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Contribution to Statistics/Forecasts/Foresights in Annual Publications such as World Robotics 2006

In 1999 a classification scheme for service robotics was developed in order to conduct a world wide service robot statistical survey. The survey was edited by the United Nations Economic Commission for Europe and published by the International Federation of Robotics (IFR) in the yearbook “World Robotics 1999” on statistics, market analysis, forecasts, case studies and profitability of robot investment.

In the sequel the service robotics classification scheme and the methods to conduct the statistics and market surveys have been gradually improved. Since 2005 the Yearbook is edited by the IFR Statistical Department which is located in Frankfurt/Germany.

Today, World Robotics is the reference in statistics for both industrial and service robots (please refer to a Google search). The publication is accompanied by a press conference which usually is held in September/ October. Since 2006 the Yearbook is published and distributed electronically through its website http://www.ifrstat.org/index.php.

From beginning on, EURON particularly through its industrial link coordinators, contributed to the book by researching and editing the chapters on service. EURON material was intensely used to produce the accompanying survey on existing products, technologies and trends in the field of service robots.

The statistical material is communicated and distributed to the EURON community at the Yearbook’s publication date. Statistical tables, graphs etc. are made available for EURON members via the EURON email distribution list and the network’s website http://www.euron.org/resources/statistics.html. This material is used in coursework, publications and market research projects.

For the 2007 statistics the service robotics classification scheme has been revised again. In February the questionnaires have been sent out to the ~200 service robotics companies world wide. Currently data are processed and the revision of the chapters on service robotics will follow soon. The publication of the 2007 Yearbook issues is to be expected in September/October 2007.

Attached are the files of the chapters:

- World_Robotics_Chapter_7A_Service_Robotics_2006.pdf
- World_Robotics_Chapter_7B_Service_Robotics_2006.pdf

VII SERVICE ROBOTS[1]

VII.1 Introduction

In 2006, the IFR Statistical Department carried out a market survey of service robots for the 7th time. A questionnaire was sent to more than 170 companies worldwide, asking for data on accumulated sales up to the end of 2005, sales in 2005, and projections for 2006-2009. 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).

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 Robotics 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 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 Robotics 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. 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 on 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 consulting companies. In the 2005 survey, more companies were surveyed than in the 2004 survey.

Close to 60% of the 172 companies surveyed provided market data. 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 2005, by application areas, and forecasts for the period 2006-2009

Types of robots	Stock at end 2005	Installations 2006-2009	Sales in 2005	Stock at end 2005	Installations 2006-2009
	No. of units	No. of units	No. of units	$ million	$ million
SERVICE ROBOTS FOR PROFESSIONAL USE:					
Field robotics	**3,560**	**6,360**	**1,260**	**716**	**1,277**
Agriculture					
Milking robots	3,500	6,350	1,260	706	1,276
Forestry					
Mining systems					
Space robots					
Others	60	10		10	1
Professional cleaning	**5,350**	**1,935**	**200**	**77**	**39**
Floor cleaning	340	35		31	2
Window and wall cleaning (including wall climbing robots)	10	900		3	24
Tank, tube and pipe cleaning					
Pool cleaning	5,000	1,000	200	44	14
Other cleaning tasks					
Inspection systems	**275**	**1,370**	**41**	**28**	**119**
Sewer robots	120	1,200	28	8	86
Tank, tubes and pipes*					
Other inspection systems	155	170	13	20	33
Construction and demolition	**3,580**	**1,235**	**286**	**241**	**85**
Demolition systems: nuclear demolition & dismantling,	90	40	8	24	12
other demolition systems	3,410	1,100	265	213	64
Construction support robots: maintenance or construction	70	85	11	2	8
other types of construction	10	10	2	2	2
Logistic systems	**1,130**	**1,710**	**290**	**63**	**92**
Courier/Mail systems	310	210	46	20	23
Factory logistics (incl. Automated Guided Vehicles)	820	1,500	244	43	68
Other logistics					
Medical robotics	**3,355**	**2,310**	**476**	**689**	**790**
Diagnostic systems**					
Robot assisted surgery of therapy	3,330	2,300	476	689	787
Rehabilitation systems**					
Other medical robots	25	10		1	3
Defence, rescue & security applications	**5,080**	**10,760**	**2,475**	**2,597**	**4,303**
Demining robots	70	70	14	18	27
Fire and bomb fighting robots	530	390	90	63	106
Surveillance/security robots	780	2,500	114	39	54
Unmanned vehicles * **	**3,700**	**7,800**	**2,257**	**2,477**	**4,117**
Unmanned aerial vehicles	3,100	5,100	2,100	2,454	4,014
Unmanned ground based vehicles	600	2,700	157	23	103
Others					
Underwater systems	**5,680**	**2,000**	**375**	**2,216**	**950**
Mobile Platforms in general use	**3,400**	**6,100**	**679**	**73**	**99**
Public relation robots	**30**	**400**		**1**	**25**
Hotel & restaurant robots					
Guide robots					
Robots in marketing					
Others (i.e. library robots)					

Sources: IFR and UNECE (up to 2004).

*included in other inspection systems

** no data available

*** values are estimated

Table VII.1 (concluded)

Estimated number and value of service robots installed up to the end of 2005, by application areas, and forecasts for the period 2006-2009

Types of robots	Stock at end 2005	Installations 2006-2009	Sales in 2005	Stock at end 2005	Installations 2006-2009
	No. of units	No. of units	No. of units	$ million	$ million
SERVICE ROBOTS FOR PROFESSIONAL USE:					
Special Purpose	**55**	**30**		**8**	**1**
- refuelling robots	55	30		8	1
- others					
Customized robots **					
Other professional service robots not specified above	**115**	**85**	**21**	**6**	**4**
Total number of units / estimated value of professional service robots	**31,610**	**34,295**	**6,103**	**6,714**	**7,784**
SERVICE ROBOTS FOR PERSONAL/DOMESTIC USE:					
Robots for domestic tasks	**1,902,500**	**3,890,000**	**760,500**	**700**	**1,676**
- vacuuming cleaners	1,823,500	3,680,000	727,500	624	1,466
- lawn mowing	79,000	210,000	33,000	76	210
- others					
Entertainment and leisure robots	**1,024,480**	**1,558,628**	**105,149**	**707**	**955**
- Toy/hobby robots	913,600	1,538,005	101,000	649	935
- Robot rides *					
- Education and training	20,700	20,400	4,086	26	8
- Others	90,180	223	63	32	12
Handicap assistance	**360**	**650**	**70**	**2**	**16**
- Robotized wheelchairs					
- Personal rehabilitation					
- Other assistance functions					
- Others					
Personal transportation					
Home security & surveillance	**140**	**5,000**		**18**	**25**
Other Personal/domestic robots					
Total number of units / estimated value of personal/domestic service robots	**2,927,480**	**5,454,278**	**865,719**	**1,427**	**2,672**
Total number of units / estimated value of service robots	**2,959,090**	**5,488,573**	**871,822**	**8,141**	**10,456**
of which robotics R&D* **					

Sources: IFR and UNECE (up to 2004).

* included in other entertainment and leisure robots

* * Included in other professional robots.

*** Only a few companies provided data.

Despite this improvement in the response rate, the data reported here probably understate the true sales figures and installed base of robots significantly, especially the 2005 sales. 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 2005

With 5,680 units, **underwater systems** accounted for 18% of the total number of service robots for professional use installed up to the end of 2005 (see table VII.1 and figure VII.6a). Thereafter followed **cleaning robots** with 17%, **defense, rescue and security applications** with 16% and **construction and demolition robots,** **milking robots** and **medical robots** and **mobile robot platforms for general use,** accounting for 11%, each. . Minor installation numbers were counted for logistic systems (1,130 units), inspection systems (275 units) and public relations robots (30 units).

Of the total value (about $6.7 billion) of service robots for professional use installed up to the end of 2005, **defense, rescue and security applications** accounted for around 38% (see table VII.1 and figure VII.6b and VII.6c). The values for this group are more or less estimates, as the companies providing data are often unwilling to give price information. They were followed by underwater systems, which had a share of 33%. **Milking robots** had a share of 11% followed by **medical robots** with 10%. 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 **defense, rescue and security robots and underwater systems** (from $50,000 to more than $1,000,000), **medical robots,** with a wide range from $100,000 to some $1,000,000, and **milking robots** (about $200,000).

(b) Service robots for personal and domestic use; stock of installations up to the end of 2005

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.7a).

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® (Sweden). The market expanded during 2002 and 2003 and several other companies, e.g. Kärcher (Germany) and iRobot (USA) have since entered the market. More robot vacuum cleaner products (from companies such as Hitachi (Japan), Hanool International (Thailand), Samsung (Korea), LG electronic (Korea), and others) have been launched, resulting in accumulated sales up to end 2005 of 1.8 million units. iRobot launched a floor washing robot in 2005, the Scooba®.

At the end of 2005, the stock of **lawn mowing robots** amounted to 79,000 units. The market is dominated by the Ambrogio™ of Zucchetti Centro Sistemi (Italy) and Electrolux's auto mower (Sweden).

At the end of 2005, it is estimated that 1.9 million domestic robots, all types included, were in use, of which 760,000 units were sold in 2005. The actual number might, however, be significantly higher, as the IFR survey is far from having full coverage.

As far as **entertainment and leisure robots are concerned**, it is estimated that more than 1 million units had been sold up to the end of 2005. It is expected that the merging of PC, home entertainment and robot technologies will become a very substantial business area in the near future. Nonetheless, production of the well-known example of these kinds of robots, Sony's AIBO™ (Japan), was discontinued in 2005 because of disappointing sales. The LEGO® Mindstorms® programme is running successfully. Other products which have been launched or announced are mostly of Japanese and Korean origin, and include the PaPeRo of NEC (Japan), ApriAlpha™ and ApriAttenda™ by Toshiba (Japan), amongst others.

Accumulated sales of **toy robots** are estimated at about 910,000 units. An example of **entertainment robots**, which is still a rather limited market segment, is the ROBOCOASTER® by KUKA (Germany). 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 20,700 **education and training robots** were sold up to 2005.

The total value of the stock of **entertainment and leisure robots** amounted to $700 million. Compared to professional service robots, these robots are rather low-priced. The average prices are between $200 and $1,000.

Accumulated sales of **robots for handicap assistance** amounted to 360 units up to the end of 2005. These robots have not yet taken off as might be expected given their potential with 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. Longer term, say in the next 10 years, and taking into account demographic shifts and advances in technology, assistive robots for disabled and handicapped persons are certain to be a key area for service robots. Important research institutions are focussing on developing prototypes of this kind of robot.

(c) Projections for the period 2006-2009: service robots for professional use

Turning to the projections for the period 2006-2009, the stock is forecast to increase by some 34,300 units (see table VII.1 and figures VII.6a). **Robots in public relations** had no significant sales up to and including 2005 and estimates were cautious.

In the period 2006-2009, sales of **underwater systems** are projected to surpass 2,000 units, **defence, rescue, and security applications** about 10,800, **professional cleaning robots** 1,900, and **mobile robot platforms for multiple use** 6,100. The accumulated sales of **medical robots** were expected to increase by 2,300. Last year's forecast for **refuelling robots** and **public relations robots** will also not be reached. Less than 50 robots were expected to be sold in the period 2006-2009. 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 2006-2009: 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, and sales rose to some 390,000 units in 2003. The price was significantly reduced. The forecast of sales in the period 2006-2009 is about 3.7 million units (see table VII.1), which is compatible with the estimates of 3.9 million units for the period between 2005 and 2008 (see table VII.1 in World Robotics 2005). 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 2006-2009 - about 210,000 units.

It is projected that sales of **all types of domestic robots** (vacuum cleaning, lawn-mowing, window cleaning and other types) could reach some 3.9 million units in the period 2006-2009, with an estimated value of $1.7 billion (see table VII.1 and figures VII.7a).

The size of the market for **toy robots and hobby systems** is forecast at about 1.5 million units, most of which, of course, are very low cost (see table VII.1 and figure VII.1b). An application area with strong growth might be **humanoid robots** mostly as toys and hobby systems. 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 (Fujitsu, Kawada, ZMP) developing these robots for use as general purpose robot assistants beyond the toy and leisure scope. First sales started in 2004, mostly in Japan or to international research laboratories.

About 20,000 **robots for education and training** are expected to be sold in the period 2006-2009, compared with an installed base of 21,000 units up to and including 2005.

Sales of all types of **entertainment and leisure robots** are projected at well beyond 1.6 million units, with a value above $ 0.9 billion (see table VII.1 and figures VII.7b).

Total world stock of service robots for professional use at the end of 2005 is estimated at some 31,600 units. Some 34,000 units are forecast to be added in the period 2006-2009.

The world stock of service robots for domestic (household) use at the end of 2005 is estimated in the order of 1,900,000 units. Some 3.9 million units may be added in the period 2006-2009.

The world stock of entertainment and leisure robots at the end of 2005 is estimated in the order of 1 million units. Some 1.6 million units may be added in the period 2006-2009.

Figure VII.1a Service robots for professional use. Stock at the end of 2005 and projected installations in 2006-2009

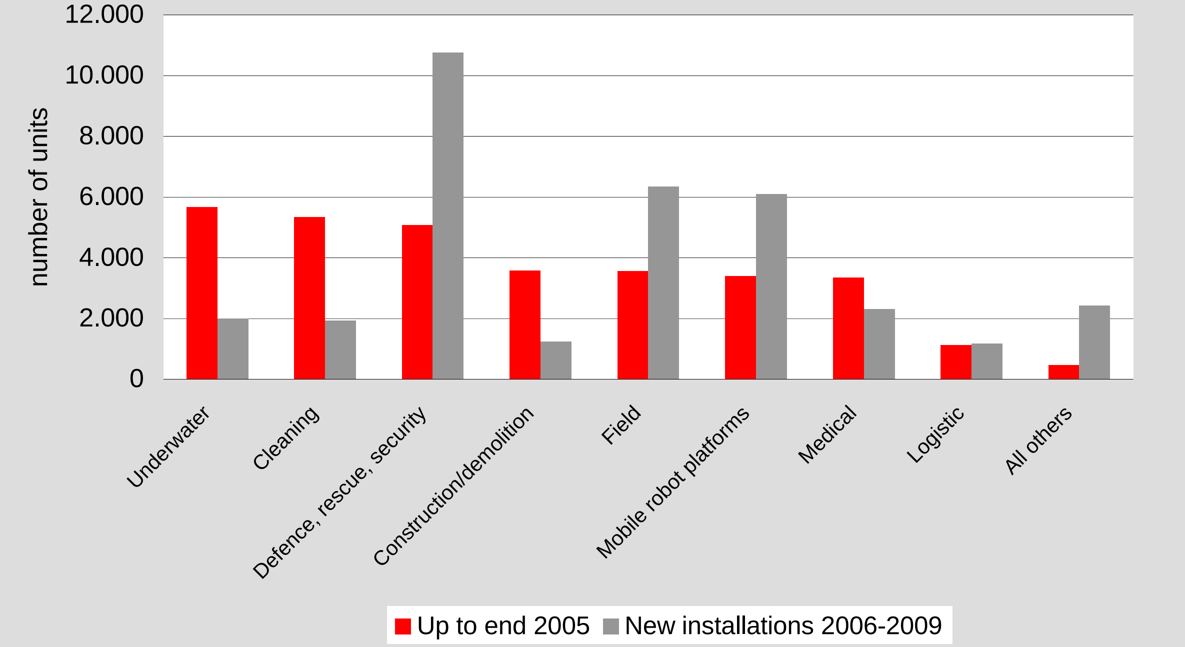


Figure VII.1b Service robots for professional use. Value of stock at the end of 2005 and value of projected installations in 2006-2009

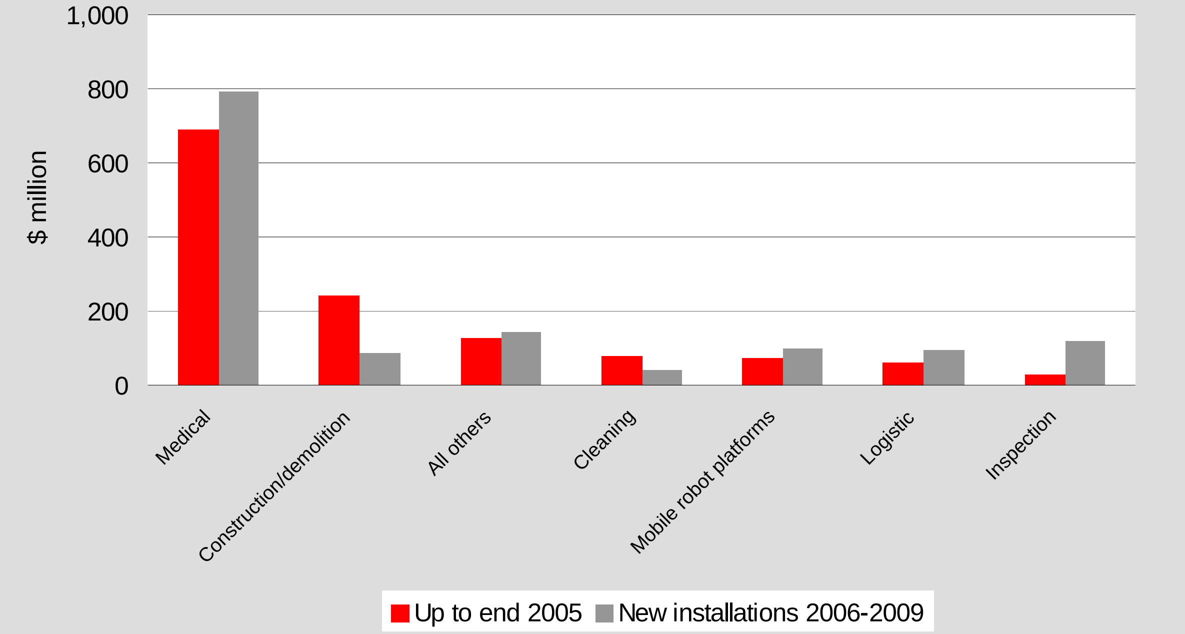


Figure VII.1c Service robots for professional use. Value of stock at the end of 2005 and value of projected installations in 2006-2009

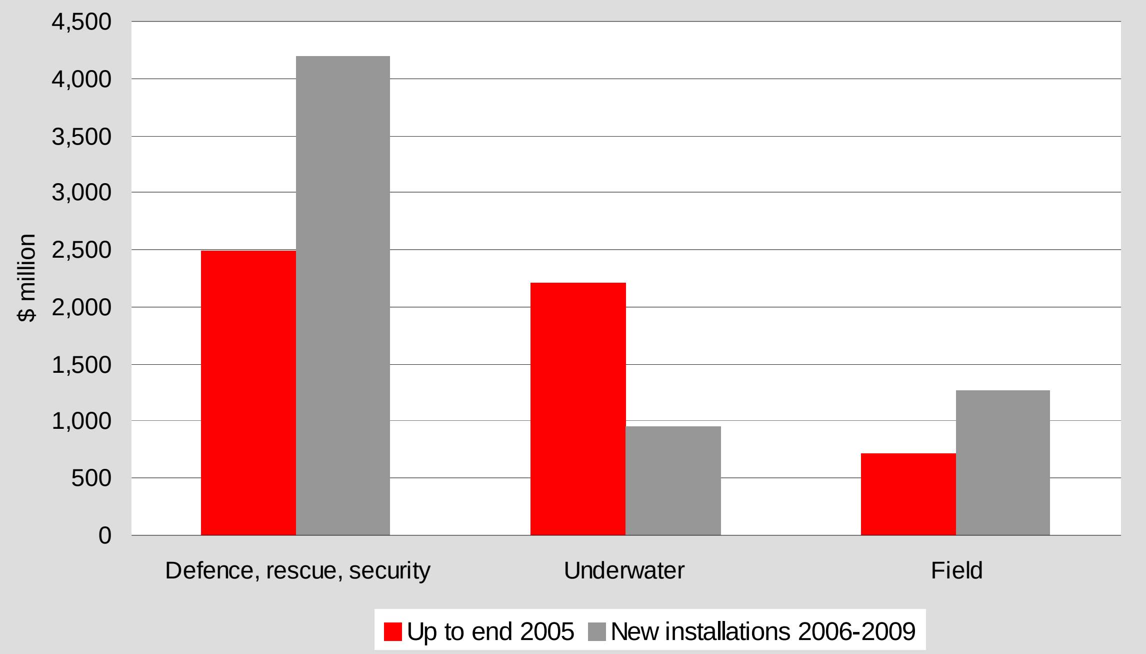


Figure VII.1d Service robots for personnel/domestic use. Stock at the end of 2005 and projected installations in 2006-2009

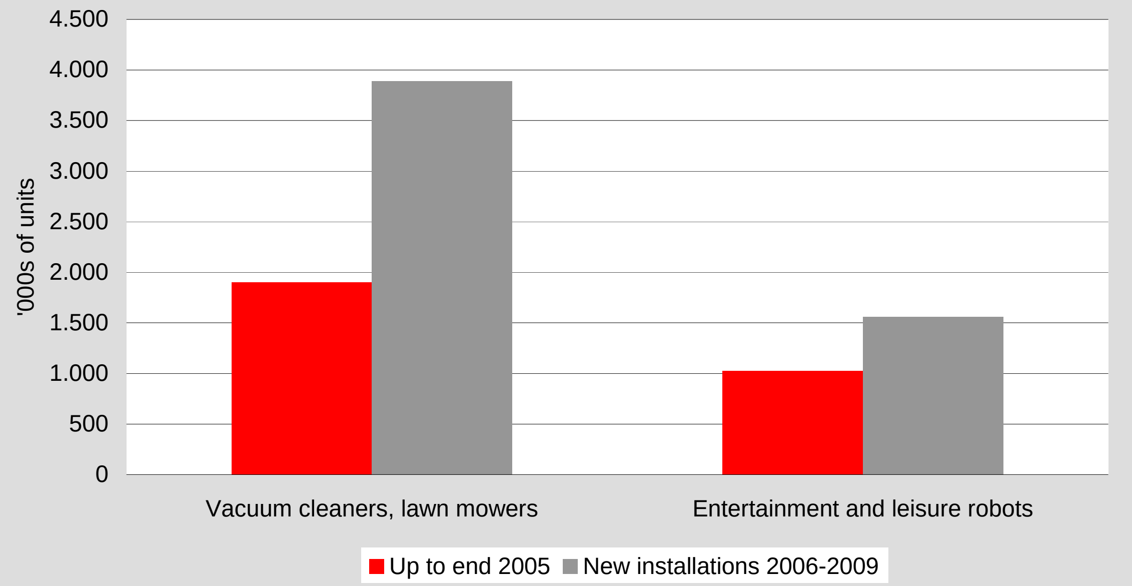
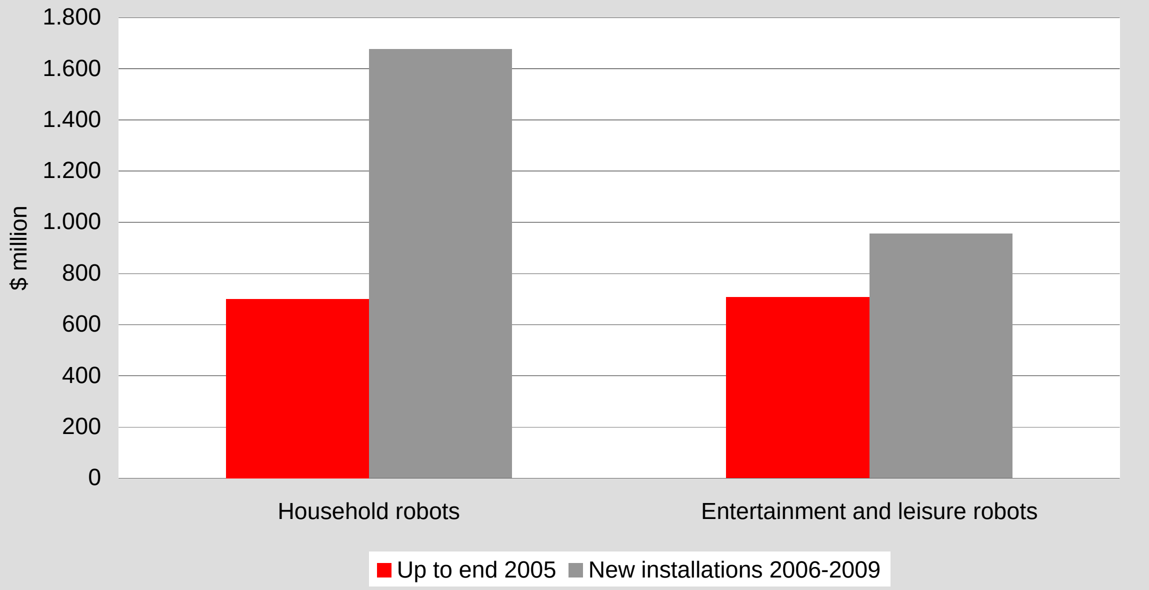


Figure VII.1e Service robots for personal/domestic use. Value of the stock at the end of 2005 and of the projected installations in 2006-2009



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 eventually 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, of which many are documented in, for example, Engelberger's pioneering book and succeeding publications destined for robotics experts[1, 2, 3]. Applications for these customised robot designs ranged from professional jobs in therapy, construction, maintenance, and inspection to use in rehabilitation and home care.

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 lives: at home, at work, in public environments, and in more remote locations such as deep-sea, battlefields and space. In the recent past, experts have seriously discussed the possibilities of emulating the success of the PC by way of a roadmap with the goal of creating a personal robot which would assist the individual in his or her daily life. Even though these robot companions or assistants offer up the prospect of appealing to a mass market, it is felt that the requisite technological progress, attractive product designs and low-cost manufacturing pose significant challenges and may make this idea more of a long-term project that would not reach full maturity before the year 2020. As the statistics demonstrate, today's service-robot market is composed of many niche products for professional services and a few high-volume applications in the domestic environment. Pioneers in the field of service robotics stress the serious opportunities for new companies to enter this growth market[4] with innovative products beyond the occasional robotics hype.

A rough guide to current service robotics categories and their rough maturity level is given in figure VII.2. Other, more comprehensive product and technology catalogues have been elaborated in various assessments by funding agencies, national organisations and government bodies[5, 6, 7, 8].

This section reviews a selection of the major application areas of service robots, both for professional and personal use. It follows the service robotics statistical scheme introduced in chapter VII.2 At the end of the chapter, table VII.2 provides an overview, in the form of a matrix, of the specific application areas in which, currently, 175 service-robot producers and developers are active.

Figures VII.3 to VII.16, 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.

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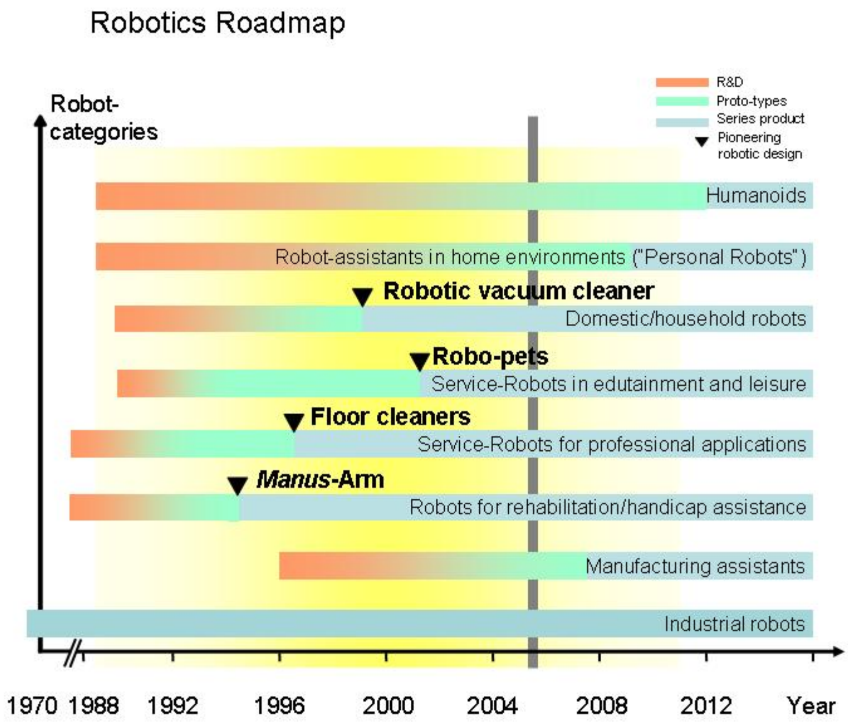
[1] J.F. Engelberger: Robotics in Service. Cambridge, MA. MIT Press. 1989.
[2] Japan Robot Association: *The Specifications and Applications of Robots in Japan*. Non-Manufacturing Fields, 1997.
[3] R. D. Schraft, G. Schmierer: Service Robots. AK Peters, Wellesley, MA, 2000.
[4] A. Vance: "Vacuum king calls for end to robotics hype"; www.theregister.co.uk/2006/06/23/irobot_angle
[5] Workshop on Review of U.S. Research in Robotics www.wtec.org/robotics/us_workshop/agenda.html
[6] http://www.robotics-platform.eu.com/pdf/EUROP_Official_Launch.pdf
[7] National Technology Roadmap: http://www.apecforesight.org/trm/docs/KoreaTRM.pdf
[8] Trends in the Japanese Robotics Industry. JETRO Japan Economic Monthly, March 2006. www.jetro.go.jp/en/market/trend/industrial/pdf/jem0603-2e.pdf

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



VII.3.2 Service robots for professional use

Although service robots are as diverse as their applications, three categories of designs can be distinguished[9]:

- 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 include 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.

Since 1999 a statistical scheme has been established for service robots for professional use which classifies the robots according to application areas. In the following, typical robot systems for each category are described and further information about their usage, technological maturity level and manufacturers are given.

[9] 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.

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, they have the potential of freeing 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 have been under development in about 10 countries. They detect and locate ripe fruit mostly via a colour or contour 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).

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 currently being produced in significant numbers by DeLaval (Sweden), Fullwood (UK), and Lely (UK). The company INSENTEC (Netherlands) has announced the development of a novel milking robot for SAC (Denmark) based on a customized stainless steel robot arm. Up to and including 2005, some 3,500 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 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 detect and localize the teats.
- Multipurpose arm(s) that can accommodate udder and teat irregularities, handle teat cleaning, cup attachments and disinfection. The robot arms are either customized kinematics or modified industrial robot arms.
- 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 (Sweden), Fullwood (UK), Lely (UK), Milka-Ware (Australia), Prolion (Netherlands).

c) Forestry

In forestry, a main concern is that vehicles on tyres or hoops or using chain drive will damage the lea. If the work unit were mounted on a base with a number of centrally manipulated "legs", less damage could 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. With such considerations in mind, Plustech, now owned by Deere and Company, developed a giant forest-walking spider robot which adapts automatically to the forest floor terrain on its six articulated legs.

A harvester based on caterpillars, Valmet 911.3X3M (marketed by Komatsu (Japan)), is also entering this market for semi-autonomous systems. They have in particular focussed 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 identify trees with lasers. They have multiple uses: preparing land for the 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 force behind mining robot developments. 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.[10].

A 3500-tonne, 75-metre tall dragline recently demonstrated the role that robotics could soon play in mining operations. The system was the result of a project funded through a consortium comprising the Australian Coal Association Research Program (ACARP), Rio Tinto, BHP Australia Coal and the CSIRO ICT Centre, and involved fitting the dragline with a 'brain' to automate repetitive movements such as coordinating the hoist and drag/swing functions.

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

[10] 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.

overcome such hazards. A project supported by the U.S. Department of Energy aims at developing an innovative robot-human control architecture for typical surface mining operations[11]. There, the University of Nevada, Reno (UNR), along with Newmont Mining Corporation and the Bobcat Company are developing a robot-human control architecture for typical surface mining operations in which coordinated movement of several machine links is required.

e) Space robots

Unmanned vehicles used in space have to be either tele-operated from an extreme distances or move autonomously. As signals take time to be transmitted 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.[12]

Another robotic device contained in space laboratories is the Personal Satellite Assistant (PSA) which is under development at NASA. The PSA is about the size of a softball and has sensors for measuring gases, temperature, and air pressure. Furthermore, the PSA is able to perform video conferencing and can communicate with electronic support devices such as computer servers, avionics systems, and wireless LAN bridges[13].

The ROKVISS robot arm, developed at the Institute of Robotics and Mechatronics (Germany), is mounted on the International Space Station (ISS) and is now operational. After a year's qualification phase, the goal is to have a robot arm tested for supporting astronauts in tedious tasks, or to repair and maintain space structures and satellites[14].

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[15]. These robots are still in operation transmitting valuable information on the atmosphere and geology of the Red Planet.

NASA is also developing a humanoid robot to meet increased demands for human safety during extra-vehicular activity (EVA).The Robonaut project seeks to develop and demonstrate a

[11] U.S. Department of Energy: Robot-Human Control Interactions in Mining Operations. U.S. Department of Energy. http://*www*.eere.energy.gov/industry/mining/pdfs/robot.pdf
[12] Canadian Space Agency. See http://www.space.gc.ca.
[13] http://ic.arc.nasa.gov/projects/psa/
[14] http://www.dlr.de/rm/en/: ROKVISS: Robot arm moves in space.
[15] http://marsrovers.jpl.nasa.gov/overview/.

robotic system that can function as an 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[16].

Within a study awarded by ESA at the end of 2003, EADS Space (Netherlands) is defining future milestones for Europe's exploration of Mars within the so called 'Aurora' Exploration Programme. Two of the studies focus on the Exo-Mars mission, while the third looks forward to bringing the first samples of Mars back to laboratories on Earth - the Mars Sample Return Mission[17].

The most important producers are Jet Propulsion Laboratory (USA), MacDonald Dettwiler Space (Canada), EADS Space (Netherlands) 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") 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

Among the first examples of floor cleaning robots were the ACROMATIC by HAKO (Germany) and the Auror, Baror and CAB-X by Cybernétix (France) robots where CAB-X has been designed to Paris' Metro stations. Further designs cover the RoboKent's robots (now Servus Robots (USA)),

[16] http://vesuvius.jsc.nasa.gov/er_er/html/robonaut/robonaut.html.
[17] http://www.space.eads.net/press-center/archives/2004/300/view?searchterm=space%20robots

which are cleaning in over 150 locations throughout the United States.[18] 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.[19] 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 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.3. New concepts towards low-cost strategies in cleaning robot navigation use smart tags. These RFID tags which are invisibly attached to carpets or hard floors allow a most robust navigation. This smart floor-concept has been presented at CeBIT 2006 with cleaning and transport robots safely navigating[20].

Up to the end of 2005, an estimated 340 professional floor cleaning robots have been sold. From 2006 to 2009, 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

[18] M. Schofield: *Cleaning Robots: Engineering Dream or Commercial vision?*, 29th International Symposium on Robotics, Birmingham, United Kingdom, 27 April – 1 May 1998.
[19] G. Lawitzky: *A Navigation System for Cleaning Robots*. In: Autonomous Robots, Volume 9, Number 3, December 2000, pp. 255-260.
[20] http://www.vorwerk-teppich.de/sc/vorwerk/vorwerk_presents_RFID.html

by OEM providers (such as the SINAS™[21] system by Siemens, CURONA® by InMach[22], the ERSP 3.1 platform by evolution robotics[23] or the ANT system by Bluebotics[24]) 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 (Japan), Nilfisk-Advance (Denmark), Robosoft (France).

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.3). 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).

The V-Robot of URAKAMI (Japan) is a remotely controlled robot system with a suction-adhering and self-propelled mechanism. It reduces the need for human labor used in abrasive blasting, waterjetting, painting, inspecting and other work on surfaces such as ships, oil storage tanks, gas holders and buildings.

(ii) Level of distribution

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.3 depicts the RobuGLASS™ robot, developed by Robosoft (France), which is a four-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.

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[21] http://www.ad.siemens.de/sinas/index_00.htm
[22] http://www.inmach.de
[23] http://www.evolution.com
[24] http://www.bluebotics.com/automation/ANT/

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 (France).

c) 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.

- **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).

d) 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) (see figure VII.4), Maytronics (Israel).

e) 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.

(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.5: The Responder platform from RedZone Robotics (USA) performs inspection and rehabilitation tasks in interceptor and tunnel pipe ranging from 36 inches to 50+ feet in diameter. Responder can deploy for up to one mile through a single 24-inch manhole. With its on-board hydraulics and ability to navigate by sonar, laser, or video, the robot can access the most challenging environments.

(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 2005, amounted to some 120 units. The forecast for 2006 to 2009 is for about 1,200 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), 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[25] 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.

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

The Nanomag of Inuktun Services (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).[26]

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 (USA), Inspector Systems (Germany), Inuktun (Canada), Quality & Innovation (Japan), 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.5 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.[27] 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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[26] http://www.automatika.com/products_oilspore.htm.

[27] 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.

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 2005, about 155 units have been sold. For the period from 2006 to 2009, close to 170 units 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[28](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.5.

[28] IntelligeNDT Systems & Services, http://www.intelligendt.de/en/.

(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 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 3,500 robots are already in use and it is estimated that about 1,200 more units will be added in 2006-2009.

(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.7 for some examples of robots that operate in hostile environments. Similarly, the BEAST of Autonomous Solutions (USA) 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

Autonomous Solutions (USA), Brokk (Sweden), Cybernétix (France), IntelligeNDT Systems and Services (Germany), Mitsubishi Heavy Ind. (Japan), R.U.Robotics (UK), RedZone Robotics (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).[29]

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 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.7.

(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 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[30] 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 80 robots have been produced, with a forecast of nearly 100 for the years 2006 to 2009, 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.

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

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 Fujita Corporation (Japan), Putzmeister (Germany), R.U.Robotics, (UK), Shimizu Corporation (Japan), Taisei Corporation (Japan). Tele-manipulated building machinery has been developed by Cybernétix (France), Hazama Corporation (Japan), and Tokyo Construction (Japan).

(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.

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.

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. An example for new ways of road demolition is offered by the company Conjet which produces automated high pressure water jetting machines. This process called hydro-demolition uses a high pressure water jet to remove concrete from sensitive structures such as bridges, parking decks, dams, canals, tunnels, quays and jetties in conjunction with concrete repair. These robots are also used for other waterjet applications such as scarifying or roughening surfaces, cleaning and paint removal.

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 (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 (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 Cardinal Health (USA), a leading provider of medication and supply dispensing systems to health care facilities. So far more than 100 units have been installed. Helpmate® (Germany) 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[31]. The Staffetta robot marketed by Genova Robot (Italy) is carries out similar tasks (see figure VII.8 for some of the typical courier robot developments). A system for telemedicines and patient supervision has been introduced by intouch-health (USA). Under the direct control of a physician, the robot can be safely manoeuvred throughout a hospital environment.

(ii) Level of distribution

Whereas 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 310 units have been sold. Sales in the period 2006-2009 are estimated at about 200 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.[32] In addition, the

[31] Press release Matsushita Electric Works, http://www.mew.co.jp/e-press/2003/0304-01.htm.
[32] R. D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions*. London: A K Peters, 2000.

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.[33] 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), Aethon (USA), Atlas Copco Mining Trucks (Sweden), Cardinal Health (USA), Cybernétix (France), Fraunhofer IPA (Germany), Gecko Systems (USA), Genova Robot (Italy), Swisslog (Switzerland), Transbotics Corporation (USA).

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[34], 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

[33] Ibid.
[34] 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,.

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. Another robot design following the classical master-slave operation principle has been successfully introduced into operation scenarios: DaVINCI™ of Intuitive Surgical Solutions (USA) which acts 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.[35] The robots can be used in neurosurgery, microsurgery, orthopaedics, ophthalmology, cardiology, and for further future therapies.

The novel Vectorbot® of BrainLAB (Germany) will enable surgeons to reliably align medical instruments, including endoscopes, biopsy needles, catheters and pedicle screw drills to a predefined trajectory with millimeter precision. Similar to a human arm in its ability to move in seven degrees of freedom, the joints of this Intelligent Instrument Guide are equipped with integrated sensors for both joint position and joint torque that enables an extremely high level of movement flexibility.

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.

(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 3,300 systems are in use, sales of 2,300 units are projected for 2006-2009 (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. Also patient positioning systems qualify use exact robot drives and controls to align and orient

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

patient relative to a diagnostical device such as a Scanner. An example is the ExacTrac X-Ray of BrainLAB (Germany) which interfaces with most treatment couches, allowing accurate set-up verification and automated patient positioning. After precise determination of the required correction shift, ExacTrac X-Ray 6D interfaces with couches for immediate and fully automatic table motion. Patient set-up becomes more efficient, saving time for the therapist and guaranteeing clinical throughput.

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 cement less implants is thus estimated to be 2.5 times higher.[36] 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.

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), BrainLAB (Germany), CEREM-CEA (France), Computer Motion (USA), Elekta (Sweden), EndoVia medical (USA), Engineering Services (Canada), Integrated Surgical (USA), Intuitive Surgical Solutions (USA), KUKA (Germany), Mobile Robotics (Sweden).

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

VII.3.2.7 Defence, rescue & security applications

In the context of the employed statistical scheme the categories demining, fire and bomb fighting, and surveillance refer to mostly civil service robot applications whereas the category unmanned (ground and aerial) vehicles sum up defence and military related robots. The latter category has recently shown strong growth and the emergence of specific robot designs.

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 autonomously, fire-fighting robots approach the fire and 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 precise manipulating arm is mounted. While the robots are able to perform certain tasks on their own, the operator can always interfere via remote control.

As an example of new types of arm designs, 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 with a 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 security, surveillance and nuclear applications.

The Japanese rescue robot «T52 Enryu» is a mobile, manned or tele-controlled two-armed vehicle which is able to handle loads of one ton. It is designed for maximum strength and high dexterity[37].

Competitions and product shows such as the latest announcement of the *The Civilian-ELROB (C-ELROB) - 2nd European Land-Robot Trial* aim at benchmarking existing products or prototypes and help to promote this technology[38].

(ii) Level of distribution

Up to the end of 2005, some 530 fire- and bomb-fighting robot systems have been sold and projected units are 390 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 fire-fighting 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.[39] Using only one robot to position

[37] http://www.enryu.jp/.
[38] http://www.c-elrob.eu/, to take place 13th - 16th of August 2007 in Monte Ceneri, Ticino, Switzerland

several cheap 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 or collapsing environment. 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.

A wide range of bomb disposal robots has been developed in the past. Today these – usually teleoperated – robots play an increasing role in home security efforts. The typical bomb disposal robot configuration is a mobile base with manipulator arm and gripper, a set of diagnostic instruments (camera, chemical detectors), bomb-disposal instruments and a tele-operation unit (tethered or wireless). As the manipulating arm of bomb-disposal robots can carry weight, change tools and pick up new ones, manual help is not needed. Additionally, bomb-disposal instruments such as on-board freezing units or water guns can deactivate explosive devices on-site, so that the operators can stay at a safe distance throughout the operation. From there they rely on camera pictures, and thus good positioning is crucial in order to perform the required precision work. Of course, skilled operators capable of precise handling and with experience of such robots are another prerequisite for successful operation. Additional diagnostic instruments such as X-ray photography give precise information immediately and allow rapid and information-based decision taking.

(iv) Major producers

CDL Systems (Canada), Cybernétix (France), Engineering Services (Canada), Inuktun Services (Canada), Kentree (Ireland), MRISAR (USA), OCRobotics (U.K.), 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 applications. These mobile robots carry, depending on their specific application or mission environment, a variety of sensors which help detect human presence, camera equipment (including infrared) for tele-operation and -presence, microphones, and chemical or smoke sensors.

At this early stage, these robots have been confined to environments where surveillance by personnel is tedious, costly or hazardous and justifies the still relatively high cost of these systems (typically stretching from $25,000 to $150,000 and beyond depending on the robot’s performance and sensor equipment). Mission environments are usually inside buildings (factories, museums, and corporate headquarters), chemical plants, military arsenals, nuclear power stations etc.

A design of a typical surveillance/security robot (Neobotix) is shown see figure VII.9 where the outdoor-suitable mobile platform is equipped with a variety of sensors (microphones, radar, teleoperated pan-tilt camera, motion detector). Its typical 8 hour mission can be extended by automatically recharging the robot. In order to continuously cover large spaces, either several robots can be coordinated or - as an interesting option - a robot can automatically place active sensor probes on the ground which transmit information to the parent robot so that a sensor network is formed. Either these sensor probes are lost (when their energy is used up) or they are collected by the robot at the end of the mission to be reused [40].

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

[40] K. Pfeiffer, Kai; R. D. Schraft: Decentralized Sensor Probe Positioning for Security, and Rescue Robotics, In: SSRR 2004: IEEE International Workshop on Safety, Security, and Rescue Robotics. CD-ROM (2004)

(ii) Level of distribution

So far, about 780 units have been put into use and the producing firms expect sales of 2500 units in 2006-2009 (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. Often, the cost is consequently of secondary importance, which has allowed for relatively early adoption of the technology.

The robots can detect more than humans if appropriate sensor equipment is used. 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.[41] Flame, heat and smoke sensors assure fire prevention. Additional gas 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.

(iv) Major producers

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

c) Unmanned ground based vehicles

(i) Types of operations carried out by the robots

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, to search for explosives, and for hostage rescue. Intense development in the fields of defence and security robot technologies is underway as part of the Department of Defense's transformation program[42].

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. Battle scenarios will be based increasingly on unmanned systems over the next 10 to 15 years. Numerous producers of mobile platforms (for urban and non-urban application scenarios) have designed models that have been deployed in military operations on different scales[43].

[41] R. D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions*. London: A K Peters, 2000.
[42] http://www.pentagon.mil/transformation/.
[43] http://robot.spawar.navy.mil/.

Extreme efforts are currently being made to make robots a functional and reliable component of future defence scenarios. This effort is also reflected by highly visible and prestigious competitions of autonomous mobility in offroad environments such as the Grand Challenge 2005[44] and the Elrob 2006[45].

Examples are the TALON robots of Foster Miller (USA), recently acquired by QinetiQ (UK), which 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 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 Deere & Company 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.

The “Aurora” of Automatika (USA) is an example of a portable 10 kg reconnaissance robot system for use in fire-fighting, policing, explosive-ordinance disposal, counter-terrorism and military 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.

(ii) Level of distribution

Currently, some 600 units are reported to be in service with forecasts of 2700 additional systems to be delivered between 2006 and 2009. Most of the systems have been delivered to the American armed forces.

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

As these unmanned vehicles are used to support soldiers in missions by gathering intelligence, supporting in logistics, offering tele-presence and tele-operation, their value extends beyond simple cost calculations. In their first large scale missions (Bosnia, Afghanistan, Iraq) the value of these systems has been repeatedly reported[46] in the media.

(iv) Major producers

Unmanned ground based vehicles are produced by Base Ten Systems Electronics (Germany), Deere & Company (USA), Diehl BGT Defence (Germany), EADS (Netherlands), Engineering Services (Canada), Gecko Systems (USA), General Dynamics Robotic (USA), Inuktun Services (Canada), iRobot (USA), Macroswiss (Switzerland), MRISAR (USA), QinetiQ (U.K.), Probotics (USA), Telerob (Germany).

d) Unmanned aerial vehicles

(i) Types of operations carried out by the robots

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 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.

44 http://www.grandchallenge.org
45 http://www.elrob2006.org
46 http://www.irobot.com/sp.cfm?pageid=219

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.[47] 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 Defence[48, 49].

(ii) Level of distribution

An interesting classification scheme on UAVs for civil and military purposes can be accessed at http://uav.wff.nasa.gov. In addition to producers of defence and civil-type UAVs, there are groups which engage in private developments (including an UAV open source project), educational and research activities (including an International Aerial Robotics Competition[50])

The numbers of UAV in service is expected to grow from currently 3,100 to 5,100 by the year 2009.

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

The use of UAVs has shown a tremendous rise during the past few years as the benefits of their use become increasingly obvious. Gathering intelligence, surveillance, target acquisition and reconnaissance in full personal safety at low cost has been made possible by a wide range of UAVs. Recent developments aim at UAVs on the mini and micro scale to survey populated areas, or even the inside of buildings and rooms.

(iv) Major producers

Major producers are Aerovironment (USA), CDL Systems (Canada), Dassault Aviation (France). EADS (NL), Elbit (Israel), IAI (Israel), Sagem Défense Sécurité (France), Schiebel (Austria). A more complete list of manufacturers can be accessed at www.aeronautics.ru[51]

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.

[47] Unmanned Systems, Vol. 19, No. 1, Jan/Feb 2001: UAVs in Europe.
[48] http://uav.wff.nasa.gov.
[49] http://www.defenselink.mil/specials/uav2002/.
[50] http://avdil.gtri.gatech.edu/AUVS/IARCLaunchPoint.html
[51] http://www.aeronautics.ru/uavlist.htm

a) At a size of 0.5-1 m^3 and a weight of less than 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) Shallow water AUVs are used, among other tasks for pipeline follow and water quality monitoring. An example of such an AUV with sophisticated control is the TAIPAN-H160 which resulted from a cooperation of Université de Montpellier and the company ECA HYTEC of France. For this the AUV has to show a high degree of manoeuvrability and its capability of diving at zero pitch even with a single heck propeller.

c) 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. A report describes the use and future challenges of AUV in the off-shore oil industry[52].

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.10 shows two types of underwater robots (crawlers and AUVs).

(ii) Level of distribution

At the end of 2005, estimated 5,700 underwater robots were in use (see table VII.1). Inspection robots made up the lion's share of the units sold. For 2006-2009, sales are projected to reach another 2,000 units.

The market for underwater robots is very promising. Sales of unmanned underwater vehicles are expected to grow to more than $ 925 million in the period 2006 to 2009. EurOcean - European Centre for Marine Science and Technology - maintains a database of the European underwater vehicles used in research by the scientific community[53].

(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.[54]

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.

[52] D. Bingham, T. Drake, A. HILL, R. Lott: "The Application of Autonomous Underwater Vehicle (AUV) Technology in the Oil Industry – Vision and Experiences". http://www.fig.net/pub/fig_2002/Ts4-4/TS4_4_bingham_etal.pdf

[53] http://www.eurocean.org/uvdb/

[54] Hydrovision company information

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), Bluefin (USA), Cybernétix (France), Deep Ocean (USA), ECA HYTEC (France), Hydrovision (UK), Inuktun Services (Canada), ISE (Canada), KOBE Mechatronics (Japan), Kongsberg Simrad (Canada), MacArtney (Denmark), Maridan (Denmark), Oceaneering (USA), Production Technology (USA), Robo Probe Technologies, (USA), Sias Pattersson (USA), and Perry Slingsby (UK).

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.

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 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.

Obvious criteria to use to distinguish mobile platform types are their suitability for in- and outdoor-operation, their drive (wheeled drives against caterpillars) and their drive kinematic (three-wheel differencial or tri-cycle drive) or four wheel-drive. A special case are so called holonomic robot platforms, which can freely navigate in any direction of a surface. These holonomic robots are based on either fully steerable wheels or so called Mecanum wheels which are conventional wheels with a series of rollers attached to its circumference.

RoboMotio (Canada) offers a modular system for creating different mobile platforms. Similarly, Volksbot of Fraunhofer IAIS (Germany) is a modular construction kit for mobile robots designed for applications in research and industry. Its modular concept enables the user to enormously reduce his development expenditure in the area of mobile robotics. Almost all types of drive kinematics can be easily configured so that robots for different applications can be built with little effort.

(ii) Level of distribution

While so far about 3,400 units are in use, producers expect 2006-2009 sales of about 6,100 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 (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 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. Also, sushi robots have been developed and introduced to the market by a company called Fine-Techno of South Korea (www.roboticsushi.com).

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.[55].

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.11). 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.[56] These robots have covered more than 20,000 km since March 2000. A group of 10 museum guides was presented with great success at the EXPO'02 in Switzerland. Similar robot installations have been reported at an OPEL sales centre at Berlin. Here, two robots personify a female and a male character (Mona and Oskar) who engage in dialogues and role-plays with the user. The robots have been developed by Fraunhofer IPA.

(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.[57]

(iv) Major producers

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

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.11 displays an interactive arrangement of two mobile robots at the OPEL sales centre in Berlin. The manufacturer of these platforms is GPS/Neobotix (Germany).

The Public Guide Robot of ROBOTECH (Korea) is a service robot used as an information kiosk in postal offices. Similar in appearance is the C4 of ALSOK (Japan) which can be used

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[55] 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.
[56] See http://www.museumsstiftung.de/berlin/d211_rundgang.asp.
[57] http://www.ics.forth.gr/tourbot/.

interchangeably as an information kiosk and as security agent. Robot personifications of female receptionists have been introduced by kobalab (Japan) and Kokoro (Japan).

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

VII.3.2.11 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.12). 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[58].

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.[59]

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,

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

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

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 of Anton Bauer (Germany) 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), Textron (USA).

Currently, robot refuelling stations at the Franz-Josef-Strauss-Airport, Munich gather information on hydrogen refuelling.[60]

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™ (now Electrolux) 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.14. Another important producer is Friendly Robotics (Israel) and Zucchetti Centro Sistemi (Italy).

Feasibility studies for consumer window cleaning robots include the RACCOON and the Quirl concept developed by Fraunhofer IPA[61]. The robot depends on a caterpillar equipped with passive

[60] 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.

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 Trilobite of Electrolux 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 decreased from some € 1,200 to about € 1,000. 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 estimated sales up to mid 2003 of more than 100.000 units. In 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 electronic (Korea) announced small vacuum cleaners for the Asian market. Since then, several providers (in particular in Japan and Korea) have launched vacuum cleaners onto the market such as Matsushita (Japan), Hanool (Korea), ubot (Korea), the iclebo (intelligent cleaning robot) of Yujin Robot (Korea), and ECOVacª (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 1,824,000 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 2006-2009 is over 3,890,000 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.

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.[62]

[61] 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.

[62] 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.

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

While manual domestic appliances, whether vacuum cleaners or lawn mowers, are 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 mowers from Electrolux), 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 1,800m^2 of lawn.[63] 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: Electrolux (Sweden), Gecko Systems (USA), iRobot (USA), Kärcher (Germany), LGelectronic (Korea), Matsushita Electric Works (Japan), Probotics (USA), Real World Interface (USA), The Eureka Comp. (USA), Wany (France)

- for lawn mowers: Zucchetti Centro Sistemi (Italy), Friendly Robotics (Israel), Husqvarna (now Electrolux) (Sweden), Wany (France)

VII.3.3.2 Entertainment robots including toy robots and hobby systems

a) Robots in entertainment industries

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

Other robots are used for the animation of animals or zoological characters and personifications. These devices, called animatronics, have received significant amounts of attention, particularly in Japan. One of the producers is Kokoro (Japan).

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

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[63] http://www.automower.com
[64] R.D. Schraft and G. Schmierer: *Service robots: products, scenarios, visions*. London: A K Peters, 2000.

b) Robots for private entertainment (toys and hobby)

Robots have been fascinating people from the beginning, as they represent a human dream to create devices which can mimic human perception, mobility and even cognition. In the past years companies have started to create an impressive spectrum of entertainment and toy robots 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.[65] [66]

A major producer in the field is Sony, which claims to have sold more than 350,000 units of a new type of electronic pet – the AIBO™, at more than $1,500 each. However, production of the well-known AIBO™ was discontinued in 2005. Lego is another major producer of toy robots. Other embodiments of animal or fantasy characters which on command move around in home settings, dance, or serve as mobile multimedia kiosks have been suggested in the last few years. Usually these devices are mobile (or equipped with simple arms), networked to a local area network or mobile phone, thus combining entertainment, fascination and access to multimedia information. Manufacturers comprise IZI robotics (Korea), "ifbot" of Business Design Laboratory (Japan), the "sharp ear robot" ApriAlpha of Toshiba (Japan) and the "BN-17" of Bandai (Japan).

A spectrum of small humanoid robots have been launched which are mostly very dexterous machines built on the basis of compact servo drives and which make use of mobile computing and cell phones for their programming and operation. These mostly miniature humanoids can be trained to perform walking movements, gymnastic exercises, fighting and dancing. Through the use of compact miniature servo drives, their cost is relatively low given their high level of mobility and dexterity. Companies producing these devices on different performance and cost levels are Robovie of Vstone (Japan), Manoi of Kyosho (Japan), the **nuvo** of ZMP (Japan), and a spectrum of toy robots by Wowee (Hongkong), and DrRobot (Canada).

At least 1,024,480 entertainment, toy and hobby robots are estimated to have been sold up to the end of 2005. About 1.5 million unit sales are forecast for 2006-2009.

Major producers are: Atlas Robotics (USA), Bandai (Japan), DrRobot (Canada), GPS/Neobotix (Germany), Happy Field Technology (USA), Johuco Mobile Robots (USA), KUKA (Germany), Kyosho (Japan), Lego Mindstorms (USA), Lego (Denmark), Lynxmotion (USA), Merlin Robotics (UK), Smart Robotics (Israel), Toshiba (Japan), Vstone (Japan), Wany (France), Wowee (Hongkong), ZMP (Japan)

c) Robots in education and training

A variety of robot developments, mostly initiated in Japan, aims at creating machines which serve a person in daily tasks, mostly as a mobile communicator or as an information kiosk. These robots are characterized by their mobility, arm manipulation and on board multimedia equipment. Although they have been introduced on many occasions, it is only this year that sales of any significance have started to a small clientele.

PaPeRo from NEC (Japan), 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.[67]. PaPeRo also identifies people it knows, using advanced face-recognition technology and two cameras for eyes. PaPeRo can be used in 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.

[65] 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).

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

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

- 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.

Related to the PaPeRo concept, several more robots with additional communication skills, arms and head motions had been introduced:

The Wakamaru of Mitsubishi Heavy Industries (Japan) is a two-arm wheeled robot character which recognizes approximately 10,000 words necessary for daily life, recognizes its owner by face recognition and incorporates body gestures into his conversation.

The EMIEW from Hitachi (Japan), standing for "Excellent Mobility and Interactive Existence as Workmate", applies a self-balancing two-wheel-motion mechanism that enables it to move in compact spaces swiftly and thus in the same environment as a person. It performs natural arm movements with hands for grasping light objects. A voice system allows it to interact with a user for instruction and accessing multimedia data.

SmartPal by Yaskawa (Japan) is an omni-directional mobile platform that is equipped with an arm unit with 7 degrees of freedom, and multiple sensors for environment recognition and communication with humans. It can recognize and grab a tray of food and drink using sensors, and conduct demonstration experiments.

An abundance of robot kits are on sale which 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 enable them 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 sometimes end effectors and arms.

Major producers are: DrRobot (Canada), Festo (Germany), Genova Robot (Italy), Hitachi (Japan), IdMind (Portugal), Intelitek (USA), Johuco Mobile Robots (USA), K-Team (Switzerland), Lynxmotion (USA), Mekatronix (USA), Merlin Robotics (UK), Mitsubishi (Japan), NEC (Japan), Parallax (USA), Robix (USA), Robosoft (France), The Robot Factory (USA), Vstone (Japan), Wany (France), Yaskawa (Japan), Zagros Robotics (USA).

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.[68]

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.[69]

[68] See http://www.dekaresearch.com/ibot.html and www.indetech.com.
[69] Research on autonomous robotic wheelchairs in Europe. IEEE Robotics & Automation Magazine, Vol. 8 (1), Mar 2001.

Major producers are: Active Media (USA), Independence Technology (USA), Rehabilitation Technologies (Australia).

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 360 systems are in use, another 650 are projected to be sold in 2006-2009 (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 (USA), Independence Technology (USA), MRISAR (USA), Rehabilitation Technologies (USA), Robosoft (France), Shadow Robot (UK).

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.[70] 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.

[70] http://www.care-o-bot.de/english/ and http://www.assistor.de/.

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.[71] 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.[72]

Another design, the CyberCab of the company 2getthere (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.16.

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

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[73]. Security agent T63 ARTEMIS of the same company is a wheeled robot with two arms
- Cybermotion (USA), Gecko Systems (USA), MRISAR (USA), Wany (France)

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[71] http://www.rehabrobotics.com/.
[72] *Automated People Transportation Applications, Technologies and Perspectives*. http://www.robosoft.fr.
[73] *First Public Exhibition of Super-remote-controlled Robot across Japan*. Press release 24th March, 2003; tmsuk. http://www.banryu.jp/press/pdf/030309e.pdf.

VII.3.3.6 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 studies have appeared in which long term experiments with humanoid robots have been reported.[74] 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.[75]

A highlight for humanoid robot technology has been the EXPO 2005 in Aichi, which staged a robot week in June of that year with a large variety of demonstrators and prototype robots from companies, research institutes and universities.[76] Humanoid robots have been a highlight in particular as these were displayed in impressive shows and settings. Some of these robot exhibits were shown again at the 2005 International Robot Exhibition at Tokyo. There, a wide spectrum of service and personal humanoid robot applications was on display.

(ii) Level of distribution

Humanoid robots have not entered the market yet as products, but rather as prototypes, and demonstrators have received wide attention as they might point to future products which could execute everyday tasks and serve humans on request. The Honda ASIMO has been used for showcasing technological advances in biped walking. Further developments address cognitive skills such as object and person face and posture recognition in everyday environments, task and motion planning[77]. Other designs by Toyota Motor Company have introduced a whole family of so called 'partner robots', designed to function as personal assistants for humans[78]. These include a walking robot primarily intended as a carer for the elderly; a rolling, two-handed robot for use as an assistive system in manufacturing, and a mountable model capable of carrying its passengers almost anywhere they need to go. A standard humanoid robot prototype (HRP-2) was developed and manufactured as the final robotic platform for the Humanoid Robotics Project (1999-2004) headed by the Manufacturing Science and Technology Center (MSTC) under sponsorship by the Ministry of Economics, Trade and Industry (METI).

The humanoid robot HOAP-2 of Fujitsu utilizes smooth motions to perform gestures, expressions, head and waist motions. It interfaces to a PC for use as a human robotics research tool for studying movement control and communications with humans.

A very good survey of current humanoid robot developments can be found at http://www. androidworld.com or at a conference suite dedicated to this fascinating technology[79]. Other humanoid developments in Korea have been reported[80].

[74] 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.

[75] 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.

[76] http://www-1.expo2005.or.jp/en/robot/index.html.

[77] http://world.honda.com/ASIMO/

[78] http://www.toyota.co.jp/en/special/robot/

[79] IEEE-RAS International Conference on Humanoid Robots (Humanoids2005). Dec. 5-7th , 2005, Tsukuba, Japan. http://www.humanoidrobots.org/humanoids2005/. Follow-up conference: http://humanoids06.epfl.ch/.

[80] http://nobunaga.t.u-tokyo.ac.jp/ICRAWS/Handout/ohICRAWS2006.pdf

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

Humanoid robots represent in many ways the ultimate human machine, as their mobility, dexterity, cognitive and perceptive function follow the example of humans themselves. Thus they are destined to execute tasks in natural environments and through their familiar appearance would facilitate instruction, physical interaction and social behaviour. Being able to potentially cover a wide variety of jobs there is a potentially a large market, which would allow reduced unit costs through economies of scale. However, technological and manufacturing challenges still remain to be solved until reliable machines can be produced in significantly high quantities.

(iv) Major producers

Major developers/producers are, HONDA (Japan), Robos (Japan), Kawada Industries (Japan), Fujitsu (Japan), Kawada (Japan), Toyota (Japan).