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VII SERVICE ROBOTS[1]

VII.1 Introduction

In spring 2005, the IFR Statistical Department carried out a market survey of service robots for the sixth time. A questionnaire was sent to more than 170 companies worldwide, asking for data on accumulated sales up to the end of 2004, sales in 2004, and projections for 2005-2008. Data was reported according to the classification shown in table VII.1 below. It should be noted that this classification has been slightly revised compared to previous years' surveys. In total, about 172 companies have now been identified as producers/developers of service robots (see table VII.2, placed at the end of the present chapter). For the third time, the survey also included information concerning service robot related components and services such as **sensing systems, actuation, navigation and control, and R&D, see chapter VII.3.4**.

The overall result of the survey is shown in section VII.2 below. Detailed information about the application areas of service robots is given in section VII.3. The analysis for each application area is organized under the following headings (where applicable):

- **(i) Types of operations carried out by the robots**
- **(ii) Level of distribution**
- **(iii) Cost/benefit analysis, particular attributes, and major restraints on further diffusion**
- **(iv) Major producers**

As the amount of information available differs considerably between application areas, some headings might contain only a few pieces of information or even be empty.

IFR Service Robotics Group: On 9 October 2002, a Service Robot Group was founded under the auspices of the International Federation of Robotics (IFR). The IFR has recognized, through its national affiliates, the growing commercial activities associated with service robots. At the same time, it has been found that there is little current support for the mostly small and young companies working or entering this area to assist them in market assessment and in raising their profile in the eyes of other industries, the media, and/or government bodies. In response to these facts, IFR operates the Group to further the interests of this emerging industry. The IFR Service Robot Group is open to all interested service robot companies offering service robot products, components or related services. For further information please contact Martin Hägele at mmh@ipa.fhg.de or visit the group's website at www.ifr.org.

Further readings: For a very detailed review of state-of-the-art of service robots, the reader could consult: *R. D. Schraft, M. Hägele and K. Wegener:* **Service Roboter Visionen.** München: Hanser, 2004. This book presents, besides a thorough analysis of service robots, a large number of high-quality pictures and photographs of service robots in different applications. The relation between automation, service robots and the emerging Information Society is described in: *J. Neugebauer and M. Höpf:* **The Role of Automation and Control in the Information Society.** Stuttgart, Fraunhofer IRB Verlag, 1999. An Internet site dedicated to service robots can be found at **www.service-robots.org**.

VII.2 Distribution of service robots

Table VII.1 below gives details about the results of the IFR Statistical Department survey of sales of service robots, broken down by application areas. The figures are based on sales data reported by companies, as well as on other sources such as annual reports and market surveys of individual application areas, carried out by professional organizations and/or consultant companies. In the 2004 survey, the same number of companies was surveyed as in the 2003 survey. In some cases, companies seem to have reported far too optimistic projections, in which case the data has been excluded.

Close to 60% of the 172 companies surveyed provided market data, compared with a response rate of about 50% to the 2004 survey. In many ways, the statistical information has been improved in comparison with the previous year, for example regarding plausibility checks of reported data, more precise assignment of service robots to application areas, etc.

[1] This chapter is authored by Martin Hägele, Head of Department "Robot Systems" Fraunhofer IPA, Stuttgart, Germany (mmh@ipa.fhg.de)

Table VII.1

Estimated number and value of service robots installed up to the end of 2004, by application areas, and forecasts for the period 2005-2008

Types of robots	Stock at end 2004	Installations 2005-2008	Sales in 2004	Stock at end 2004	Installations 2005-2008
	No. of units	No. of units	No. of units	$ million	$ million
SERVICE ROBOTS FOR PROFESSIONAL USE:					
Field robotics	2,290	1,510	352	460	306
Agriculture					
Milking robots	2,230	1,500	350	450	305
Forestry					
Mining systems					
Space robots					
Others	60	10	2	10	1
Professional cleaning	3,590	2,000	215	72	52
Floor cleaning	330	35	3	31	2
Window and wall cleaning (including wall climbing robots)		900			24
Tank, tube and pipe cleaning					
Pool cleaning	3,200	1,000	200	29	15
Other cleaning tasks	60	65	12	12	11
Inspection systems	235	265	21	27	29
Sewer robots	90	165	7	4	8
Tank, tubes and pipes*					
Other inspection systems	145	100	14	23	21
Construction and demolition	3,250	1,220	233	213	101
Demolition systems: nuclear demolition & dismantling,	80	45	10	22	18
other demolition systems	3,100	1,110	212	187	74
Construction support robots: maintenance or construction	70	65	11	3	9
other types of construction					
Logistic systems	270	790	45	16	51
Courier systems					
Mail delivery *					
Factory logistics					
Other logistics*					
Medical robotics	2,800	2,000	386	501	670
Diagnostic systems*					
Robot assisted surgery of therapy	2,800	2,000	386	501	670
Rehabilitation systems*					
Other medical robots *					
Defence, rescue & security applications	1,180	5,625	380	97	461
Demining robots	40	50	10	4	15
Fire and bomb fighting robots	440	390	61	40	106
Surveillance/security robots	630	2,685	255	30	80
Unmanned vehicles	70	2,500	54	23	260
Unmanned aerial vehicles					
Unmanned ground based vehicles					
Others					
Underwater systems	5,320	2,190	397	2,117	1,257
Mobile Platforms in general use	2,660	5,760	450	28	41
Laboratory robots	3,460	3,155	402	38	73
General material handling					
Clean room robots					
Others					
Public relation robots	20	5	8	1	0
Hotel & restaurant robots *					
Guide robots					
Robots in marketing					
Others (i.e. library robots)*					

Sources: UNECE and IFR.

*no information available.

Table VII.1 (concluded)

Estimated number and value of service robots installed up to the end of 2004, by application areas, and forecasts for the period 2005-2008

Types of robots	Stock at end 2004	Installations 2005-2008	Sales in 2004	Stock at end 2004	Installations 2005-2008
	No. of units	No. of units	No. of units	$ million	$ million
SERVICE ROBOTS FOR PROFESSIONAL USE:					
Special Purpose	55	30		10	2
- refuelling robots	55	30		10	2
- others					
Humanoid robots		24,000			430
Customized robots **					
Other professional service robots not specified above	10	1,000	3	1	30
Total number of units / estimated value of professional service robots	**25,140**	**49,550**	**2,892**	**3,580**	**3,503**
SERVICE ROBOTS FOR PERSONAL/DOMESTIC USE:					
Robots for domestic tasks	1,152,000	4,470,000	547,000	448	2,971
- vacuuming cleaners	1,106,000	3,870,000	538,000	407	1,587
- lawn mowing	46,000	200,000	9,000	41	185
- pool cleaning		100,000			900
- window cleaning		300,000			300
- others					
Entertainment and leisure robots	919,725	2,521,970	125,360	1,483	4,367
- toy robots	810,000	2,500,000	120,150	1,423	4,350
- entertainment	80	70	54	4	6
- hobby systems	2,700	4,300	1,050	1	2
- education and training	16,800	17,500	4,065	32	10
- others	90,145	100	41	23	0
Handicap assistance	325	750	65	2	19
- robotized wheelchairs					
- other assistance functions					
- personal rehabilitation*					
- others					
Personal transportation	390	700	181	14	30
Home security & surveillance	140	5,180	40	18	293
Other Personal/domestic robots					
Total number of units / estimated value of personal/domestic service robots	**2,072,580**	**6,998,600**	**672,646**	**1,965**	**7,680**
Total number of units / estimated value of service robots	**2,097,720**	**7,048,150**	**675,538**	**5,545**	**11,183**
of which robotics R&D* **					

Sources: UNECE and IFR.

* No information available.

* * Included in other professional robots.

*** Only a few companies provided data.

Despite this improvement in the response rate, the data reported here probably underestimates the true sales figures and installed base of robots significantly, especially the sales in 2004. They should therefore be seen as **a minimum level of the installed base of service robots**. The amount of sales information available also differs significantly between various application areas, medical robots and underwater robots being the areas with the best coverage.

(a) **Service robots for professional use, stock of installations up to the end of 2004**

With 5,320 units, **underwater systems** accounted for 21% of the total number of service robots for professional use installed up to the end of 2004 (see table VII.1 and figure VII.1a). Thereafter followed **cleaning robots** and **laboratory robots** with 14%, each, and **construction and demolition robots** with 13%. **Medical robots** and **mobile robot platforms for general use** accounted for 11%, each. **Field robots**, e.g. milking robots and forestry robots, had a share of nearly 9% and **defense, rescue and security applications** 5%. Minor installation numbers were counted for logistic systems (270 units), inspection systems (235 units) and public relation robots (20).

Of the total value (nearly $3.6 billion) of service robots for professional use installed up to the end of 2004, **underwater systems** accounted for around 59% (see table VII.1 and figure VII.1b). They were followed by **medical robots,** which had a share of 14%. **Field robots** had a share of 13% followed by **construction and demolition robots** with some 6%. The unit prices for professional service robots differ significantly – from less than $10,000 to more than $300,000, depending upon the type of application. The most expensive robots are **underwater systems** (from $300,000 to more than $1,000,000), **medical robots,** with a wide range from $100,000 to some $1,000,000, and **milking robots** ($200,000).

(b) **Service robots for personal and domestic use; stock of installations up to the end of 2004**

Service robots for personal and domestic use are recorded separately, as their unit value is only a fraction of that of many types of service robots for professional use. They are also produced for a mass market with completely different marketing channels.

So far, service robots for personal and domestic use are mainly in the areas of **domestic (household) robots**, which include vacuum cleaning and lawn-mowing robots, and **entertainment and leisure robots**, including toy robots, hobby systems and education and training robots (see table VII.1 and figure VII.1c).

The market for **robots for handicap assistance** is still small, but is expected to double in the next four years. Robots for **personal transportation** and **home security and surveillance robots** will also increase in importance in the future.

Vacuum cleaning robots were introduced to the Swedish market at the end of 2001 with the Electrolux Trilobite. The market expanded during 2002 and 2003 and several other companies, e.g. Kärcher and iRobot, have since entered the market. More robot vacuum cleaner products (from companies such as Hitachi, Hanool, Samsung, LG, Sharper Image and others) have been launched, resulting in accumulated sales up to end 2004 of 1 million units.

At the end of 2004, the stock of **lawn mowing robots** amounted to 46,000 units. The market is dominated by the “Robomower” of Friendly Robotics, Israel, and the “Automower” of Electrolux, Sweden.

At the end of 2004, it is estimated that nearly 1,152,000 domestic robots, all types included, were in use, of which 547,000 units were sold in 2004. The actual number might, however, be significantly higher, as the IFR survey is far from having full coverage.

As for **entertainment and leisure robots**, it is estimated that more than 900,000 units have been sold up to the end of 2004. It is expected that the merging of PC, home entertainment and robot technologies will become a very substantial business area in the near future. A well-known example of these kinds of robots is the AIBO™ by Sony, which has been improved in the several generations since its introduction in 1999. Other products, which have been launched or announced, comprise the PaPeRo of NEC, ApriAlpha and ApriAttenda by Toshiba.

Accumulated sales of **toy robots** are estimated at about 810,000 units. An example of **entertainment robots**, which is still a rather limited market segment, is the ROBOCOASTER® by KUKA. Its basis is a modified industrial articulated robot, but developed as an attraction system for robot exhibitions and leisure parks such as Legoland. In total, about 2,700 **hobby systems** and 16,800 **education and training robots** were sold up to 2004.

Accumulated sales of **robots for handicap assistance** amounted to 325 units up to the end of 2004. These robots have not yet taken off as could be expected given their potential in regard to both the supposable need and the existing technological level of the equipment. Some of the most apparent reasons for this are explained in section VII.3. In a longer perspective, say in the next 10 years, and taking into account demographic shifts and advances in technology, assistive robots for disabled and handicapped people are certain to be a key area for service robots. Important research institutions are focussing on developing prototypes of this kind of robot (see section about research in Annex C of **World Robotics 2000**).

Just over 390 vehicles for **automated transportation of people** were sold up to the end of 2004.

The total value of the stock of **entertainment and leisure robots** amounted to $1,965 million. Compared to professional service robots, these robots are rather low-priced. The average prices are between $200 and $4,000.

(c) Projections for the period 2005-2008: service robots for professional use

Turning to the projections for the period 2005-2008, the stock is forecast to increase by some 49,550 units (see table VII.1 and figures VII.1a and VII.1b). An application area with strong growth might be **humanoid robots**. One company estimates sales of more than 24,000 robots. Up till now there have been no significant sales of this type of robot. There are quite a few Japanese companies (Sony, Toyota, Honda, Fujitsu, Kawada, ZMP) developing these robots for multiple use. First sales started in 2004, mostly in Japan or to international research laboratories. **Robots in public relations** had no significant sales up to and including 2004 and estimates were cautious.

In the period 2005-2008, sales of **underwater systems** are projected to surpass 2,190 units, **defence, rescue, and security applications** 5,625, **professional cleaning robots** 2,000, and **mobile robot platforms for multiple use** 5,760. The accumulated sales of **medical robots** were expected to increase by 2000. Last year's forecast of **refuelling robots** and **public relations robots** will also not be reached. Less than 50 robots were reported to be sold in the period 2005-2008. These forecasts are, as mentioned earlier, mainly based on individual sales projections by companies and professional organizations. It is the opinion of the IFR statistical department that the forecasts should be seen as market estimates rather than actual sales forecasts.

(d) Projections for the period 2005-2008: service robots for personal and domestic use

Domestic (household) vacuum cleaning robots were introduced on the market at the end of 2001. The initial interest within the Swedish market (some 5,000 units sold in the last two months of 2001) indicated a significant appeal. The price was rather high, €1,400, but this did not discourage "early adopters". In 2002-2003, several other companies entered the market, giving rise to sales of some 390,000 units in 2003. The price was significantly reduced. The forecast of sales in the period 2005-2008 is about 3.8 million units (see table VII.1), which is compatible with the estimates of 3.4 million units for the period between 2004 and 2007 (see table VII.1 in World Robotics 2004). The prerequisites for its realization are discussed further in section VII.3.

Regarding **lawn mowing robots,** a huge increase in sales is forecast for the period 2005-2008 - about 200,000 units. The market for other household devices such as robotic pool cleaners and window cleaners is "very promising", and a distribution of 400,000 units in the period 2005-2008 is expected.

It is projected that sales of **all types of domestic robots** (vacuum cleaning, lawn-mowing, window cleaning and other types)could reach some 4.47 million units in the period 2005-2008, with an estimated value of $2.97 billion (see table VII.1 and figures VII.1c and VII.1d).

The size of the market for **toy robots** is forecast at about 2.5 million units, most of which, of course, are very low cost (see table VII.1 and figure VII.1b).

About 4,300 **hobby systems** are expected to be sold in the period of 2005-2008 as well as some 17,500 **robots for education and training**, compared with an installed base of 16,800 units up to and including 2004.

Sales of all types of **entertainment and leisure robots** are projected at well beyond 2.5 million units, with a value above $4.4 billion (see table VII.1 and figures VII.1c and VII.1d).

Total world stock of service robots for professional use at the end of 2004 is estimated at some 25,140 units. Some 50,000 units are forecast to be added in the period 2005-2008.

The world stock of service robots for domestic (household) use at the end of 2004 is estimated in the order of 1,152,000 units. Some 4.47 million units may be added in the period 2005-2008.

The world stock of entertainment and leisure robots at the end of 2004 is estimated in the order of 920,000 units. Some 2.5 million units may be added in the period 2005-2008.

Figure VII.1a. Service robots for professional use. Stock at the end of 2004 and projected installations in 2005-2008

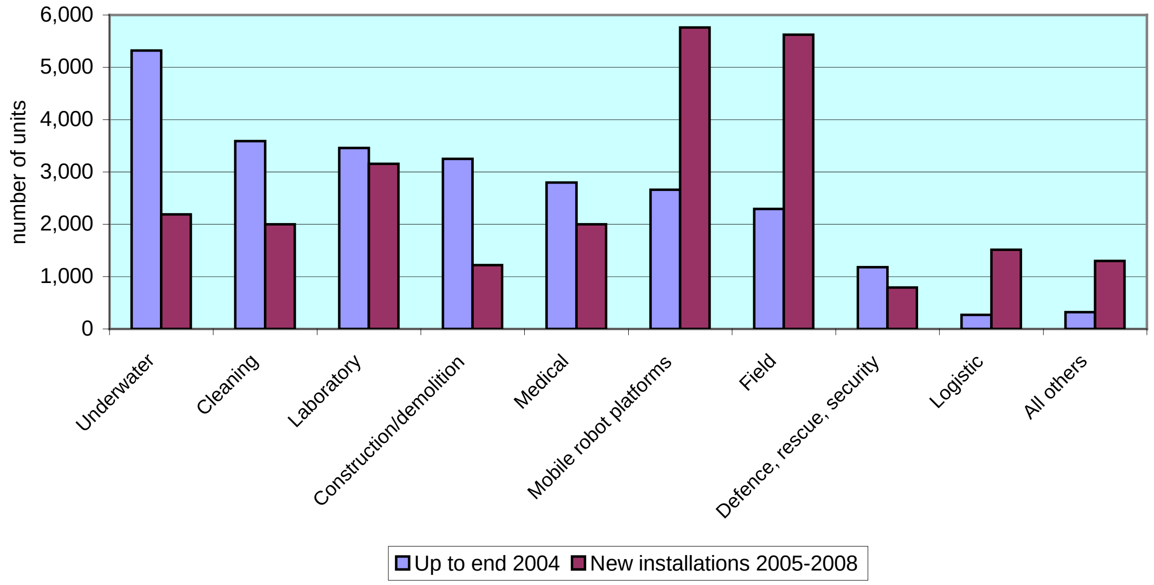
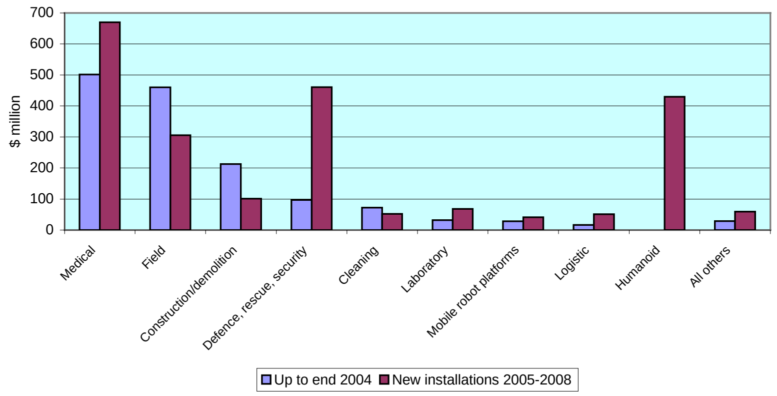


Figure VII. 1b Service robots for professional use. Value of stock at the end of 2004 and value of projected installations in 2005-2008



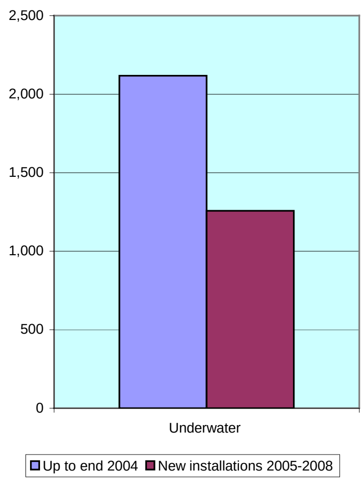


Figure VII.1c. Service robots for personnel/domestic use. Stock at the end of 2004 and projected installations in 2005-2008

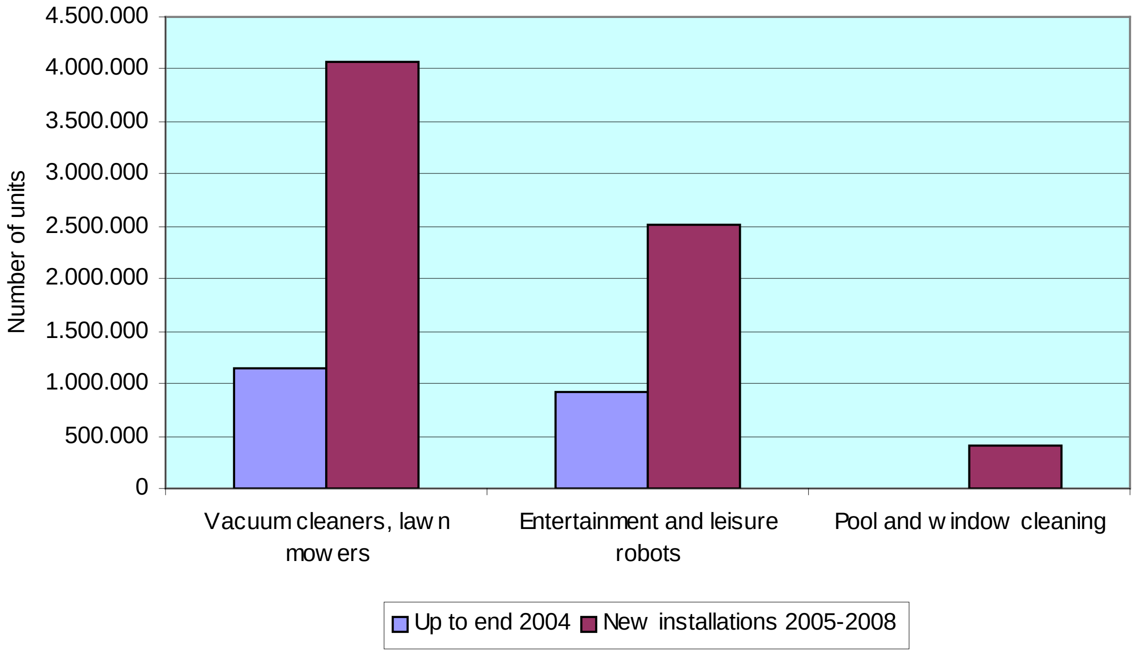
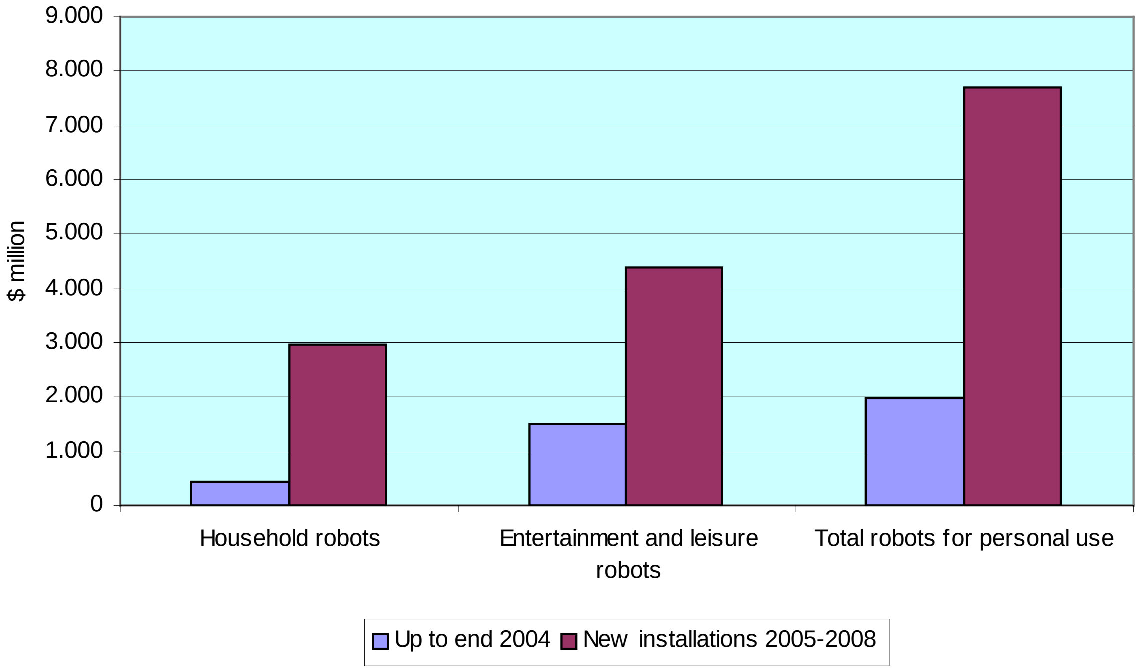


Figure VII.1d. Service robots for personal/domestic use. Value of the stock at the end of 2004 and of the projected installations in 2005-2008



VII.3 Major application areas for service robots

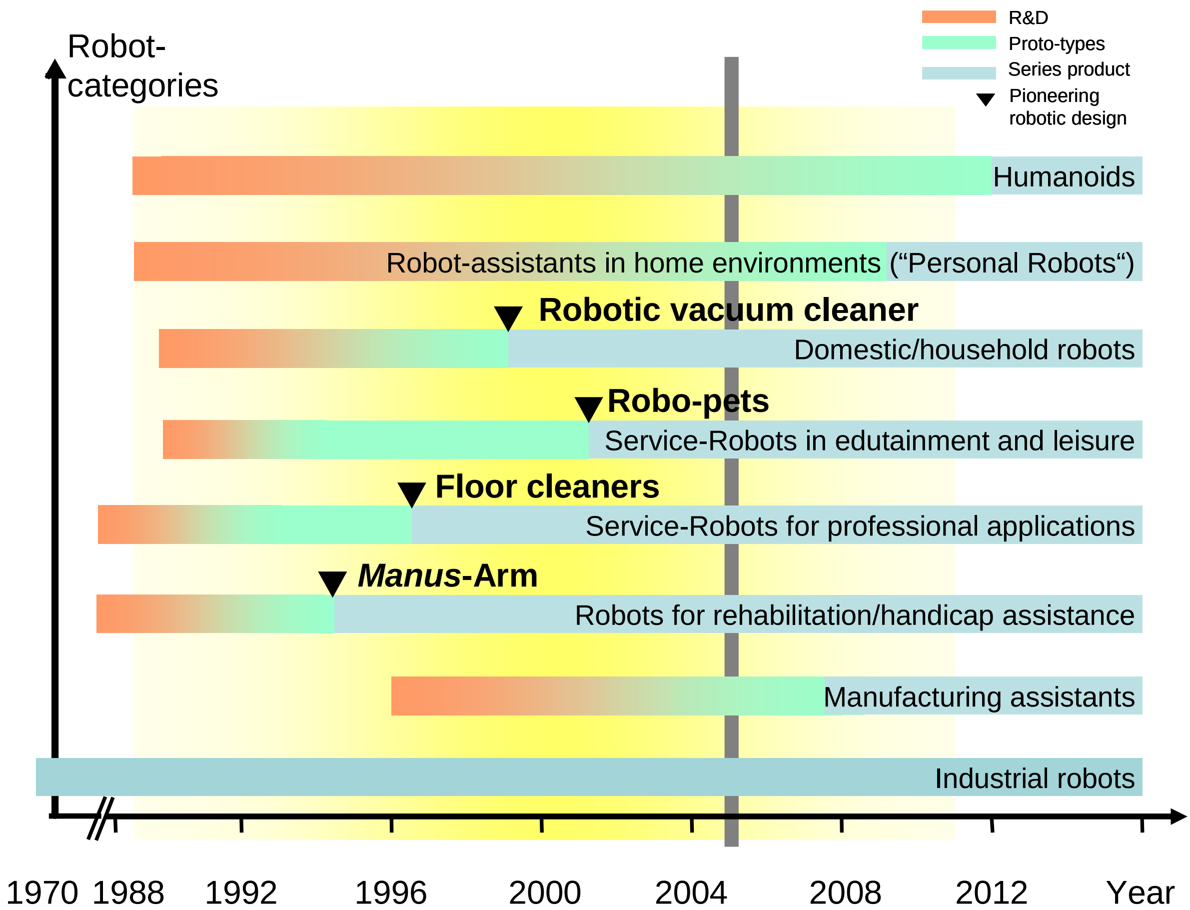
VII.3.1 Introduction

Soon after the introduction of industrial robots in manufacturing, efforts were made to utilise robot technology for jobs where manual task execution is dangerous, impossible or unacceptable. Depending on the individual tasks, these mobile platforms or manipulators (or a combination of both) were typically applied in hazardous environments (nuclear power stations, nuclear fuel reprocessing, bomb disposal, sewer and pipe inspection). Their degree of automation slowly progressed from pure tele-operation to the implementation of autonomous functions, e.g. for mobile navigation, automatic execution of machining or handling sequences under uncertain environmental conditions etc.

During the 1980s and early 1990s, advances in sensor technology, computer controls and servo-drives resulted in more than 200 demonstrators, or prototype developments of robots, for non-manufacturing applications[3]. Applications of these customised robot designs ranged from professional jobs in therapy, construction, maintenance, and inspection to their use in rehabilitation and home care[4].

Even though many ideas have been introduced in the past, there is still an abundance of product opportunities to be taken up by companies. Service robots provide mobility, functionality and multi-media possibilities in all areas of our daily life: at home, at work, for professional service and for leisure. A rough roadmap of service robotics is given in figure VII.2.

Figure VII.2: Systematic and roadmap of service robot systems



[3] Japan Robot Association: *The Specifications and Applications of Robots in Japan*. Non-Manufacturing Fields, 1997.

[4] R. D. Schraft: *From Service Robots to Assistant Systems*.. International Advanced Robotics Programme IARP 2001. International Workshop on Opportunities & Challenges of Advanced Robotics Research & Application at the Outset of the New Century: April 15-17, 2001, Shanghai, China, Shanghai, 2001.

This section reviews a selection of the major application areas of service robots, both for professional and personal use. At the end of the chapter, table VII.2 provides an overview, in terms of a matrix, of the specific application areas in which, currently, some 170 service-robot producers and developers are active.

Figures VII.4 to VII.17, placed at the end of the chapter, contain photos of service robots in various applications. They serve to give concrete illustrations of what service robots look like and how they are used.

VII.3.2 Service robots for professional use

Although service robots are as diverse as their applications, three categories of designs can be distinguished[5]:

- Modification of industrial robot components for application outside of the manufacturing environment which is increasingly pursued by industrial robot systems integrators looking for new markets. Examples being refuelling robots, automated warehousing or medical robots.
- Use of advanced robot technology for the upgrading of high-end systems of existing product lines with automation functions. This product philosophy can often be found in service robots for professional use such as cleaning, inspection etc.
- New robotic designs “from scratch” without past examples by using robot technologies and components (navigation, environmental perception etc.). Examples are space robots, window cleaners, security robots.

VII.3.2.1 Field robotics

a) Agriculture

In agriculture, most of the developments have been observed in the field of harvesting. Some other prototypes have been introduced in fruit picking. However, service robots have not reached a wider use so far. Still, significant research is underway exploring the functionality, robustness and cost-effectiveness of automated machinery.

In the United States and Japan, systems have been developed to autonomously lead agricultural machinery over the fields such as tractors or combine harvesters. With optical sensors (scanners and/or a video camera) and on-board computer, these systems follow the border of the previous cut. Working uninterruptedly 7 x 24 hours a week, they free labour from hot and noisy activities. Their commercial viability, though, depends on the size of the application area to a far greater extent than manually led machinery.

Fruit picking robots are being developed in about 10 countries. They detect and locate ripe fruit via a colour analysis of video pictures. Other designs even maintain the plants, e.g. by removing limp leaves. Picker arms then grab the fruit and cut it off, resulting in 2,400 fruits/h being picked. Using a torsion technique, this amount can be increased to 5,000 fruits/h. To be economically advantageous for the farmer, picking times should not exceed 16 s/fruit. Remotely guided robots can climb trees of 15 to 40 cm diameter with a speed of 0.5m/s. This approach, which would enable the harvest of so far unreachable fruit, is, however, still far from being commercialised.

Autonomous agricultural machines are produced by: Genova Robot (Italy), ISE (Canada), NREC (USA), Yanmar Agricultural (Japan) (see table VII.2). Prototypes of large autonomous mobile machinery have been demonstrated by Deere and Company (USA), and by Silsoe Research Institute (UK)

[5] R. D. Schraft, M. Hägele, K. Wegener,: *Service Roboter Visionen.* München: Hanser, 2004; http://www.hanser.de/buch.asp?isbn=3-446-22840-3&area=Technik.

b) Milking Robots

Cow-milking robots were among the first robotic systems in use in agriculture. They consist of a stationary unit into which the cow walks voluntarily to be milked. A transponder around her neck informs the robot about the cow's details, i.e. when it was last milked, how many litres, etc. During the milking process, milk flow and quality are controlled online. The farmer thus has more precise information about his herd. Such milking robots are meanwhile produced in significant numbers by Delaval (Sweden), Lely and Meko (The Netherlands). Up to and including 2004, some 2,230 milking robots have been reported to be in use (see table VII.1).

The advantages for farmers are obvious: no more early morning milking in the middle of the winter. The benefits for the cows are just as significant: being able to choose when they want to be milked. The systems allow "free-flow cow traffic". Experience has shown that, left to themselves, cows will enter the unit to be milked 2 to 4 times a day, almost any time of the day or night.

A milking robot system incorporates a milking management system which relies on the identification of each cow by ear-tags, transponders or pedometers. Each robot typically handles some 50 to 60 cows. When a cow is identified, the system decides if it is going to be milked or not. As a rule, a cow should produce about 7 litres of milk before being milked. If a cow returns to the milking system too early, it is not milked.

Other features of automated milking systems are:

- Lasers and vision systems make it possible to actually see and recognise the teats.
- Multipurpose arm(s) that can accommodate udder and teat irregularities, handles teat cleaning, cup attachments and disinfection.
- Indicators for measuring flow, quantity, milking time and quality from individual teats as well as yield.
- When the cow is identified, the manger frame is adjusted to the individual cow's length and the feed is dispensed to the manger according to the requirements for the particular cow.
- Automatic disposal of manure and cleaning.

The future dairy industry will be far more automated than today, using automated milking systems which besides high productivity and cost efficiency will satisfy the demand for higher milk quality and more humane conditions for dairy herds.

The major producers are: Delaval International AB (Sweden), Fullwood (UK), Lely Benelux (Netherlands), Milka-Ware (Australia), Prolion (Netherlands), Welger Agrartechnik (Germany). WestfaliaSurge, (Germany), ceased manufacturing milking robots in 2003.

c) Forestry

In forestry one main concern is that vehicles on tyres or hoops or using chain drive will irreparably damage the lea. If the work unit is mounted on a base with a number of centrally manipulated "legs", less damage should be done. Such constructions can turn on the spot without ruining the soil, and even allow for walking over fallen trees or climbing up hills.

Considering growing environmental concerns, this system, created by Deere's Finnish subsidiary, Plustech, may be an alternative. This giant forest-walking spider robot adapts automatically to the forest floor terrain on its six articulated legs.

Partek Forest (now owned by Komatsu Ltd. (Japan)) is also entering this market for semi-autonomous systems. They have in particular focused on adding advanced control methods for crane-control to vehicles. Through semi-autonomous control of the crane, the stress induced on the driver is limited. An operational prototype has been developed and is currently undergoing user tests.

Since 1995, joint research has taken place in Sweden, Finland, and Canada towards the development of a robot for thinning forests. The development focuses on walking robots which navigate with the help of GPS and GIS and which identifies the trees with lasers. The market is estimated at some 1,000 units. They have multiple uses: preparing land for planting of trees as well as the planting of trees, cleaning of ditches etc.

d) Mining systems

Again, the desire to keep human labour away from dangerous, tedious and dirty environments has been the driving factor to develop robots for mining. Typical robot tasks in mining include mapping of galleries, laying explosives, going underground after blasting to stabilise a mine roof or mining in areas where it is impossible for humans to work or even survive. Expensive pieces of mining machinery also make use of robot technologies for mobile navigation or to control trajectories. Here numerous prototypes have demonstrated the technical feasibility of tasks such as autonomous excavation, haul truck automation or autonomous underground (LHD) haulage.[6]

Researchers from the U.S. Department of Labor's Mine Safety and Health Administration, Carnegie Mellon University and the Pennsylvania Department of Environmental Protection developed a prototype of a wheeled robot capable of exploring and mapping underground structures. The 'Groundhog' is designed to handle roof fall, rotting equipment, and flood waters below the surface. Besides optical sensors for mine mapping, it is equipped with an array of cameras and gas, tilt and sinkage sensors to overcome such hazards.

e) Space robots

Unmanned vehicles used in space have to be either tele-operated from a distance of some thousand kilometres or move autonomously. As the signal takes time to pass and often not all obstacles can be perceived, the robot can change to “safeguarded tele-operation”. That is, it overrules the tele-operated mode, when it considers the commands to be wrong.

When the terrain is unknown and difficult to access, manoeuvrability is crucial. Therefore the robots are able to change the distance between wheels as well as the gauge.

“Panospheric cameras” allow for an all-round picture of the robot’s surroundings to be sent without constant change of direction.

The price of such robots will remain high, as economies of scale will not occur. The additional costs of sending the robot into space are another great expenditure and require availability of a shuttle.

Well-known robot arm designs have been developed for use in space such as the CAT arm of Tecnospacio, which is a dextrous anthropomorphic 6-axis robot developed as part of the Columbus Automation Test bed. The arm is mounted on a two-axis gantry.

One of the most spectacular arms is the Canadarm2 robotic arm which was successfully installed on the International Space Station in July 2001. This robotic system plays a key role in space station assembly and maintenance: moving equipment and supplies around the station, supporting astronauts working in space, and servicing instruments and other payloads attached to the space station.[7]

The ROKVISS robot arm, developed at the Institute of Robotics and Mechatronics (Germany), is mounted on the International Space Station (ISS) and has started its operational mode. After a year’s qualification phase, the goal is to have a robot arm tested for supporting astronauts in tedious tasks, or repair and maintain space structures and satellites[8].

Mobile robots for exploration have proved indispensable for this task, as well as data collection, as the Mars rovers demonstrated . NASA's latest twin robot geologists, the Mars Exploration Rovers, are assisting in determining the history of water on Mars. They landed on Mars on January 3 and January 24, 2004[9]. NASA is also developing a humanoid robot to meet the increased demands for human safety during extra-vehicular activity (EVA). The Robonaut project seeks to develop and demonstrate a robotic system that can function as an

6 See the proceedings of the IARP International Advanced Robotics Program: *1st International Workshop on Advances in Robotics for Mining and Underground Applications*. Oct 2-4, 2000, Brisbane Australia; http://www.cat.csiro.au/cmst/pub/IARP/wshop.html.

7 Canadian Space Agency. See http://www.space.gc.ca.

8 http://www.dlr.de/rm/en/: ROKVISS: Robot arm moves in space.

9 http://marsrovers.jpl.nasa.gov/overview/.

EVA astronaut equivalent. The Robonaut design aims at eliminating the robotic scars (e.g. special robotic grapples and targets) and specialised robotic tools of traditional on-orbit robotics[10].

The most important producers are Jet Propulsion Laboratory (JPL) (USA), MacDonald Dettwiler Space (Canada) and Advanced Robotics (Canada).

VII.3.2.2 Professional cleaning

A distinction should be made between professional cleaning robots and those used domestically in private homes. As neither the degree of utilisation nor the market size in terms of units and value of professional and domestic robots can be compared, they will be treated in different sections. These sections have been determined on the basis of current existing robots used in comparable environments and/or accomplishing a set of comparable tasks.

Below, in the area of professional cleaning, the activities of floor, tank, window, boat and vehicle cleaning will be reviewed.

a) Floor cleaning

(i) Types of operations carried out by the robots

Floor cleaning robots are essentially standard cleaning machines equipped with the necessary robot functions to drive themselves around the cleaning area, i.e. navigation control system, and sensors (distance counter, gyro, ultrasonic, laser, bumper switches, etc.) to detect and prevent collision with obstacles.

Several designs offer dual mode operations, as they can be used as manual machines during the day and function automatically during the night. The navigation systems vary from the very simplest, requiring plots or cables on the floor, to the most sophisticated that cover surfaces automatically without human intervention. The most common navigation systems use an initial programming cycle (“teach-in drive”) to memorise the path around the area and then control the movements of the robot in the cleaning area.

Cleaning robots drive to their working area, carry out the cleaning process (sweeping, scrubbing, drying, etc.) and return to the loading station when they run short of power or fresh water. It is possible for some to use personnel elevators by radio command and thus operate on different building levels.

Similar to manually guided machinery, the robots are most efficient on large surface areas, i.e. halls, corridors, railway stations, hospitals, large industrial or research centres and supermarkets.

(ii) Level of distribution

Examples of floor cleaning robots already in daily use are the HAKO (Germany) and Cybernétix (France) robots, which have been cleaning Paris’ Metro stations since 1994, or RoboKent’s robots (now Servus Robots (USA)), which are cleaning in over 150 locations throughout the United States.[11] Also Kärcher (Germany) is producing cleaning robots for automated cleaning in various settings.

Cleaning robots are starting to be bought by supermarkets, shopping malls and hotel chains where large surfaces have to be cleaned at regular intervals. Generally, the level of distribution of floor cleaning robots still falls behind earlier projections, despite proven technical maturity and excellent field experience.[12] As an extension to fully manual floor cleaning systems, costs for these low-series products are still considered high, mostly due to costly sensor equipment and low series volumes.

In view of the fact that the floor cleaning industry has a turnover of more than € 53 billion in Europe alone, that labour costs make up 70 to 80% of this sum, and that floor cleaning represents 60% of the cleaning task, there is potential for an increase in the sales of floor cleaning robots. The target cost of a professional

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[10] http://vesuvius.jsc.nasa.gov/er_er/html/robonaut/robonaut.html.

[11] M. Schofield: *Cleaning Robots: Engineering Dream or Commercial vision?*, 29th International Symposium on Robotics, Birmingham, United Kingdom, 27 April – 1 May 1998.

[12] G. Lawitzky: *A Navigation System for Cleaning Robots*. In: Autonomous Robots, Volume 9, Number 3, December 2000, pp. 255-260.

cleaning robot is estimated to be twice that of a typical cleaning machine which, on the basis of today's available components, is still difficult to achieve. The Robo40 of Cleanfix (Switzerland), is an example of novel low cost strategies towards cleaning robots. It claims to be sold at a price which is a magnitude below the price of previous cleaning robots for professional use; see figure VII.4.

Up to the end of 2004, an estimated 330 professional floor cleaning robots have been sold. From 2005 to 2008, producers project sales of a relatively modest 35 units (see table VII.1).

(iii) Cost benefit analysis and major restraints on further diffusion

For the investor the main aim of using cleaning robots is to reduce labour costs. The economic viability of cleaning robots depends very much on their degree of labour savings, which in turn depends, above all, on their degree of utilisation, but also on the degree of autonomy and simplicity of the installation and the teaching process.

Although freed from monotonous and tedious work, cleaners might be reluctant to work with robots. Awkwardness with the new machinery could lead to overcautious behaviour, which could slow down the process. On the other hand, the opposite attitude is also possible: the workers can be motivated in working for a firm that uses the latest robot technology.

A major restriction in the diffusion of cleaning robots is that cleaning firms in most cases have little experience in using advanced technology (cleaning is often based on manual unskilled operations). For optimal use it is also necessary to change the work organisation and to invest in training which would require significant changes to a mostly entry level job culture. In order to overcome these barriers, vendors should act as partners to the end-user industries, informing them about possibilities, working out special solutions and helping to implement the robots, as well as offering maintenance and advice.

The professional cleaning industry is short-term focused and works with low capital budgets and profit margins. Hence, the price of a cleaning robot, still at some € 25,000, might be a constraint, if a high degree of utilisation cannot be assured. Above all, the navigation controllers and sensors are expensive, still accounting for about one third of the total system cost. The aim of the producers is to reduce the cost of these devices in order to reach a market price where a wide diffusion of these robots can commence. The producers are aided in this task by the fact that important academic research is being carried out concerning sensors and navigation systems for mobile platforms, which are the basis for cleaning robots. This has led to a fast improvement in the sensors used and in the "intelligence" of the navigation systems. Recently, off-the-shelf navigation systems have been offered by OEM providers (such as the SINAS™[13] system by Siemens, CURONA® by InMach[14], the ERSP 3.0 platform by evolution robotics[15] or the ANT system by Bluebotix[16]) to simplify development and reduce deployment costs for the cleaning machine producers.

Cleaning robots eliminate certain types of cleaning work, which frees employees to do more skilled tasks. Potentially labour cost savings can vary from 80% to 90%. The payback period of the investment can vary from 1.5 year to 3 years. The overall cost is still considered the major obstacle to more widespread adaptation of the technology. It is estimated that the interest in consumer cleaning robots will have a significant backlash on the commercial systems both in regard to technologies and user acceptance.

(iv) Major producers

Major producers of cleaning robots are in the commercial range: Cyberclean (USA), Cleanfix (Switzerland), Cybernétix (France), Cyberworks (Canada), Dyson Appliances (UK), Hitachi Kiden Kogyo (Japan), Matsushita Electric (Japan), Minolta Co. (Japan), Nilfisk-Advance A/S (Denmark), RENOSOL (France), Robosoft (France).

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13 http://www.ad.siemens.de/sinas/index_00.htm.

14 http://www.inmach.de.

15 http://www.evolution.com.

16 http://www.bluebotics.com/automation/ANT/.

b) Window cleaning and wall cleaning

(i) Types of operations carried out by the robots

For optical as well as for maintenance reasons, glass facades have to be cleaned every few months. Window cleaning robots consist of a remotely controlled or a fully automated cleaning unit, which is mounted on a mobile climbing base (see figure VII.4). The mobile unit either follows a track or, suspended from the roof, moves freely over the facade. While for large buildings specific solutions may be worthwhile, smaller buildings will rely on standard systems. Current developments aim at a combination of facade elements and mechanical robot platforms.

Other efforts aim at window cleaning systems for the consumer market at a target sales price of less than $ 200. Basic requirements are that these devices should be easy to use, safe and maybe even applicable for bathroom tile cleaning (see chapter VII.3.3.1).

(ii) Level of distribtion

Custom robots designed for a particular building are already in use on the Louvre pyramid, produced by Robosoft (France), the Messehalle in Leipzig (Fraunhofer IFF (Germany)), and the Landmark Tower in Yokohama. Although the number of units sold is still low, producers project increases. Figure VII.4 depicts the RobuGLASS™ robot, developed by Robosoft (France), which is a 4-track platform moving along the external glass surface of the Pyramid.

(iii) Cost benefit analysis and major restraints on further diffusion

Window cleaning robots bring about cost reductions mainly through improved safety and higher productivity. As the robot can either be remotely controlled from below or move fully autonomously, human cleaners no longer have to climb the facades. This reduces the risk of accidents immensely, and accounts for the less stringent safety provisions which robots face as opposed to human cleaners.

As robots are not affected by weather, they can perform without interruption and to a higher standard. Additionally, the mobile “climbing base” can be used for other tasks such as inspection.

In order to optimally employ window cleaning robots, certain criteria in the design of a building have to be met. Architects, however, are often reluctant to adapt their construction plans to the needs of robots. Consequently, construction peculiarities (such as arcades, balconies or inlets) frequently prevent the use of robots.

(iv) Major producers

Next to the Japanese pathfinders (who developed the first window cleaning robot in the late 1980s) and the other companies mentioned in the text above, robots have also been developed by Cybernétix (France), Robosoft, (France), and Wany SA (France).

c) Wall-climbing robots

(i) Types of operations carried out by the robots

There are different systems, which allow robots to climb walls:

- The sucker robot produces a negative pressure between the sucker and the wall and then moves with motor-driven crawlers.
- Biped wall-climbing robots use several small suction cups. Fixing one and moving the others, the robot can walk, turn and move between ground, wall and ceiling.
- A very different technique is used by the wall-driving robot. Two propellers account for the upward force while a slight inclination towards the wall produces a frictional force between the wheels and wall surface for adherence to the wall.
- The flight robot, finally, can jump over obstacles right onto the wall. To mount further, it uses a propeller system similar to that of the wall-driving robot.

A gradation from (1) to (4) can be made out. While (1) first is able to climb walls, see figure VII.4, (2) can already overcome obstacles, i.e. transition between ground and wall. Robot (3) is faster and more freely moving. Being remotely or manually controlled (via radio controller), it can change direction and even stop on the wall. Finally, (4) can mount buildings whose bottom area is not accessible. Once on the wall, it can get over irregularities such as window frames and can thus be used for various purposes.

Ultrastrip Systems (USS) has developed the first version of a robotic, water-jet-based, paint stripping machine for rapid removal of paint from the hulls of large ships. A high-pressure water-jet is used to strip the hull down to bare metal when the ship is docked. The water is recovered and recycled and the paint as residue is automatically dumped into containers for disposal.

Another example is a suction cup operated modular platform which can be equipped with various tools or sensors for surface cleaning, inspection or maintenance. A special form of usage of the mobile platform is as an animated advertisement board as “Animated Ads”. A tether secures the platform from falling.

(ii) Level of distribution

These systems have just reached the stage of prototypes. They are not yet fully commercialised.

(iii) Cost benefit analysis and major restriction in the diffusion

Wall-climbing robots are helpful when access to the structure is not possible or too time consuming. They are also useful for inspecting or working in environments not safe for human beings, such as nuclear sites and bridges.

For the moment, the mechanisms only allow for light weights to be transported, which requires specially designed instruments to be mounted onto them. Additionally, staying on the wall necessitates constant engine power, so working time is limited by the amount of fuel carried.

(iv) Major producers

Most of the designs come from specialist machine manufacturers. Cybernétix produces wall-climbing robots mainly for use in nuclear plants ;those of UltraStrip Systems machine ship hulls. Prototypes of wall-climbing robots have been developed by Dr. Nishi's Laboratory at Miyazaki University, Japan (see table VII.2). The European Thematic Network CLAWAR is currently investigating the development and use of climbing robots.[17]

d) Tank, tube and pipe cleaning

(i) Types of operations carried out by the robots

Even though tank, tube and pipe cleaning are obvious tasks for robots, only a few, mostly customised, systems have found their way into practice.

- **Fuel tank cleaning**

Above-ground fuel storage tanks have to be cleaned regularly. The sludge is removed to eliminate fuel contamination and recover lost storage capacity. Removing the sludge by conventional methods requires an empty tank, which results in long down times (typically 10 hours).

Tank cleaning robots use a method of dilution that does not require the tank to be emptied. Diluting the sludge and heating it (to approx. 60° C), they constantly control the sludge’s viscosity such that it reaches and maintains a consistency at which it can be pumped out of the tank. This method permits the recovery of fuel that is trapped in the sludge. Subsequent centrifugation separates small particles and frees them from the oil, which further reduces toxic waste. While operating inside the tank, tank cleaning robots can be guided from outside via remote control and light-sensitive cameras.

[17] CLAWAR: *European Network for Climbing and Walking Robots*; http://www.clawar.com.

- **Water tank cleaning**

A new and emerging market is the cleaning of fresh water tanks. Water-towers have to be cleaned typically every 12 months to comply with national laws. Up to now, professional divers have been deployed for this task. Owing to poor working conditions and high salaries, the potential for using robots has been explored. The basic principle is to deploy a vehicle that automatically traverses the water tower as an underwater vacuum cleaner. The vehicles are typically equipped with ultra-sonic sonar for navigation. In addition, video is often provided to allow an operator to monitor the progress of the vehicles and document the cleaning process. This industry is relatively recent and products have only just started to enter the market. Given the legislation in this area, it is expected that this market will grow significantly over the next few years.

(ii) Level of distribution

Low tank cleaning frequencies – although this is increasing – are a restriction in terms of making a robot acquisition financially viable. However, increasingly stringent environmental and health and safety regulations seem to favour a wider usage of these systems.

(iii) Cost benefit analysis and major restraints on further diffusion

Using robots improves overall safety. Their sensors (for detecting waste, materials, pollution etc.) are more suitable than visual observation and experience of human workers so that possible ignition sources, combustible fumes and electrostatic charges are eliminated.

In "high risk" tanks, such as those where emissions from the tank venting or pyrophoric materials preclude gas freeing, a robot can work under a nitrogen blanket or other inert atmosphere. It can be guided from outside via remote control and light sensitive cameras, isolating workers from dangerous in-tank work. As robots are built small enough to pass through the tank opening or can expand themselves, in-tank robot assembly is no longer needed, further reducing in-tank man-hours.

The robotic method significantly reduces cleaning time (3 to 5 times quicker). Firstly, the robots can stay in the tank far longer than humans, which save long recovery breaks. Secondly, pumping the sludge out is much faster than the conventional method. Additionally, the tank does not have to be completely emptied (and could even be kept in use during the process), which significantly reduces down time. There are large reductions in the amount of waste (up to 90%), partly due to the high fuel recovery rates (up to 98%).

(iv) Major producers

KOBE Mechatronics (Japan), RedZone Robotics (USA), RENOSOL (France).

e) Pool Cleaning

A variety of robots have found their way on to the market. These devices are starting to be produced in large quantities at attractive prices, paving the way to their being used in private pools. The mobility of pool cleaning robots depends on wheels. Their motion control follows different and sometimes most interesting strategies for best coverage of both pool floors and walls. Manufacturers in this field are: Aqua Products (USA), Weda (Sweden), Maytronics (Israel), (see figure VII.5).

f) Other cleaning tasks (e.g. robotic reservoir cleaning)

Almost all objects require cleaning. Vehicle, ship, boat, train and aircraft cleaning have all led to a multitude of robot designs, most of which have not passed the prototype stage. In many cases, the cleaning tasks have to be performed for technical reasons, such as the decontamination of military vehicles or removing barnacles from ship hulls, see figure VII.6.

(i) Types of operations carried out by the robots

For security and maintenance reasons, aircraft and ships have to be cleaned regularly, the intervals often being specified by law. The traditional cleaning procedures require boats to be taken out of the water and aircraft to be brought into a special hangar equipped with cranes or other long instruments. The actual cleaning process is lengthy and inconvenient.

Robots for boat cleaning have been suggested in the past as fixed installations where a boat hull is towed over a cleaning device, which automatically cleans the hull.

(ii) Level of distribution

As both aircraft and ship cleaning robots are rather new on the market, sales have not yet started to expand broadly. In Sweden, where chemical coatings of ships and boats are illegal on inland waters, mobile underwater washing units are already in use.

(iv) Major producers

RedZone Robotics (USA), Weda (Sweden), both robotic reservoir cleaning.

VII.3.2.3 Inspection systems

a) Sewer robots

(i) Types of operations carried out by the robots

Sewer robots can clean pipes of 200 to 600 mm inner diameter, which are inaccessible to humans. They are usually based on multi-segment platforms, which allow them to follow bends, cross junctions and even overcome steps. Instead of being limited in their range of operation by the friction of the cable, they operate autonomously with possible remote interference. An example of a sewer robot is displayed in figure VII.7: The Micro VGTV or Variable Geometry Tracked Vehicle for remote inspection or observation applications can transform from conventional crawler tracks to triangular tracks during operation, allowing the vehicle to negotiate obstacles and operate in confined spaces and rough terrain.

(ii) Level of distribution

Sewer robots are all still very new. Some have not yet left the prototype stage. Their sales, up to the end of 2004, amounted to some 90 units. The forecast for 2005 to 2008 is for about 165 units (see table VII.1).

(iii) Cost benefit analysis and major restraints on further diffusion

Using sewer robots, productivity improvements are mainly attained through a) the autonomous operation, which allows the robot to work without dragging cables behind it, and b) the increased mobility, which enlarges the range of operation and thus allows for longer working periods without resetting. The whole cleaning process is thus more rapid and economical. In some cities there is a lack of detailed plans of the complete sewer system. In these cities, robots can also be used for mapping the sewer system to ensure that information is easily accessible when leakage is detected.

The major constraint on commercial viability is the usage limitation to pipes of 200 to 600 mm inner diameter. Especially for smaller operators, this specialisation can make it difficult to attain sufficient utilisation.

(iv) Major producers

Cybernétix (France), Inuktun Services (Canada), ISE (Canada), Jenoptik Silmetric (Germany), Omnitech Robotics (USA), ProKasro Mechatronik (Germany), QinetiQ (UK), RedZone Robotics (USA), Robo Probe Technologies (USA).

b) Tank, tubes and pipes

Inspection and maintenance of tanks, tubes and pipes is a task that is clearly suitable for robots. There have been numerous developments in tube and pipe inspection, many of these with specific requirements:

The 5-foot-long Explorer, developed by National Robotics Engineering Consortium[18] in Lawrenceville, can crawl through kilometres of live natural gas lines, using fish-eye cameras at either of its ends to search for leaks or for pools of water that have seeped into the system. Once inside a 6- or 8-inch pipe, Explorer can make 45- or 90-degree turns at pipe joints when necessary. And it operates without a tether; so human controllers on the surface direct it by means of a wireless remote control. A similar application has been suggested by Westinghouse Savannah River Company. WSRC has developed a new pipe crawler with high load capacity designed to move through 3 to 4 inch diameter pipes.

The Nanomag of Inuktun (Canada) is designed to adhere magnetically to metal surfaces: horizontally, vertically, and even upside down. Cameras in the front acquire high-quality images while the rear camera is mainly used for tether management.

Oil-Spore is a small-scale autonomous oil pipeline inspection system which measures and stores in-situ physical and chemical properties of two or three-phase flow conditions. The system is produced by Automatika (USA).[19]

Maverick, of Solex Robotics (USA), is a rugged inspection system for service in above-ground storage tanks. The system performs floor inspections from inside the tank while submerged in refined petroleum products. The robot is a remote-controlled, purged and pressurised, submersible inspection platform, with an instrumentation payload that includes a multi-channel ultrasonic sensor system to map and correlate metal thickness data, an on-board video system to record inspections, and position tracking sensors.

Other systems have been developed to inspect vents and ducts of air systems. Similarly these systems have to negotiate inclines, bends and junctions.

In addition to the companies mentioned above producers are Automatika Inc. (USA), Inspector Systems (Germany), Inuktun (Canada) and Solex Robotics (USA).

c) Other inspection systems: Inspection robots for power plants, nuclear sites, bridges

(i) Types of operations carried out by the robots

This category includes inspection robots for general use and work in power plants or nuclear sites. Under extreme (or unfavourable) conditions, these robots should replace human workers performing tasks such as lifting and moving heavy barrels, handling toxic materials etc. As they can be guided via a video system, the operator does not have to enter the area of operation. As there is no alternative to machines taking over jobs which would put human workers at risk, there has been great impetus for the development of inspection and maintenance robots. In many cases these technologies have contributed to the emergence of service robots. Figure VII.7 shows robot systems for various inspection tasks.

A large variety of robot systems have been developed, both robots for special tasks such as the inspection of reactor cores, and mobile robot arms which are operated semi-autonomously for general handling, machining and inspection tasks.

In some cases, the guiding system used is very sophisticated. It consists of a mobile control station, contained in a truck. One robot model uses up to 11 video monitors corresponding to a similar number of cameras allowing overall system overview and control. A special camera is used for fine manipulations. Robots for use in nuclear sites are protected by special shields against radiation.

Another system is a six-axis robotic scanner equipped with an ultrasonic phased-array inspection system. The reactor core is scanned and the material pattern mapped so that the growth of material flaws may be monitored . Both programming and operator training are supported by full off-line functionality.

A recently introduced system is the Explorer which is an assessment robot introduced into the gas piping system.[20] By means of a movable segment design it is able to follow bends in pipes. Communication between robot and surveillance personal is achieved by a specially designed radio antenna.

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[18] http://www.rec.ri.cmu.edu/.

[19] http://www.automatika.com/products_oilspore.htm.

Other inspection robots aim at reconnaissance in hostile environments such as Urbie. Here the operational mode is termed semi-autonomous, combining local autonomous navigation and tele-operation. The purpose of these robots is to gather visual or other sensory information in specific environments.

(ii) Level of distribution

Up to the end of 2004, about 145 units have been sold. For the period from 2005 to 2008, close to 100 unit sales are forecast. It is anticipated that in the context of increased home security and anti-terror programmes these sales figures will be surpassed.

(iii) Cost benefit analysis and major restraints on further diffusion

The camera guidance system allows the operator to stay well away from the potentially dangerous area. This is a major improvement in worker safety, since despite protection requirements, an element of risk will otherwise always remain. As a side effect, the high costs of complying with stringent safety provisions are reduced.

As these robots are less sensitive to radiation, toxic gases and high temperature (up to 70° C for Telerob), they can stay in the area far longer than humans. Thus, productivity and safety are improved.

The steering of remotely controlled robots requires much experience and dexterity, especially for fine adjustments. Depending on the task, the robot may have to interact with other machinery, which further complicates matters.

Economic viability will depend on the degree of utilisation, that is, on the number of applications that require the use of the robot.

(iv) Major producers

Inspection robots have been produced by Advanced Robotics Vehicles (USA), Cybernétix (France), Everts VIT (USA), Fraunhofer IPA (Germany), Inuktun Services (Canada), iRobot (USA), ISE (Canada), Robo Probe Technologies (USA), Perry Slingsby (UK), Telerob (Germany).

VII.3.2.4 Construction and demolition

a) Nuclear & dismantling demolition systems

This category includes demolition robots and robots for servicing and/or dismantling nuclear, chemical, refuse, military and other hazardous complexes.

Extreme safety standards in nuclear power stations require regular inspections of weld seams in reactor cores and pipes by ultrasonic and eddy-current systems. The inspection equipment is squeezed in a narrow gap between the biological shield and the reactor core. The gap size is some 15 mm wide and between 250 and 500 mm deep. Only automated inspection systems can gain access to the inspection area. IntelligeNDT[21](Germany), has introduced a foldable, modular robotic system for this purpose which is introduced into the gap on a rail system. The robot scans the areas to be inspected with an array of inspection sensors. The robot moves along the rails of the reactor and thus covers the entire surface in segments. The inspection trajectories are generated by off-line programming systems. All controllers and electrical equipment are integrated into the robot’s structure or on the servo drives so as to be independent of a switching cabinet, see figure VII.7.

(i) Types of operations carried out by the robots

Demolition of structures often brings with it a considerable risk as the different pieces come apart. In most cases, these robots consist of a mobile part with an on-board hydraulic manipulator that has a tool for

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[20] H. Schempf et al.: *Explorer: untethered real-time gas main assessment robot system.* In: Proceedings of the ASER '03: 1st International Workshop on Advances in Service Robotics. March 13-15, 2003 - Bardolino, Italy.

[21] intelligeNDT Systems & Services GmbH & Co. KG, http://www.intelligendt.de/en/.

demolition mounted at the end. The robots are primarily tele-operated by an operator who is either in a safe cabin or operating them from a safe distance.

(ii) Level of distribution

Robots for general demolition of construction complexes and for dismantling or servicing nuclear plants, chemical industries, waste treatment or military complexes have a large market potential. Some 3,250 robots are already in use and it is estimated that about 1,220 more units will be added in 2005-2008.

(iii) Cost benefit analysis and major restraints on diffusion

When dismantling nuclear power plants it is often difficult or impossible to use manual labour owing to radiation. On the contrary, it is possible here to place a demolition robot in the area to be dismantled or demolished. To be truly effective, the robot must be agile in the sense that it must be able to cut pipes, package material into containers, demolish walls etc. Finally, it must itself be dismantled for transportation to a storage area. A major challenge here is that the robot must be extremely reliable, as it is virtually impossible to repair or upgrade the system once it has been deployed. Owing to safety considerations and the complexity of the task, these robots are typically remote-controlled with a very limited degree of autonomy. The challenge of combining robust sensing/feedback with high durability and flexibility represents a significant obstacle to wider deployment.

Even in non-nuclear environments, there is often a considerable risk associated with the demolition of structures. An example is the tearing-down of a ceiling. To this end, a special breed of robots has been developed. The robots are typically tele-operated from a wireless operator panel. It is, however, characteristic that this is a niche market and many of the providers do not consider their vehicles to be robotic systems, but rather a demolition vehicle with a hydraulic crane for handling walls, ceilings, pipes etc.

Examples of advanced work platforms in the nuclear environment are systems which were designed by Cybernétix and CEA such as the TOTEM, a work platform support which includes a vertically motorised trolley supported by a mast. The trolley hosts one or more manipulator arms for dextrous manipulation tasks in nuclear disassembly. Another example is the BROKK heavy duty manipulator for demolition of building structures. See figure VII.8 for some examples of robots that operate in hostile environments. Similarly, the BEAST of Autonomous Solutions INC. is built for hazardous environments and is operated remotely for typical tasks such as bomb disposal, obstacle clearance, and waste site sampling.

(iv) Major producers

Brokk (Sweden), Cybernétix (France), intelligeNDT Systems and Services (Germany), Mitsubishi Heavy Ind. (Japan), R.U.Robotics (UK), RedZone Robotics (USA), Autonomous Solutions Inc. (USA).

b) Construction support robots

Numbers of construction robots surged in the 1980s, especially in Japan, as a way of improving human working conditions and thereby add attractiveness to an often less-appreciated profession. Numerous applications for construction robots have been suggested, such as (A) construction of multi-storey buildings, (B) building roads or (C) drilling and (D) maintenance operations. A good overview of current research activities in construction robotics may be obtained from the annual International Symposium on Automation and Robotics in Construction (ISARC).[22]

As an example, Fujita's (Japan) unmanned construction method introduced controls and interfaces for operating a wide variety of construction machines:

- The Tele-Earthwork system (for large scale unmanned construction) creates remote-controlled construction machines by incorporating commercially available wireless communication systems into construction vehicles. This, together with the installation of monitoring cameras and wireless image communication systems on the construction machines and at various locations around the site, enables operators to control these vehicles from control rooms without needing to be able to

[22] The International Association for Automation and Robotics in Construction (IAARC); http://www.iaarc.org/.

see the machinery directly (the maximum distance between the control rooms and sites is around 2 km).

- A portable tele-operated robot system (“Robo-Q”) for small scale unmanned construction vehicles comprises a set of components that can quickly be installed into most conventional excavators to allow unmanned operation. The low weight (ca.100 kg) and ease of installation renders the system easily transportable to any locations on a wide variety of vehicles, see Figure VII.8.

(A) Multi-storey buildings

(i) Types of operations carried out by the robots

Robots used in the construction of multi-storey buildings unload the material at the ground floor and transport it to the top floor where it is assembled. The roof is built first and then moves up with every new storey built. Such robot construction is already used in Japan, while in Europe there has been little development in that direction. An example of this type of computer-controlled machinery has been marketed by Putzmeister AG since 2001. Their concrete booms can be equipped with a computer control to efficiently guide and program a hydraulically powered redundant kinematic chain. It is reported that time effectiveness, damage reduction and the quality of concrete delivery was dramatically improved, so that a very good return on the controller investments can be achieved. The controller is a spin-off of the Skywash[23] aircraft-cleaning system.

After natural catastrophes such as earth-quakes, the devastation left behind is often vast and in many cases it is too dangerous to send construction crews to repair the damage. In such circumstances, remotely controlled unmanned construction equipment could play a valuable role in performing initial construction work, making it safe for human construction workers to continue. Remotely controlled unmanned construction equipment has been applied in four sites in Japan. Human operators were located 2 km from the site. The system contains portable tele-operated robots.

(ii) Level of distribution

It is estimated that some 70 robots have been produced, with a forecast of 65 for the years 2005 to 2008, see table VII.1.

(iii) Cost benefit analysis and major restraints on further diffusion

The robot brings the material up autonomously, making the time- and manpower-intensive usage of cranes superfluous. Robot construction is thus up to 30% faster. It is not reliant on weather conditions as building activity takes place inside, which also makes it less dirty and noisy.

The building architecture has to be adapted to suit the method of construction. Hydraulic cylinders have to be placed in the building foundations to allow the transport unit to glide up and down.

A sufficient demand for such uniform buildings is essential to amortise the costs of construction robots.

(iv) Major producers

Partly automated systems to construct multi-storey buildings have been developed by Taisei Corporation (Japan), Shimizu Corporation (Japan), Fujita Corporation (Japan), Taisei (Japan), R.U.Robotics, (UK), and Putzmeister (Germany). Tele-manipulated building machinery has been developed by Tokyo Construction Co. Ltd. (Japan), Hazama Corporation (Japan), and Cybernétix (France).

(B) Road construction

The building of roads is still mainly done manually. Working next to highway lanes is a noisy and dangerous job, which for these reasons is suitable for automation.

[23] http://www.putzmeister.de.

The road robot navigates itself by computer, no longer needing workers for guidance. It combines the tasks of several conventional machines, so that instead of engaging in a number of consecutive working steps and phases, the robot immediately produces the final pavement.

One robot requires far less space than several conventional machines. Where traffic flow needs to be maintained alongside roadworks, for example, when adding a lane to a busy highway, this is an important feature.

Robotic road building is very environmentally friendly, as it produces 50% less exhaust gas and uses 50% less fuel.

Working autonomously, the robot requires a much smaller number of people to be engaged in dangerous road work. Apart from these evident advantages, the quality of its work seems to be better as well.

So far, the robot system has not been widely commercialised. Restrictions on usage are for example that it is dedicated to the task of paving new roads. For repairs and other partial tasks, workers are still required. As often with specialised machinery, a sufficient degree of utilisation may thus be hard to reach, as it very much depends on the demand for new roads.

(C) Drilling

Drilling has to be done for various reasons, for example when installing telephone cables or electricity wires under riverbeds etc. In order to achieve this, the surface has to be removed along the way.

The trenchless drilling method first drills along a predefined route and then washes and widens the tunnel with a reamer. When the cavity has the correct size, the product is fitted through.

Such trenchless drilling can be used on crossings up to 2,000 m in length and 300 m in depth with a diameter below 1.40 m.

This method is environment friendly as there is less damage to tree roots and other underground objects. There is less dust, dirt and noise, and it requires 20% less operating space.

It is cost effective as it is faster, and streets, or other nearby facilities, do not have to be closed. Although fewer workers are needed, they have to be well trained, as the robots require more operational knowledge than conventional machines.

Just as in road construction, the application area of drilling robots is more or less limited to new drillings, as repairs and other maintenance tasks on pipelines often require a full opening.

A trenchless drilling robot is produced by the firm Tracto-Technik GmbH (Germany) (see table VII.2).

VII.3.2.5 Logistic systems

(i) Types of operations carried out by the robots

In larger offices and in hospitals, maintenance tasks such as circulating mail, emptying bins etc. are simple, but time-consuming activities which are performed by special employees who pass round the aisles with trolleys.

Courier robots can take over some of these tasks. Based on a mobile platform, they are equipped with special devices such as a laser scanner to locate the bin, a storage room to carry the post and such like. They operate on their own, not needing any supervision.

In hospitals, the robots are typically point-to-point delivery systems. Typical transportation tasks include meals, linen, laboratory samples etc. The materials to be transported are placed in a storage area and loading and unloading is carried out by the staff. Navigation is achieved using laser scanners, ultrasound sensors and strategically located landmarks (often placed in the ceiling). The robots also have devices allowing for communication with automated doors and elevators to allow coverage of the entire building. More recently there have also been attempts to enable the robots to pick up other mobile units such as trailers and transport them between different stations placed throughout a facility.

The intelligent TransCar LTC of Swisslog AG (Switzerland) meets the bulk material transport needs between centralised functions such as kitchens, laundries and storerooms. These automated guided vehicles can load and unload carts to transport them between delivery points. The vehicles (AGVs) are taught to find their own way on a basic route between two locations, or can be programmed to travel throughout complex hospital corridors, including interfacing with elevators, powered doors and other devices.

A different approach is The Tug from Aethon, which offers a compact mobile base which is connected to a regular cart, thus adding autonomous mobility to wide variety of carts.

Another kind of service robot used in hospitals is the Helpmate®. The concept dates back to the mid 1990s where it broke new ground in autonomous mobile robot technology. This courier robot system has recently been acquired by CardinalHealth Inc., a leading provider of medication and supply dispensing systems to health care facilities. So far more than 100 units have been installed. Helpmate® transports meals to patients, drugs to other departments, etc. It frees skilled staff from doing unskilled courier tasks. A similar courier robot system has been introduced by Matsushita Electric Works in Japanese hospitals[24]. The Staffetta robot marketed by Genova Robot is carries out similar tasks (see figure VII.9 for some of the typical courier robot developments).

(ii) Level of distribution

Wheras some of the systems developed up to now have served as prototypes to gather experience with human interaction, other systems are directly aimed at commercial usage.

So far, about 270 units have been sold. Sales in the period 2005-2008 are estimated at about 790 units (see table VII.1). If prices come down to a more reasonable level, which might be the case due to recent developments in sensor technology, demand might increase significantly.

(iii) Cost benefit analysis and major restraints on further diffusion

Courier robots aim at reducing labour costs. Due to their novelty, some customers, such as hotels, might want to integrate the robots' services in order to demonstrate modernity.[25] In addition, the costs in some sectors such as the health care sector imply that there is a need to automate certain transportation tasks. Domain studies have indicated that nurses and other healthcare workers might spend as much as 20% of their workday performing transportation tasks that could easily be automated. If this could be reduced to 5%, there would be significant savings.

Often, additional changes are necessary before the robots can be used. Mail delivery robots, for example, require special post boxes to be located in the aisle. Moving at about 0.5 m/s, they are slower than humans.[26] Current progress in navigation in cluttered environments does however suggest that speeds of up to 1.5 m/s might be within reach, giving them a performance equivalent to humans. In addition, navigation methods are gradually allowing operation in densely populated areas.

To recover the considerable purchase costs, a high degree of utilisation is a prerequisite to obtaining a sufficient return on the investment.

(iv) Major producers

Active Media (USA), Swisslog (Switzerland), Aethon (USA), Atlas Copco Mining Trucks (Sweden), Cybernétix (France), Fraunhofer IPA (Germany), Gecko Systems Inc. (USA), Genova Robot (Italy), CardinalHealth (USA).

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24 Press release Matsushita Electric Works, Ltd.: http://www.mew.co.jp/e-press/2003/0304-01.htm.

25 R. D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions*. London: A K Peters Ltd., 2000.

26 Ibid.

VII.3.2.6 Medical robots

All types of robots that are employed for diagnosis, therapy and patient care are, for the purpose of this survey, categorised as medical robots, from manually guided active kinematics for diagnosis to complex surgical robot workstations. Most of the robots surveyed are, however, used for surgery, especially in combination with minimal access surgery.

a) Robot Assisted Surgery and Therapy

Minimal access surgery (MAS) is increasingly used and becoming a widely accepted technique. The benefits for patients are enormous. They experience much less pain and a fast postoperative convalescence. This is particularly important for elderly patients. Insurance costs are reduced as a result of shorter hospital stays. MAS is increasingly employed in more specialised areas of surgery.

(i) Types of operations carried out by the robots

Various devices have been developed to facilitate the task. The main areas for surgical assistance, as categorised by R. H. Taylor[27], are:

- assistant functions, such as holding instruments,
- tele-surgical functions,
- navigation,
- positioning, and
- specific surgery activities, such as mill-cutting the inner part of a bone.

Assistant functions are performed by robotic arms, which hold the endoscopic camera. They can even be voice controlled or autonomously follow the surgeon's head movements.

Telesurgical instruments allow the surgeon to use the robot as an extension of his own direct manipulative capabilities.

A navigation system provides accurate positional feedback about the location of surgical instruments relative to the patient's anatomy. They typically consist of a 3D localising device and workstation to display positions relative to volumetric medical images. Some systems even integrate pre-surgical images and models.

Robots for precise positioning insert and align a tool guide, relative to the target anatomy. They follow a co-ordinate system, which is registered to pre-surgical images of the patient. During the insertion of instruments, the robots are turned off for security reasons.

For specific surgery jobs, such as cutting the inner part of a bone, "craft tools" can perform the task autonomously and with high accuracy following a preoperative plan.

The emergence of new techniques and therapies, such as neurosurgery, cell implants etc. will require surgical moves into the microstructure, which are impossible without technical assistance. A hexapod system, developed for sub-millimetre manipulation, already reaches a respectable positioning accuracy of 10 μm. Two other robot designs following the classical master-slave operation principle have been successfully introduced into operation scenarios: DaVINCI™ of Intuitive Surgical Solutions (ISS) and ZEUS® of ComputerMotion, which act as counterparts for heart and laparoscopic surgery. This means that the surgeon operates precision input devices which translate hand and finger movements to the end effector which can carry tools, diagnostic devices or optical lenses for visual guidance and inspection. Additionally, special ergonometric operating chairs are being developed to give visual and tactile feedback and support the surgeon's concentrated, steady moving hand and optimise the dexterity enhancement effect.[28] The robots can be used in neurosurgery, microsurgery, orthopaedics, ophthalmology, cardiology, and for further future therapies.

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[27] R. H. Taylor: *Robots as Surgical Assistants: Where We Are, Wither We are Tending , and How to Get There*. In: Lecture Notes in Artificial Intelligence #1211, Berlin, Heidelberg: Springer-Verlag,.

[28] R. D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions.* London: A K Peters Ltd., 2000.

Furthermore, classical robot systems are being used for radio therapy such as the CyberKnife™ of Accuray (USA). Incorporating a compact linear accelerator mounted on an industrial robotic arm, the system provides the surgeon with unparalleled flexibility in targeting. Advanced image guidance technology tracks patient and target positions during treatment, ensuring accuracy without the use of an invasive head frame.

In September 2001, the so-called "Operation Lindberg" took place. It was the first remote transatlantic robot operation ever. Surgeons in New York operated on a patient in Strasbourg, some 7,500 km away, with the help of the robot system Zeus. Also in 2001, the first heart operation with robots in Scandinavia took place at the Karolinska Institutet, Stockholm. Specific market studies point out long-term market opportunities, forecasts, and strategies[29].

(ii) Level of distribution

With the experience and knowledge gained from the systems already in use, acceptance of surgical robots is in general growing. The number of operations requiring technically advanced methods is increasing, and as a result, new methods are being sought. In addition, many more systems are being developed or are currently in their prototype phase and awaiting approval from medical authorities. While so far about 2,800 systems are in use, sales of 2,000 units are projected for 2005-2008 (see table VII.1).

(iii) Cost benefit analysis and major restraints on further diffusion

The MAS procedure lets the surgeon lose tactile sense and restricts his manipulative capability. Telesurgical devices are set to remedy this. "Virtual instruments", in addition to pictures, supplied by the camera system convey tele-presence. In other words, although standing at a distance, where he has more manipulative freedom, the surgeon has the feeling that he is operating directly.

Positioning robots allow for faster and more convenient positioning. Sensor information is used to quickly correct goal co-ordinates representing the area of intervention. This is important where deformable soft tissue and patient motion (e.g. for respiration) is involved. The system also allows the surgeon to go back to a specific place on exactly the same path, so as not to destroy more tissue.

Active robotic surgery can be extremely precise. Systems used for orthopaedic surgery, such as cementless implantation, reduce gaps between implant and bone to 0.05 mm compared with 1-4 mm in the case of manual surgery. While a manual broach often leaves holes oversized by more than 30%, and only 20% of the implant is in contact with the bone, robotic milling raises this level of contact to 96%. The tenability of the cementless implants is thus estimated to be 2.5 times higher.[30] Some robot systems allow the surgeon to choose between different operating modes:

- manipulator mode: directly controlled by the surgeon;
- semi-active mode: the robot carries and positions tool guides. Work on bones itself is performed by the surgeon;
- active-mode supported: the robot performs the three-dimensional motion with high positional accuracy.

In all cases, the surgeon supervises the procedure.

Overall advantages from using robot-assisted surgery and surgery robots are significant improvements in precision, greater independence from human error and reduced operating times, increased efficiency and cost savings.

Since the postoperative complication rates associated with many orthopaedic procedures are directly related to surgical accuracy, any measure that enhances surgical performance can lead to significant clinical and financial benefits.

Intense training and experience with the new equipment are prerequisites for a successful operation. The surgeon's task is complicated by the increasing number of support systems deployed.

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29 *North American Industrial Robotics Markets for Medical and Pharmaceutical Applications.* Frost & Sullivan, February 2005.

30 J. Pransky: *Surgeon's Realization of RoboDoc*, 29th International Symposium on Robotics, Birmingham , United Kingdom, 27 April –1 May 1998.

The different systems are not necessarily compatible with each other. However, the overall trend is to build devices that use the same software and operating system and can communicate with each other in order to provide an integrated system inside the surgery room. Some systems that are already available combine several functions. An interesting example is the combination of intra-operative image acquisition, planning and execution. Another example is the Cyber Motion Hermes Control Center, a centralised system which allows the surgeon to control a network of smart medical devices using his voice.

The acquisition costs for medical robots are still very high. Often a sufficient degree of utilisation can only be realised for generally applicable systems, which allow overhead costs to be spread. To solve these problems, companies are increasingly building more flexible robots: one robot can be used for a whole range of robot-assisted procedures and in several disciplines.

(iv) Major producers

Producers are Accuray (USA), Armstrong Healthcare (UK), CEREM-CEA (France), Computer Motion (USA), Elekta (Sweden), EndoVia medical Inc. (USA), Engineering Services (Canada), Integrated Surgical (USA), Intuitive Surgical (USA), KUKA (Germany), Medtronics (USA) (acquired Elekta surgiscope).

VII.3.2.7 Defence, rescue & security applications

a) Fire and bomb fighting robots

(i) Types of operations carried out by the robots

The risk of an explosion as well as the extreme heat that develops during a fire, especially when oil is involved, forces fire fighters to work from a great distance. Consequently, positioning of the water beam is less precise and water pressure is lost over the distance, resulting in decreased efficiency. Using fire- and bomb-fighting robots removes humans from dangerous environments, such as in or around houses which are likely to collapse, or near bombs which are likely to explode.

Guided by remote control or moving on their own, fire-fighting robots approach the fire and automatically bring the mounted water or foam cannons into position. The extinguisher used is either carried along or supplied through a hose, which is dragged behind and ensures a constant flow.

Alternatively, robots can be used to simply position a separate, ordinary water cannon and return thereafter. The separate water cannon carries a detector to find and readjust the operating direction. The robot’s power, size, weight and manoeuvrability vary according to the method of operation used.

Bomb-fighting robots consist of a mobile unit on which a very precise manipulating arm is mounted. Their several degrees of freedom allow for enhanced manoeuvrability so that precision work can be carried out. While the robots are able to perform certain tasks on their own, the operator can always interfere via remote control.

The Japanese rescue robot «T52 Enryu» is a mobile, manned or tele-controlled two-armed vehicle which is able to handle loads of 1 ton. It is designed for maximum strength and high dexterity[31].

(ii) Level of distribution

Up to the end of 2004, some 440 fire- and bomb-fighting robot systems have been sold and projected sales are very optimistic for the years to come (see table VII.1).

(iii) Cost benefit analysis and major restraints on further diffusion

Heat shields and CO_2 cooling from inside allow <u>fire-fighting</u> robots to withstand great heat and their navigation system lets them find their way through thick smoke.

The high costs of fire-fighting robots (starting at € 50,000) prevent fire fighting services from keeping several systems, which could be employed for large fires.[32] Using only one robot to position several cheap

[31] http://www.enryu.jp/.

ordinary extinguishers near the fire takes maximum advantage of the robots' features and reduces the risk of losing the expensive navigating robot in the event of an explosion. This, of course, requires the cannon equipment to be compatible with the robot.

A major problem that these robots do not solve is that of getting to the fire quickly.

As the manipulating arm of bomb-disposal robots can carry weight, change tools and pick up new ones, manual help is not needed. Additionally, the on-board freezing units can deactivate explosive devices on site, so that the operators can stay at a safe distance throughout the operation. There they rely on camera pictures, so that 3D and good positioning are crucial in order to do the required precision work. Of course, skilled operators capable of precise handling and experienced with the robots are another prerequisite for a successful operation.

Additional devices such as X-ray photography give precise information immediately and allow rapid and information-based decision taking.

(iv) Major producers

CDL Systems Ltd. (Canada), Cybernétix (France), Engineering Services (Canada), Inuktun Services (Canada), Kentree (Ireland), MRISAR (USA), Omnitech Robotics (USA), Rotundus (Sweden), QinetiQ (UK), Shadow Robot (UK), Telerob (Germany).

b) Surveillance/security robots

(i) Types of operations carried out by the robots

Surveillance robots are used to assist human guards covering a large territory or to keep vigil in potentially dangerous areas. They are based on a mobile robot platform, on which a number of specialised instruments can be mounted so that they can be adapted to particular tasks in a variety of application areas (see figure VII.10). In military operations, surveillance robots put distance between troops and danger. Several systems have been introduced and tried out in combat situations as scouts for reconnaissance, search for explosives and hostage rescue. Intense efforts towards robot technologies in defence and security are being conducted by the Department of Defense as part of its transformational program[33].

(ii) Level of distribution

So far, about 630 units have been put into use and the producing firms expect sales of 2,685 units in 2005-2008 (see table VII.1).

(iii) Cost benefit analysis and major restraints on further diffusion

The autonomous operation frees guards from regular patrol. They can stay at a central “office” and follow the robots via video transmission. Where several robots operate in this way, much larger areas can be covered with fewer personnel.

In some areas such as monitoring of chemical plants, nuclear storage facilities, etc. the visit to various parts of the plant might be associated with considerable risk and it is here advantageous to deploy robot systems. Recently the military has also started to use such robots for coverage of remote and inaccessible places. The primary objective is here to eliminate/reduce the risk. The cost is consequently of secondary importance, which has allowed for relatively early adoption of the technology.

The robots can detect more than humans. In dark rooms their infrared sensors trace a human being by its body warmth (at room temperature from a 20-50 metre distance) and microwave sensors notice even the smallest movements from up to 20 m.[34] Flame, heat and smoke sensors assure fire prevention. Additional gas

[32] R. D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions.* London:, A K Peters Ltd., 2000.

[33] http://www.pentagon.mil/transformation/.

[34] R. D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions.* London: A K Peters Ltd., 2000.

sensors, measuring the concentration of carbon monoxide, acetone vapour or methane, can be added to monitor the surrounding air and to prevent accidents.

The different sensors are additional equipment, and the price of a security robot very much depends on the number and kind of sensors mounted. The cheapest and thus simplest versions do not have a quality advantage over humans and a human guard remains necessary in order to take action in case of emergency.

More refined versions with good perception abilities can work under inconvenient or even extreme conditions, as for example in power plants or places where gas could escape. Their value thus lies mainly in safety improvements.

Trends to minimise the number of people in military operations and particularly to reduce risks for soldiers have been strong factors in the increased interest in various types of robots and autonomous systems. Future battle scenarios during the next 10 to 15 years will be increasingly based on unmanned systems Numerous producers of mobile platforms (for urban and non-urban application scenarios) at different scales have been introduced in military operations[35].

Example are the TALON robots of Foster Miller (USA), recently acquired by QinetiQ (UK), have been in continuous, active military service since 2000 when they were successfully used in Bosnia for the safe movement and disposal of live grenades.

The “Aurora” of Automatika (USA) is a 10 kg reconnaissance robot system for use in firefighting, police, explosive-ordinance disposal, counter-terrorism and other reconnaissance applications. The system is unique in that it incorporates a steerable and pitchable mono-tread locomotor to climb over obstacles such as ditches, curbs, and steps.

OCRobotics has introduced a mobile manipulator capable of reaching into awkward spaces. Where a rigid-link robot is restricted by the "elbows" in its arms, its flexible, but rigid snake-arm of 2.5 m reach can follow its nose to reach through small gaps and around narrowly spaced obstacles. The arm can be fully sealed to cope with hostile environments, such as in defence and underwater applications.

The R-Gator™, an intelligent unmanned ground vehicle for military operation combines off-the-shelf rugged vehicles with autonomous navigation modules to perform dangerous and taxing missions. Using available systems, iRobot and John Deere have begun pilot production of the R-Gator which is designed to act as an unmanned scout, a "point man", a perimeter guard, and a pack/ammunition/supply carrier.

(iv) Major producers

Systems of surveillance robots have been produced by Active Media (USA), Angelus Research Corp. (USA), Cybermotion (USA), Deere & Company (USA), Engineering Services (Canada), Gecko Systems Inc. (USA), General Dynamics Robotic (USA), Genova Robot (Italy), GPS/Neobotix (Germany), Inuktun Services (Canada), iRobot (USA), MRISAR (USA), OCRobotics (UK), Probotics Inc. (USA), Rotundus (Sweden), R.U.Robotics (UK), Robowatch (Germany), SOHGO Security Services (Japan), tmsuk (Japan), Wany SA (France).

c) Unmanned aerial vehicles – surveillance systems

Recently, solar-powered aircraft for high-altitude, long-endurance flights have been developed. Within a few years, solar-powered aeroplanes, incorporating energy storage for night-time flights, will be capable of continuous flight for months at a time at altitudes of over 60,000 feet, powered only by the sun. Even more ambitious plans aim at applications for such aircraft that include telecommunications, reconnaissance and atmospheric measurement.

A major problem with unmanned aerial vehicles (UAVs) has been the issue of airworthiness. To operate in civilian air-space, they have to obey the same safety rules as normal aircraft. During 2002 and 2003 major steps were taken to change the rules. As part of the American effort in Afghanistan, the Predator RQ-1 was deployed for reconnaissance missions to provide imagery of remote regions. The vehicle is operated by a pilot and two sensor operators. They operate the vehicle from a ground control station that can be very far away

[35] http://robot.spawar.navy.mil/.

from the actual site of deployment. The vehicle can operate for 40 hours and has a maximum speed of 85 mhp. In total the vehicle has been used for more than 22,000 hours. By the end of the involvement in Afghanistan, the systems were upgraded to carry weapons.

Until recently the European authorities did not allow the use of these vehicles in European airspace, except in specially designated areas (commercial no-fly zones). By the summer of 2002, the rules were changed to allow deployment even in civilian airspace, but the vehicles must be able to adhere to the same rules as normal aircraft. For the detection of other vehicles in the airspace, the system relies on a radar system and a pan-tilt camera system.

UAVs are today used primarily in imaging missions, where they allow coverage of significant areas either for strategic missions or for generating an inventory of agricultural areas or forestry. In addition, an industry is evolving around sales of imagery to external parties. In some areas such as South America, it is of interest to provide information about the rain forest and the development of new areas. In addition, some UAVs are used for meteorological missions.

The rate of diffusion is growing rapidly in response to the strategic successes in Afghanistan and Iraq. Civilian use has in particular been promoted in Europe.[36] The exact numbers are difficult to obtain as in several cases they are confidential. Databases of unmanned aerial vehicles are made public by NASA and the Department of Defense.[37, 38]

Major producers are Aerovironment Inc. (USA), CDL Systems Ltd. (Canada), Schiebel (Austria).

VII.3.2.8 Underwater systems

Underwater robots are used to work on or to inspect sites where human beings cannot work in a safe way or to which they cannot even gain access.

(i) Types of operations carried out by the robots

As the application areas differ considerably and solutions cannot be used interchangeably, a distinction should be made between a) light inspection robots and b) heavy, more robust work-class robots.

a) At a size of 0.5-1 m^3 and a weight of under 50 kg, inspection robots can perform routine inspections of, for example, harbour walls, ships or oil platform jackets as well as surveillance tasks such as monitoring the safety of divers or underwater drillings, up to a depth of about 300 metres. Equipped with a good camera system (360°, wide-angle) and strong lights (100 watt quartz halogen lights), they can be guided from above. Small repairs can be performed with a manipulator arm.

b) The more robust work-class robots can go down a few thousand metres (up to 4,500 metres). They thus have to be much heavier (up to 5 tonnes) and bigger (295/183/200 cm) than inspection robots. When used for underwater pipeline or oil platform construction, manoeuvrability of manipulator arms, lights, camera and guidance systems is essential, especially as, at that depth, they cannot be replaced or aided by humans. Another category are off-shore burial systems which operate on the sea bed for ploughing cables, tubes etc. into the ground.

Another method of classification for underwater robots is to distinguish between manipulators, ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles). The latter types of robots are the most sophisticated ones. They are pre-programmed robots and can stay underwater almost indefinitely , recharging themselves on underwater power stations. They started to be commercialised in 2000. Figure VII.11 shows two types of underwater robots (crawlers and AUVs).

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36 Unmanned Systems, Vol. 19, No. 1, Jan/Feb 2001: UAVs in Europe.

37 http://uav.wff.nasa.gov.

38 http://www.defenselink.mil/specials/uav2002/.

(ii) Level of distribution

At the end of 2004, an estimated 5,320 underwater robots were in use (see table VII.1). Inspection robots made up the lion's share of the units sold. For 2005-2008, sales are projected to reach another 2,190 units.

The market for underwater robots is very promising. Sales of unmanned underwater vehicles are expected to grow to more than $ 1,200 million in the period 2005 to 2008.

(iii) Cost benefit analysis and major restraints on further diffusion

Robots can go deeper and stay under water for longer periods of time than divers, who would have to come up every so often to take new oxygen bottles and recover. This should allow operations to be completed faster, more cheaply and with fewer personnel. Considering these savings, the less expensive version of remote underwater robots, the inspection robot (e.g. at £ 40,000 - 60,000), may with good utilisation soon pay for itself.[39]

Using robots also means a safety improvement, as even in difficult conditions or during longer repairs there is no risk of damaging divers' health. The robots are easy to handle as they only consist of small guidance boxes (monitor included).

The price of large work class robots is in the order of £ 1 million. Additional equipment, such as a crane to lift the robot in and out of the water, has to be purchased.

The reachable water depth is continuously increasing and so is the sophistication of the navigation systems.

Most of the producers cover a variety of products which aim at various off-shore applications such as ROV, hull and anchor cleaning and inspection and crawlers for pipeline inspection.

(iv) Major producers

Alstom Automation Schilling, (USA), Androtech, (Germany), Bluefin, (USA), Cybernétix, (France), Deep Ocean, (USA), Hydrovision, (UK), Inuktun Services, (Canada), ISE, (Canada), KOBE Mechatronics, (Japan), Maridan, (Denmark), Oceaneering, (USA), Production Technology, (USA), Robo Probe Technologies, (USA), Sias Pattersson, (USA), Perry Slingsby, (UK), Perry Slingsby, (USA).

VII.3.2.9 Mobile platforms in general use

(i) Types of operations carried out by the robots

So far machines had to be guided either directly or via remote control, thus requiring personnel. Mobile robot platforms allow for independent movement of the machine and thus constitute the basis for (all) mobile robots.

To autonomously move in an unstructured environment, mobile robot platforms need a precise navigation system. Being the vital part of a mobile robot, it accounts for the main differences between systems and is the area in which important future changes and improvements are most likely to be made and are most needed in order to find simpler solutions and cut costs.

Some systems require a kind of programming (or teach-in) of the area of operation before they can start working on their own. With the help of magnetic pins in the ground, beacons in walls or other artificial landmarks, sensors allow the robots to find their way. The most sophisticated versions do not need these landmarks. Components, which are often jointly used, are:

- ultrasonic waves / sonar
- infrared sensors
- laser sensors
- computer vision.

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39 Hydrovision Ltd. company information.

Mobile robot platforms also need to be able to identify, stop for and possibly evade unexpected obstacles. Other components used in most advanced applications are:

- tactile sensors
- whiskers
- electronic compass and GPS
- light, water and temperature sensors
- tilt sensors to detect inclines
- sound sensors and recorders
- motor speed and battery voltage sensors
- infrared emitters to communicate with other robots.

All these sensors, combined with Artificial-Intelligence-navigation systems and network communication capabilities, can let a "community" of intelligent mobile platforms interact with the environment at various degrees of autonomy from a central control.

(ii) Level of distribution

While so far about 2,660 units are in use, producers expect 2005-2008 sales of about 5,760 units (see table VII.1). However, the number of mobile platforms in use is much higher if the integrated and specially adapted versions are counted. The reader should note that some of the robots, which in previous surveys were classified as mobile robots, are now reclassified as laboratory robots.

(iii) Cost benefit analysis and major restraints on further diffusion

Autonomous movement makes guiding personnel obsolete. It allows for 24-hour operation and frees labour for other tasks. In certain application areas the use of mobile platforms can significantly improve safety, which in a second step translates into cost reductions through less stringent safety provisions and reduced risk of health damage. These are the basic advantages on which very many service robots are based. Apart from that, most benefits are connected to the specific application area and are therefore referred to in more detail under the relevant application.

For some guidance systems, additional devices, such as beacons in walls or magnetic lines for navigation, have to be installed. Stopping and evading unexpected objects slow down the operating process.

The acquisition costs of mobile robot platforms are significantly higher than those of mere mobile platforms. As the working units mounted on them are usually similar - if not identical - to those of manually led systems and seldom more efficient, economic viability is highly dependent on the degree of utilisation.

Progress on mobile robots has recently led to a number of standardised systems for navigation that can be placed on a mobile platform. The availability of such standard components significantly reduces the cost of deployment. In addition, a number of toolkits for simple instruction of such mobile platforms is becoming available which implies that the setup of new applications will be simplified tremendously.

(iv) Major producers

Active Media, (USA), Andro Tec (Germany), Applied AI Systems (Canada), Arrick Robotics (USA) Atlas Copco Mining Trucks (Sweden), BlueBotics (Switzerland), BRIC Engineering Systems (Canada), Cybermotion (USA), Engineering Services (Canada), Gecko Systems Inc. (USA), Genova Robot (Italy), iRobot (USA), Intelligent Robotics Corp. (Canada), Mekatronix (USA), Merlin Systems (UK), Omnitech Robotics (USA), Roboscience (UK), Robosoft (France), GPS/Neobotix (Germany), Shadow Robot (UK), The Robot Factory (USA), White Box Robotics (USA), Zagros Robotics (USA).

VII.3.2.10 Laboratory robots

An estimated 3,460 laboratory robots have been installed. In the period 2005-2008, some 400 more robots are forecast to be added to the installed base.

Laboratory robots are produced by K-Team (Switzerland), Cybernétix (France) and Diversified Enterprises (USA).

VII.3.2.11 Public relation robots

a) Hotel and restaurant robots

Using robots in restaurants frees personnel from routine tasks and ensures constant quality and no risk of ruining food as a result, for example, of imprecise timing. McDonald's, Frymaster and Gas Research Institute have developed a frying robot for French fried potatoes, which is already in use in the United States.

In hotels, robots can carry out the tasks of carrying suitcases to rooms, delivering room service or transporting laundry. Mobile robot systems for hotel use are still under development. Examples of research efforts were presented by the University of Karlsruhe.[40]

b) Guide robots

(i) Types of operations carried out by the robots

Guide robots are used in museums or other places open to the public to assist or to replace guides (see figure VII.12). Usually these robots are autonomous mobile platforms with multimedia features added. They go round the museums following a planned path, providing video and audio enhancements to the exhibits. Like mobile platforms, they have sensors and navigation systems to avoid collisions. During the night or at pre-defined times, the robots go to a charging station and automatically plug in to charge their batteries.

(ii) Level of distribution

Guide robots are mainly at the prototype stage. Very few models have been commercialised. One interesting example is the Sage robot, developed by the Robotics Institute of Carnegie Mellon University, which has been in use at the Carnegie Museum of Natural History. The robot was recently taken out of operation after more than 1 year in use. Other successful installations are three robots at the *Museum für Kommunikation* in Berlin which share tasks in welcoming, guiding and entertaining museum visitors.[41] These robots have covered more than 15,000 km since March 2000. A group of 10 museum guides was presented with great success at the EXPO'02 in Switzerland.

(iii) Cost benefit analysis and major restraints on further diffusion

The robots might be an interesting cost-saving alternative in the management of a museum. Experience shows that a clever installation may contribute significantly to the museum's attractiveness, especially among children and teenage visitors. Other approaches consider the use of robots as virtual museum guides as an extension of the access to museum exhibits. A camera-equipped robot takes close-up pictures of artefacts following commands via the Internet. A European Community project investigated the feasibility and potential of such an approach.[42]

(iv) Major producers

Producers or developers are: Active Media (USA), BlueBotics (Switzerland), Genova Robot (Italy), GPS/Neobotix (Germany), MRISAR (USA).

c) Robots in marketing

Some 20 robots are estimated to be in use. As mobile platforms have reached technical maturity and modest unit costs, these robots are increasingly being used as attractions or mobile information kiosks to promote goods and services. The first mobile platforms have been installed at car sales centres, interacting with interested visitors. Fig VII.12 displays an interactive arrangement of two mobile robots at the OPEL sales centre in Berlin. The manufacturer of these platforms is GPS/Neobotix (Germany).

Major Producers are Fraunhofer IPA (Germany), Honeybee Robotics (USA), ISE (Canada), K-Team (Switzerland), Smart Robotics (Israel), GPS/Neobotix (Germany), The Robot Factory (USA).

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[40] R. Graf, M. Rieder, R. Dillmann: *A new driving concept for a mobile robot.* March, 22-24, 1998, Sevilla, Spain; http://idw-online.de/public/zeige_pm.html?pmid=6271.

[41] See http://www.museumsstiftung.de/berlin/d211_rundgang.asp.

[42] http://www.ics.forth.gr/tourbot/.

VII.3.2.12 Special Purpose

a) Refuelling robots

(i) Types of operations carried out by the robots

Refuelling automobiles has become a routine activity. Nevertheless it is in general not perceived as pleasant and, especially for the professional drivers of buses or taxis, takes up a lot of time.

First used on uniform bus fleets, robotic refuelling has now been developed for cars as well (see figure VII.13). Once parked near the gas pump, the driver enters his credit card and designates the amount of fuel needed. The robot then opens the fuel cap and enters the right kind and amount of fuel. Systems working with a coded transmitter can even check how much fuel is left in the tank.

(ii) Level of distribution

Regarded as a future growth area, several automatic refuelling systems have been developed. In the USA alone there are 200,000 gasoline filling-stations, a number which gives an indication of the size of the potential market. In addition to the bright prospects for gasoline driven vehicles, the mechanism has a feature that is a prerequisite for the utilisation of renewable fuels such as liquid hydrogen: it seals hermetically.

(iii) Cost benefit analysis and major restraints on further diffusion

Using refuelling robots, the customer can remain seated in the car throughout the process. For old and disabled people, for whom refuelling can otherwise be a difficult task, this is a major advantage. Other people may also find it convenient to stay inside, especially in bad weather . In dangerous areas and at night this can also be an improvement in safety[43].

The robots are environmentally friendly as they do not spill fuel and hold back over 90% of the toxic vapours, as compared with 60% when using modern manual equipment.

A robot would be able to complete an average refill of 35 litres in two minutes, , which is significantly faster than the manual mode. The equipment can also be used more efficiently. Taking into account that the robot price is less than double (€ 75,000) that of a manual machine (€ 40,000), economic viability seems to be feasible.[44]

The diversity of car models makes special fuel caps, transmitters or similar devices a prerequisite to usage. They have to be purchased by the customer and will thus act as a curb on demand until the system is more widely available.

While the extent to which manual oil and gas refilling will be substituted by high-investment automatic refuelling systems in the future is uncertain, there is no question that this technology will be introduced with the emergence of fuel cell-powered vehicles. Since these will depend on new fuels, investigations are being conducted into logistics associated with the new fuels, as well as the kind of refuelling equipment and refilling interfaces on the car that will be required.

(iv) Major producers

Refuelling robots were first used for buses in 1993 by Robin Anton Bauer GmbH., Autofill and Robosoft (whose robots are in use in major bus companies in France). Other producers/developers are American Controls (USA), Autofill (Sweden), David Brown Union Pump (USA), ISE (Canada), Robosoft (France), Textron (USA).

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[43] R. D. Schraft, M. Hägele, E. Kroth, A. Fischer: *Robot System for Automatic Fueling of Automobiles*. Robotic Industries Association, Ann Arbor/Mich.; International Federation of Robotics; Automated Imaging Association: International Robots & Vision Conference 1997; pp 7-9 - 7-19.

[44] R. D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions.* London: A K Peters Ltd., 2000.

Currently, robot refuelling stations at the Franz-Josef-Strauss-Airport, Munich gather information on hydrogen refuelling.[45]

VII.3.2.13 Humanoid robots

(i) Types of operations carried out by the robots

Our everyday work and home environments are organised with a view to human comfort. The physical layout of the environment is thus adapted to humans and not to robots. Most robots have a problem traversing stairs and opening/closing drawers. To address some of these problems and to use robots to study "human behaviour", the area of "humanoid robotics" has been established. Humanoid robots are still at the prototype stage. The robots developed have been used for transportation tasks in factories and for operation in hazardous areas such as nuclear power plants and petrochemical plants. The first experiments have been reported in which long term studies with humanoid robots were performed.[46] A detailed study on the future development of humanoid applications, technologies and research can be found in the ProRobot study which was conducted within a European Commission project.[47]

A highlight of humanoid robot technology has been the EXPO 2005 in Aichi staging a robot week in June with a large variety of demonstrators and prototype robots from companies, research institutes and universities.[48] Humanoid robots have been a highlight in particular as these were displayed in impressive shows and settings. Fig. VII.14 gives an impression of the displayed robots.

(ii) Level of distribution

Humanoid robots have not entered the market yet, but series production has taken place at Sony and Honda. The Honda robot has been used for showcasing technology in manufacturing, while Sony has demonstrated prototypes for entertainment robots (SDR-3x and SDR-4x). These robots are capable of dancing, and might provide a new generation of entertainment systems. SONY has announced that a system will enter the market during late 2003, at a price of more than $ 10,000. As part of the MITI Humanoid Project (1999-2004), a standard prototype (H8) is being mass manufactured for the involved partners in Japan. The robot has been produced in a total of 10-12 systems. A very good survey of current humanoid robot developments can be found on http://www.androidworld.com/ or at a conference suite dedicated to this fascinating technology.[49]

(iii) Cost benefit analysis and major restraints on further diffusion

The primary initial market is considered to be in entertainment, where Sony has been successful in selling a large number of dog-like robots (AIBOs). The expected cost is estimated to be in the range of $ 10,000. The benefit of entertainment robots cannot be guaged merely by reference to costs, but rather in the intellectual stimulation of users, and consequently the price tag is difficult to estimate. If flexible humanoid systems can be developed, the potential set of uses as assistance to humans in their houses or in factories might be tremendous. The development of flexible humanoids does, however, require the development of inexpensive robust mechanics and robust control methods. A significant problem here is the handling of variable loads. Humans are extremely good at varying their posture to ensure flexible control and such ability must be embedded in humanoids. In addition, operation in everyday environments requires automatic recognition of places and objects, which is a significant challenge to computer vision. Flexible interfaces for interaction with humans must also be developed. Consequently, there are a number of hard challenges that must be overcome before humanoids will find widespread use in industry and our homes.

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45 W. Strobl: *Hydrogen Vehicle Research: Milestones during the last 25 years.* 2002 CleanEnergy Seminar, Sacramento, http://www.arb.ca.gov/msprog/zevprog/CleanEnergy/Strobl.pdf.

46 Takayuki Kanda, Takayuki Hirano, Daniel Eaton, Hiroshi Ishiguro: *Interactive Robots as Social Partners and Peer Tutors for Children: A Field Trial.* In: Journal of Human Computer Interaction (Special issues on human-robot interaction), Vol. 19, No. 1-2, pp. 61-84, 2004. http://www.irc.atr.co.jp/~kanda/pdf/kanda-interactive-robots-as-social-partner.pdf.

47 Ralf Regele, Wolfgang Bott, Paul Levi: *ProRobot – Predictions for the future development of humanoid robots*; http://www.fzi.de. Funded in the Competitive and Sustainable Growth (GROWTH) Programme by the European Commission. Project no. G1MA-CT-2002-00015.

48 http://www-1.expo2005.or.jp/en/robot/index.html.

49 IEEE-RAS/RSJ International Conference on Humanoid Robots (Humanoids 2004); November 10-12, 2004, Santa Monica, Los Angeles, CA, USA. http://www.humanoids.ws/humanoids04/.

(iv) Major producers

Major developers/producers are Dr. Robot (Canada), HONDA, (Japan), MRISAR, (USA), Robos (Japan), Shimizu (Japan), Sony (Japan), Fujitsu (Japan), Kawada (Japan), Toyota (Japan), VISTONE (Japan).

VII.3.3 Service robots for personal/domestic use

VII.3.3.1 Robots for domestic tasks

As domestic cleaning takes place in private households, there is huge market potential in terms of new and replacement units. Due to the relatively low degree of utilisation, the price has to be far lower than that of commercial cleaning robots. This is achieved through simplifications such as the random walk system. In combination with a sensor which detects already worked areas, it is regarded to be as efficient as pre-planned path systems. It can evade obstacles and continue its work right away. In areas with many obstacles, such as furnished rooms or gardens with many plants, this should be especially advantageous.

Vacuum cleaning robots can be used not only for private homes, but also for offices, doctors' surgeries, etc.

(i) Types of operations carried out by the robots

The idea behind robotic domestic devices is to liberate people from unpleasant daily chores and give them more free time. The robots are simply set in their working area, where they operate by themselves. Manual interference is thus only needed to change the overall operating area, e.g. the room.

Vacuum cleaning robots are small enough to pass under furniture and their round shape allows them to easily manoeuvre themselves out of traps They are equipped with optical sensors to detect the degree of soiling, so that the robots can distinguish previously cleaned areas and pass on to remaining areas. The robots automatically return to a charging station when their batteries are low. The dust bag is emptied during the reloading process. Magnetic strips or infrared sensors protect them from falling down steps. Vacuum cleaning robots are slower than a normal vacuum cleaner, but they do nothing else but clean all day long. They are also more accurate in cleaning the area and the power consumption is lower than that of conventional vacuum cleaners.

Lawn-mowing robots are the modern replacement for sheep. They stay in the garden over the summer and ensure a neatly cut lawn. Grass cuttings from the mowing robots do not have to be removed either. Regular cutting keeps the lawn so short that they can be left to act as fertilizer.

Husqvarna produces various models of lawn-mowing robots. The price, depending on the model, is about CHF 3,200. Recently a new model has entered the market and the projections are for sales of more than 10,000 units/year; see figure VII.15. Another important producer is Friendly Robotics (Israel) and the personal gardener Ambrogio of Zucchetti Centro Sistemi (Italy).

Feasibility studies for consumer window cleaning robots include the RACCOON concept developed by Fraunhofer IPA and Procter&Gamble[50]. The robot depends on a caterpillar equipped with passive suction cups. These cups are evacuated through the caterpillar motion. Further efforts aim at a dramatic miniaturisation and simplification of the design on the basis of vacuum chambers which glide almost effortlessly on a fluid film.

(ii) Level of distribution

The first vacuum cleaner robot entered the market in November 2001. The Electrolux Trilobite was initially only available on the Swedish market. During 2002 distribution was extended to most European countries. In addition it is being sold in Japan under a licence to Toshiba. The price of the Trilobite is still some € 1200. Early in 2002, the American company iRobot released the Roomba robot onto the US market. The price was $199 and it was distributed through major chain stores and the web. The product has limited navigation sensors and operates by a random walk. It has become a major sales item in the United States with

50 R. D. Schraft, F. Simons: *Concept of a miniature window cleaning robot - development potentialities for a mass product*. International Federation of Robotics: ISR 2004. 35th International Symposium on Robotics. Proceedings : March 23-26, 2004, Paris.

estimated sales up to mid 2003 of more than 100.000 units. During autumn 2002, Kärcher (Germany) released a robot which has similar characteristics. The exact volume of sales is not known. About the same time Samsung and LG (Korea) announced small vacuum cleaners for the Asian market. Since then, several providers (in particular in Japan) have launched vacuum cleaners onto the market such as Matsushita (Japan), Hanool (Korea), and ECOVac[a] (Israel). The early predictions of a major market potential have been met, and the future predictions indicate a major economic prospect.

At the moment, some 1,106,000 robot vacuum cleaners are estimated to have been sold. The forecast for the overall market of vacuum cleaning robots, lawn-mowing robots and other household robots for the period 2005-2008 is over 4,470,000 units.

Information society and domestic robots: future scenarios

Taking a longer-term perspective, say 10-15 years from now, domestic robots may very well have started a diffusion process similar to that which the PC, mobile telephone or the Internet have had in recent years. In fact, the wide usage of the latter type of equipment greatly facilitates the introduction of service robots. In the next few years almost all homes in Western Europe will have mobile phones, PCs and Internet connections. This is particularly likely following the decisions of the European Commission to implement the so-called “e-Europe” programme.[51] A well-established "digital knowledge" or at least familiarity with it, in particular among young and middle-aged persons, will facilitate the acceptance of robots working in our homes. As a move to generate further interest in this area, the EU has also recently launched a new programme termed “Beyond Robotics”, concerning robots outside the manufacturing environment. The programme was started 1st January, 2004.

Increasingly various types of tools and equipment in our homes (heating systems, fire and burglary alarms, stoves, ovens, refrigerators etc.) will incorporate microcomputers and, above all, will be able to communicate with each other, either by cable, electric wiring, infrared or other wireless modes of communication. Users will be able to control them from remote places, using mobile phones as terminals. In this environment, domestic robots will serve as an important link between the various types of computer-controlled equipment and systems in our “wired” homes.

With the complementary technology described above in place, and with improved performance of domestic robots at a lower price (i.e. following a similar curve of price/performance ratio as other electronic goods), there is a potentially huge market within reach. Modular designed robot platforms, to which various types of utilities, e.g. for vacuum and other types of cleaning, can be attached as well as articulated robot arms, various types of sensors and vision systems, could carry out a variety of tasks in our homes. They could vacuum clean, scrub the floors, empty the dishwasher and place the china in the cupboards, lay the table, take out the garbage, open doors, guard the house against intruders and fire, mow the lawn, increase the mobility and security of old and disabled persons and much more. Increasing functional flexibility will allow one robot system to free us from a number of routine jobs.[52]

How much do we value our leisure time? It is reasonable to assume that it is a function of our hourly income and of the amount of leisure time we have left after having carried out our professional work and the necessary household tasks. If the time saved through using domestic robots is used for paid work, then it is rather easy to relate a value to the freed time. For high earners there will thus be strong incentives to use domestic robots.

While our real incomes are following an increasing trend, the price of domestic robots tends rather to fall, which results in falling relative prices. Economies of scale will make the price decrease considerably and will allow a wide distribution of domestic robots. All this supports the scenario that by 2015 domestic robots might be as common in our homes as the PC is today.[53]

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[51] See also: http://www.europa.eu.int/comm/information_society/eeurope/index_en.htm.

[52] For an extensive analysis see: J. Neugebauer and M. Höpf*: The role of automation and control in the Information Society.* Stuttgart: Fraunhofer IRB Verlag, 1999.

[53] B. Graf, M. Hans, R. D. Schraft: *Mobile robot assistants*. IEEE Robotics & Automation Magazine 11 (2004), Nr.2, pp 67-77.

(iii) Cost benefit analysis and major restraints on wider diffusion

While manual domestic appliances, whether vacuum cleaners or lawn mowers, are very noisy and require a guiding person to walk them up and down, robots operate quietly and autonomously. This saves the owner time and liberates him from unpleasant and unrewarding tasks. The robots can be left in operation without supervision as, whenever they run low on energy (every 2 hours for Husqvarna mowers), they return to the recharging station on their own. In the case of solar mowers, they have a solar panel to create their own energy: the internal computer decides whether to send the energy straight to the motor or to the batteries. A low current loop, which is placed below ground, limits their working area and keeps them in place. The robots also have an acoustic alarm to prevent their theft.

The silent electronic motors allow for round-the-clock operation without disturbing anybody nearby. Operating in that way, robotic mowers can cover up to 1,200m^2 of lawn.[54] In contrast to traditional gasoline-driven mowers, which are very polluting, electronic ones have no emission. The operating costs, in particular for solar powered mowers, are lower than for gasoline driven ones and they require less maintenance.

The robots are not as strong or fast as manual devices, therefore they have to be in daily round-the-clock operation to reach the same result. Due to their relatively low degree of utilisation, and the availability of equally effective manual devices, domestic robots stand in direct comparison. The difference in purchase price must not exceed the value accorded to personal free time. As today domestic robots are still significantly higher priced than manual devices, they are mainly marketed among high-income people, who assign a higher price to their alternative use of time gained by the robots and can afford them. This of course acts as a curb on mass consumption.

(iv) Major producers

- for vacuum cleaning: AB Electrolux (Sweden), Dyson Appliances (UK), Gecko Systems Inc. (USA), iRobot (USA), Kärcher (Germany, LGelectronic (Korea), Matsushita Electric (Japan), Probotics Inc. (USA), Real World Interface (USA), The Eureka Comp. (USA), Wany SA (France)

- for lawn mowers: Centrosistemi (Italy), Friendly Robotics (Israel), Husqvarna (Sweden), Wany SA (France)

- for window cleaning: Smart Robotics, (Israel)

VII.3.3.2 Entertainment robots including toy robots and hobby systems

To portray spectacular sequences or scenes involving animals, the film industry often uses robots. As they are usually joystick-controlled, it may take several people, each operating one body part, to achieve complex movements. The robots used in the making of the film Jurassic Park, for example, were operated by up to six people. Where shapes similar to the human physiognomy are concerned, an anthropomorphic robot controlled by a single person wearing a sensor suit can be used.[55]

The robots are dependent on electricity and thus have to carry cables, which must be retouched for the final pictures.

Companies working with these kinds of entertainment robots are Edge Innovations and SES Sarcos Entertainment Systems.

A larger number of entertainment robots belong to the category of pet and SCARA type robots. The aim of these miniature robots is not to alleviate work, but to entertain. Equipped with a rich suite of sensors, they have a learning function, which allows them to respond to external stimuli and make their own judgements.

A major producer in the field is Sony, which claims to have sold more than 350,000 units (up to end 2002) of a new type of electronic pet – the AIBO, at $1,500 each. Lego is another major producer of toy robots.

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54 Husqvarna company information.

55 R.D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions*. London: A K Peters Ltd., 2000.

Recently, companies have started to manufacture robot systems that have basic dialogue capabilities that can be programmed to perform transportation tasks from one place to another and that can pick up a limited set of objects. The target here are techno-savvy people that buy these robots for home-entertainment. The price range is typically $500-1500 and thus within reach of a large number of people. One challenge is still to make these robots sufficiently simple to use, so that people without or with limited computer training can use them after no or minimum training.

Currently many different types of entertainment and edutainment robots are being created. The ROBODEX 2003 fair in Yokohama as well as the EXPO 2005 in Aichi, Japan displayed a surprising variety of ideas on future high tech robot products in our daily life.[56] [57]

At least 919,725 entertainment, toy and hobby robots are estimated to have been sold up to the end of 2004. About 2.5 million units are forecast for 2005-2008.

Major producers are: Happy Field Technology (USA), Johuco Mobile Robots (USA), Lego Mindstorms (USA), Lego (Denmark), Lynxmotion (USA), Smart Robotics (Israel), Sony (Japan), Wany SA (France), Atlas Robotics (USA), GPS/Neobotix (Germany), KUKA (Germany), Merlin Robotics (UK),

Education and training

An abundance of robot kits are on sale to serve as experimental platforms for education, leisure, and robot competitions. These robots are sold at relatively low-prices, often through on-line shops which also integrate platforms to connect to a user community to exchange software, designs and general advice. Most of these platforms are mobile robots equipped with sensor components and sometime end effectors and arms.

PaPeRo, which stands for partner-type personal robot is a small robot with advanced interface technology. It "hears" with four microphones, can understand 650 phrases, and can speak more than 3,000 words.[58]. PaPeRo also identifies people it knows, using advanced face-recognition technology and two cameras for eyes. Using PaPeRo can cover scenarios such as:

- Networking: Email recipes and directions for preparing dinner to a robot or computer and the "intelligent" appliances in your home cook the meal.
- Security and safety: A home security system scans the faces of intruders to see if they are known visitors.
- Healthcare: A personal robot that lives with the elderly or sick monitors a patient's vital signs and alerts a doctor if it detects any problems.
- Education: Advanced and intelligent interfaces help children access the Internet for homework or creative projects. Robots talk to children about their day at school, play games, and dance.

Major producers are: Genova Robot (Italy), IdMind (Portugal), Intelitek (USA), Johuco Mobile Robots (USA), K-Team (Switzerland), Living Machines (USA), Lynxmotion (USA), Mekatronix (USA), Merlin Robotics (UK), NEC (Japan), Parallax (USA), Robix (USA), Robosoft (France), The Robot Factory (USA), Wany SA (France), Zagros Robotics (USA)

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[56] ROBODEX is a tradefair in Yokohama for robots outside the manufacturing field and is held annually. The show has received huge attention lately due to the wealth of creative robot concepts and products (close to 40 exhibits with 90 types of robots in 2003).

[57] http://www-1.expo2005.or.jp/en/event/calendar7.html.

[58] http://www.nec.com/global/features/index13/index.html.

VII.3.3.3 Handicap assistance

a) Robotized wheelchairs

Typical examples of robotic handicap assistance are electric wheelchairs with an added obstacle avoidance system. This helps people who have difficulties steering and manoeuvring. They only have to signal the overall travelling direction and the system finds the way around fixed and unforeseen obstacles. Following numerous research efforts to demonstrate safe autonomous navigation in peopled environments, the iBot wheelchair robot has been introduced which is able to effectively raise itself to human height and climb stairways, thus adding a critical feature for making handicapped peoples' lives easier.[59]

Other robots for assisting the mobility of vision-impaired or blind persons specialise in offering active guidance. Either a goal could be specified or the person guides the robot which safely overrides the user commands by guiding the person around obstacles. One of these designs is the Haptica Guido system. An overview of the technology of robotized wheel-chair-systems can be found in an IEEE special issue on robotic wheelchairs.[60]

Major producers are: Active Media (USA), DEKA Research & Development (USA), Rehabilitation Technologies (USA).

b) Other assistance functions

People with disabilities involving little or no control of hand and arm functions or limited strength or reach rely heavily on carers for most of their daily activities, leaving them highly dependent and often creating an attitude of passivity and apathy.

Assistive robot systems can help with eating and drinking, personal hygiene, work and leisure, mobility and general tasks. Depending on the particular task, the robotic manipulator can be mounted directly on the user's wheelchair, to an autonomous powered base or within a fixed workstation. It should be easy to operate for the user and adapted to his ability of manipulation. The *Handy*, for example, uses a single switch system, which can easily be modified according to the patient's particular needs.

While so far some 325 systems are in use, another 750 are projected to be sold in 2005-2008 (see table VII.1). This is a rather disappointing result, which may be a consequence of tight social and health-care budgets. But there are several factors speaking in favour of a rapid growth, in the longer term, in the market for assistive robotic systems for elderly and disabled persons. The growing number of temporarily and permanently disabled persons as well as the increasing proportion of the elderly in the age pyramid increases the need for care. Considering the decline, in the next 10-15 years, in the number of people of active age available to perform the resulting carer role, there is a huge potential demand for assistive robotic devices. For this reason, important research institutions working on service robots are developing new prototypes of assistive robots. One example is the Movaid project developed under a European consortium co-ordinated by the ARTS Lab of the Scuola Superiore Sant'Anna in Pisa, Italy (see Annex C in **World Robotics 2003**).

Major producers are: 3-Sigma Robotics, USA, Active Media, USA, Armstrong Healthcare, UK, CEREM-CEA, France, Deka Research, USA, Exact Dynamics, Netherlands, Gecko Systems Inc., USA, Independence Technology, USA, MRISAR, USA, Rehabilitation Technologies, USA, Robosoft, France, Shadow Robot, UK.

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59 See http://www.dekaresearch.com/ibot.html and www.indetech.com.

60 Research on autonomous robotic wheelchairs in Europe. IEEE Robotics & Automation Magazine, Vol. 8 (1), Mar 2001.

c) Other handicap assistance

Assistive systems are increasingly being considered as the ultimate multi-purpose robot products in our living environment. They not only address the needs for mobility of impaired persons, but also of future households. A concept of an assistive robot has been presented by Fraunhofer IPA in the form of its Care-O-bot experiments.[61] A mobile robot arm is equipped with a handle for tactile guidance of persons, a multi-media user interface, sensors for 3D environmental recognition and a 3-finger gripper for handling a wide variety of objects. The robot is capable of conducting simple instructional dialogues through spoken commands or simple inputs on a portable computer. The user input is then processed into appropriate actions. Typical jobs comprise fetch and carry tasks, passing objects from and to the user, surveying homes, guiding persons, acting as a mobile information kiosk etc. A freshly begun European research project, COGNIRON, will address the most challenging scientific and technological tasks such as learning, intuitive human-robot interaction and task and motion planning in dynamic environments for the emergence of assistive robots in everyday environments.

(i) Cost benefit analysis and major restraints on further diffusion

Assistive robots give disabled people scope to participate, boosting their self-confidence. They can occupy themselves instead of waiting in boredom. The use of robots stimulates and, apparently, can improve co-ordination and physical condition.

The implementation of an assistive system is a complex and demanding process; it has to be fitted to the user's particular needs, staff have to be trained and after a tryout period the robot has to be readjusted. Once in use, there are no significant work reductions for the carers. Their tasks merely change, so that instead of feeding, they now prepare the tray and set up the machine.

Once installed though, sophisticated assistive robotic devices can have a technical life length of up to 15 years. As the maintenance costs are very limited, the total yearly costs ought to be in an affordable range for quite a large number of people. A supply structure based on leasing might be a way to gain the support of insurance companies and social security agencies.

Prices vary widely among systems and degrees of specialisation and can amount to $50,000. But even the cheapest system cannot be purchased for less than several thousand dollars.[62] Although large-scale production will always be limited by the level of specialisation, economies of scale in the production of the main components can be realised and will, together with the continuously improved cost effectiveness of robot technology in general, bring down the prices.

VII.3.3.4 Personal transportation (Automated transportation of persons)

Robotic transportation systems have been suggested for flexible point to point transportation of people in theme parks, industrial sites and campuses, historic city centres, exhibition areas, train stations and airports etc. ROBOSOFT has developed two types of vehicles: robuCAB™ (automatic cabs and shuttles) and robuRIDE™ (interactive rides) which can be operated in fleets or as single vehicles. At *Fort of Simershof*, in Bitche (France), ROBOSOFT has installed the first entirely robotized mass transportation system for cultural tourism. Other installations are currently under investigation. ROBOSOFT anticipates large future markets for people movers.[63]

Another design, the CyberCab of the company 2getthere b.v. (The Netherlands) suggests a 4 seated automatic taxi which is ideally suited for internal transportation in resorts or on company estates. The vehicle is also suited for Personal Rapid Transit (PRT) networks in city centres, see also figure VII.17.

Major producers are: Frog Navigation Systems (Netherlands), Robosoft (France)

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61 http://www.care-o-bot.de/english/ and http://www.assistor.de/.

62 http://www.rehabrobotics.com/.

63 *Automated People Transportation Applications, Technologies and Perspectives.* http://www.robosoft.fr.

VII.3.3.5 Home security and surveillance

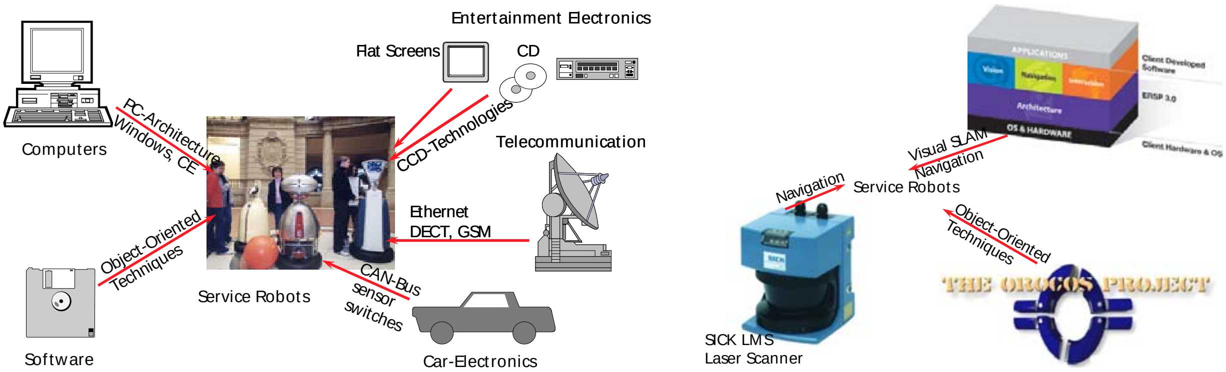
Up to now only few home security or surveillance devices have been presented on a product level. A possible way to introduce this functionality is either by mobile domestic robots, such as vacuum cleaners, to take over the additional task of safeguarding or tele-operated mobile robots which can roam around in rooms on command. Mobile robots to achieve tele-presence have been introduced by several companies such as:

- The Banryu from tmsuk (Japan), which is a legged robot offering interfaces by mobile phone[64].
- The iRobot LE is an internet avatar, allowing users to see, hear and move around distant environments through a wireless internet connection and a browser. It allows users to check on their homes from a distance, even climbing stairs.[65]
- Cybermotion (USA), Gecko Systems (USA), MRISAR (USA), Wany SA (France)

VII.3.4 Robotics R&D

The development and diffusion of service robots has been particularly dependant on technological progress. The technology push can be divided into two main categories: Developments in technologies outside the field of robot automation, particularly in large volume markets, and focussed research and developments in key technologies and components in the robotics sphere, see figure VII.3.

Figure VII.3: Migration of technologies into service robotics from large volume industries (left) and emergence of key technologies and components within the service robotics industries



Large production quantities which are typical for consumer electronics, automotive industries and telecommunications encourage the development of cheap high performance hardware (sensors, controls, drives, interfaces, signal transmissions) and software as key components of intelligent, mechatronic products:

- The performance/cost and reliability ratio of key robot components namely sensors, computer-controls and man-machine-interfaces (displays, voice processors, graphics) has been increasing dramatically.
- Latest PC technologies are absorbed by service robots such as high-performance hardware, advanced operating systems (Linux, Windows[66]), broadband data transmissions (Ethernet)
- Object-oriented technologies for cost-optimized and reliable software-engineering, platform independent languages and protocols (JAVA, Jini, CORBA, etc.[67])
- low cost, but reliable components are available from the automotive industry in the form of switches, sensors, transmissions, cable, connectors and batteries.

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[64] *First Public Exhibition of Super-remote-controlled Robot across Japan*. Press release 24th March, 2003; tmsuk Co., Ltd. http://www.banryu.jp/press/pdf/030309e.pdf.

[65] http://www.irobot.com/about/history_detail.cfm?id=4.

[66] All of these names are registered trademarks.

[67] All of these names are registered trademarks.

An increasing number of key technologies and components have been developed specifically for the needs of service robotics. Examples are:

- The SICK LMS Navigation laser scanner from the basis of high-precision time of flight measurements.
- Visual navigation components from the basis of a low cost video camera[68]
- Open source software repositories for rapid and inexpensive software development for mobile and manipulative service robots.[69]

Furthermore, significant research efforts have been started in dedicated programmes to provide technologies, methods and components for specific capabilities for assistive systems, autonomous intelligent household devices and professional service robots:

- The *Beyond Robotics Programme* within the European Community 6th Framework Programme focusses on three Integrated Projects (IPs) for developing machine methods, architectures and components for machine intelligence in physical mobile artifacts ("robots"): (1) COGNIRON - The Cognitive Robot Companion,[70] (2) I-SWARM - Intelligent Small World Autonomous Robots for Micro-Manipulation,[71] (3) NEUROBOTICS - The Fusion of Neuroscience and Robotics for Augmenting Human Capabilities[72]
- Recently, Korea has launched a national R&D initiative in 10 technical fields for the purpose of building up the technological basis of a future service robot industry.

EURON, as a European Network of Excellence, aims at implementing and maintaining the co-ordination of research, promoting teaching and education, implementing academic-industry collaboration, organising publications and conferences in the area of robotics, and facilitating the addressing of issues of interest to institutions and companies throughout Europe.[73] This network has entered its next phase from 2004 to 2007, which aims to promote intense cross-fertilisation between research and industry.

VII.3.4.1 Research and Development Challenges

Robot application drivers

Application driver denotes a robot application or a robot system which is of pioneering significance regarding market potential or socio-economic impact. The following challenges regarding future robot products have been discussed intensely in robotics research:

- **Robot companions in private and public environments**. It is widely recognised that robots that combine assistance in everyday tasks (such as fetch-and-carry jobs, mobility aid, multi-media-support etc.) at acceptable cost and appealing appearance represent a bright business case. The robot companion’s functionality depends on meeting the requirements of untrained users, on situation awareness in everyday settings, mobility in home environments, and the ability to identify, manipulate and grasp almost any kind of object. Application areas of robot companions could range from being a helper in family homes to executing tasks in offices, public environments and in services. Furthermore, elderly and mobility-impaired persons will be able to stay longer in their homes, as a robot companion could help them achieve some independence from full time caring personnel. This market potential has been well outlined in recent years so that large research programs and R&D efforts of large corporations are geared towards a convincing robot companion product.

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68 Evolution Robotics Software Platform (ERSP™). Product Information http://www.evolution.com/about/.
69 Open Robot Control Software Open Realtime Control Services (OROCOS); http://www.orocos.org/ index.php.
70 http://www.cogniron.org/.
71 http://microrobotics.ira.uka.de/.
72 http://www.neurobotics.info/.
73 http://www.euron.org.

- **Personal robots**. Future consumer robot products will go beyond simple household robot designs (i.e. robotic lawn mowers, vacuum cleaners) in that they might come in customisable product families with scaled functionality. Very similar to other personal, customisable product families such as mobile phones, the Swatch wrist watch etc., these mobile robots will allow the adding and customising of different functional modules (multi-media interfaces, IT added value services, simple robot arms/grippers for manipulation, expressive heads equipped with sensors, actors and voice, vacuuming aggregates etc.). Typical operating environments are homes, offices and public spaces. The overall design has to follow a fully modular approach to quickly adjust the designs to changing customer preferences, to account for individualisation and the development of rapidly succeeding product generations.

- **Ubiquitous robots and robotic networks**. “Instead of robots populating the environment the environment will evolve into robots”. This means that low-cost mobile platforms, arms, sensors, actors, and man-machine-interfaces will be imbedded into networks which will result in active home, public or office environments. This vision is an extension to the current concept of ambient intelligence in the sense that the environment will be physically interacting with persons, objects and infrastructure. Mobile platforms (e.g. personal robot families) can offer ubiquitous access to edutainment, IT services and tele-presence, low-cost arms imbedded into furniture could assist in handling and cleaning.

Although numerous research activities have been started, major technological challenges persist, of which some of the principal aspects are listed in the following.

Primary Robotic Research Challenges

- **Dependable Robot Assistants**

Robot assistants can be thought of as intelligent helpers that execute a variety of tasks on demand or perform jobs cooperatively with the user. Such functions lead directly to basis requirements such as situation assessment of everyday environments and an effective interface for intuiting the user’s commands or to safely interact with people in complex situations. Furthermore, the robot should be a constant learner: It should acquire new skills in an active, open-ended way, and develop as a result of constant interaction and co-operation with humans.

- **From perception to cognition**

Perception describes the processing of sense data into suitable descriptions of the robot’s environment. Thus perception is a prerequisite to situation assessment, which comprises in general descriptions of objects, operational areas, surroundings, pose and mimics of persons etc. Computer vision is considered the ideal sensing modality as it is capable of supplying rich environmental information. Nevertheless, situation assessment is limited due to sensor instability in uncontrolled situations and due to complexity in the number and variety of objects and states.

- **Human-robot-interaction**

Interaction and information exchange between robot and user should be based on speech and supportive modalities such as gesture, graphics, mimics and gaze. The use of natural speech in robotics has largely been dependent upon off-the-shelf speech recognition systems (from consumer and office automation industries). Medium-term goals in intuitive human-robot-interaction will be to use domain-specific language constituents with deictic gestures. Long-term goals comprise the simultaneous use of clarifying dialogue systems and recognition systems for mimics and natural human gestures.

Overcoming the challenges in effective physical interaction between robot and user will require the perception of human motion in arbitrary poses and the generation of natural robot motion patterns following human ergonomics and fluidity of movement. Furthermore, motion generation for physical assistance (workouts or training) require kinematic and dynamic adaptation to human motions.

- **Mobility and manipulative ability for assistants, personal and domestic robots**

Mobile autonomous navigation has reached a high level of maturity. However, examples such as the SICK laser scanner show that this is still at relatively high costs. Future developments should aim at using standard vision sensors for truly low-cost solutions (for as low as 10 € sensor cost). Vision-based methods and algorithms have to be developed for robust situation assessment and visual navigation in uncontrolled environments (visual, cognitive simultaneous localisation and mapping; SLAM). A target manufacturing cost for autonomous mobile platforms could be as low as 150 €.

Light weight robot arms and biologically inspired manipulator kinematics and grippers have been suggested. However these arms and grippers have not found their way into practice and still constitute a major obstacle to low cost systems. A breakthrough has to be achieved in low-cost manipulative ability for high volume markets. A thorough product design for high volume manufacturing may lead to alternative arms based on active materials with integrated drives and sensors.

Intrinsically safe robot arms may be a way to operate kinematics without safety precautions in public environments. Forces and impacts may be limited by a combination of elastic materials, clever weight distribution and innovative transmission techniques.

- **Intelligent environments and robotic networks**

Environments both at home, in public and at work will get smarter through ubiquitous embedded systems for collecting, transmitting and processing data. These components for domotics, infotainment, and situation assessment may significantly support robots in their task execution. Furthermore, robot teams and robot swarms for distributed task execution could share information and learning experience. Challenges include creating interoperability between intelligent environments and robot agents as well as their integration within global networks, as a means for access to, and generation of combined applications and services.

- **Mechatronic design and open control for service robots in professional applications**

The cost-effective development and manufacturing of service robots for professional applications is still dependent on the availability of key components within standard architectures for easy integration. Furthermore software components have to be provided to the developer so that development costs can be adequately reduced. The first open-source repositories have become available. However, there is still a need to certify software modules according to typical benchmarks or other performance criteria. Challenges relate to both refining the repositories and to offer certified components and test cases for assessment of software solutions.

VII.3.4.2 Innovation Related Challenges

Besides joint R&D, the diffusion of service robot will be, dependent upon accompanying activities relating to the protection and dissemination of knowledge, activities to promote the exploitation of the results, and effective "take-up" actions. These activities are closely interrelated with R&D. Challenges which have been named by service robotics manufacturers are given in the following:

- **L2B: From lab to business**

Two forms of tech-transfer have a strong effect on the emergence of a strong service robotics industry:

- The creating of spin-off companies, e.g. out of universities and research laboratories.
- The constant flow of technology in terms of knowledge, components (HW/SW) and human resources from labs to companies.

Adequate instruments and incentives have to be implemented to promote the various forms of tech transfer.

- **Safety and standardisation**

The operation of service robots has not yet been regulated by a specific set of standards or guidelines. This is inconvenient for both manufacturers and end-users of un-caged robot arms, as for each development a costly risk assessment and clearance from a regulatory body has to be filed. Up to now, existing standards from general machinery, automated guided vehicle or robotics had to be applied. Currently standardisation activities aim at reformulating the new ISO 10218 standard on robot safety in such a way that man-machine co-operation is also covered and a minimal legal basis for service robots becomes available. In parallel, efforts will be started in 2005 to establish a body to specify a standards on service robot safety design and operation. At the moment, an ISO Advisory Group on Mobile Service Robots has been established to investigate various standardisation aspects for mobile service robots.

Table VII.2

Inventory of service robot manufacturers by application areas

			I. Personal/Domestic Robots														
			Robots for domestic tasks					Entertainment and leisure robots					Handicap assistance				
Application code			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Company	Country	No.	Vacuuming cleaning	Lawn mowing	Pool cleaning	Window cleaning	Other Robots for domestic tasks	Toy robots	Entertainment	Hobby systems	Education and training	Other entertainment robots	Robotized wheelchairs	Other assistance functions	Personal rehabilitation	Other handicap assistance	**Personal transportation**
Denning Branch	Australia	1	■	■							■	■		■			
Milka-Ware	Australia	2															
Schiebel	Austria	3															
Robonetics	Belgium	4															
Sony Europe	Belgium	5						■									
Applied AI Systems	Canada	6															
BRIC Engineering Systems	Canada	7															
CDL Systems Ltd.	Canada	8															
Cyberworks	Canada	9															
Dr. Robot	Canada	10															
Engineering Services	Canada	11															
Intelligent Robotics Corp.	Canada	12															
Inuktun Services	Canada	13															
ISE	Canada	14										■					
MacDonald Dettwiler	Canada	15															
Optimal Robots	Canada	16															
Lego	Denmark	17						■									
Nilfisk-Advance A/S	Denmark	18															
Starkmatic Oy	Finland	19															
CEREM-CEA	France	20												■		■	
Cybernétix	France	21									■						
RENOSOL	France	22															
Robosoft	France	23									■			■			■
Wany SA	France	24	■	■	■	■		■		■	■						
Andro Tec gmbH	Germany	25															
Androtech	Germany	26															
D.T.I. Dr. Trippe	Germany	27															
Fraunhofer IPA	Germany	28					■										
GPS/Stuttgart	Germany	29							■								
Hans Wälischmiller	Germany	30															
Inspector Systems	Germany	31															
IntelligeNDT	Germany	32															
Jenoptik Silmetric	Germany	33															
Kärcher	Germany	34	■														
KUKA	Germany	35							■								
ProKasro Mechatronik	Germany	36															
Robowatch	Germany	37															
Rotundus	Germany	38															
Telerob	Germany	39															
Welger Argrartechnik (Lely)	Germany	40															
Kentree	Ireland	41															
Friendly Robotics	Israel	42	■	■													
Smart Robotics	Israel	43				■		■									
Centrosistemi	Italy	44		■													
Genova Robot	Italy	45									■						
Tecnospacio	Italy	46															
Fuji Heavy Ind.	Japan	47															
Fujita Corp.	Japan	48															
Hitachi Kiden Kogyo	Japan	49															
HONDA	Japan	50															
KOBE Mechatronics	Japan	51															
Matsushita Electric	Japan	52	■														
Minolta Co.	Japan	53															
Mitsubishi Heavy Ind.	Japan	54															
Robos	Japan	55															
Seiko-Epson	Japan	56															
SHIMIZU Corp.	Japan	57															
SOHGO Security Services	Japan	58															
Sony	Japan	59						■									
TASEI Corp.	Japan	60															
Tmsuk	Japan	61															
Toki	Japan	62															
Toyota Motor Corp.	Japan	63															
VISTONE	Japan	64															
Yanmar Co.	Japan	65															

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			I. Personal/ Domestic Robots		II. Professional service robots															
					Field robotics						Professional cleaning					Inspection systems		
Application code			16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Company	Country	No.	Home security & sur-veillance	Other Personal/ domestic robots	Agriculture	Milking robots	Forestry	Mining systems	Space robots	Other field robotics	Floor cleaning	Window and wall cleaning (incl. wall climbing robots)	Tank, tube and pipe cleaning	Pool cleaning	Other cleaning tasks	Sewer robots	Tank, tubes and pipes	Other inspection systems
Denning Branch	Australia	1			■						■							■
Milka-Ware	Australia	2				■												
Schiebel	Austria	3																
Robonetics	Belgium	4							■									
Sony Europe	Belgium	5																
Applied AI Systems	Canada	6																
BRIC Engineering Systems	Canada	7																
CDL Systems Ltd.	Canada	8																
Cyberworks	Canada	9									■							
Dr. Robot	Canada	10																
Engineering Services	Canada	11																
Intelligent Robotics Corp.	Canada	12																
Inuktun Services	Canada	13														■		■
ISE	Canada	14			■				■							■		■
MacDonald Dettwiler	Canada	15							■									
Optimal Robots	Canada	16																
Lego	Denmark	17																
Nilfisk-Advance A/S	Denmark	18									■							
Starkmatic Oy	Finland	19													■			
CEREM-CEA	France	20																
Cybernétix	France	21									■	■	■		■	■		■
RENOSOL	France	22									■		■					
Robosoft	France	23									■	■						
Wany SA	France	24	■									■						
Andro Tec gmbH	Germany	25																
Androtech	Germany	26																
D.T.I. Dr. Trippe	Germany	27														■		
Fraunhofer IPA	Germany	28																■
GPS/Stuttgart	Germany	29																
Hans Wälischmiller	Germany	30																
Inspector Systems	Germany	31											■					
IntelligeNDT	Germany	32																■
Jenoptik Silmetric	Germany	33														■		
Kärcher	Germany	34																
KUKA	Germany	35																
ProKasro Mechatronik	Germany	36														■		
Robowatch	Germany	37																
Rotundus	Germany	38																
Telerob	Germany	39	■															■
Welger Argrartechnik (Lely)	Germany	40				■												
Kentree	Ireland	41																
Friendly Robotics	Israel	42																
Smart Robotics	Israel	43																
Centrosistemi	Italy	44																
Genova Robot	Italy	45			■													
Tecnospacio	Italy	46							■									
Fuji Heavy Ind.	Japan	47																
Fujita Corp.	Japan	48																
Hitachi Kiden Kogyo	Japan	49									■							
HONDA	Japan	50																
KOBE Mechatronics	Japan	51											■	■				
Matsushita Electric	Japan	52									■							
Minolta Co.	Japan	53									■							
Mitsubishi Heavy Ind.	Japan	54																
Robos	Japan	55																
Seiko-Epson	Japan	56																
SHIMIZU Corp.	Japan	57																
SOHGO Security Services	Japan	58																
Sony	Japan	59																
TASEI Corp.	Japan	60																
Tmsuk	Japan	61																
Toki	Japan	62																
Toyota Motor Corp.	Japan	63																
VISTONE	Japan	64																
Yanmar Co.	Japan	65			■													

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots														
			Construction and demolition					Logistic systems			Medical robotics				Defense, rescue & security applications		
Application code			32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Company	Country	No.	Nuclear demolition & dismantling	Other demoltion systems	Construc-tion support and mainte-nance	Construc-tion	Other types of con-struction	Courier/ Mail systems	Factory logistics (incl. Automated Guided Vehicles)	Other logistics	Diagnostic systems	Robot assisted surgery of therapy	Rehabili-tation systems	Other medical robots	Demining robots	Fire and bomb fighting robots	Sur-veillance / security robots
Denning Branch	Australia	1						■								■	■
Milka-Ware	Australia	2															
Schiebel	Austria	3															
Robonetics	Belgium	4															
Sony Europe	Belgium	5															
Applied AI Systems	Canada	6															
BRIC Engineering Systems	Canada	7															
CDL Systems Ltd.	Canada	8														■	
Cyberworks	Canada	9															
Dr. Robot	Canada	10															
Engineering Services	Canada	11		■								■				■	■
Intelligent Robotics Corp.	Canada	12															
Inuktun Services	Canada	13			■											■	■
ISE	Canada	14															
MacDonald Dettwiler	Canada	15															
Optimal Robots	Canada	16															
Lego	Denmark	17															
Nilfisk-Advance A/S	Denmark	18															
Starkmatic Oy	Finland	19															
CEREM-CEA	France	20										■		■			
Cybernétix	France	21	■					■								■	
RENOSOL	France	22															
Robosoft	France	23															
Wany SA	France	24															■
Andro Tec gmbH	Germany	25															
Androtech	Germany	26															
D.T.I. Dr. Trippe	Germany	27															
Fraunhofer IPA	Germany	28						■									
GPS/Stuttgart	Germany	29							■								■
Hans Wälischmiller	Germany	30															
Inspector Systems	Germany	31															
IntelligeNDT	Germany	32	■														
Jenoptik Silmetric	Germany	33															
Kärcher	Germany	34															
KUKA	Germany	35										■					
ProKasro Mechatronik	Germany	36															
Robowatch	Germany	37															■
Rotundus	Germany	38															■
Telerob	Germany	39														■	
Welger Argrartechnik (Lely)	Germany	40															
Kentree	Ireland	41														■	
Friendly Robotics	Israel	42															
Smart Robotics	Israel	43															
Centrosistemi	Italy	44															
Genova Robot	Italy	45						■									■
Tecnospacio	Italy	46															
Fuji Heavy Ind.	Japan	47					■										
Fujita Corp.	Japan	48				■											
Hitachi Kiden Kogyo	Japan	49															
HONDA	Japan	50															
KOBE Mechatronics	Japan	51															
Matsushita Electric	Japan	52															
Minolta Co.	Japan	53															
Mitsubishi Heavy Ind.	Japan	54	■														
Robos	Japan	55															
Seiko-Epson	Japan	56															
SHIMIZU Corp.	Japan	57															
SOHGO Security Services	Japan	58															■
Sony	Japan	59															
TASEI Corp.	Japan	60				■											
Tmsuk	Japan	61															■
Toki	Japan	62															
Toyota Motor Corp.	Japan	63															
VISTONE	Japan	64															
Yanmar Co.	Japan	65															

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots													
			Defense, rescue & security applications					Laboratory robots			Public relation robots				Special Purpose	
Application code			47	48	49	50	51	52	53	54	55	56	57	58	59	60
Company	Country	No.	Unmanned aerial vehicles	Unmanned ground based vehicles	Other defense, rescue & security applications	**Under-water systems**	**Mobile Platforms in general use**	General material handling	Clean room robots	Other laboratory robots	Hotel & restaurant robots	Guide robots	Robots in marketing	Others (i.e. library robots)	Refueling robots	Other special purpose robits
Denning Branch	Australia	1					■		■		■					
Milka-Ware	Australia	2														
Schiebel	Austria	3	■													
Robonetics	Belgium	4														
Sony Europe	Belgium	5														
Applied AI Systems	Canada	6					■									
BRIC Engineering Systems	Canada	7					■									
CDL Systems Ltd.	Canada	8	■													
Cyberworks	Canada	9														
Dr. Robot	Canada	10														
Engineering Services	Canada	11					■	■								
Intelligent Robotics Corp.	Canada	12					■									
Inuktun Services	Canada	13				■										
ISE	Canada	14				■				■			■		■	
MacDonald Dettwiler	Canada	15														
Optimal Robots	Canada	16									■					
Lego	Denmark	17														
Nilfisk-Advance A/S	Denmark	18														
Starkmatic Oy	Finland	19														
CEREM-CEA	France	20														
Cybernétix	France	21				■										
RENOSOL	France	22														
Robosoft	France	23		■			■			■					■	
Wany SA	France	24	■													
Andro Tec gmbH	Germany	25					■									
Androtech	Germany	26				■										
D.T.I. Dr. Trippe	Germany	27														
Fraunhofer IPA	Germany	28														
GPS/Stuttgart	Germany	29										■				
Hans Wälischmiller	Germany	30														
Inspector Systems	Germany	31														
IntelligeNDT	Germany	32														
Jenoptik Silmetric	Germany	33														
Kärcher	Germany	34														
KUKA	Germany	35														
ProKasro Mechatronik	Germany	36														
Robowatch	Germany	37		■												
Rotundus	Germany	38														
Telerob	Germany	39														
Welger Argrartechnik (Lely)	Germany	40														
Kentree	Ireland	41														
Friendly Robotics	Israel	42														
Smart Robotics	Israel	43											■			
Centrosistemi	Italy	44														
Genova Robot	Italy	45					■					■				
Tecnospacio	Italy	46														
Fuji Heavy Ind.	Japan	47														
Fujita Corp.	Japan	48														
Hitachi Kiden Kogyo	Japan	49														
HONDA	Japan	50														
KOBE Mechatronics	Japan	51				■										
Matsushita Electric	Japan	52														
Minolta Co.	Japan	53														
Mitsubishi Heavy Ind.	Japan	54														
Robos	Japan	55														
Seiko-Epson	Japan	56														
SHIMIZU Corp.	Japan	57														
SOHGO Security Services	Japan	58														
Sony	Japan	59														
TASEI Corp.	Japan	60														
Tmsuk	Japan	61														
Toki	Japan	62														
Toyota Motor Corp.	Japan	63														
VISTONE	Japan	64														
Yanmar Co.	Japan	65														

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots			III. Robotics R&D									
							Actuation								
Application code			61	62	63	64	65	66	67	68	69	70	71	72	73
Company	Country	No.	Humanoid robots	Custo-mized robots	Other pro-fessional service robots not specified above	Sensing systems, Per-ception	Mobile platforms	Manipulation & grasping	Materials	Nano / Micro robots	Architec-tures & integration	Navigation and control	User interfaces and other interfaces	Other applied R&D efforts not specified	Basic research
Denning Branch	Australia	1	■	■		■	■			■		■			■
Milka-Ware	Australia	2													
Schiebel	Austria	3													
Robonetics	Belgium	4													
Sony Europe	Belgium	5													
Applied AI Systems	Canada	6					■					■			
BRIC Engineering Systems	Canada	7													
CDL Systems Ltd.	Canada	8										■		■	
Cyberworks	Canada	9													
Dr. Robot	Canada	10	■												
Engineering Services	Canada	11													
Intelligent Robotics Corp.	Canada	12													
Inuktun Services	Canada	13													
ISE	Canada	14													
MacDonald Dettwiler	Canada	15													
Optimal Robots	Canada	16													
Lego	Denmark	17					■								
Nilfisk-Advance A/S	Denmark	18													
Starkmatic Oy	Finland	19													
CEREM-CEA	France	20													
Cybernétix	France	21				■	■	■		■	■	■	■	■	
RENOSOL	France	22													
Robosoft	France	23					■								
Wany SA	France	24													
Andro Tec gmbH	Germany	25													
Androtech	Germany	26													
D.T.I. Dr. Trippe	Germany	27													
Fraunhofer IPA	Germany	28		■											
GPS/Stuttgart	Germany	29					■	■				■			
Hans Wälischmiller	Germany	30			■										
Inspector Systems	Germany	31													
IntelligeNDT	Germany	32													
Jenoptik Silmetric	Germany	33													
Kärcher	Germany	34													
KUKA	Germany	35													
ProKasro Mechatronik	Germany	36													
Robowatch	Germany	37													
Rotundus	Germany	38													
Telerob	Germany	39													
Welger Argrartechnik (Lely)	Germany	40													
Kentree	Ireland	41													
Friendly Robotics	Israel	42													
Smart Robotics	Israel	43													
Centrosistemi	Italy	44													
Genova Robot	Italy	45				■						■		■	
Tecnospacio	Italy	46													
Fuji Heavy Ind.	Japan	47													
Fujita Corp.	Japan	48													
Hitachi Kiden Kogyo	Japan	49													
HONDA	Japan	50	■												
KOBE Mechatronics	Japan	51													
Matsushita Electric	Japan	52													
Minolta Co.	Japan	53													
Mitsubishi Heavy Ind.	Japan	54													
Robos	Japan	55	■												
Seiko-Epson	Japan	56								■					
SHIMIZU Corp.	Japan	57	■												
SOHGO Security Services	Japan	58													
Sony	Japan	59	■												
TASEI Corp.	Japan	60													
Tmsuk	Japan	61													
Toki	Japan	62								■					
Toyota Motor Corp.	Japan	63	■												
VISTONE	Japan	64	■												
Yanmar Co.	Japan	65													

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			I. Personal/Domestic Robots														
			Robots for domestic tasks					Entertainment and leisure robots					Handicap assistance				
Application code			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Company	Country	No.	Vacuuming cleaning	Lawn mowing	Pool cleaning	Window cleaning	Other Robots for domestic tasks	Toy robots	Entertain-ment	Hobby systems	Education and training	Other entertain ment robots	Robotized wheelchairs	Other assistance functions	Personal rehabili-tation	Other handicap assistance	**Personal transpor-tation**
Hanool Robotics	Korea	66	■														
Yujin Robotics	Korea	67									■						
Exact Dynamics	Netherl.	68												■			
Frog Navigation Systems	Netherl.	69															■
Lely Benelux	Netherl.	70															
Prolion	Netherl.	71															
IdMind	Portugal	72							■		■	■					
AB Electrolux	Sweden	73	■	■													
Atlas Copco Mining Trucks	Sweden	74															
Brokk	Sweden	75															
Delaval International AB	Sweden	76															
Elekta	Sweden	77															
Husqvarna *	Sweden	78		■													
Weda	Sweden	79															
4DigitalBooks	Switzerl.	80															
BlueBotics	Switzerl.	81									■						
Cyberbotics	Switzerl.	82									■						
Didel SA	Switzerl.	83								■		■					
K-Team	Switzerl.	84									■						
Swisslog	Switzerl.	85															
Alstom Schilling Robotics	UK	86															
Armstrong Healthcare	UK	87												■			
Dyson Appliances	UK	88	■														
Fullwood	UK	89															
Hydrovision	UK	90															
Merlin Robotics	UK	91							■		■						
Ocrobotics	UK	92															
QinetiQ	UK	93															
R.U.Robots	UK	94															
Roboscience	UK	95															
Shadow Robot	UK	96												■			
Slingsby	UK	97															
3 Sigma Robotics	USA	98												■		■	
Accurray	USA	99															
Active Media	USA	100											■	■			
Advanced Robotics Inc	USA	101															
Advanced Robotics Vehicles	USA	102															
Aerovironment Inc.	USA	103															
Aethon	USA	104															
Alstom Automation Schilling	USA	105															
American Controls	USA	106															
Angelus Research Corp.	USA	107									■						
Aqua Products	USA	108			■												
Arrick Robotics	USA	109															
Atlas Robotics	USA	110							■								
Automatika Inc	USA	111															
Autonomous Solutions	USA	112															
Bluefin	USA	113															
Cobotics	USA	114														■	
Cyberclean	USA	115															
Cybermotion	USA	116															
David Brown Union Pump	USA	117															
Deep Ocean	USA	118															
Deka Research	USA	119											■	■			
Edge Innovations	USA	120										■					
EndoVia medical Inc.	USA	121															
Everest VIT	USA	122															
Evolution Robotics	USA	123								■							
Fujita Research	USA	124															
Gecko Systems Inc.	USA	125	■											■			
General Dynamics Robotic	USA	126															
Gettig Engineering	USA	127										■					
Happy Field Technology	USA	128						■									
Honeybee Robotics	USA	129															
Hydro Chem	USA	130															

* Operations taken over by AB Electrolux, Sweden

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			I. Personal/ Domestic Robots		II. Professional service robots														
					Field robotics						Professional cleaning					Inspection systems			
Application code			16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Company	Country	No.	**Home security & sur-veillance**	**Other Personal/ domestic robots**	Agriculture	Milking robots	Forestry	Mining systems	Space robots	Other field robotics	Floor cleaning	Window and wall cleaning (incl. wall climbing robots)	Tank, tube and pipe cleaning	Pool cleaning	Other cleaning tasks	Sewer robots	Tank, tubes and pipes	Other inspection systems
Hanool Robotics	Korea	66																
Yujin Robotics	Korea	67	■															
Exact Dynamics	Netherl.	68																
Frog Navigation Systems	Netherl.	69																
Lely Benelux	Netherl.	70				■												
Prolion	Netherl.	71				■												
IdMind	Portugal	72																
AB Electrolux	Sweden	73																
Atlas Copco Mining Trucks	Sweden	74																
Brokk	Sweden	75																
Delaval International AB	Sweden	76				■												
Elekta	Sweden	77																
Husqvarna *	Sweden	78																
Weda	Sweden	79												■	■			
4DigitalBooks	Switzerl.	80																
BlueBotics	Switzerl.	81							■									
Cyberbotics	Switzerl.	82																
Didel SA	Switzerl.	83																
K-Team	Switzerl.	84																
Swisslog	Switzerl.	85																
Alstom Schilling Robotics	UK	86																
Armstrong Healthcare	UK	87																
Dyson Applliances	UK	88									■							
Fullwood	UK	89				■												
Hydrovision	UK	90																
Merlin Robotics	UK	91																
Ocrobotics	UK	92																
QinetiQ	UK	93														■		
R.U.Robots	UK	94																
Roboscience	UK	95																
Shadow Robot	UK	96							■									
Slingsby	UK	97																■
3 Sigma Robotics	USA	98																
Accurray	USA	99																
Active Media	USA	100																
Advanced Robotics Inc	USA	101																
Advanced Robotics Vehicles	USA	102										■						■
Aerovironment Inc.	USA	103																
Aethon	USA	104																
Alstom Automation Schilling	USA	105																
American Controls	USA	106																
Angelus Research Corp.	USA	107																
Aqua Products	USA	108												■				
Arrick Robotics	USA	109																
Atlas Robotics	USA	110																
Automatika Inc	USA	111											■					
Autonomous Solutions	USA	112																
Bluefin	USA	113																
Cobotics	USA	114																
Cyberclean	USA	115									■							
Cybermotion	USA	116	■															
David Brown Union Pump	USA	117																
Deep Ocean	USA	118																
Deka Research	USA	119																
Edge Innovations	USA	120																
EndoVia medical Inc.	USA	121																
Everest VIT	USA	122														■		■
Evolution Robotics	USA	123																
Fujita Research	USA	124																
Gecko Systems Inc.	USA	125	■															
General Dynamics Robotic	USA	126																
Gettig Engineering	USA	127																
Happy Field Technology	USA	128																
Honeybee Robotics	USA	129																
Hydro Chem	USA	130											■					

* Operations taken over by AB Electrolux, Sweden
Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots														
			Construction and demolition					Logistic systems			Medical robotics				Defense, rescue & security applications		
Application code			32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Company	Country	No.	Nuclear demolition & dismantling	Other demoltion systems	Construc-tion support and mainte-nance	Construc-tion	Other types of con-struction	Courier/ Mail systems	Factory logistics (incl. Automated Guided Vehicles)	Other logistics	Diagnostic systems	Robot assisted surgery of therapy	Rehabili-tation systems	Other medical robots	Demining robots	Fire and bomb fighting robots	Sur-veillance / security robots
Hanool Robotics	Korea	66															
Yujin Robotics	Korea	67													■		
Exact Dynamics	Netherl.	68															
Frog Navigation Systems	Netherl.	69															
Lely Benelux	Netherl.	70															
Prolion	Netherl.	71															
IdMind	Portugal	72															
AB Electrolux	Sweden	73															
Atlas Copco Mining Trucks	Sweden	74						■									
Brokk	Sweden	75	■	■													
Delaval International AB	Sweden	76															
Elekta	Sweden	77										■					
Husqvarna *	Sweden	78															
Weda	Sweden	79															
4DigitalBooks	Switzerl.	80															
BlueBotics	Switzerl.	81			■		■		■								
Cyberbotics	Switzerl.	82															
Didel SA	Switzerl.	83															
K-Team	Switzerl.	84															
Swisslog	Switzerl.	85								■							
Alstom Schilling Robotics	UK	86															
Armstrong Healthcare	UK	87										■		■			
Dyson Appliances	UK	88															
Fullwood	UK	89															
Hydrovision	UK	90															
Merlin Robotics	UK	91															
Ocrobotics	UK	92															
QinetiQ	UK	93													■	■	
R.U.Robots	UK	94	■		■	■											■
Roboscience	UK	95															
Shadow Robot	UK	96														■	
Slingsby	UK	97															
3 Sigma Robotics	USA	98												■			
Accurray	USA	99										■					
Active Media	USA	100						■	■								■
Advanced Robotics Inc	USA	101															
Advanced Robotics Vehicles	USA	102															
Aerovironment Inc.	USA	103															
Aethon	USA	104						■									
Alstom Automation Schilling	USA	105															
American Controls	USA	106															
Angelus Research Corp.	USA	107															■
Aqua Products	USA	108															
Arrick Robotics	USA	109															
Atlas Robotics	USA	110															
Automatika Inc	USA	111															
Autonomous Solutions	USA	112	■	■													
Bluefin	USA	113															
Cobotics	USA	114															
Cyberclean	USA	115															
Cybermotion	USA	116															■
David Brown Union Pump	USA	117															
Deep Ocean	USA	118															
Deka Research	USA	119															
Edge Innovations	USA	120															
EndoVia medical Inc.	USA	121										■					
Everest VIT	USA	122															
Evolution Robotics	USA	123															
Fujita Research	USA	124				■											
Gecko Systems Inc.	USA	125						■									■
General Dynamics Robotic	USA	126															■
Gettig Engineering	USA	127															
Happy Field Technology	USA	128															
Honeybee Robotics	USA	129															
Hydro Chem	USA	130															

* Operations taken over by AB Electrolux, Sweden

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots													
			Defense, rescue & security applications					Laboratory robots			Public relation robots				Special Purpose	
Application code			47	48	49	50	51	52	53	54	55	56	57	58	59	60
Company	Country	No.	Unmanned aerial vehicles	Unmanned ground based vehicles	Other defense, rescue & security applications	**Under-water systems**	**Mobile Platforms in general use**	General material handling	Clean room robots	Other laboratory robots	Hotel & restaurant robots	Guide robots	Robots in marketing	Others (i.e. library robots)	Refueling robots	Other special purpose robits
Hanool Robotics	Korea	66					■									
Yujin Robotics	Korea	67			■											
Exact Dynamics	Netherl.	68														
Frog Navigation Systems	Netherl.	69														
Lely Benelux	Netherl.	70														
Prolion	Netherl.	71														
IdMind	Portugal	72														
AB Electrolux	Sweden	73														
Atlas Copco Mining Trucks	Sweden	74					■									
Brokk	Sweden	75														
Delaval International AB	Sweden	76														
Elekta	Sweden	77														
Husqvarna *	Sweden	78														
Weda	Sweden	79														
4DigitalBooks	Switzerl.	80												■		
BlueBotics	Switzerl.	81					■				■	■		■		
Cyberbotics	Switzerl.	82														
Didel SA	Switzerl.	83														
K-Team	Switzerl.	84								■			■			
Swisslog	Switzerl.	85														
Alstom Schilling Robotics	UK	86				■										
Armstrong Healthcare	UK	87														
Dyson Applliances	UK	88														
Fullwood	UK	89														
Hydrovision	UK	90				■										
Merlin Robotics	UK	91					■									
Ocrobotics	UK	92														
QinetiQ	UK	93														
R.U.Robots	UK	94														
Roboscience	UK	95					■									
Shadow Robot	UK	96					■			■						
Slingsby	UK	97				■										
3 Sigma Robotics	USA	98														
Accurray	USA	99														
Active Media	USA	100					■			■		■				
Advanced Robotics Inc	USA	101														
Advanced Robotics Vehicles	USA	102														
Aerovironment Inc.	USA	103	■													
Aethon	USA	104														
Alstom Automation Schilling	USA	105				■										
American Controls	USA	106													■	
Angelus Research Corp.	USA	107														
Aqua Products	USA	108														
Arrick Robotics	USA	109					■									
Atlas Robotics	USA	110														
Automatika Inc	USA	111														
Autonomous Solutions	USA	112														
Bluefin	USA	113				■										
Cobotics	USA	114														
Cyberclean	USA	115														
Cybermotion	USA	116					■									
David Brown Union Pump	USA	117													■	
Deep Ocean	USA	118				■										
Deka Research	USA	119														
Edge Innovations	USA	120														
EndoVia medical Inc.	USA	121														
Everest VIT	USA	122														
Evolution Robotics	USA	123														
Fujita Research	USA	124														
Gecko Systems Inc.	USA	125					■									
General Dynamics Robotic	USA	126														
Gettig Engineering	USA	127														
Happy Field Technology	USA	128														
Honeybee Robotics	USA	129											■			

* Operations taken over by AB Electrolux, Sweden
Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots			III. Robotics R&D									
							Actuation								
Application code			61	62	63	64	65	66	67	68	69	70	71	72	73
Company	Country	No.	Humanoid robots	Custo-mized robots	Other pro-fessional service robots not specified above	Sensing systems, Per-ception	Mobile platforms	Manipulation & grasping	Materials	Nano / Micro robots	Architec-tures & integration	Navigation and control	User interfaces and other interfaces	Other applied R&D efforts not specified	Basic research
Hanool Robotics	Korea	66													
Yujin Robotics	Korea	67													
Exact Dynamics	Netherl.	68													
Frog Navigation Systems	Netherl.	69													
Lely Benelux	Netherl.	70													
Prolion	Netherl.	71													
IdMind	Portugal	72		■											
AB Electrolux	Sweden	73													
Atlas Copco Mining Trucks	Sweden	74													
Brokk	Sweden	75													
Delaval International AB	Sweden	76													
Elekta	Sweden	77													
Husqvarna *	Sweden	78													
Weda	Sweden	79			■										
4DigitalBooks	Switzerl.	80													
BlueBotics	Switzerl.	81		■				■				■			
Cyberbotics	Switzerl.	82				■								■	■
Didel SA	Switzerl.	83													
K-Team	Switzerl.	84									■				■
Swisslog	Switzerl.	85													
Alstom Schilling Robotics	UK	86													
Armstrong Healthcare	UK	87													
Dyson Appliances	UK	88													
Fullwood	UK	89													
Hydrovision	UK	90													
Merlin Robotics	UK	91													
Ocrobotics	UK	92			■										
QinetiQ	UK	93			■	■	■							■	■
R.U.Robots	UK	94					■				■	■	■	■	
Roboscience	UK	95													
Shadow Robot	UK	96	■				■	■						■	■
Slingsby	UK	97													
3 Sigma Robotics	USA	98		■		■	■					■		■	
Accurray	USA	99													
Active Media	USA	100			■							■		■	■
Advanced Robotics Inc	USA	101					■					■		■	
Advanced Robotics Vehicles	USA	102													
Aerovironment Inc.	USA	103													
Aethon	USA	104													
Alstom Automation Schilling	USA	105													
American Controls	USA	106													
Angelus Research Corp.	USA	107													
Aqua Products	USA	108													
Arrick Robotics	USA	109													
Atlas Robotics	USA	110													
Automatika Inc	USA	111													
Autonomous Solutions	USA	112													
Bluefin	USA	113													
Cobotics	USA	114													
Cyberclean	USA	115													
Cybermotion	USA	116													
David Brown Union Pump	USA	117													
Deep Ocean	USA	118													
Deka Research	USA	119													
Edge Innovations	USA	120													
EndoVia medical Inc.	USA	121													
Everest VIT	USA	122													
Evolution Robotics	USA	123				■	■					■	■	■	
Fujita Research	USA	124													
Gecko Systems Inc.	USA	125													
General Dynamics Robotic	USA	126													
Gettig Engineering	USA	127													
Happy Field Technology	USA	128													
Honeybee Robotics	USA	129													
Hydro Chem	USA	130													

* Operations taken over by AB Electrolux, Sweden

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			I. Personal/Domestic Robots														
			Robots for domestic tasks					Entertainment and leisure robots					Handicap assistance				
Application code			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Company	Country	No.	Vacuuming cleaning	Lawn mowing	Pool cleaning	Window cleaning	Other Robots for domestic tasks	Toy robots	Entertain-ment	Hobby systems	Education and training	Other entertain ment robots	Robotized wheelchairs	Other assistance functions	Personal rehabili-tation	Other handicap assistance	**Personal transpor-tation**
Independence Technology	USA	131												■			
Integrated Surgical	USA	132															
Intelitek	USA	133									■						
InterSense	USA	134															
Intuitive Surgical	USA	135															
iRobot	USA	136	■														
Jet Propulsion Lab.	USA	137															
Johuco Mobile Robots	USA	138						■			■	■					
Kirtas Technology	USA	139															
Lego Mindstorms	USA	140						■									
Living Machines	USA	141									■	■					
Lynxmotion	USA	142						■			■	■					
Medtronic	USA	143															
Mekatronix	USA	144									■	■					
MRISAR	USA	145												■			
NASA/Jet Propulsion Lab	USA	146															
NREC	USA	147															
Oceaneering	USA	148															
Omnitech Robotics	USA	149															
Parallax	USA	150									■						
Probotics Inc.	USA	151	■														
Production Technology	USA	152															
Pyxis	USA	153															
Real World Interface	USA	154	■														
RedZone Robotics	USA	155															
Rehabilitation Technologies	USA	156											■	■			
Robix	USA	157									■						
Robo Probe Technologies	USA	158															
SARCOS	USA	159									■						
Schiebel	USA	160															
Sias Pattersson	USA	161															
Slingsby	USA	162															
Solex Robotics	USA	163															
Textron	USA	164															
The Eureka Comp.	USA	165	■														
The Robot Factory	USA	166									■						
UltraStrip Systems	USA	167															
White Box Robotics	USA	168															
Zagros Robotics	USA	169									■						

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			I. Personal/ Domestic Robots		II. Professional service robots													
					Field robotics						Professional cleaning					Inspection systems		
Application code			16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Company	Country	No.	**Home security & sur-veillance**	**Other Personal/ domestic robots**	Agriculture	Milking robots	Forestry	Mining systems	Space robots	Other field robotics	Floor cleaning	Window and wall cleaning (incl. wall climbing robots)	Tank, tube and pipe cleaning	Pool cleaning	Other cleaning tasks	Sewer robots	Tank, tubes and pipes	Other inspection systems
Independence Technology	USA	131																
Integrated Surgical	USA	132																
Intelitek	USA	133																
InterSense	USA	134																
Intuitive Surgical	USA	135																
iRobot	USA	136																■
Jet Propulsion Lab.	USA	137							■									
Johuco Mobile Robots	USA	138																
Kirtas Technology	USA	139																
Lego Mindstorms	USA	140																
Living Machines	USA	141																
Lynxmotion	USA	142																
Medtronic	USA	143																
Mekatronix	USA	144																
MRISAR	USA	145	■															
NASA/Jet Propulsion Lab	USA	146							■									
NREC	USA	147			■													
Oceaneering	USA	148																
Omnitech Robotics	USA	149														■		
Parallax	USA	150																
Probotics Inc.	USA	151																
Production Technology	USA	152																
Pyxis	USA	153																
Real World Interface	USA	154																
RedZone Robotics	USA	155											■		■	■		
Rehabilitation Technologies	USA	156																
Robix	USA	157																
Robo Probe Technologies	USA	158														■		■
SARCOS	USA	159																
Schiebel	USA	160																
Sias Pattersson	USA	161																
Slingsby	USA	162																
Solex Robotics	USA	163											■					
Textron	USA	164																
The Eureka Comp.	USA	165																
The Robot Factory	USA	166																
UltraStrip Systems	USA	167										■						
White Box Robotics	USA	168																
Zagros Robotics	USA	169																

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots														
			Construction and demolition					Logistic systems			Medical robotics				Defense, rescue & security applications		
Application code			32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Company	Country	No.	Nuclear demolition & dismantling	Other demoltion systems	Construc-tion support and mainte-nance	Construc-tion	Other types of con-struction	Courier/ Mail systems	Factory logistics (incl. Automated Guided Vehicles)	Other logistics	Diagnostic systems	Robot assisted surgery of therapy	Rehabili-tation systems	Other medical robots	Demining robots	Fire and bomb fighting robots	Sur-veillance / security robots
Independence Technology	USA	131															
Integrated Surgical	USA	132										■					
Intelitek	USA	133															
InterSense	USA	134															
Intuitive Surgical	USA	135										■					
iRobot	USA	136		■													
Jet Propulsion Lab.	USA	137															
Johuco Mobile Robots	USA	138															
Kirtas Technology	USA	139															
Lego Mindstorms	USA	140															
Living Machines	USA	141															
Lynxmotion	USA	142															
Medtronic	USA	143										■					
Mekatronix	USA	144															
MRISAR	USA	145														■	■
NASA/Jet Propulsion Lab	USA	146															
NREC	USA	147															
Oceaneering	USA	148															
Omnitech Robotics	USA	149														■	
Parallax	USA	150															
Probotics Inc.	USA	151															■
Production Technology	USA	152															
Pyxis	USA	153						■									
Real World Interface	USA	154															
RedZone Robotics	USA	155	■														
Rehabilitation Technologies	USA	156															
Robix	USA	157															
Robo Probe Technologies	USA	158															
SARCOS	USA	159															
Schiebel	USA	160															
Sias Pattersson	USA	161															
Slingsby	USA	162															
Solex Robotics	USA	163															
Textron	USA	164															
The Eureka Comp.	USA	165															
The Robot Factory	USA	166															
UltraStrip Systems	USA	167															
White Box Robotics	USA	168															
Zagros Robotics	USA	169															

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (continued)

Inventory of service robot manufacturers by application areas

			II. Professional service robots													
			Defense, rescue & security applications					Laboratory robots			Public relation robots				Special Purpose	
Application code			47	48	49	50	51	52	53	54	55	56	57	58	59	60
Company	Country	No.	Unmanned aerial vehicles	Unmanned ground based vehicles	Other defense, rescue & security applications	**Under-water systems**	**Mobile Platforms in general use**	General material handling	Clean room robots	Other laboratory robots	Hotel & restaurant robots	Guide robots	Robots in marketing	Others (i.e. library robots)	Refueling robots	Other special purpose robits
Independence Technology	USA	131														
Integrated Surgical	USA	132														
Intelitek	USA	133														
InterSense	USA	134														
Intuitive Surgical	USA	135														
iRobot	USA	136					■									
Jet Propulsion Lab.	USA	137														
Johuco Mobile Robots	USA	138														
Kirtas Technology	USA	139												■		
Lego Mindstorms	USA	140														
Living Machines	USA	141														
Lynxmotion	USA	142														
Medtronic	USA	143														
Mekatronix	USA	144					■									
MRISAR	USA	145										■				
NASA/Jet Propulsion Lab	USA	146														
NREC	USA	147														
Oceaneering	USA	148				■										
Omnitech Robotics	USA	149					■									
Parallax	USA	150														
Probotics Inc.	USA	151														
Production Technology	USA	152				■										
Pyxis	USA	153														
Real World Interface	USA	154														
RedZone Robotics	USA	155														
Rehabilitation Technologies	USA	156														
Robix	USA	157														
Robo Probe Technologies	USA	158				■										
SARCOS	USA	159														
Schiebel	USA	160	■													
Sias Pattersson	USA	161				■										
Slingsby	USA	162				■										
Solex Robotics	USA	163														
Textron	USA	164													■	
The Eureka Comp.	USA	165														
The Robot Factory	USA	166					■						■			
UltraStrip Systems	USA	167														
White Box Robotics	USA	168					■									
Zagros Robotics	USA	169					■									

Sources: UNECE, IFR and Fraunhofer IPA.

Table VII.2 (concluded)

Inventory of service robot manufacturers by application areas

			II. Professional service robots			III. Robotics R&D									
							Actuation								
Application code			61	62	63	64	65	66	67	68	69	70	71	72	73
Company	Country	No.	Humanoid robots	Custo-mized robots	Other pro-fessional service robots not specified above	Sensing systems, Per-ception	Mobile platforms	Manipulation & grasping	Materials	Nano / Micro robots	Architec-tures & integration	Navigation and control	User interfaces and other interfaces	Other applied R&D efforts not specified	Basic research
Independence Technology	USA	131													
Integrated Surgical	USA	132													
Intelitek	USA	133													
InterSense	USA	134										■			
Intuitive Surgical	USA	135													
iRobot	USA	136													
Jet Propuslion Lab.	USA	137													
Johuco Mobile Robots	USA	138													
Kirtas Technology	USA	139													
Lego Mindstorms	USA	140													
Living Machines	USA	141								■					
Lynxmotion	USA	142													
Medtronic	USA	143													
Mekatronix	USA	144													
MRISAR	USA	145	■												
NASA/Jet Propulsion Lab	USA	146					■					■		■	
NREC	USA	147													
Oceaneering	USA	148													
Omnitech Robotics	USA	149				■	■					■			
Parallax	USA	150													
Probotics Inc.	USA	151													
Production Technology	USA	152													
Pyxis	USA	153													
Real World Interface	USA	154													
RedZone Robotics	USA	155			■										
Rehabilitation Technologies	USA	156													
Robix	USA	157													
Robo Probe Technologies	USA	158													
SARCOS	USA	159													
Schiebel	USA	160													
Sias Pattersson	USA	161													
Slingsby	USA	162													
Solex Robotics	USA	163													
Textron	USA	164													
The Eureka Comp.	USA	165													
The Robot Factory	USA	166													
UltraStrip Systems	USA	167													
White Box Robotics	USA	168													
Zagros Robotics	USA	169													

Sources: UNECE, IFR and Fraunhofer IPA.

Examples of Service Robots:

Figure VII.4 Professional Cleaning and Window cleaning

Cleanfix Robo40. An autonomous floor cleaner, Cleanfix (Switzerland).

robuGLASS of Robosoft (France). First unit developed for the Louvre Museum in 2003.

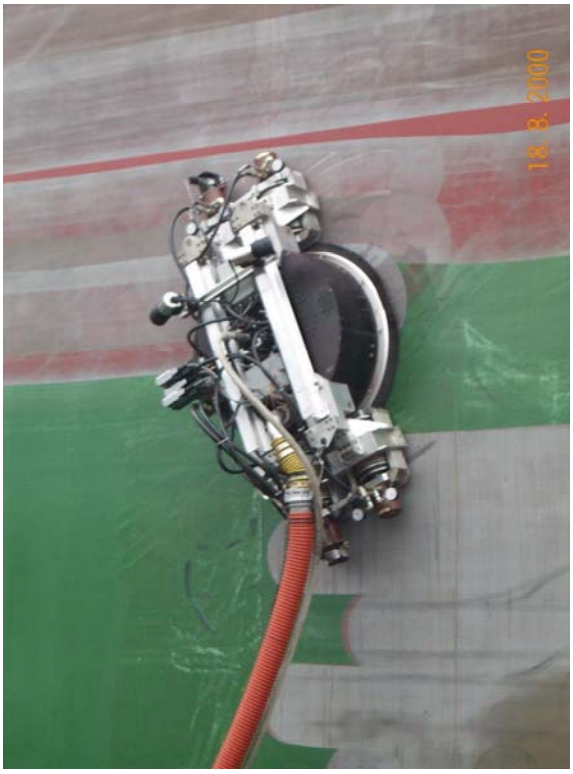
Figure VII.5 Pool cleaning and robotic reservoir cleaning

Weda B680, Pool Cleaner of Weda (Sweden)

Weda VR 600 Robotic Reservoir Cleaner of Weda, (Sweden)

Figure VII.6 Wall-climbing robot

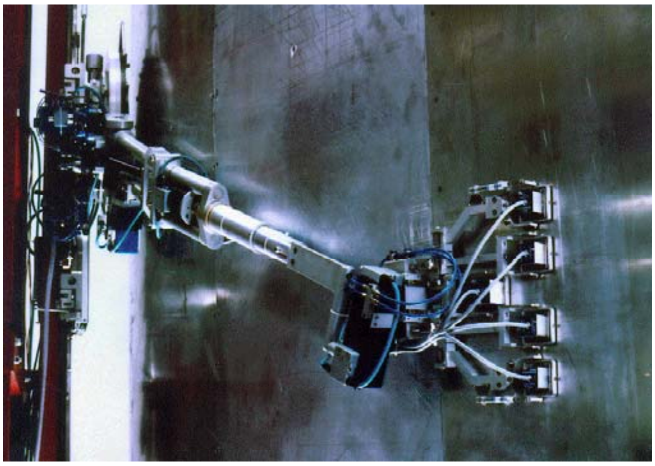
M2000 Paint Stripping Robot by NREC Pittsburgh (USA) and UltraStrip Systems Inc. (USA)



The OCTOPUS of Cybernetix (France) adheres to a hull and can be equipped with brushes or other tools. It can work above or below the water line.

Figure VII.7 Inspection systems

6-axis manipulator for outer reactor core inspection. intelligeNDT (Germany)



The Micro Variable Geometry Tracked Vehicle (VGTV) of INUKTUN (Canada).

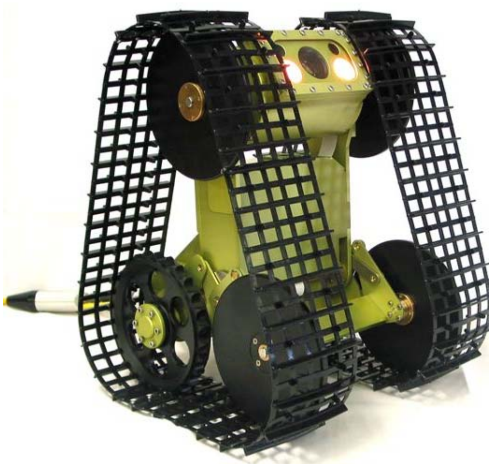


Figure VII.8 Construction and demolition systems

The BROKK B 330 demolition system for house use, Brokk AB (Sweden)

Fujita (Japan): Portable tele-operated robot for the manipulation of a backhoe shovel

Figure VII.9 Logistic systems

Autonomous robot to support hospital workflow by Matsushita Electric Works (Japan)

MobileArm-PA10 of GPS/Neobotix, (Germany)

Figure VII.10 Surveillance systems

Surveillance robot of GPS/Neobotix (Germany)

Camcopter® Unmanned aerial vehicle of Schiebel (Austria)

Rotundus (Sweden): Durable mobile robots for extreme conditions. It can run in most terrain - snow, mud, sand, water.

OFRO of Robowatch (Germany): Outdoor security

Figure VII.11 Underwater systems

The Nanomag of INUKTUN (Canada) adheres magnetically to metal surfaces in any orientation.

ALIVE: AUV for light interventions on deepwater or deepwater subsea fields, Cybernétix (France)

Figure VII.12 Public relation robots

Robots OSKAR and MONA at Opel (produced by Fraunhofer IPA (Germany) and GPS/Neobotix (Germany))

Robot guides of the Museum für Kommunikation, Berlin, Germany (produced by Fraunhofer IPA (Germany) and GPS/Neobotix (Germany))

Figure VII.13 Refueling robots

Hydrogen refueling at the Munich airport. The robot is provided by Reis Robotics (Germany). All components fulfil safety requirements.

Bus refueling by the MK6 Robot from Robosoft (France)

Figure VII.14 Humanoid Robots

The HRP-2P of Kawada (Japan) at the EXPO 2005 in Aichi.

QRIO, The Sony dream robot from Sony (Japan)

Wabian humanoid robot at the EXPO 2005, Waseda University (Japan)

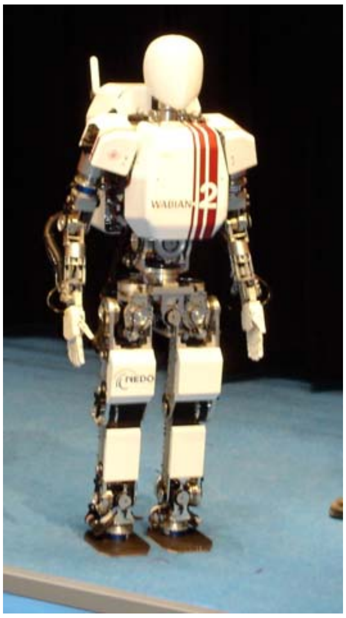


Figure VII.15 Lawn mowing

Lawn Mower of Husqvarna (Sweden)

Robomow® of Friendly Robotics (Israel)

Figure VII.16 Entertainment and leisure robots

Khepera, Edutainment robot of K-team (Switzerland)

MRISAR (USA): Inexpensive interactive, science and art exhibits that are featured in science centres and museums

Figure VII.17 Automated guided vehicles

Automated guided vehicle of Frog Navigation (The Netherlands)

robuRIDE of Robosoft (France): Automatic fleet control allows to accurately manage a flow of visitors and coordinate a scenography.