are considered:

- Teamwork among agents, from low-level skills like passing the ball to a teammate, to higher level skills involving execution of team strategies.
- Agent modeling, from primitive skills like recognizing agents' intents to pass the ball, to complex plan recognition of high-level team strategies.
- Multi-agent learning, for on-line and off-line learning of simple soccer skills for passing and intercepting, as well as more complex strategy learning.

For the robotic agents in the real robot leagues, for both the small and middle-size ones, the following issues are considered:

- Efficient real-time global or distributed perception possibly from different sensing sources.
- Individual mechanical skills of the physical robots, in particular target aim and ball control.
- Strategic navigation and action to allow for robotic teamwork, by passing, receiving and intercepting the ball, and shooting at the goal.

More strategic issues are dealt in the simulation league and in the small-size real robot league while acquiring more primitive behaviors of each player is the main concern of the middle-size real robot league.

Architectural Analysis

There are two kinds of aspects in designing a robot team for RoboCup:

1. Physical structure of robots: actuators for mobility, kicking devices, perceptual (cameras, sonar, bumper sensor, laser range finder) and computational (CPUs, microprocessors) facilities.
2. Architectural structure of control software.

In the simulation league, both of the above issues are fixed, and therefore more strategical structure as a team has been considered. On the other hand, in the real robot leagues, individual teams have devised, built, and arranged their robots. Although the small league and the middle one have their own architectural constraints, there are variations of resource assignment and control structure of their robots. Table 1 shows the variations in architectural structure in terms of number of CPUs and cameras, and their arrangement.

Three types A, B, and C indicate a variation adopted in the real robot small-size league. Type A is a typical structure many teams used in this league: the centralized control of multiple bodies through a global vision. Type B is a kind of multiagent system in which decision making is distributed and independent from each other although they share the global vision. CMUnited-98 in the small-size league took this sort of architecture. Type C features sensor coordination of global and local views based on the centralized control with multiple bodies. I-space (a joint team of Utsunomiya Univ. and Univ. of Tokyo, Japan) in the small-size league adopted this type architecture.

On the other hand, type E is a typical architecture adopted in both the simulation league and the real robot middle-size league: a completely distributed multiagent system. Type D used C. S. FVeiburg team in the middle-size league adopted a combination of types A and E utilizing laser range finders mounted on players which make it possible to reconstruct the global view and to localize observed objects (teammates, opponents, and ball) in the field. That is, they changed the problem in the middle-size league into one in the small-size league.

Communication between agents is possible in all of the leagues. The simulation league is the only that uses it except one team Uttori in the middle-size league. In the following, we attempt to analyze the achievements in RoboCup-97 and 98 in terms of each league.

2.3 Simulation League

The simulation league continues to be the most popular part of the RoboCup leagues, with 34 teams participating in RoboCup-98, which is a slight increase over the number of participants at RoboCup-97. In RoboCup-98, because of the offside rule introduced from 1998, most of matches are carried out in 'compact soccer' style like human soccer which provides two research issues closely related to each other: dynamic formation and opponent monitoring. This means the change from position based role assignment to context sensitive dynamic role assignment.

Teams in the RoboCup simulation league are faced with three strategic research challenges: multi-agent learning, teamwork and agent modeling. All three are fundamental issues in multi-agent interactions. The learning challenge has been categorized into on-line and off-line learning both by individuals and by teams (i.e., collaborative learning). One example of off-line individual learning is learning to intercept the ball, while an

Table 1: Variations in architectural structure

Type	CPU	Vision	issues	league
A	1	1 global	strategy	small-size
B	n	1 global	sharing of information	small-size
C	1	1 global + n local	sensor fusion; coordination	small-size
D	1+n	n local	multiple robots	middle-size
E	n	n local	sensor fusion; teamwork	middle-size & simulation

example of on-line collaborative learning is to adaptively change player positions and formations based on experience in a game. The detailed analysis is given in the paper in [Kitano and Asada, 1999].

The stage in RoboCup-98 is still in the preliminary level. For example, tactics to escape from off-side traps was still passive even in champion teams. In future RoboCup, such tactics will require recognition of intention of opponent players/teams. In this stage, opponent modeling and management of team strategies would become more important. Similarly, on-line learning will become more important, because team strategies should be changed during a match according to strategies of opponent teams.

2.4 Small-Size Real Robot League

The environment in the small-size league is highly dynamic with robots and the ball moving at speeds between Ira/s and 2m/s. An interesting research issue consists of the prediction of the motion of the mobile objects to combine it with strategy. In the case of the CMUnited-98 team, prediction of the movement of the ball was successfully achieved and highly used for motion (e.g., ball interception) and strategic decisions (e.g., goaltender behavior and pass/shoot decisions).

One of the main interesting open questions is the development of algorithms for on-line learning of the strategy of the opponent team and for the real-time adaptation of one's strategy in response. Finally, similarly to the simulation and middle-size leagues, we want to abstract from our experience algorithms that will be applicable beyond the robotic soccer domain.

2.5 Middle-Size Real Robot League

The performance of robot behaviors in RoboCup-98 was better than in RoboCup-97 although the number of teams in the middle-size league drastically increased from 5 to 16, more than three times. However, the level of skills is under development, mainly putting more focus on individual behavior acquisition than cooperative teamwork. Engineering issues such as precise robot control and robust object detection are still main issues in this league.

The focus on colors to visibly distinguish objects exerts a strong bias for research in *color-based* vision methods. It is desirable to permit other approaches as well, such as using *edges, texture, shape, optical flow* etc., thereby widening the range of applicable vision research within RoboCup.

Finally, the use of communication in the different leagues is also an active research topic. Communication allows interesting research in a variety of topics, including multi-robot sensor fusion and control. We want to explore limited communication environments and its relationship to agent autonomy, and learning of cooperative behavior.

2.6 New Leagues

In RoboCup-98, Sony Legged Robot exhibition games and demonstration were held, and they attracted many spectators, especially boys and girls, for its cute style and behaviors. Figure 2 shows a scene from their demonstrations. In 1999, Sony Legged Robot league will be one of the RoboCup official competitions with more nine teams around the world.

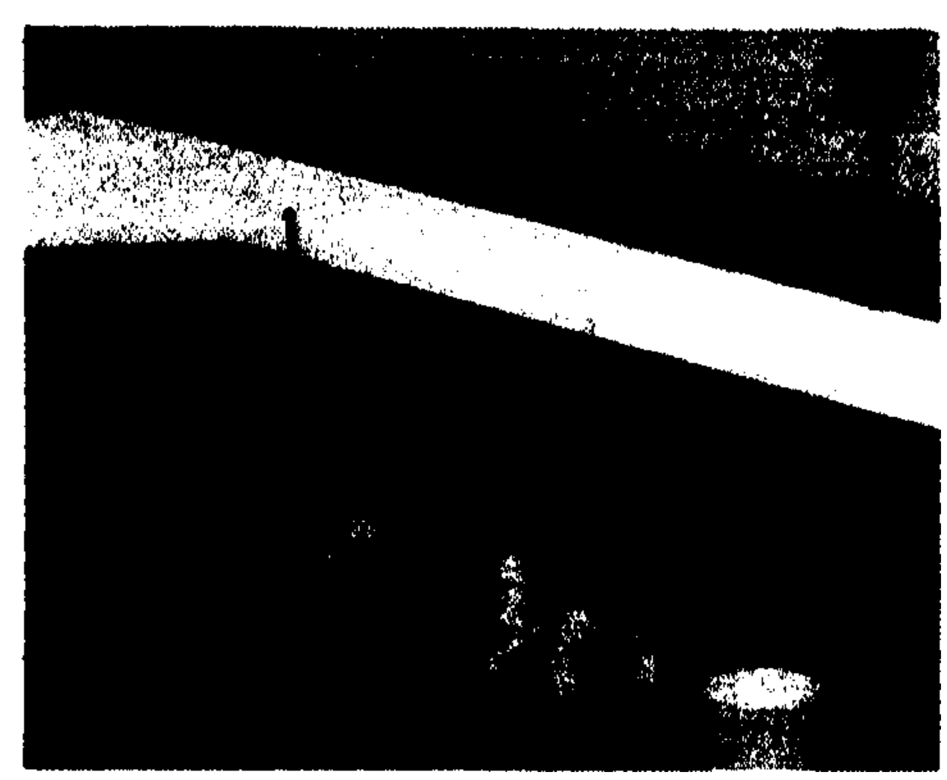


Figure 2: A scene from Sony legged robot demonstration

Currently, except for Sony Legged Robot League, games are played by wheel-based robots, soccer game by humanoid robot is the next major leap in the field which leads to the ultimate goal of the RoboCup [Kitano and Asada, 1998].

Before, actually play soccer with human players, RoboCup organize humanoid leagues in following categories, and start Humanoid league competition from RoboCup-02 (2002). Fig.3 shows the performances by Honda P3 in 1998, and they will show 3 by 3 humanoid

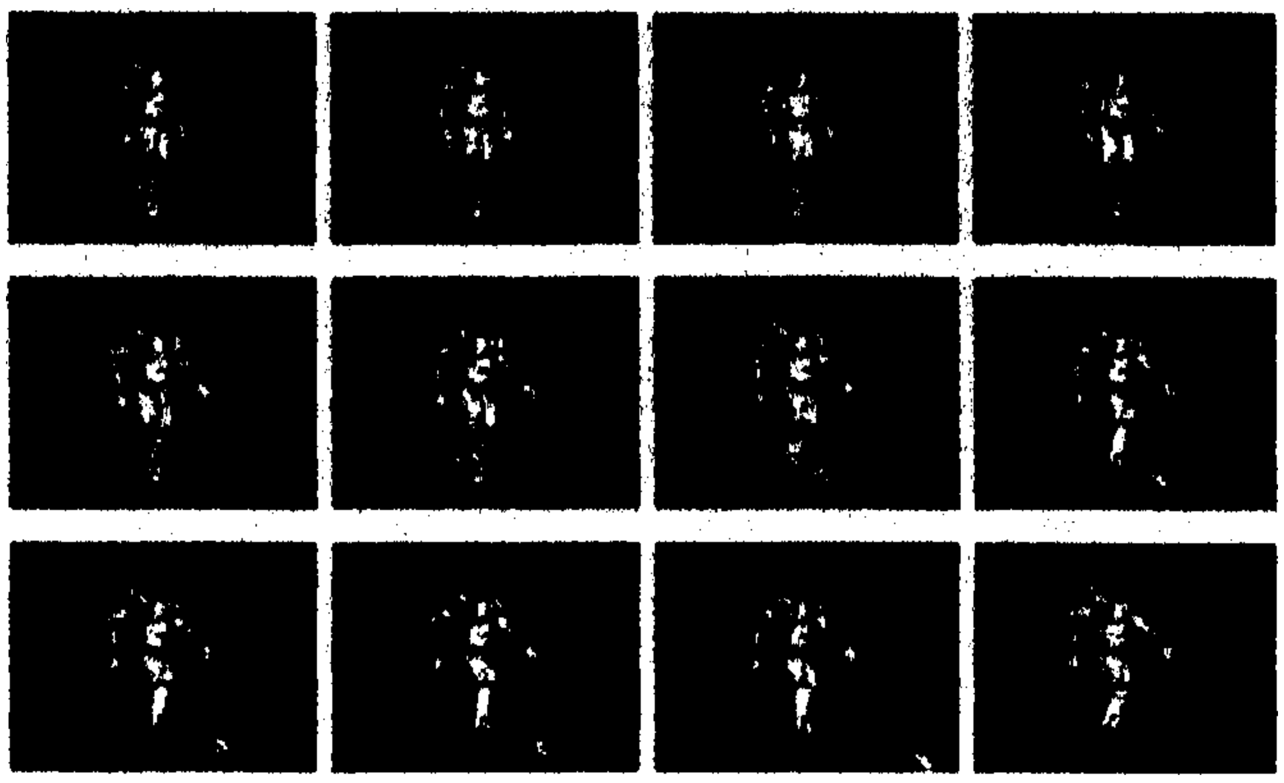


Figure 3: Shooting Play by Honda P3

games in RoboCup-2002, the year of World Cup in Japan and Korea.

2.7 RoboCup New Activities

The comprehensive nature of RoboCup makes it an ideal subject for project-oriented AI and robotics courses. Already, a few undergraduate and graduate courses are now being planned using RoboCup. Further, an education infrastructure named RoboCup Jr. is proposed, reflecting the needs of educational institutions. RoboCup Jr. will use cheaper robots and a much simpler task domain, rather than the highly challenging arrangement seen in the current RoboCup competition. A prototype of platforms will make a debut in 2000 or 2001, and the official league RoboCup Jr. will start from 2002.

Disaster rescue is one of the most serious social issue which involves very large numbers of heterogeneous agents in the hostile environment. RoboCup-Rescue intends to promote research and development in this socially significant domain by creating a standard simulator and forum for researchers and practitioners. While the rescue domain intuitively appealing as large scale multi-agent domains, it has not yet given through analysis on its domain characteristics. RoboCup-Rescue targets search and rescue activities for large-scale disaster like Kobe earthquake in 1995.

3 Service Robotics

Service robotics covers a range of robot applications including office automation, lawn moving, assistance to handicapped and elderly, and domestic services. The vision of a domestic servant is at least three decades old, yet little progress has been achieved until recently. By 1989 Engelberger [Engelberger, 1989] predicted that service robotics would be a major commercial market for robotics by the end of the century, yet the large scale commercial potential is yet to be demonstrated.

The most dominating problems in development of service robots are reliable mapping and interaction with the environment. For operation in a regular home it is impossible to make strong assumptions about the layout, the materials encountered, the behaviour of other agents like dogs, children, etc. To provide a viable solution it is necessary to provide systems that are fully autonomous and which have extensive facilities for error detection and recovery.

Research in perception, intelligent control, probabilistic mapping and human-robot interaction has generated results that recently have allowed demonstration of a range of service robots applications with a significant potential. In the following we will briefly outline several of these systems.

3.1 Hospital Automation

Over the last five year the company HelpMate Robotics have deployed more than 120 HelpMate systems in hospitals. The robot system provides delivery services to the staff. Typical services includes pick-up and delivery of meals and transport of medical records and specimens between the different departments and the laboratory. The system uses a touch screen in combination with spoken feedback for communication with users. The navigation is based on ultra-sonic sonars for obstacle detection, ceiling mounted landmarks for absolute localisation, and a laser radar for docking. The system operates in pre-specified environments and have no facilities for error-recovery. In the event of an error a radio modem is used for signalling for assistance. The HelpMate system is one of the most widely deployed service robot today. The autonomy of the system has first and foremost been achieved through careful engineering of the system and its environment. This implies that the cost of deployment is significant and due to its limited ability to perform error recovery there is need for trained staff to operate the vehicle.

3.2 Commercial cleaning

Another area that has received significant attention over the last 5 years is commercial cleaning of hotel corridors, conference facilities and more recently supermarkets. During early 1990 the company Kent Inc. automated a series of their floor cleaners. The system uses a combination of ultra-sonic ranging and inertial sensing for navigation. The system, named RoboKent, drives through a specific area and builds up a map of the environment. Once a map is available a zamboni pattern is used for traversal of the area. The system requires fairly well structured environment for its operation. I.e., it is unable to clean small niches and narrow passages. The robot uses a simple depth-first strategy for traversal of multiple corridors. A total of 50-100 units have been sold. The units are all deployed in the US, as the unit is too large for operation in European style corridors.

Recently Siemens and Hefter demonstrated a new vehicle for cleaning of supermarkets during opening hours [Rencken *et* al., 1999]. This vehicle uses also ultra-sonic and laser ranging for mapping of the environment and avoidance of dynamic obstacles like customers. This particular system can be seen as the next generation of cleaning robots with a more advanced user interface and the ability to operate in highly cluttered environments.

A characteristic feature of these systems is a very simple user interface as it is to be operated by unskilled labor. The user interface is typically a pimple 80 character display and four buttons. The system have a the same time very limited facilities for handling of errors. If an error situation arises then the operator is simply notified.

3.3 Domestic cleaning

Domestic cleaning is a very tough task as few or no assumptions can be made about the environment. Thus, few have tried to automate this market. Recently the company Electrolux demonstrated a behaviour based robot for automatic vacuuming of rooms. The system is a new ultra-sonic ranging system and a tactile array for mapping of the environment and detection of collisions. The robot drives along the perimeter of the room and afterwards it moves through the room at random. The robot uses a truly behaviour based method for navigation and room coverage [Brooks, 1986]. The robot is expected to be available in Europe and Asia in a few years. This will be the first fully autonomous system for domestic use that will be mass-produced for regular customers. The robot is expected to cost less than $500.

3.4 Tour guides

All of the above examples have been commercial systems. There are however also a number of very interesting research platforms. One of the applications that has received the most attention is probably tour guides. The system that has been in operation the longest for autonomous navigation in an office environment is probably XAVTER that was developed at CMU by Simmons et. al. [Simmons *et a/.*, 1999]. This system uses a hybrid-deliberative architecture combined with Partially Observable Markov Processes (POMPS) for automatic localisation, handling of obstacles and planning of missions. The robot has been in daily operation for more than four years and has a remarkable robustness of more than 98%.

At the University of Bonn the RHINO system was developed for tour guiding at the Deutsches Museum Bonn [Burgard *et* al., 1997; Beetz *et* al., 1998]. The uses a probabilistic (Markov) approach to localisation. Combined with methods for obstacle avoidance the system was capable of guiding visitors between different displays at the museum over a period of six days. The user specified desired tours using a touch screen. The robustness of probabilistic localisation is most impressive. Revised and updated version of the system have later been deployed by CMU in the Minerva system, that operated for 2 weeks at the Smithsonian Institute during August - September 1998 [Thrun *et* al., 1999]. The Minerva system included both vision and sonar for localisation. Recently the use of CONDENSATION for robot localisation has been reported {Dellart *et* al., 1999]. Through use of Monto-Carlo based sampling of multi-modal distributions it is possible to achieve real-time localisation in cluttered environments.

The SAGE system deployed at the Carnegie Museum of Natural History was also developed at CMU [Nourbaksh, 1998]. This system is a permanent part of the Dinosaur hall where it provides tours and multi-media information about the items on display. The system, which has been in operation for since 1998, uses color vision and artificial markers for navigation while sonars, infra-red ranging and bumpers are used for handing of obstacles.

3.5 Office/Domestic services

Service robots are gradually moving into the domestic market. The applications will here involve more complex tasks like cleaning of a table, locating objects, and assisting humans. One example of such a system is the intelligent service robot developed at the Royal Institute of Technology [Andersson *et* al., 1999]. For operation in a natural environment it is necessary to use navigation techniques like the probabilistic mapping mentioned earlier, as robustness is an absolute requirement. To achieve robustness the robot uses vision, laser and ultra-sonic ranging. The system uses a hybrid deliberative architecture [Arkin, 1998] with dedicated behaviours for exploration, door traversal, user-interaction, object recognition, point-to-point based navigation. The system uses a topology graph for planning of missions which in turn are expected by combinations of behaviours. The system is presently capable of delivering mail to a range of different researchers in the laboratory and operation in a natural IKEA style living room. The robot is shown in Figure 4. In addition to robust navigation the system

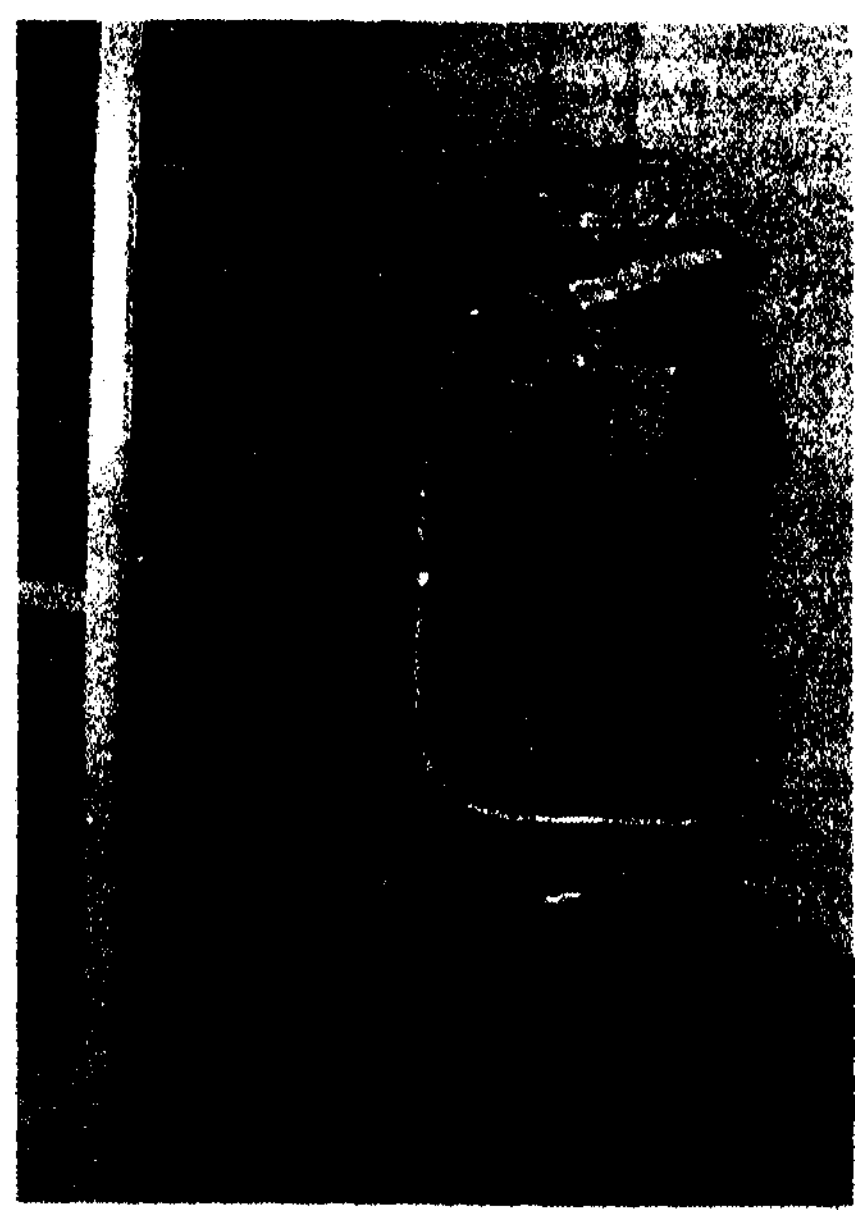


Figure 4: Mail Delivery by a Service Robot

must have excellent facilities for interaction with users. Speech technology is gradually reaching a level of maturity that enables a natural dialogue. Large vocabulary speech recognizers like IBM Via-Voice and Dragon Dictate require user training to achieve reasonable performance, but research prototypes that uses limited vocabularies do provide an adequate robustness without user training. One major obstacle is natural language processing. It is unrealistic to require that end-users will be trained to instruct the robot. There is thus a need for natural language interpretation of spoken input to enable a flexible dialogue between the user and a robot. In addition there is a need for probabilistic (re-)planning of tasks to enable handling of a diverse set of situations and errors [Kristensen, 1997].

3.6 Research Issues

Fully autonomous service robots for domestic applications is not yet possible. To provide such systems a number of fundamental issues must be resolved, including:

- Robust methods for localisation in cluttered dynamic environments. Today methods exist for robust localisation in static environments, but in a dynamic setting there is a need for automatic classification of structure into static and dynamic, which requires stronger temporal integration.
- Error recovery. For operation in dynamic setting it is essential to have facilities for automatic error detection and recovery. On research platforms a robustness of 99% might be enough, but that still corresponds to 15 minutes down-time per day, which is clearly unacceptable. Methods for robust computing using methods like voting might be a possible solution to this problem.
- Intuitive user interfaces. Almost all systems have a rudimentary interface that is acceptable to researchers but for regular users an intuitive interface is needed which requires new methods for dialogue interaction, natural language processing and methods for combination of speech and gesture.
- Software methods for configuration and deployment. Today a significant amount of resources is needed to deploy a system in a particular setting. To make these systems useful to a wider audience and to enable easy transfer of methods from one application to another there is a need for new methods that allow modular design and integration of different techniques. This in turn call for standard architectures and benchmarks.
- Object recognition. To enable intelligent interaction with objects in the environment there is a need for methods for robust recognition of diverse set of objects and object categories. This involved new methods for invariant recognition, memory organisation and task oriented sensing.

4 Summary

Using the domains of RoboCup and Service Robotics we have tried out outline recent trends in robotics and their dependency on new research results in Artificial Intelligence. Robotics requires integration of techniques into operational systems to demonstrate operation in and outside of the laboratory. For such applications robustness is a key issues. It is not enough that techniques operate 80-90% of the time. Robustness must at least be of the order 98-99% to make the systems useful for entertainment or commercial tasks. To be useful in realistic tasks there is at the same time a need for high-level reasoning and planning about goals, contexts, actions and interaction to make these systems useful to end-users. The next generations of these systems will thus rely on a wide range of artificial intelligence techniques.

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