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EURON

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Research Roadmap V.3

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List of contributors

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Contents

1 Introduction

1.1 What is EURON?

The European Robotics Research Network (EURON)[1] is a community of people with a common interest: robots. Its purpose is to bring together the best groups and resources in research, industry and education in Europe and to demonstrate Europe's world class position in robotics.
In EURON, scientists, industrialists and educators work together towards the dream of the next generation of robots.

Community: EURON creates a forum for members to meet and exchange news and results. From this existing friendships are strengthened so that new ideas and collaborations are born, and old ideas are reviewed and extended. Through EURON, the world sees the scope and quality of European robotics.

Research: EURON helps to focus European research efforts towards more productive goals. This happens partly through its community activities which allow us to exchange ideas and techniques, and partly through identifying the topics where research efforts are best spent and advertising them to scientists and policy-makers.

Education: If Europe is to maintain its world-class position in robotics, new skilled researchers, innovators, engineers and teachers are needed. EURON's educators develop and train this new skilled workforce through general science promotion activities and advanced summer schools.

Industry: EURON actively encourages the exchange of ideas and people between the research and industrial communities. The Network sponsors a prize for the successful transfer of good ideas from the research world to the robotics industry.

Promotion: EURON members are in the forefront of robotics worldwide and take part in policy-making and promotion activities both in Europe and across the world.

Summary: EURON exists to improve and promote robotics in Europe. It does this by building bridges between researchers in different countries and between researchers, industry, educators and the people of Europe.

1.2 Introduction to the purpose of this roadmap

This document *provides the required background for deciding on potential future programmes* in robotics and places the on-going IPs in a broader context. In particular, it

- documents the state-of-the-art
- identifies major economic and societal driving forces
- recognizes major bottlenecks to progress

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[1] `http://www.euron.org`

- describes major emerging trends and opportunities
- identifies relevant technological driving forces
- develops a roadmap to ensure continued progress.

To both cover the large and highly heterogeneous field of robotics with in-depth analyses and provide a lucid general view, the field is divided in a taxonomy of *five key areas*:

- Advanced production systems, covering all sorts of robots applied in industrial environments,
- Adaptive robot servants and intelligent homes, dealing with robotic technologies applied in home and living surroundings
- Network robotics, covering the massive interaction and cooperation between (nano-) robotic agents
- Outdoor robotics, handling all outdoor applications like driving assistants and autonomous cars, planetary exploration, mining, agricultural and forestall robots, underwater and rescue robots
- Health care and life quality, covering surgical robots as well as intelligent devices used in examination, diagnosis and rehabilitation.

This arrangement resulted from the experiences gained during the creation of the EURON-I Roadmap and is driven by the intent to *avoid unnecessary duplications* of topics. It places the *focus on the applications and challenges* of robotics in the next years and decades. This method stresses the need for integrated solutions and systems, reflects real societal and economical needs and provides convenient performance measures for determining, whether the goal is attained and the challenge is met.

The following section gives an overview on the research activities conducted within FP-6. It introduces the six European Integrated Projects. The remaining sections each treat one of the five key areas in robotics, advanced production systems, adaptive robot servants and intelligent homes, network robotics, outdoor robotics and health care and life quality. Economical and societal driving forces are listed and analysed, the objectives in each key area are stated and the state of the art is summarized. Furthermore, both bottlenecks to and driving technologies of progress are identified. The scientific challenges in the next decades are stated, as well as potential future research activities for the next five years.

Executive summaries

Today robotics is first and foremost used in *discrete manufacturing* and for extending human capabilities in *hazardous and inaccessible environments*. In this area Europe is already the market leader. Recent progress in mechanical engineering, human factors, sensory perception and computing is at the same time opening up a number of *new potential application domains* for robotics. In particular there are a number of new application domains in which computers are augmented with facilities for physical interaction with the environments. This opens up new possibilities.

In parallel, society is facing a number of *new challenges*. First of all the *aging* of society throughout the western world is posing a challenge to the health care and the living standards for retired and handicapped. It is thus vital that adequate facilities are provided to ensure a dignified *living standard for our elderly*. While the number of citizens actively involved in production and economic growth is decreasing the *economic gain is required* to increase significantly to allow maintenance of the same living standards, which call for new industries and radical *increases in productivity*. This again calls

for new methods in automation and manufacturing. There is thus a need for a significant growth in production (in new and established industries). Through adaptation of a holistic approach to robotics research it is considered likely that such new industries and economic growth factors can be provided.
This document states and deals with five major areas of application of and challenges to robotics: *Advanced production systems, adaptive robot servants and intelligent homes, network robotics, outdoor robotics* and *health care and life quality*.
For each of these key areas the *driving forces* behind the scenes are investigated. This involves the careful analysis of *economical* as well as *societal* backgrounds. *Objectives* and goals for achievement in each of the key areas are derived.
On the technological side, a comprehensive review of *state of the art* of robotics in each key area is provided as a basis for an in-depth analysis. From the state of the art the major *obstacles to progress* in terms of manufacturing, acceptance, market penetration, technological issues, etc are identified. These obstacles are the major factors that limit added economic growth through deployment and use of robotic technology. The opportunities to address these obstacles are reviewed with special focus on the *technological driving forces*. *Benchmarks* that serve as future evaluation testbeds are briefly introduced.
Finally, the *scientific challenges* that tackle the found obstacles are formulated. These are long-term visions that serve as integration platforms and demonstrators for a holistic approach to robotics in the key areas. The plan for implementation of the research in terms of concrete action and initiatives within a five-year timeframe is put forward to enable a continous progress towards the scientific challenges. These future research activities form a sound background for deciding on potential future programmes in robotics.
The expected deliverables of an robotic initiatives will involve both *new applied and basic science*, a number of *new technologies* which also have *applications beyond robotics*, a number of *new industries* and strengthening of existing companies, and finally *training of new human resources* as a basis for the implementation of the plan and the social impact in terms of growth and quality of life.

2 Status of robotics research in the 6th Framework Program

In this section a short overview on the research that is actually conducted in Europe is given. Here the three Integrated Projects (IPs) COGNIRON[2], I-SWARM[3], NEUROBOTICS[4], CoSy[5], RobotCup[6] and SMERobot[7], funded from the 6th Framework Program, are outstanding landmarks that have to be regarded in greater detail. A complete list of projects currently conducted within and funded by the EU Framework Programme can be found at the "Robotics-related Projects in IST and the Framework Programme"-Website[8].

2.1 Integrated Project COGNIRON

The aim of the COGNIRON project is to develop cognitive robots whose purpose in life is to server humans as assistants of companions. These robots should be able to learn new skills and tasks in an active, open-ended way and to grow in constant interaction and co-operation with humans. In the focus of this research endeavour is the development of a robot whose ultimate task is to serve humans as a companion in their daily life. The robot is not only considered as a ready-made device but as an artificial creature, which improves its capabilities in a continuous process of acquiring new knowledge and skills. Besides the necessary functions for sensing, moving and acting, such a robot will exhibit the cognitive capacities enabling it to focus its attention, to understand the spatial and dynamic structure of its environment and to interact with it, to exhibit a social behaviour and communicate with other agents and with humans at the appropriate level of abstraction according to context.
The projects strategic objectives can be summarized as:

- Study the perceptual, representational, reasoning and learning capabilities of embodied robots in human centred environments
- Develop methods and technologies for the construction of such cognitive robots able to evolve and grow their capacities in close interaction with humans in an open ended fashion

By the end of the project, the following results will be yielded for embodied robots:

- Basic methods,
- algorithms,
- architectures,
- their integration
- and long-term experimentation and scientific evaluation in different settings and situations.

The IP COGNIRON is coordinated by Laboratoire d'Analyse et d'Architecture des Systmes, France and involves the following partners:

- Ecole Polytechnique Fdrale de Lausanne, Switzerland

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[2] `www.cogniron.org`
[3] `http://www.i-swarm.org/`
[4] `http://www.neurobotics.info/`
[5] `http://www.cognitivesystems.org/`
[6] `http://www.robotcub.org/`
[7] `http://www.smerobot.org/`
[8] `http://cordis.europa.eu.int/ist/so/advanced-robotics/proj-related.htm`

- Fraunhofer Institute for Manufacturing Engineering and Automation, Germany
- Kunglika Tekniska Hgskolan, Sweden
- Universiteit van Amsterdam, The Netherlands
- Universitt Bielefeld, Germany
- University of Hertfordshire, United Kingdom
- Universitt Karlsruhe TH, Germany

2.2 Integrated Project I-SWARM

The I-SWARM project aims to take a leap forward in robotics research by combining experts in micro-robotics, in distributed and adaptive systems as well as in self-organising biological swarm systems. The project will create technological advances to facilitate the mass- production of microrobots, which can then be employed as a "real" swarm consisting of up to 1,000 robot clients. These clients will all be equipped with limited, pre-rational on-board intelligence. The swarm will consist of a huge number of heterogeneous robots, differing in the type of sensors, manipulators and computational power. Such a robot swarm is expected to perform a variety of applications, including micro assembly, biological, medical or cleaning tasks. The project's strategic objectives can be summarized as:
The Realisation of a "real" microrobot swarm, i.e.

- collective task execution
- by a thousand micro manufactured autonomous robots
- by the collective intelligence of these robots in terms of
  - co-operation
  - collective perception
- using integrated sensors and tools for the manipulation in the small world

By the end of the project, the following will be achieved:

- realisation of collective intelligence of these robots
  - in terms of co-operation and
  - collective perception
  - using knowledge and methods of pre-rational intelligence, machine learning, swarm theory and classical multi-agent systems
- development of advanced microrobots hardware
  - being extremely small (proposed size of a single robot: 2 x 2 x 1 mm3)
  - by integrating novel actuators, miniaturised powering and miniaturised wireless communication
  - with ICs for on-board intelligence and
  - integrating sensors and tools for the manipulation in the small world.

The IP I-SWARM is coordinated by University of Karlsruhe, Germany and involves the following partners:

- Uppsala University, Sweden
- Ecole Polytechnique Federale der Lausanne, Switzerland
- Fraunhofer Institute for Biomedical Engineering, Germany
- Karl-Franzens-University Graz, Austria
- National Technical University of Athens, Greece
- Sheffield Hallam University, United Kingdom
- Scuola Superiore Sant'Anna Pisa, Italy
- University of Barcelona, Spain
- University of Stuttgart, Germany

2.3 Integrated Project NEUROBOTICS

The ultimate objective of the NEUROBOTICS project is to introduce a discontinuity in the robot design, thus going literally Beyond Robotics. This discontinuity will be pursued by a strategic alliance between Neuroscience and Robotics, which will go well beyond present, mostly fragmented, collaborations, and lead to overcome state-of-the-art of robotics worldwide. The scientific, technological and cultural environment in Europe is mature to face this challenge, whose impact in engineering and medicine could be comparable to that recognized to big science projects. NEUROBOTICS will systematically explore the area of Hybrid Bionic Systems (HBSs). NEUROBOTICS will investigate thee platforms that involve different degrees of hybridness:

- Beyond Teleoperation
- Beyond Ortheses
- Beyond Prostheses

The main objectives of the IP NEUROBOTICS are

- Providing a comprehensive definition of the scientific domain of Hybrid Bionic Systems
- Defining and assessing a set of formal methodologies, intended as new design methods for radically innovative HBSs
- Investigating and developing new biomorphic actuation, sensing and neural interfacing technologies
- Designing and developing new integrated robotic artefacts, as much biomorphic as required to be effectively interfaced with human body and brain

The expected outcome during the 5-year timeframe of the project is:

- New scientific knowledge and new technologies for Hybrid Bionic Systems (HBSs)

- Appropriate physical and cognitive bi-directional interfaces for the integration of robotic artefacts
- First solutions to the human augmentation problem related to upper limb sensory-motor functions with a human brain present in the control loop

The IP NEUROBOTICS is coordinated by Scuola Superiore Sant'Anna Pisa, Italy and involves the following partners:

- College de France Paris, France
- Deutsches Zentrum fr Luft und Raumfahrt Oberpfaffenhofen, Germany
- Fraunhofer Institute for Biomedical Engineering, Germany
- Karolinska Institutet Stockholm, Sweden
- Katholieke Universiteit Leuven, Belgium
- Kungliga Tekniska Hgskolan Stockholm, Sweden
- National Technical University of Athens, Greece
- Ume University, Sweden
- Universitat Autnoma de Barcelona, Spain
- University of Genoa, Italy
- University of Parma, Italy
- Universite P. et M. Curie Paris, France
- Universita' Campus Biomedico Rome, Italy
- Universita' di Ferrara, Italy
- Brown University Providence, RI, USA
- Waseda University, Japan
- Pont-Tech Pontedera, Italy

2.4 Integrated Project CoSy

The aim of CoSy is to construct physically instantiated systems that can perceive, understand and interact with their environment, and evolve in order to achieve human-like performance in activities requiring context specific knowledge, depending on the situation and the task. In particular, the goal is to produce a body of theory, at different levels of abstraction, regarding

- requirements,
- architectures,
- forms of representation,

- kinds of ontologies,
- types of reasoning,
- kinds of knowledge, and
- varieties of mechanisms relevant to embodied, integrated, multi-functional intelligent systems.

The results should be useful both for enhancing scientific understanding of naturally occurring intelligent systems (e.g. humans) and for the design of artificial intelligent systems.
These theoretical results will be evaluated within implementations of a succession of increasingly sophisticated working systems demonstrating applications of parts of the theory, e.g. in a robot

- capable of performing a diverse collection of *tasks*
- in a variety of challenging *scenarios*,
- including various combinations of visual and other forms of *perception*,
- *learning*,
- *reasoning*,
- *communication* and
- *goal formation*.

The IP CoSy is coordinated by Kunglika Tekniska Hgskolan, Sweden, and involves the following partners:

- University of Birmingham, United Kingdom
- University of Paris V, France
- Deutsches Forschungszentrum fr Künstlische Intelligenz, Saarbrücken, Germany
- University of Freiburg, Germany
- University of Darmstadt, Germany
- University of Ljubljana, Slovenia

2.5 Integrated Project RobotCub

The main goals of RobotCub are to

- to create an open robotic platform for embodied research that can be taken up and used by the research community at large to further their particular approach to the development of humanoid-based cognitive systems, and to
- advance our understanding of several key issues in cognition by exploiting this platform in the investigation of cognitive capabilities.

The scientific objective of RobotCub is, therefore, to jointly design the mindware and the hardware of a humanoid platform to be used to investigate human cognition and human-machine interaction, called CUB or Cognitive Universal Body. It is worth remarking that the results of RobotCub will be fully open and consequently licensed following a General Public (GP) license to the scientific community. Among the activities planned in the project, there is an important component devoted to the support of the open initiative which aims at establishing an international Research and Training Site with the following institutional activities:

- Maintenance and update of the CUB. At least three complete systems will be available at the site.
- Training of scientists (both national and international) and students on the preparation, utilization, and development of new components for the CUB.
- Multidisciplinary Research Center open to scientists not yet in the position to embark on the construction and setup of a complete laboratory and/or a full humanoid to start nonetheless their research agenda in embodied cognition.

The IP RobotCub is coordinated by University of Genova, Italy, and involves the following partners:

- University of Pisa, Italy
- University of Zurich, Switzerland
- University of Uppsala, Sweden
- University of Ferrara, Italy
- University of Hertfordshire, United Kingdom
- IST Lisbon, Portugal
- University of Salford, United Kingdom
- Ecole Polytechnique Federal de Lausanne, Switzerland
- Telerobot S.r.l., Genova, Italy
- European Brain Research Institute, Rome, Italy

2.6 Integrated Project SMERobot

Small and medium enterprises are nowadays caught in the so-called automation trap: they must either opt for current and inappropriate automation solutions or compete on the basis of lowest wages. The goal of the SMErobot initiative is to offer an escape out of the automation trap through:

- Technology development of SME robot systems adaptable to varying degrees of automation, at a third of todays automation life-cycle costs
- New business models creating options for financing and operating robot automation given uncertainties in product volumes and life-times and to varying workforce qualification.
- Empowering the supply chain of robot automation by focusing on the needs and culture of SME manufacturing with regard to planning, operation and maintenance.

In particular, research and development in SMErobot is geared towards creating the following technical innovations:

- Robot capable of understanding human-like instructions (by voice, gesture, graphics)
- Safe and productive human-aware space-sharing robot (cooperative, no fences)
- Three-day-deployable integrated robot system (modular plug-and-produce components)

The IP SMERobot is coordinated by Fraunhofer Institut for Production Systems and Automation (IPA), Stuttgart, Germany and involves the following partners:

- GPS Gesellschaft für Produktionssysteme GmbH, Stuttgart
- Pro-Support B.V, An Hengelo, Netherlands
- ABB Automated Technologies Robotics, Zurich, Switzerland
- COMAU S.p.A.
- KUKA Robot Group, Augsburg, Germany
- Reis Robotics GmbH & Co. Maschinenfabrik, Obernburg, Germany
- Güdel AG, Langenthal, Switzerland
- Castings Technology International, Rotherham, United Kingdom
- Visual Components, Helsinki, Finland
- Rinas ApS, Koge, Denmark
- German Aerospace Center, Wessling, Germany
- Lund University, Sweden
- Coimbra University, Portugal
- Institute for Industrial Technologies and Automation, Rome, Italy

3 Advanced Production Systems

3.1 Introduction

The classical application field of production robots is the automation and manufacturing sector and the advance in this sector for the next future (20-25 years) is strongly related to the development of production robots as a main component of manufacturing systems. The actual trend in manufacturing industry *from effectiveness to flexibility and agility*, as a consequence of the globalization of the market place, will continue. There will be a strong need for flexible manufacturing solutions able to provide highly diversified product mixes in a short delivery time based on just-in-time small batched production.

Therefore agile manufacture is thought as a distributed system of tightly integrated mechanical and computational robotic modules endowed not only with information about their own capabilities but also with the ability to appreciate their role in the factory as a whole and to negotiate with their peers to participate in flexible factory cooperation. The *programming facilities* will reflect the trend towards small lot sizes in manufacturing and require little knowledge and skills in order to be operated by non-expert application specialists. The close cooperation between human workers and the production systems places high demands on the mandatory *safety and security* standards.

One other aspect of the use of advanced production robots will be a *diversity of different kinds of working areas*. The classical factory environment may spread from small workshop environments up to large factory environments. Taking all this reasons future production robots will have to cope with flexibility, have to be easy to use and to program, have good interfaces, include pro-active maintenance and self-adapting fixtures.

3.2 Economical and societal driving forces

In a global market comparable products are offered: the enterprises, to preserve and expand their trading positions have to continuously adapt the current products to the users satisfaction. The trend becomes more relevant, as the number of specifications includes the adaptation of the products to life-cycle standards on *safety, anti-pollution, recycling and dismantling rules*, according to prescriptions aiming at sustainable development, promulgated by every industrialised country.

Moreover, globalization forces many businesses into market niches, leading to a more and more fragmented market and much higher product customizations. Each offered artefact is, thereafter, endowed by quality ranges attributes, covering multitudes of users requests. Robot assistants have to reflect this new “economy of scope”, additionally to the economy of scale robots are well-known for. This imposes great demands on the new production assistants in terms of flexibility and re-use of investment/equippment. The actual trend is to re-propose *one-of-a-kind products*, purposely adapted to individual whims with quality figures granted by standard tolerances, as compared to craftworks.

With markets globalising, *short delivering* with customer-driven quality is becoming critical request. Actually time-to-market and product quality are vital factors for enterprises aiming at remaining, or becoming, world-wide competitors.

As society continually ages, vast *changes in the available workforce* have to be reflected in the available equippment in factory automatization. The share of the population with the ability to work is likely to decrease, leading to a fewer count of people in production that have to handle increasing lotsizes. That implies that more and more workers will be replaced by robotics systems that can take charge of the basic, repetitive tasks. Additionally, systems that can improve the productivity of elderly or physically challenged persons allowing them to practise their jobs aid the conservation of overall productivity and economic growth can be conserved. More and more un- or undereducated people are likely to work in factory or constructions jobs, leading to increased needs for user adaption and interaction.

Competing markets demand *Quality-Cost-Delivery (QCD) advances* in production. Wage differentials require to lower the labour costs per unit and increase productivity. Accelerating product life cycles and huge peak sales can be absorbed by production time reduction through even more excessive automation. Future quality requirements will be met by automated total quality inspection.

New business models demand the development of new low-cost automation assistents, trading accuracy for costs. New robot development should not neglect the new “pay equipment by the hour” and leasing mentality, driving the need for low-cost robots, especially for small and medium enterprises (SMEs).

3.3 Objectives

Europes industries have a long tradition in manufacturing robots. Robotic manufacturers in Europe have achieved a leading position in industrial robot sales. The main objective is to *retain, and extend Europes lead in manufacturing technology* over the competitors, Japan and the U.S..

One of the most important issues is to simplify and accelerate *technological transfer from Labs to business*. Universities and other research institutions across Europe have to be linked closely to the industries that transform technologies into products.

The problems of product customization have to be adressed increasing *adaptability, flexiblity, modularity and agility* of future production systems. User interfaces have to be improved, enabling true user-in-the-loop production. Faster programming methods have to be researched on, reducing time-to-market in decreasing product lifecycles. For further product customization, sensing intelligence has to be improved in terms of robustness to un-optimized and weakly specified conditions, suitable for every-day-use. This should eventually lead to new levels of really autonomous systems that perform tasks that require increased intelligence, cognitive abilities and decision making. For this, a proper understanding of the concepts of cognition and autonomy, as well as their legal implications have to be researched.

The societal changes in the work force available drive the needs for developments in easy programming interfaces, the design of ergonomic robots imposing no physical stress on human users, the preservation of (unconcious) sensory-motor skills and know-how. Human-Robot-Cooperation has to surpass current levels to finally allow the *use of robots like a tool* rather than programming. Close human-robot cooperation might support and complement humans, since in the short term robot servants will not be intelligent enough to match the human users. Cooperation might combine the robots (accuracy, speed, ...) and the humans (cognition, intelligence, ...) strenghts on a single production plant. Additionally, close interaction and cooperation between robots and humans requires new standards for safety, reliability and *certifiable* human-safe robot systems.

New *lightweight manipulation systems*, with weight/payload ratio in order of one, have to be conceived, analysed and realised in order to reduce working cycle times enabling progress on stiffness and accuracy. This requires an entire new approach to integrated mechatronic design taking into account simultaneously the new mechanisms architectures, new types of advanced materials, new actuators and new methods for control, multi-sensory feedback and calibration, considering inherent mechanical elasticity and overall system non-linearity.

New processes must be taken into account by regarding the handling of irregular products like sticky, deformable or slippery goods. QCD-advances in production cry for permanent quality improvement during the runtime of the system.

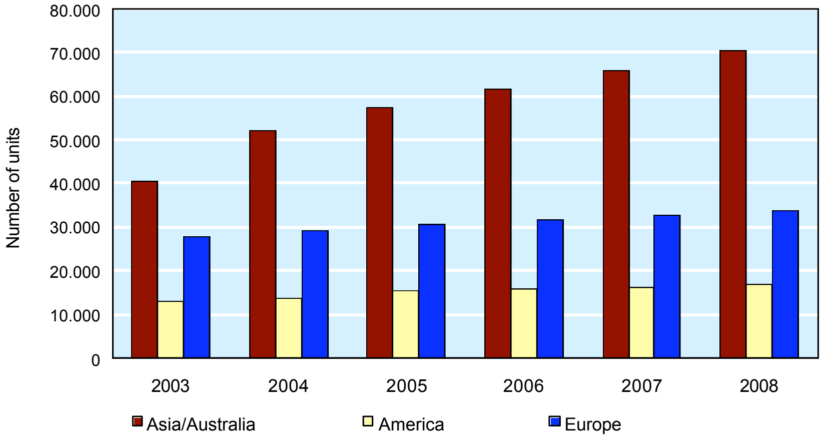


Figure 1: Yearly installations of industrial robots, 2003-2004, and forecast for 2005-2008

3.4 State of the Art

Nowadays, there exist over 40 years of experience in the application of robotics in industries and product automation. According to [Uni05], there are over 840,000 industrial robots in operational use today.

In 2004, the robot world market volume surged by 17%, driven by the increasing demands in the Asia (+17%). During the recession 2001 and 2003, the markets fell by 21% and 12% respectively, reaching 68,600 units. After the strong recovery in 2004, the markets rised to 95,400 units. In Europe, only a weak recovery of 4% from the recession was recorded, after falling by 15% in 2002. Large variations between different countries have been recorded - at the extremes an increase of 48% in the United Kingdom to a decrease of 46% in Austria. Nonetheless, between 1994 and 2001 Europe experienced rapid market increases with double digit growth.

According to [Uni05], the world market for industrial robots is projected to grow from 95,400 units in 2004 to 121,000 in 2008 or by a yearly average of 6.1% (see figure 1). The growth in Japan is mainly driven by an increasing demand for replacement investments. Between 2003 and 2007, most of the robots installed before the economic slump of 1992/1993 are likly to be replaced. Even conservative forecasts say, that the robot market in the European union is expected to grow from 27,832 units in 2003 and 29,300 in 2004 to over 33,700 units in 2008, that is an annual average growth of 3.6%. In North America the market is expected to grow by 5.3% annually, reaching 16,500 units in 2008. Since the market in Japan is mainly driven by replacement investments, its operational robot stock is likely to increase only very slowly to 390,500 units for the next years. Meanwhile, the stock of operational robots is forecast to reach 155,700 units in the United States and 348,000 units in the European Union by 2007 (see figure 2), of which 151,100 in Germany, 65,900 in Italy, 35,900 in France and 14,000 in the United Kingdom.

In the 1990s, prices of industrial robots were plummeting while at the same time their performance was improving continously (see table 1). From 1990 to 2004, prices of industrial robots have fallen from an index 100 to 57, without taking into account that robots installed in 2004 had a much higher performance than those installed in 1990 (see figure 3). When taking into account quality changes, it was estimated that the index would have fallen to less than 25. In other words, an average robot sold in 2004 would have cost only a fourth of what a robot with the same performance would have cost in 1990.

In figure 4, two different groups of countries can be distringuished with respect ro robot densities,

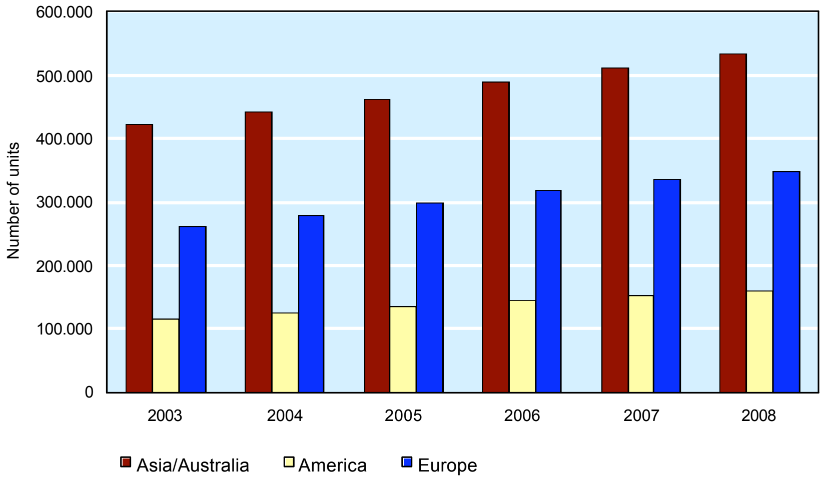


Figure 2: Estimated operational stock of industrial robots 2003-2004 and forecast for 2005-2008

List price of robot unit	-43%
Number of units delivered	+782%
Number of product variants that can be supplied to customers	+400%
Total handling capacity (including gripper module)	+26%
Repetition accuracy	+61%
Speed of the 6 axes	+39%
Maximum reach	+36%
Mean time between failures +137%	
RAM in MBytes	over 400 times
Bit size of the processor	+117%
Maximum number of axes that can be controlled	+45%

Table 1: Performance and price changes in industrial production systems from 1990 to 2000

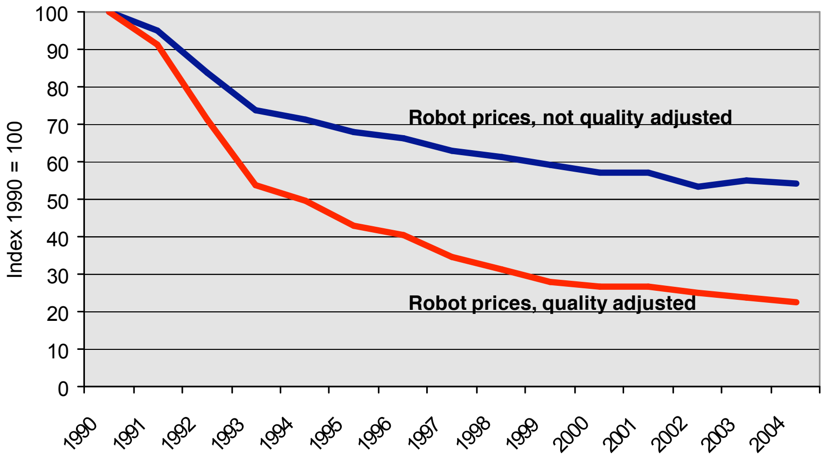


Figure 3: Price index of industrial robots for international comparision (based on 1990 $ conversion rate), with and without quality adjustment

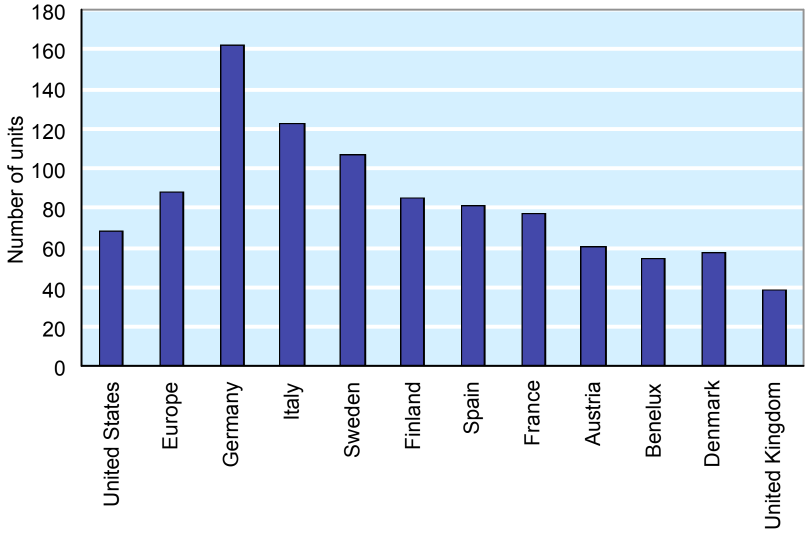


Figure 4: Number of robots per 10,000 persons employed in the manufacturing industry in 2004.

expressed as the number of robots per 10,000 persons employed in the manufacturing indistry: The first group is formed by Germany, Italy and Sweden, which have a density of 162, 123 and 107 respectively. The second group includes Finland, Spain, France, United States, Austria, Benelux, Denmark, and the United Kingdom, with between 86 and 40 robots per 10,000 employees. The The third group of the least mechanised countries, consisting of Norway, Portugal and the Czech Republic, with 36 or even significantly less robot densities, are not included in that figure.

Robotic assistants provide physical or informational assistance to the worker. They can be viewed as evolutions of industrial robots and have been under investigation for some time. A wide spectrum of robot systems with direct exposure to people, sometimes with direct interaction have been suggested: Several specialist robot solutions have been worked out where worker and robot work side by side executing complementary tasks according to the classical industrial engineering rule men are better at machines are better at.... One of the first more cooperative robots was COBOT that was suggested to provide assistance to the human operator by setting up virtual surfaces to constrain and guide motions when handling or placing objects [CWP96]

Advanced robot assistants were presented by Khatib [Kha99]. A platform mounted arm is designed to supplement the physical capabilities of a human operator, providing an ”extra pair of hands” that can move a load in response to forces he/she exerts. Also, multiple robot assistants will work co-operatively in moving, and positioning objects under the supervision of the human operator.

The *MORPHA* project funded by the German Ministry of Education and Research (bmb+f) comprising 16 partners both from research organizations and industry conducted R&D to equip robot assistants with powerful and versatile mechanisms to communicate, interact and collaborate with users in a natural and intuitive way[mor06]. A Manufacturing Assistant (co-ordinated by DaimlerChrysler AG) demonstrated the technical developments, systems integration and gained first field experience.

Low-cost, safe, human-aware robots, sharing the work-space with human workers and capable of understanding human instruction are currently researched within the SMErobot project [NJR$^+$05]. First results are high-performance, low intertia, and low-cost robots.

Man-machine-interaction has been addressed by numerous researchers and is viewed as a prime research topic by the robotics community. More general approaches focus on humanoid robots which

mimic human mobility and skills so that they can cope with complex tasks in unaltered environments both at the shop floor or in homes[hon06].
The growth in need for transporting goods within a single factory and between several factories led to the development of highly *complex logistic systems*. Decision support systems have been installed to increase transportation capacities e.g. in the container terminal of Rotterdam harbour without physical expansion of the existing facilities.

3.5 Bottlenecks to progress

In the European society the application of robot technologies is ill-reputed since robots are considered as job-killers. This acceptance problem has to be resolved and objections should be by the researchers to aim at educational changes of the public oppinion. An economical bottleneck is the lack of a community or lobby for small and medium enterprose interests, since manufacturers of robot technology usually focus their efforts on the needs of OEMs and SMEs lack the critical mass to be of interest to them.
The manufacturing of traditional components like machine-tools, robots, part-feeders, transport units etc., is usually designed as stand alone equipment. One possible reason for this is the increasing complexity of development with increasing sensor amount and quality. Up to now little explicit effort has been dedicated to enabling the *integration* of these components into a manufacturing system. Hence, high economic and technical *costs* remain associated with the manufacturing integration process that in turn severely limits the utilisation of such elements in many practical applications. The *transfer of technologies* developed at research institutions is still a risky venture, as it is not clear, how new technologies fit into existing solutions.
In the future the integration of components has to be enhanced, in order to achieve a higher *flexibility*. The use of compact, mechanically simple elements whose customisability combined behaviours fulfil the specific application requirements is foreseen to adhere to the industrially accepted model of flow-through processing while providing for the rapid deployment and reconfiguration of manufacturing systems. We expect these modules to act smoothly in concert with humans, serving as intelligent cooperating tools. The policy is expected to be a combination of flexibility and cooperation, enabling the industries to produce *"one-of-a-kind"-products*.
The *lack of established standards* in production robotics surely inhibits the development of intelligent and integrated automated manufacturing platforms. The missing of open source controllers combined with the lack of standards leads to needless redundancy of development, re-inventing old solutions again and again. Closely linked with the last issue is the lack of a common open testbeds and benchmarks that would allow the competitive development and mutual assessment of methods and systems.
One major bottleneck is the research institutions focus on functionality vs. *robustness*: In production plants, failures can cause gigantic losses of production, which make new production systems a potential risk. In systems applied in production environments, robustness and fault-tolerance have to be taken into account on every hierarchy level even at the earliest design stages. Systems have to be reliable *24 hours a day, seven days a week* in order to become accepted by the industry.
Legal prerequisites must be created that control the application of autonomous equipment. Before that, no robot manufacturer afford the risk of selling autonomous devices because of unclear liability issues.

3.6 Technological driving forces

In our understanding robot assistants should communicate and interact in a human-like way and therefore should take into account both shape and mobility of the human body, the performance and versatility of the human senses as well as the natural operating environments. Robot assistants represent a generalization of industrial robots characterized by their advanced level of interaction and their ability to cope with natural environments both at homes and shop floors.
Six technical fields have been identified for developing and putting manufacturing assistants into practice.

- Channels of *Human-Machine Communication*. User and robot assistant should co-operate and safely interact even in complex situations. This implies that the assistant understands the user intent through natural speech, haptic or graphical interfaces. In the reverse direction, the application of Augmented Reality (AR) displays and wearable computers might enhance realtime human-machine communication. Interaction and goal-directed collaboration assume the application of *fault-tolerant multi-channel communication mechanisms* and possibly *telerobotics*.

- *Scene analysis and interpretation*. Effective co-operation depends on the recognition and perception of typical production environments as well as on the understanding of tasks in their context. The basis for scene interpretation are *perceptive technologies*. Sensor technologies, especially the new trend of three-dimensional sensors and range scanners, offer the basic foundations that scene analysis builds on with increasing resolution both in time and 3d space. The increasing abilities of *information and immage processing* units catch the enlarged masses of data, originating from new sensor technologies. They ensure proper processing with appropriate speed under real-time constraints with the necessary metrical resolution.

- *Learning and self-optimizing*. Effective assistance not only requires technical intelligence of the robot but also a knowledge and skill transfer between human and robot. A typical example of learning is programming by demonstration. Methods introduced by the field of artificial intelligence (AI) are expected to build “common sense” into the machines that enables them to more efficiently and predictably interact with the human users. Application-, Task- and Process-planning and -simulation will allow the future production assistents to adapt more flexible to decreasing lotsizes, changing tasks and unstructured environments.

- *Motion planning and co-ordination*. During human-machine interaction motions have to be planned and quickly co-ordinated. For motions without physical user contact skills such as avoiding obstacles, approaching a human, presenting objects etc. have to be performed. In the more difficult case of physical contact with the user typical skills would comprise compliant motion, anthropomorphic grasping and manipulation.

- *Safety, Maintenance, Diagnoses*. A suitable safety concept must account for the integrity of the system just as it must account for the integrity of its surroundings. External events affecting the proper function of the system and internal error conditions must be identified and classified according to their inherent risk factors. RFID technology is likely to improve sensor reliability and product history tracking and therefore boost quality of products.

- *Mechatronics and Integration*. Miniaturization and weight reduction led to more compact and affordable mechatronic systems. They allow a broader application of robotic components in production and logistics. New Materials under development offer increased flexiblity and/or improved lightweight systems. New actuators like artificial muscles and miniaturisation drives the field towards new manipulation/actuation possiblities and applications. *Integrated development* of system components enable flexible composition of production units as well as inexpensive reconfigurations of assembly lines and connected systems. This enabes industries to swiftly cope with product and market changes.

3.7 Benchmarks

Several benchmarks test abilities that are needed in production robotics:

- *Manipulation and Grasping:* The following three tests have been proposed by the EURON Benchmarking activity: (1) Grasp and re-grasp of a given object. Success is measured by capability of disturbance rejection, ability of fine manipulation and the complexity of the object. (2) A pick and place operation is divided into two stages: picking and holding an object. In the first phase the evaluation concerns of measuring the statically applied picking forces to the grasped object, while in the second phase the measure of the maximum acceleration, in different moving directions, permitted before to lose the grasped object would be an interesting metric. (3) Take a set of objects and replace them as soon as possible. Here the metric would be time and statistics of failure.

- *Motion Planning:* An initiative for a repository for motion planning benchmark problems is maintained by the University of Parma (see http://mpb.ce.unipr.it). It aims at including benchmarks designed by different research groups and documentation describing the file formats currently used by the available planning tools to define their problems. Also, links and useful information regarding motion planning research projects are available. The repository is intended to serve as the basis for further discussion on the requirements and the design of benchmarks in motion planning.

3.8 Scientific challenges

Several scientific challenges can be identified:

- *Collaborative and responsive manufacturing* systems will introduce new ways of programming and control of production assistants. Human-centered interfaces, multi-modal dialogues and close interaction with the human user are still limited and not too comfortable.

- A great potential for future production applications lies in the design of *distributed, interactive and intelligent planning, programming and scheduling*. These planning, programming and scheduling abilities provide robot factories with increased flexibility, shorter production cycles, higher usage rates and shorter reconfiguration or set-up times, resulting in short product development cycles.

- Methods for *fault detection, recovery and tolerance* on every hierarchical level will increase robustness and reliability of production systems. Methodologies for considering robustness issues on every hierarchy level during the design process must be further investigated. In addition, safety issues have to be taken into account in an integrated way in order to allow secure interaction between robots and humans.

- *Intelligent sensors* will lead the way towards robust and scalable components in composite architectures. Sensors capable of *auto diagnostics* have to be investigated in order to improve reliability and assessment of the data gathered.
- Research towards *universal manipulators* (the "universal hand") has to be conducted. The challenges are located in both the mechantronical and sensorical domains, as current grippers have to be improved in terms of weight/payload-ratio, flexibility and sensitivity.

3.9 Future research acitivities

Flexible production and manipulation, rapid change of manipulation tasks have a high impact on the development of new kinds of universal gripper, including planning, motion control and mechatronics. Main research topics in the near future are:

- Improvement of *sensor technologies*: Increase in resolution, speed, accuracy, incorporation of intelligence, diagnostic tools and data processing units
- Hierarchical, modular and fault tolerant *architectures* consisting of linked reactive components
- Redundant lightweight *manipulation systems*
- Scalable, distributed and open robot control and open robot *standards and interfaces* to introduce networked robots powered by IT into manufacturing systems.
- Standard *human interfaces* with reference to communication, component integration, user and human interaction.
- Robust methods for sensory based preventive *failure detection*, knowledge based *autodiagnosis* and autonomous or semi-autonomous *repair functions*.
- Robot capability of sharing the workspace with humans in *collaborative workcells* and addressing the users need by interaction and cooperation.

Advanced production systems of the future will be an *integrated research topic* from different research areas. Possible areas that will have strong influence on the success of such systems are actuation, mechanical systems, sensor systems. Recent progress in the areas actuation, mechanical systems, sensor systems, power systems, cognition and interfaces has reached an encouraging level of success. Nevertheless, robustness and reliability are the most important elements that need to be improved significantly. The expected developments and milestones for the next 15 years are outlined in figure 5.

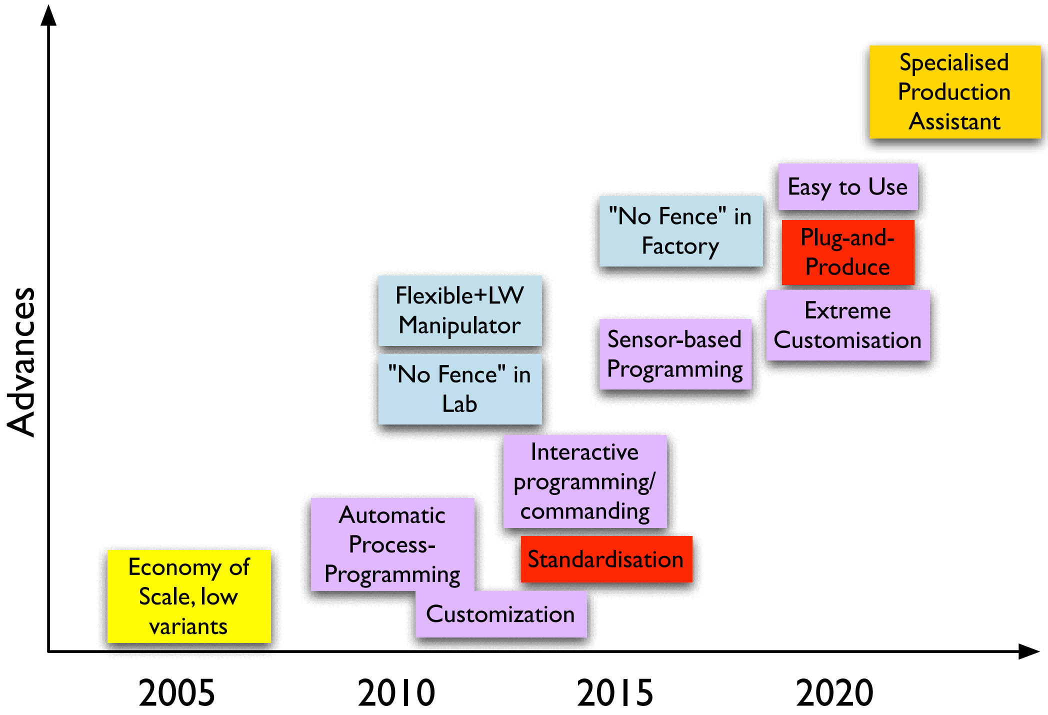


Figure 5: Approximate timeline for the future development of advanced production systems

4 Adaptive robot servants and intelligent homes

4.1 Introduction

In the next future, in a 20/25-year perspective, domestic, chore activities are expected to be something about which we will have to worry less and less. Our homes seem to become more and more comfortable and smart and a larger variety of services will be available, more effective and convenient, even without moving from home.

Two trends can be easily identified: The homes themselves will become more intelligent in terms of sensors and interconnecting processing units, and they will be populated by robotic servants that operate in these intelligent houses in close interaction and cooperation with the human user.

4.2 Economical and societal driving forces

The Society in 20-25 years is likely to be different from now. First of all, it will be older. But the *elderly people* of 2025 will be different from the idea of elderly that we have now. They will have been part of the information society and their relationship to technology will be completely different. Already now, researchers working on robotics and technologies for personal assistance are used to take into account the needs of the elderly and, especially, they are used to cope with the difficulties of proposing technological solutions to people who is culturally far from them. Even though some of the problems, related to the aging physical and mental deterioration, will be similar, some of the psychological aspects will be radically different. Elder people of the future will be probably healthier, but their *need for assistance* will be greater, due to a longer life expectance. In addition to a general grown need for personal assistance, which is envisaged to continue the trend of the last decade, a scarcity of workers in services will characterise the Society of the future, still in line with the current trend.

Another important issue that feeds the demand for home service robots with advanced capabilities are the changes in *living patterns* of the society in the next few decades. The increase in mobility and *single households*, as well as the increase in households where both partners work outside the house, cause that people will have less and less time to do the housekeeping work. This fact calls for more sophisticated homes and autonomous household servants that deal with the cumbersome household tasks.

For these reasons, robots are expected to provide services in many aspects of the humans life and, even more, to play a real social role. They are not going to replace humans in social positions, but to simply fill up the some of the positions that will be left empty by humans. The robots, regarded as mans personal robot companions, may serve, for example, as:

- housekeepers: fast and accurate, never bored;
- baby sitters: patient, talkative, able to play many games, both intellectual and physical;
- assistants to the elderly: always available, reliable, taught to provide physical support with the correct movements;
- cleaners: fast and accurate, never tired;
- handymen: able to solve many technical problems

4.3 Objectives

Recent progress in mechatronics (breaking the barrier of 1:5 in *weight/payload ratio* as an example), computer power, fuel cells, etc has to be continued and excelled in order to deploy applicable systems within the next decades. Deployment of systems does require efficient *lightweight components* that are easy to customise, which in turn calls for fully integrated mechatronic and miniaturized components. The *interaction and cooperation* with human requires soft mechanical systems (in terms of passive or active compliance) that allow safe collisions with humans, and a stiff mechanical system for assistance to humans. Such systems require integration of new materials, control, electronics, and design. Additionally, *user interfaces* have to be widely improved to allow people without knowledge of robotics to command and control their robots in a natural way. In relation to interaction with humans there is not only a need for flexible user interfaces, but also a need for methods for handling of *shared autonomy*, and methods for *efficient acquisition of methods of control* in terms of skills (basic control laws) and tasks (expertise at the level of missions). To bring robots cognitive capabilities at eye level with their human operators, more effort has to be undertaken to improve *learning and reasoning*. *Integration* of all the abovementioned robotics subsystems reuires new engineering methods for analysing and integrating robotic components.

In intelligent homes, progress has to be made in sensing the human user. This allows thee house to flexibly adapt to its residents needs, expectations, moods and tempers. *Sensing components* have to be developed as well as interconnecting mechanisms, *networks and data processing facilities* that establish the indoor intelligence. Again, *learning* mechanisms should be taking into account to adapt to a certain user. The ways the house can *influence (actuate) itself* have to be investigated and their impact n people have to be understood. Finally, home devices should be robotized as well, equiping all devices with certain levels of sensing and cognitive capabilities. This moves the traditional notion of robots as a legged or wheeled machine away to underline the onboard intelligence.

4.4 State of the Art

So far, service robots for personal and private user are mainly in the areas of domestic (houshold) robots, which include vacuum cleaning and lawn-mowing robots, entertainment robots, including toy and hobby robots. Sales of lawn-mowing robots have started to take off very strongly with sales in excess 40,000 units, and should continue to boom [**?**]. The market potential is very large. Vacuum cleaning robots were introduced on the market at the end of 2001. The market rapidly expanded in 2002-2003 and now counts at least 570,000 units. Of the 610,000 operational robots for domestic household use at the end of 2003 almost 400,000 were installed in 2003 (see figure 6).

Turning to the projections for the period 2004-2007, the sales of all types of domestic robots (vacuum cleaning, lawn-mowing, window cleaning and other types) can reach some 4,1 million units with and estimated value of $ 2.7 billion (see figure 7). The market for entertainment and leisure robots, which includes toy robots, is forecasted at about 2.5 million units, most of which, of course, are very low cost. The sales value is estimated at over $ 4 billion.

(Humanoid) robotic servants have been envisaged by the researchers for a couple of years. However, only prototypic systems have been set up today. The same holds for intelligent homes. Although important technology is already available, integrated experiments and research has been performed in the early stages. Recent progress in the development of enabling technologies like sensor systems, actuation, communication, interfaces and mechanical systems have been an important step to set up adaptive robotic servant acting in intelligent homes.

Humanoid robotics is fast and widely developing world-wide and currently represents one of the

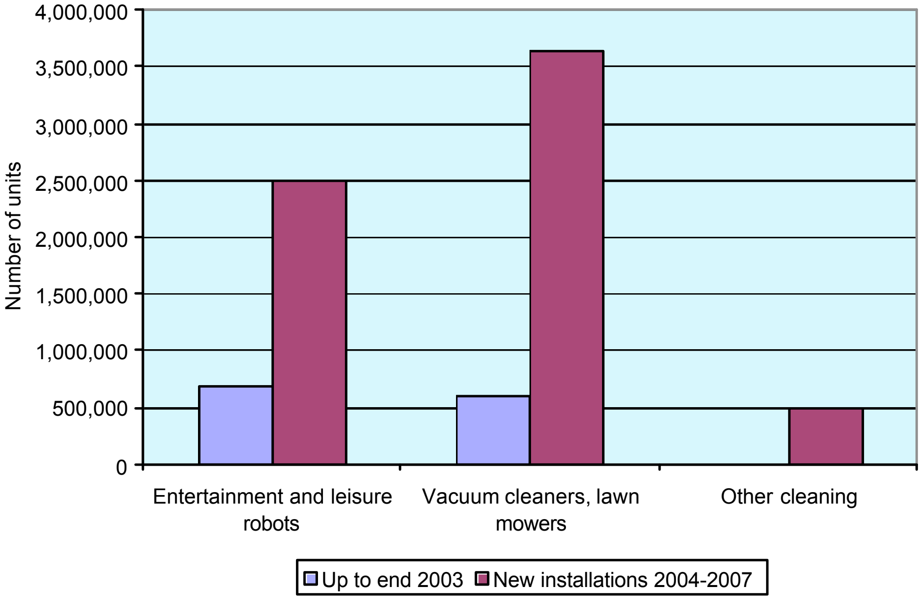


Figure 6: Service robots for personnel/domestic use. Stock at the end of 2003 and projected installations in 2004-2007

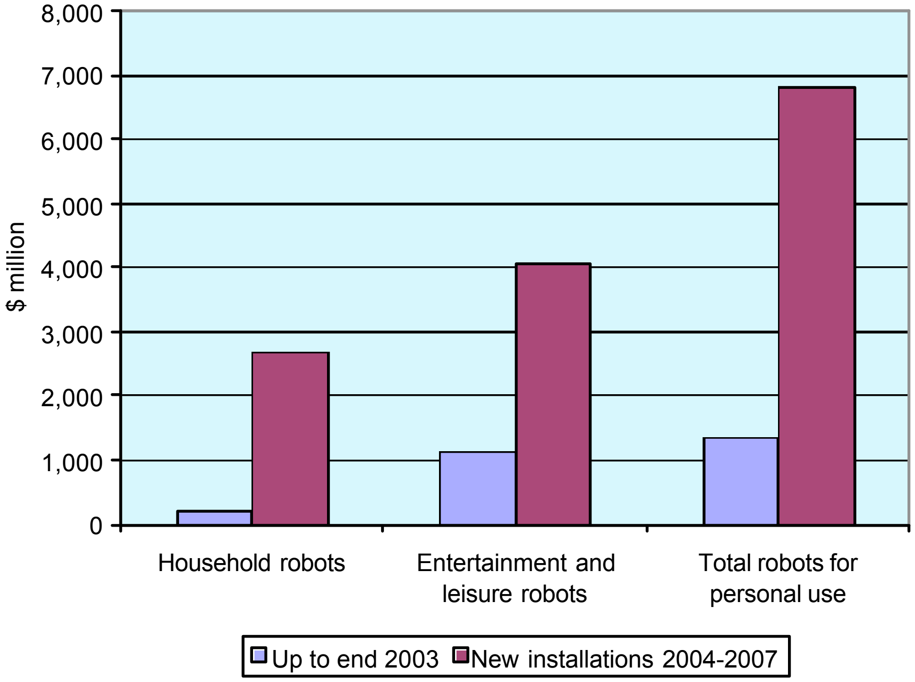


Figure 7: Service robots for persional/domestic use. Value of the stock at the end of 2003 and of the projected intallations in 2004-2007

main challenges for many robotics researchers. In *Japan*, this trend of current research is particularly evident. Many humanoid robotic platforms have been developed in the latest years, most of them with an approach especially focussed on the mechanical, or more in general, hardware problems, in the attempt to replicate as closely as possible the appearance and the motion ability of human beings. What is even more impressive in the scene of Japanese Humanoid Robotics research is that big companies are also devoting considerable efforts to this objective. The outstanding example is the Honda Humanoid Robot, whose current version is called *ASIMO*, which absorbed a dedicated Honda team in a research effort for over 15 years. ASIMO presents very advanced walking abilities and fully functional arms and hands with very limited capabilities of hand-eye coordination for grasping and manipulation. While Honda was putting its ASIMO humanoid on the market, other small humanoid robots were also proposed as hi-tech entertainment products. For instance, Sony launched the SDR-3X and Fujitsu the HOAP-1. More recently the *Pino* humanoid robot became very popular in Japan and it is successfully sold together with a variety of gadgets. In addition to the commercial aspects, one of the peculiarities of Pino is that it was designed so as to be assembled with no-specialised off-the-shelf components and materials and with an open software platform, in order to favour humanoid robotics research especially for young researchers and students. These robotic toys are now opening the way to the first commercial personal robots, i.e. still entertainment robots with some helpful functionality: the novel Papero (by NEC) is a small mobile robot with a non-anthropomorphic pleasant shape, with big eyes and speech and audition capabilities. It can recognise some faces, welcome guests and take messages for other people. On this line, the Temsuk housekeeper has a more anthropomorphic shape, resembling a feminine household figure, and is intended to provide simple services around the house.
In the *USA*, the research on humanoid robotics received its major impulse within the studies related to Artificial Intelligence, mainly through the approach proposed by Rodney Brooks, who identified the need for a physical human-like structure as prior for achieving human-like intelligence in machines. Brooks group at the AI lab of the MIT is developing human-like upper bodies able to learn how to interact with the environment and with humans. Their approach is much more focused on the robot behaviour, which is built-up by experience of the world. In this framework, research on humanoids does not focus on any specific application, as well. Nevertheless, it is accompanied by studies on human-robot interaction and sociability, which aim at favouring the introduction of humanoid robots in the Society of Humans. Still at the MIT AI Lab, the *Kismet* robot has been developed as a platform for investigation on human-robot interaction. Kismet is a pet-like head with vision, audition, speech and eye and neck motion capability. It can therefore perceive external stimuli, track faces and objects, and express its own feeling accordingly.

Europe is more cautiously entering the field of humanoid robotics, but can rely on an approach that, based on the peculiar cultural background, allows integrating considerations of different nature, by integrating multidisciplinary knowledge from engineering, biology and humanities. Generally speaking, in Europe, research on robotic personal assistants has received a higher attention, even without the implication of anthropomorphic solutions. On the other hand, in the European humanoid robotics research the application as personal assistants has always been much more clear and explicitly declared. Often, humanoid solutions are answers to the problem of developing personal robots able to operate in human environments and to interact with human beings. Personal assistance or, more in general, helpful services are the European key to introduce robots in the society and, actually, research and industrial activities on robotic assistants and tools (not necessarily humanoid) have received a larger support than research on basic humanoid robotics. While robotic solutions for rehabilitation and personal care are now at a more advanced stage respect to the market opportunities, humanoid projects are currently being carried out by several European Universities. Some joint European Projects, like the Brite-Euram *Syneragh* and the IST-FET *Paloma*, are implementing biologically-inspired sensory-motor coordination models onto humanoid robotic systems for manipulation. In Italy, at the University of Genova, the *Baby-bot* robot is being developed for studying the evolution of sensory-motor coordination as it happens in human babies. *ARMAR*, developed by the Karlsruhe University, is an autonomous mobile humanoid robot for supporting people in their daily life as personal or assistance robot. Currently, two anthropomorphic arms have been built up and mounted on a mobile base and studies on manipulation based on human arm movements are carried on.

4.5 Bottlenecks to progress

Despite the state-of-the-art has shown quite well the several possibilities to provide people with an independent life, it can be noticed that all approaches lead to a technology dominated life for the elderly and disabled with the problem of acceptance. Therefore *smarter robots* should integrate more seamlessly in the disableds and elders environment. Above, machine learning techniques that allow to recognise the elders *changing capabilities* and which tailor the behaviour of the robots accordingly. Other important problems that have to be tackled in the future are *price / performance ratio*, the *acceptance* of robots by the single user and society, natural and intuitive *interfaces*, and the *safety issues*, still remaining an unsolved problem. Especially safety and privacy related problems require a legal framework for the further establishment, development and growth of home robotics industries.

4.6 Technological driving forces

Among the main technological driving forces in robot servants is *mechatronics and miniaturization*. Future robot servants strongly rely on miniaturized and lightweight components that enable them to be introduced in human inhabited areas. These areas usually lack space for robots significantly larger than the human itself. *Interface technologies and human-robot-interaction (HRI)* will provide mechanisms for communication and cooperation between robots and humans. As information needs on the sides of both the user and the robot are vast and important to fulfil the corporate mission, interface technologies will be of major interest. *Humanoid technologies* are of critical importance for acceptance by the human users. A robot that visually and sociologically resembles the human and moves in similar ways is more likely to be accepted than robots today.

Network technologies are of critical interest to intelligent homes. Intelligent homes will be crowded by many different kinds of sensors, distributed across the domestic environment of the human. They have to exchange, process and transmit data. *Agent-based architectures and technologies* will expedite the development of failsafe and reliable intelligent homes. *Miniaturization* is important in intelligent homes as well, as the technological components of future houses should not limit the space at the users disposal.

4.7 Scientific challenges

In robot servants, *ease of use* is a key issue. The human users usually lack sound knowledge of robot control and programming, so the problem of designing simple interfaces that can be used only with commonsense knowledge is to be addressed in the future. Building autonomous systems, capable of learning from both the user and its own experiences is still an unsolved problem. *Intelligence, including learning, reasoning, cognition and autonomy*, is an large field, open for minor improvements and major breakthroughs. Probabilistic method for decisions in unstructured environments provide a first approach to many of those problems. Perception of both the user and the environment is an important prerequisite for cognition and intelligence. Though highly researched in the past decades,

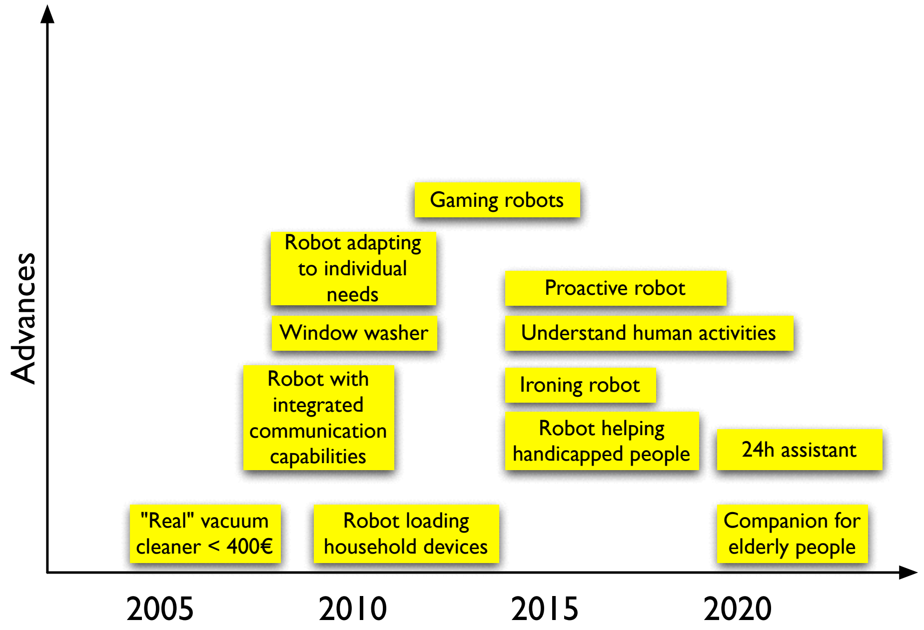


Figure 8: Approximate timeline for the future development of adaptive robot servants in intelligent homes.

perceptive technologies lack robustness and reliability to enable higher level reasoning and cognition. *3D-perception* and *navigation* in close proximity to the human user requires new methods to be developed, as well as the real understanding of human gestures and actions that outstrips todays recognition approaches.
The *coalescence of robot servants and intelligent* homes is a relatively new field of research. Robot servants should neatly fit into the new environments formed by intelligent homes. Both technologies are likely to mutually influence and improve each other, eventually leading to robotic servants efficiently using the distributed sensors in the home, improving the quality of service to its owner.

4.8 Future research acitivities

In order to facilitate the development of household service robots and intelligent homes, in the next future research should be done on the following fields of research:
Interfaces to enhance interaction and cooperation should be extensively researched. This field includes artificial skins for tactile robot guidance, visual three-dimensional tracking of humans and activity recognition to place an interaction in the appropriate context. Much work on the cognitive abilities of robot servants have to be done. Research on the topic of intentional recognition, skill and task learning, self-awareness and reasoning in dynamic environments has to be performed. Modular design architectures have to be improved and optimized for the application of robots and intelligent homes.
Funding for cooperation project for European home robot researchers will increase mobility and information exchange, which will eventually lead to common standards, platforms and methodologies for the European industries.
The forecasted development of robot servant and household companions is depicted in figure 8.

5 Network robotics

5.1 Introduction

The last decade has witnessed unprecedented interactions between technological developments in computing and communications, which have led to the design and implementation of robotic and automation systems consisting of networked vehicles, sensors, and actuator systems. These developments enable researchers and engineers not only to design new robotic systems but also to develop visions for systems that could have not been imagined before. Now there is a need for a unifying paradigm within the robotics community to address the design of these networked automation systems.

Networked automation concerns the coordination and control of systems with evolving structure comprising sensors, controllers, actuators and inter-operated communication networks with varying degrees of autonomy and mixed initiative interactions.

Networked automation is becoming pervasive in our society. Applications include automated highway systems, environmental and oceanographic studies and interventions, industrial automation, defense, surveillance, and security, and civil protection. Mixed applications can also be envisaged in the future; for example automated highway systems may provide environmental data and means for controlling pollution.

Network robotics can be seen as one aspect of (and should be viewed in the context of) *ubiquitous computing* and *ambient intelligence*. In an environment equipped with sensors and distributed computing units, *interaction with the environment* and the user is one important aspect. The topic network robotics transcendes ”conventional” service robotics in the number of employed robots, operation mode even closer to humans, and networking not only within the robot group, but also with their environment.

5.2 Economical and societal driving forces

Today, applications of networked automation are already pervasive in most fields of human endeavor. The networked automation tools and technologies have a wide range of applications. New questions, that could not have been formulated a few years ago, are being posed, mainly due to the technological advancements in robotics, control, computing and communication. Again, these technological developments made possible to envision the implementation of systems which could have not been imagined before.

Examples of current and potential application areas are:

- Automated multi-vehicle systems: automated highways; automated waterways; air traffic control.
- Industrial automation: wireless automation and wireless factory; robot control over networks; control of systems with evolving structure; automotive automation; etc.
- Intelligent building and structures: environmental control and structural monitoring with sensor networks; inspection of civil structures with sensor networks and dedicated robotics devices.
- Health care: sensor networks for monitoring and intervention; integrated robotic help; remote interventions; automated drug delivery, etc.
- Earth sciences: networks of sensors and robotic devices for detailed scientific field studies in remote and hostile environments inaccessible to humans; studies of global warming, etc.

- Security and civil defense: deployment of interoperated sensor and communication networks in disaster scenarios; surveillance and security; intervention in disaster scenarios; fire detection, management and fire fighting, etc.
- Agriculture: crop monitoring and interventions; optimization of irrigation systems; etc.
- Management of natural resources: networks of sensors and robotic vehicle for water management; air quality; etc.
- Military: new strategic concepts and tactical deployments rely heavily on network centric concepts, which involve not only manned systems but with an increasing rate on sensor and robotic vehicle networks.

Another important aspect of networked automation systems is their multi-role capability and transferability. For example a network of sensors and robotic devices for water management can easily be used to civil defense, or can easily be re-deployed in a disaster area. This is because of the separation of physical devices from the networked applications that make use of them.

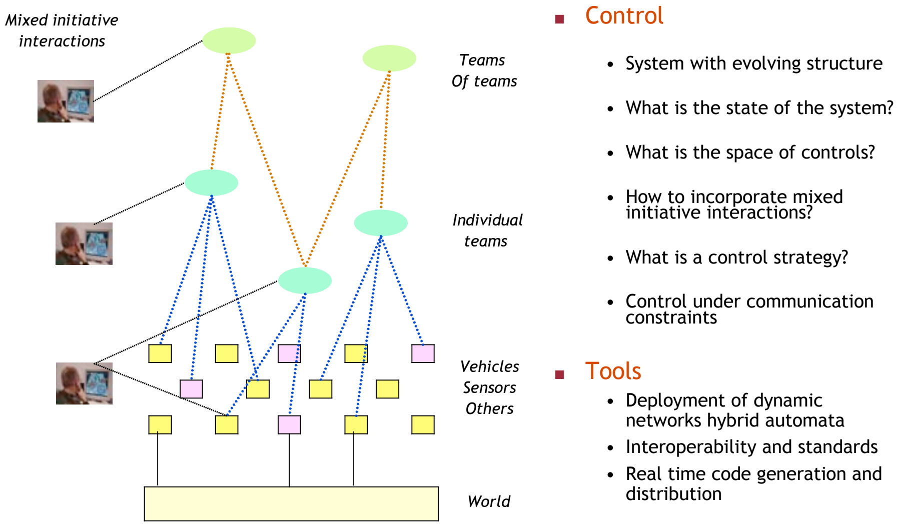
We can infer that the societal and economic driving forces behind these applications are quite pervasive and pose a significant opportunity for networked automation. The challenge is to take advantage of this opportunity.

5.3 Objectives

The common denominator of all of these applications is the concept of system of systems. In fact, in all of these applications (already deployed or envisioned for a near future) there are components, such as human operators, which intervene in a mixed initiative environment, as well as physical devices, which include sensor and robotic vehicles, which are complex systems by themselves. Now these components are part of a system, within which new properties arise, some of them as planned, some of them emergent and eventually leading to unpredictable behaviors. Moreover, since communication is not necessarily available, or instantaneous, the state of the system a network of systems with evolving structure is not accessible.

The last decade has witnessed unprecedented interactions between technological developments in computing and communications, which have led to the design and implementation of robotic and automation systems consisting of networked vehicles, sensors, and actuator systems. These developments enable researchers and engineers not only to design new robotic systems but also to develop visions for systems that could have not been imagined before. Now there is a need for a unifying paradigm within the robotics community to address the design of these networked automation systems.

The challenges to existing approaches and theories come from the distributed nature of networked automation problems. For example, in networked vehicle, sensor, and actuator systems, information and commands are exchanged among multiple vehicles and systems, and the roles, relative positions, and dependencies of those vehicles and systems change during operations. These challenges entail a shift in the focus of existing methodologies: from prescribing and commanding the behavior of isolated systems to prescribing and commanding the behavior of networked systems. The intrinsic nature of networked automation systems requires an interdisciplinary approach from robotics, control, computer and communication scientists. This is why we need to further the cooperation among these researchers and to provide them with challenges drawn from applications conceivable in a near future from robotics and automation. This requires a strong interaction with technology and tool developers,



- Control
  - System with evolving structure
  - What is the state of the system?
  - What is the space of controls?
  - How to incorporate mixed initiative interactions?
  - What is a control strategy?
  - Control under communication constraints
- Tools
  - Deployment of dynamic networks hybrid automata
  - Interoperability and standards
  - Real time code generation and distribution

Figure 9: Networked automation challenges

companies and scientists from the life sciences. It will not come as a surprise if these developments impact also other areas such as biological engineering, global environmental science, and integrative multi-scale modeling and simulation.
The objectives for further research are classified along models, tools, and technologies.
Models: The notion of system of systems leads to interesting modeling questions and to possible connections to other fields of study, namely biology:

- How to model systems with evolving structure and where properties depend on the structure of the system?
- What is the notion of state of the system?
- What are the available controls and how do we prescribe behaviors for the system, as a whole?
- How to define modular and layered abstractions?
- How do we compare one-world semantic descriptions to multiple world semantics?

Technologies: In a system of systems, a significant part of the system is embodied not as physical devices, such as sensors, robotic devices or communication networks, but as software applications which may be mobile in the sense of migrating from one computer unit to another one, as part of the evolution of the system. This poses interdisciplinary challenges to robotics, control, computer and communication scientists. These technologies include code mobility, articulation of models of computation, dynamic optimization for systems with evolving structure, mixed initiative environments for human-computer interaction, middleware systems, etc. Systems engineering (IEEE standard for the Systems Engineering Process) will definitely play an important role in the design and implementation of these systems. The Systems Engineering process will become an important tool to support technological development. Obviously this is related to the issue of design, evaluation, and real-time control. The high level of abstractions required for modeling and controlling such systems poses design and control questions at the level of layered control and semantic models, namely one-world semantics,

where hierarchies are typically flattened out, versus multiple world semantics are theories co-exist at different levels. This poses further questions, namely those concerning fault handling and recovery.
Tools: Not only the tools used in robotic systems will have to be extended to handle a system of systems, but new tools will have to be developed. These include:

- Command, coordination, and control frameworks. These frameworks mediate the interactions between human operators and physical devices and embody the software components of the system which are not directly attached to physical devices.
- Simulation. Advanced simulation tools, where realistic systems can be modeled, namely in what concerns components, interactions, communication networks, and mixed initiative interactions, are required to test and evaluate tools and technologies before deploying them. Moreover, provisions for hardware in the loop simulations should be provided as well as interfaces to scientific tools such as models from the earth sciences.
- Planning tools. The challenge is to develop tools with the required level of abstraction to prescribe the evolution of the system. These will necessarily include techniques from dynamic optimization and automata theory.
- Control design. The level of abstraction at which control design will be done requires new tools within which the state of the system can be represented, the evolution of the system prescribed, and evaluated.
- Real-time interaction. Human-system interfaces need to be developed to address the level of abstraction required for human interactions with a system of systems.
- Code generation and verification. Current code generation tools do not account for distributing code, code mobility, and dynamic interactions. Likewise, verification tools do not handle systems with evolving structure.
- Frameworks to support the systems engineering process.

5.4 State of the Art

One of the challenges to existing theories comes from the distributed nature of the problem. For example, in networked vehicles and systems information and commands are exchanged among multiple vehicles and systems, and the roles, relative positions, and dependencies of those vehicles and systems change during operations. This challenge entails a shift in the focus of control theory - from prescribing and commanding the behavior of isolated systems to prescribing and commanding the behavior of interacting systems. The formulation of concepts of operation for multi-vehicle systems poses new challenges to control engineering. First, we require vehicles, devices, and controllers with evolving access capabilities to dynamically interact with each other and with operators, by exchanging messages and data to execute tasks. Second, we need different notions of what should be observed under different circumstances, giving rise to questions of when two systems exhibit the same behavior. Third, we need motion coordination models that are highly dependent on the particular application, and that may change with time for the same application. Fourth, we need to incorporate in analysis and control synthesis the aspects of communication and concurrency that are at the heart of these complex systems. Fifth, we need to consider data-provisioning systems to manage and maintain representations of data exchanged with network-centric vehicles and systems.

The robotics, control, communication, and computer science communities address these challenges in the context of distributed hybrid systems, models of computation, mobility, and contribute complementary views and techniques. However, the inter-disciplinary nature of networked vehicles and systems requires a new description language. This language is in the process of being developed. Meanwhile, control engineers have developed a collection of idioms, patterns and styles of organization that serves as a shared, semantically rich, vocabulary among them [SG96]. However, this shared vocabulary is still deeply rooted in the underlying mathematical framework differential and difference equations and lacks some semantically rich concepts invoked by distributed computing. The cause may be that experience and functionality in computing are acquired at a rate unmatched by the rate of evolution of concepts in control systems. For example, it was only recently that the expressiveness of the language of differential equations and dynamic optimization was enlarged with concepts from mathematical logic, under the denomination of hybrid control (see for example [Pur95, LGS98, Bra95, DV95, BP02]).

The challenge to existing theories has been reflected in the rich and exciting research over the past decade concerning the description, analysis, controller design, simulation, and implementation of distributed systems [SdSV01].

From control engineering, this research has inherited the concepts and theories of optimality, stability, controlled differential equation models, and the motivation to improve the performance of increasingly complex physical processes. The problem of control of embedded systems over networks and control of networks has received significant attention recently [Joh05]. Researchers have used dynamic networks of hybrid automata (DNHA) to model systems with evolving structure and dynamic interactions [DGS97]. DNHA provide the basic constructs to model a system of systems. The problem of hierarchical control and layering has also received significant attention since the 60s but some breakthroughs are needed. The issues of one-world versus multiple world semantics may provide some contributions [Var99]. With one-world semantics, therefore, truth-claims expressed in high-level expressions (e.g. this is a minimum-length path) are interpreted as claims about trajectories, as is common in verification theory where properties of high-level abstractions can be translated into properties of lower-level behaviors. However, hierarchical controllers are not designed in this way. The design of each controller is evaluated in a mathematical world in which alternate controller designs (e.g. different path-planning algorithms) can be compared. This is multi-world semantics. The mathematical world for one controller makes implicit assumptions about the behavior of lower-layer controllers. There does not seem to be any accepted way of bridging the gap between the multi-world semantics of design and the one-world semantics of implementation.

From computer science, the research has incorporated the theories of logical specification and verification, event-driven state machine models, semantic models, consistent abstractions, behavioral equivalence, models of computation describing the mechanisms by which software modules interact, concurrent processes and object-oriented approaches [ELLSV97, NW103, ACH^{+}95]. However, the realm of interactions and processes is not captured by the formal theories behind most programming languages. This is why the theories of computation are evolving from notions like value, evaluation and function to those of link, interaction and process. One such example is the Pi-calculus, an idealized modeling programming language and a mathematical model of processes whose interactions change with time [Mil99]. This calculus inherits concepts and elements from a variety of process algebraic theories that have a formal algebraic basis and a behavioral semantics.

From communications this research has inherited the theories behind service networks, ad-hoc networks, and, more recently, what could be the next phase of the information technology revolution: the convergence of control with communication and computing.

Recently the concept of mixed initiative interactions has received significant attention, especially in multi-vehicle operations. In the mixed initiative environment experienced human operators interact, both at the planning stage and in real-time, with a distributed command and control structure. In part this is because essential experience and operational insight of these operators cannot be reflected in mathematical models, so the operators must approve or modify plans and their execution. Also, it is impossible to design (say) vehicle and team controllers that can respond satisfactorily to every possible contingency. In unforeseen situations, these controllers ask the human operators for direction.

In summary, networked vehicles and systems represent, on the one hand, a major challenge to control, computation and communication and, on the other hand, a field where major scientific developments, driven by technological advancements and applications, are expected to occur during the next decade [Per01]. Their intrinsic nature requires an interdisciplinary approach from robotics, control, computer and communication scientists. This is why we need to further the cooperation among these scientists and to provide them with challenges drawn from operational scenarios conceivable in a near future. It will not come as a surprise if these developments impact other areas such as biological engineering, global environmental science, and integrative multi-scale modeling and simulation [Mur03].

5.5 Bottlenecks to progress

A major obstacle to progress in this area is *lack of flexible mechanical structures* that are easily configurable, capable of self-assembly and have flexible methods for interconnection. Another problem is automated *task decomposition* and control in the presence of variable kinematics and heterogeneous components/robots. To this end, there is also a need for methods for rational design of components and teams, which implicitly is related to the definition of a system-level theory of operation. Recently there have been several studies of *learning* in the context of robotic teams, but in almost all cases for homogenous teams of robots, which is considered a highly limited class of systems. The problem of batteries with high *power supplies* and components with low *power consumption* limits the operation time of distributed robot swarms. Finally, the issue of *distributed control and sensing* is largely unresolved. In complex information systems this issue has recently received some attention in terms of information fusion, but so far no satisfactory solutions have been reported, that would scale to large scale systems that carry our a number of time-varying tasks.

Additionally, there exists a clear lack of standards for interoperation of vehicles and systems. The absence of experimental sites where multiple vehicles and sensors can be tested and integrated in a real system hinders the integration process, which involves defficient cooperation among R&D institutions in Europe. So far, there have only been poor interdisciplinary approaches to systems analysis, design, development and implementation. Only little effort has been spent on cooperation with potential end-users, which include scientists, civil defense and the industry. Finally, there is only poor dissemination of networked automation issues and challenges so far.

5.6 Technological driving forces

Mechatronics and *computer networking* can be considered as major driving forces of network robotics. *Miniaturization* is the mechatronic key aspect since only mechatronic systems which are sufficiently compact and integrated and evince low power consumption can be manufactured and employed in large numbers. So miniaturization is a key concept to be economically successful.

Computer networks, especially low power consuming, short range data transmission in ad-hoc structured networks, provide the needed communication facilities for the single agents to settle task distribution, scheduling and execution. One can conclude that the intelligence of network robots is formed less by the single agent but more by their close coupling and fast data distribution.

5.7 Benchmarks

Since network robotis is a comparatively young field in which many new ideas and researchers are being incorporated and, at the same time, it is an area of increasing importance and rapid expansion in terms of people and funding.

Defining benchmarks and their associated metrics is perceived by experts in the network robotics field as both very interesting and certainly possible, since there are so many proposals for system designs of networked robots, that it would be mandatory to compare performances. Otherwise everybody would get lost in all the available design proposals.

Benchmarks should include both datasets available in a public repository together with well-defined tasks and associated rules to be performed in a way similar to robot competitions. Also, suitability of the one datasets or the other competitions mainly depends on the given tasks. The emphasis should be in the comparison of different approaches/algorithms running on different hardware. Interest is increasing to form a working group or forum on networked robotics to deal with these issues.

Since networked robotics covers a number of areas, so a number of different benchmarks might be appropriate e.g. online robots. In this sub-area one performance-oriented benchmark would be the time required for a remote robot system to respond to an instruction from an operator. A server could be set up that aimed to attack a remote robot site with instructions (good and bad) and get a measure of reaction/return to the operators site. Such a site could be set up for different types of networked robotics scenarios. In this domain, performance is very much influenced by link bandwidth and inherent link delays, a fact that should clearly be taken into account by the benchmarking procedure in order not to render the validity of the benchmark useless.

5.8 Scientific challenges

Research on networked semi-autonomous and autonomous vehicles and systems presents challenging topics to robotics, control, computer and communication scientists. Although we have witnessed over the last decade impressive advancements in control, communication and computation, and a trend to the convergence of their methods and theories, we are still far from being able to design these systems in a systematic manner and within an appropriate scientific framework. As a result of these impressive advancements, research groups in Europe, and in the United States, have developed world class expertise in specific topics within control, communication, and computation. Moreover, and pushed by technological developments and applications requirements, practitioners and technology developers have developed visions for systems that could have not been imagined before thus pressing for further scientific developments.

Advances in these areas will require a significant expansion of the basic tool sets from each area. The complexity of the dynamics and control problems involved in the operation of these systems are on the boundary of what can be done with available methods. Future applications in science and information systems are well beyond what we can do now. It is not be enough to simply take existing tools and apply them in new areas: fundamentally new techniques must be developed that expand and complement the existing state of the art. Furthermore, these advances will require an inherently interdisciplinary approach, bringing together researchers from traditionally separate communities to work on problems at the forefront of science and technology.

Now it is the time for synthesis. The time is ripe to bring together niches of expertise disseminated throughout Europe to promote an interdisciplinary approach to these challenges and to explore the possibilities of developing future collaborative actions based on a shared view of the challenges and of the underlying scientific issues. This is a long term effort which has to be maintained synchronized with specific technological developments in order to respond properly to the necessary paradigm evolution. There are several reasons for this:

1. Potential contribution to new research developments and to a new collaborative research model.
2. The novelty of the networked automation.
3. The topic can add value to existing theories and technologies developed in niches of European expertise, by enhancing their potential to address these scientific challenges.
4. The topic may leverage the activities and research at the European level in cooperative robotics, embedded systems, and service networks by providing a scientific framework where integration is the keyword, and where we can start envisioning systems of systems.
5. A research program in this area will contribute to mitigate the emigration of promising young researchers to other countries where there is great potential for synergistic research on this topic.
6. Cooperation at the European level is probably the only effective way of spearheading research on networked vehicles and systems due to the intense international competition that the European scientific institutions will be facing on this topic in a near future.
7. Potential contribution to Europes research agenda.
8. The research challenges are posed by a wide variety of applications, aviation, automotive, communications, (road, railway, air and ocean) transportation, space, etc., at the European scale.

The success, or failure, of European research and development on networked automation strongly depends on research and development model adapted to the specific aspects of networked automation discussed above:

- Interdisciplinary approach to bring together the fields of expertise required to address the scientific and technological challenges.
- Technological push and applications pull to link technological developments to applications as soon as possible so that societal and economic benefits become immediately tangible, and also to contribute to the dissemination of results, and the exploitation of developments. This means the interaction of the robotics community with scientists and application developers, as well as with the industries supporting these applications.
- Involvement in the development of standards and lobbying for new standards concerning interoperability of systems.
- Develop new courses to provide future researchers with the level of understanding required to address a broad collection of problems in science and technology. It will be especially useful to involve industry, university and research institutes in these initiatives, and to promote mobility through internships and visiting positions.
- Strengthen international cooperation with leading institutions outside Europe to promote technological exchange and to define a background against which EU developments are measured and compared.

In summary, research and development on networked automation will strongly benefit from a model of networked cooperation both at the EU level and at the international level, articulating a technological push and applications pull, and contributing to the development to new curricula, more adapted to the underlying technological and scientific challenges.

Typically, technology experimentation for networked vehicles and systems is quite complex and demanding due to the sheer complexity of the system, to the lack of appropriate testing grounds, the lack of previous experience in experimental deployments of such dimension, and also to the lack of interoperability of vehicles and systems.

Open simulation experimental platforms, where researchers and developers can evaluate and test their technologies are a fundamental enabling technology to facilitate testing and development and to decrease the time to real experimentation, as well as the integration of tools and technologies.

This suggests two parallel tracks for technological development and simulation experimentation and for technological experimentation in applications. By focusing efforts on these parallel tracks and on transitioning technologies the development stage to the experimentation stage the benefits of synergies are maximized and the time-to-new applications reduced. Moreover, this facilitates the involvement of all types of players, from the big institutions to the small companies and universities.

5.9 Future research acitivities

Experimental sites: Cooperation with on-going activities on several application domains is sought so that permanent or quasi-permanent experimental sites are available for technology experimentation and transitioning. Relevant applications are:

- Earth sciences.
- Civil defense.
- Automated highways.
- Automated transportation.

Standards:

- Inter-operability of communication and sensor networks. These are in the process of being developed.
- Inter-operability of vehicles and systems. These are some standardization efforts being developed by the military. Similar efforts are required for civilian applications.

Technologies:

- Models of distributed systems with evolving structure. Several avenues are possible: articulation of models of computation; dynamic networks of hybrid automata; Pi-calculus and derivations; configuration automata.
- Hierarchic and layered control. This poses questions in terms of multiple world semantics versus one-world semantics, aggregation of models and consistency, equivalence of behaviors and specification.
- Code mobility. This is especially important when application upgrades are required for components of a system which is required to operate without interruptions, and where components come and go. The deluge dissemination model presents an interesting research avenue.

- Middleware for distributed and real-time systems. This area of research is still in its infancy and it aims at providing the glue behind the operation of the system.
- Group coordination and control. Work on this topic has been restricted to formation planning and control. More advanced concepts and controllers are needed, especially in relation to systems whose components come and go, and with several levels of interoperability, which may include for example handover of controller links. This can be done in the framework of dynamic networks of hybrid automata, within adequate layers of distributed controllers.
- Simultaneous localization and tracking. The integration of sensor networks with vehicles carrying sensors leads to new problems in this field. The challenges come from the distributed nature of the system, from active sensing capabilities provided by vehicles, and from limited communication capabilities.
- Control and coordination over networks. This field is still in its infancy and developments should parallel developments in hierarchical control where problem decoupling is addressed.
- Control of networks. In networked vehicles and systems the communication networks presents different properties which depend on the positions and roles of these vehicles and systems. This poses new communication network control problems in addition to the ones which represent the current state of the art.
- Closing control loops on natural phenomena. The problems of using motion controlled sensors, i.e. vehicles with sensor payloads, to track natural phenomena or to find phenomena occurring in nature are basically open, especially in what concerns coordinated motion planning and sensing.

Tools: The development of these tools should be accompanied by the development of interoperability standards.

- Command, coordination, and control frameworks.
- Open simulation platforms.
- Planning tools.
- Control design tools.
- Human-computer interaction.
- Code generation and verification.
- Frameworks to support the systems engineering process.

The importance of attempts to predict the future of technological development is probably more significant for its role as a discussion enabler, than for its accuracy. This is exactly the approach taken in this outline. An attempt to organize these efforts is proposed in table 2 and 10.

Sequence	Standards	Tools	Technologies	Demonstrations
1	Vehicle interoperability	Command control and coordination, Open simulation platforms	Models of distributed systems with evolving structure, Hierarchic and layered control, Middleware for distributed and real-time systems, Group coordination and control, Control and coordination over networks, Control of networks, Closing control loops on natural phenomena	Heterogeneous vehicles and sensor networks under a coordination and control framework with mixed initiative interactions with low levels of interoperability, Wireless automation in factories
2	System interoperability	Human-computer interaction, Code generation and verification, Frameworks to support systems engineering process	Models of distributed systems with evolving structure, Hierarchic and layered control, Middleware for distributed and real-time systems, Group coordination and control, Control and coordination over networks, Control of networks, Closing control loops on natural phenomena, Code mobility, Simultaneous localization and tracking	Air, ocean going and sensor networks under a coordination and control framework with mixed initiative interactions with high levels of interoperability, Automated transportation systems
3	Revisions	Command, coordination, and control frameworks, Human-computer interaction, Code generation and verification, Planning tools, Control design tools	Evolutions	Evolutions

Table 2: Future research goals in network robotics in the next 15 years

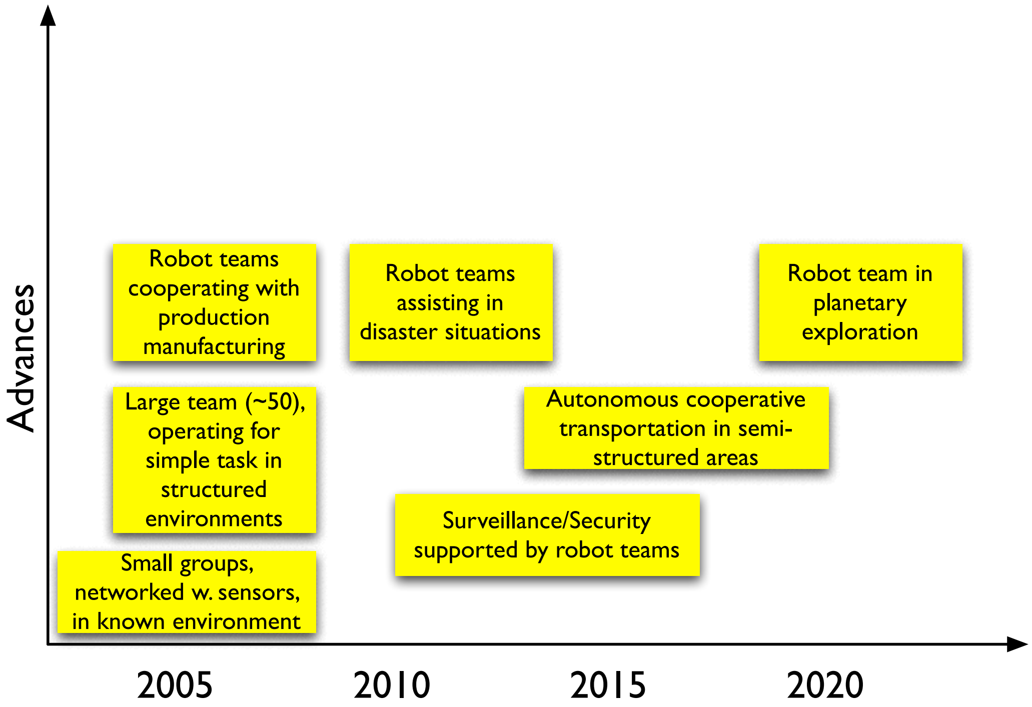


Figure 10: Approximate timeline for the future development of network robotic systems

6 Outdoor robotics

6.1 Introduction

The domain of outdoor Robotics encompasses the applications where the robots are usually acting in outdoor semi-structured or unstructured environments. Examples span from agriculture and forestry over mining, construction, rescue, fire surveillance and fighting, intervention in hazardous environments to planet exploration (including natural landscapes on Earth, such as Antarctica), autonomous driving and military. Outdoor robotics does not only include terrestrial robots but also extends to other kinds of vehicles such as blimps, helicopters and drones, especially for reconnaissance in military applications.

6.2 Economical and societal driving forces

Among the problems of todays mobility, *safety* is probably of a the major concern (in Europe, there is an average of 150 deaths due to automobile accidents each single day. the equivalent of an airplane crash). The *increasing transportation problems*, partially caused by the *changing living patterns* including mobility in European cities are also one of the problems to be addressed at both the research and industrial level. With resources becoming scarce and *climbing oil prices* the issue of reducing fuel consumption with semi-autonomous driving aids is receiving more and more attention. On the other side, autonomous cars and driving assistants are expected to provide additional *convenience* to travelling people. Solving these problems require to develop emerging technologies in the field of ITS (Intelligent Transportation Systems) and of IV (Intelligent Vehicles). Automobile industries have a great interest in improving technologies like adaptive cruise control, lane departure warning or night vision enhancement to gain and defend technological competitive advantages.

Desaster management, underwater vehicles, the detection of natural resources and the *exploration of foreign planets* drive the need for vehicles and robots that (semi-) autonomously explore rough terrains with only little supervision of a human operator. They are applied in areas where it is higliy dangerous or impossible for humans to soujourn and operate.

Agrarian applications of outdoor robotics are likely to become an important trend in outdoor robotics in the near future. Pricing pressure and high labor costs require agriculturists to introduce highly specialized and productive machines to the fields and plantations. Walking robots might become important for forestry applications, as they exert less destruction to the soil structure and the covering vegetation.

The *military* is very interested in autonomous vehicles for logistics and troop carriers. Following September 11th, there is an increased need for airspace surveillance that could be performed using unmanned aerial vehicles, which could show different levels of autonomy.

6.3 Objectives

The main objective in outdoor robotics and all application areas listed in the preceding section are to *increase the autonomy* of the systems already working. These systems also lack *robustness and reliability*, which becomes of vital importance as systems are permitted a larger autonomy. *Fault detection*, fault *correction* and fault *tolerance* measures on all system levels will be of high relevance to achieve higher reliability and autonomy.

The main objective in semi-autonomous assistive systems is to accelerate the development of *driving assistance* techniques like adaptive cruise control and of novel transportation systems. A major part of the work will involve the improvement and testing of key technologies for better guidance, *collision* *avoidance, fleet management*, and for the development of simple standard *user interfaces*. The operational objectives will be a significant improvement in the performances of the various components and/or a significant decrease in cost. Great efforts have to be made to establish new technologies like pedestrians safety systems. The aim is to improve the safety of automobiles considering increasing traffic and the one hand and on the other hand to enhance the comfort of the human driver.

Public use of some outdoor robots should be a short-term goal for outdoor robotics in order to get European people to see the use and potential of robots in the future. This is expected to generate a robotics market, industries and jobs.

6.4 State of the Art

Large R&D programmes for developing technologies in the field of ITS and IV have been launched in the last decade in Europe, USA, and Japan; large scale demonstrations have also been conducted in these countries : Prometheus demo on Driving Assistance in France (1994), IV exhibition in Netherlands (1998), Automated Highway System (AHS) demo in Japan (1995, 1996), Smart-Cruise 2000 demo in Japan, AHS demos in USA (1997, 1999), IV Technology Showcase 2000 in USA. Some of the demonstrated technologies are almost ready for being transferred to industry, but most of them require further developments for being really applicable in real life situations.

Japan is strongly involved in the development of IV technologies for both the domestic market and the international market (including Europe). The related R&D is conducted through both several Government/Public projects and some Private Sector product developments. The government/public projects are conducted and supported by several ministries including the MLIT (Ministry of Land, Infrastructure and Transport), and by a public-private partnership organization called AHSRA (Advanced Cruise-Assist Highway Systems Association); the main projects are the followings: Advanced Safety Vehicle (ASV), Advanced Cruise-Assist Highway Systems (AHS), Super-Smart Vehicle Systems (SSVS). The private sector (i.e. the Japanese automotive constructors and OEMs suppliers) is strongly interested in developing and selling advanced vehicle control and safety systems. The Japanese industry takes advantage of the atypical characteristics of the domestic market, which allows them to introduce products that would not be considered acceptable in maturity in other parts of the world; the main developments are the followings: Advanced Cruise Control (ACC), various warning systems such as lane departure warning systems or collision warning systems, and fully automated driving systems such as the Intelligent Multimode Transit System (IMTS) of Toyota or the Intelligent Community Vehicle System (ICVS) of Honda.

Several large R&D projects on ITS have been launched in the last decade in the *USA* at both the Government/Public level and the Private Sector level. Some of these projects have recently been stopped, some of them are still alive with a 10 years perspective. Among the existing Government/Public projects, the most significant results and programmes are those related to the California Path program aimed at developing vehicle-highway automation technologies (since 1988), the Intelligent Vehicle Initiative program aimed at enhancing driving safety, and the Minnesota DOT programs aimed at developing IV technologies for snowplows, trucks, or buses. The DARPA has announced a challenge for autonomous vehicles (http://www.darpa.mil/grandchallenge/). The aim is to motivate researchers to develop vehicles which are able to drive a certain distance of approximately 400km in partially unstructured environment. The first demonstration in 2003 showed, that non of the vehicles was able to fulfil the whole course. Only two years later, in 2005, the DARPA challenge has been met by several cars. R&D developments in the private sector includes technologies for ACC, collision and lane departure warning, manoeuvring aids, and night vision enhancement.

Research on transport in *Europe* is carried out at basically three levels : at the Industrial level without any government support (sometimes with the involvement of public or private research organisations under contract from the industry), at the National level through contracts or research grants, usually involving several partners, and at the European level through research contracts awarded by the European Commission under different procedures (see section 8). There exists also another light procedure to do research between two or more European partners with public funding: the Eureka procedure. Several countries such as Germany, Italy, Netherlands, and France have national programmes for encouraging and supporting R&D in the fields of ITS and IV. The Netherlands is probably one of the pioneers in transportation research in Europe, with the support of the ministry of transport and public work (Rijkswaterstaat), of private research organisations such as TNO, and of industry; the estimated budget for this national program should be in the order of 150M. In France, the research on this topic is mainly supported by the government through several ministries (ministry of research, ministry of transport, ministry of industry, ministry of city) and research organisations such as INRETS (National Research Laboratory on Transport and Safety) or LCPC (National Research Laboratory on Road Infrastructures). The research is organised under global four years duration programmes (like European programmes), e.g. the Predit1 programme (1998-2002) or the Predit2 programme (2002-06) having a large part focussing onto Intelligent Road. Under these programmes, the ARCOS project for driving safety enhancement involves about 50 French industrial and academic (including INRIA and CNRS) partners with a budget of about 12M

CMU has undertaken a large number of projects in *Field robotics: mining, agriculture* (robotized harvester and tractor), *planetary exploration* (Ambler, Dante, Nomad) . Worthy of note is that Nomad is the only robot that operated autonomously in Antarctica in 1999. Indeed, planetary exploration was one of the motivations for several developments in field robotics, with applications in terrestrial robots in extreme environments.

There have been comparatively few projects funded by the EU on this topic in the late 80s and early 90s. The ESPRIT PANORAMA project aimed at studying perception and navigation for field robotics applications (forestry, mining). The Eureka AMR project objective was autonomous intervention robots for civil security applications. The Eureka projects CITRUS (robot for citrus harvesting and handling) and ROSAL (robot for the handling and grafting of rose plants), funded by Spain and France, and MAGALI (apple harvesting) are examples of the European research effort in agriculture robotics during the nineties.

6.5 Bottlenecks to progress

Nowadays field and service robots are already employed in adverse or inaccessible environments or are performing dirty works like cleaning or transporting etc. But at the moment, there are still huge overall problems in areas like *navigation* or *sensor systems* and *processing sensor data*. Another main issue is the interaction with humans and the ability to learn and cope flexibly with new situations and tasks. So far, these systems are not able to interact with humans beyond their control systems and are very limited in terms of learning, adaptivity, cooperation etc.

In automobile robotics and autonomous driving systems, *cognitive perception* is the main bottleneck to further progress. Existing sensors are exposed to huge ranges in *weather conditions*. The amount of noise and drift depend on the environmental situation and the sensors should are not yet robust to rain, wind, fog or darkness. *Real-time analysis* of accumulating data, especially visual data, is still a challenging problem. On higher cognitive levels, there are many unsolved problems like *scene interpretation, decision making* and the unconditional compliance with *safety standards* at every moment.

In underwater robotics, it is still a great challenge for an autonomous robot to *navigate safely* to a certain point on the sea ground. This issues is even worse taking into account the drift by *underwater* *currents*. Problems like navigation, control etc. occur comparably in other areas of field robotics. New, biologically inspired *propulsion technologies* have not displayed good, scalable results yet. *Communication bandwidths* are very limited, which reduces telemanipulative human interventions to an absolute minimum and requires a very high level of autonomy.

6.6 Technological driving forces

Two driving forces in outdoor robotics are nearly the same for all fields of application:
Mechatronics will continue to improve existing components. One of the main critical issues is *miniaturization*, as it allows to build lightweight systems with lower energy consumption. Additionally, smaller components are more easily shielded from adverse conditions in the environment, like high pressure in underwater missions, weather conditions in autonomous vehicles or radiation, insolation and rapid temperature changes in space applications.
Sensor components have to be adapted to cope with the specific environmental conditions they are subjected to during their missions. This is, e.g. the low range of vision in underwater robotics. Reliable high-resolution 3d sensors will take over important jobs in perception and navigation.

6.7 Benchmarks

Several benchmarks test and compare outdoor robots:

- The *2005 DARPA Grand Challenge* wass a field test that required autonomous robotic ground vehicles to successfully navigate a course that covers approximately 200 miles of off-and on-road terrain that is cleared of non-participating vehicles. Competitors entries had to be unmanned, autonomous ground vehicles, and could not be remotely driven. Boundaries defined the course, and vehicles that got outside of them were disqualified. Each vehicle was trailed on the course by a manned control vehicle equipped with an emergency stop system to prevent collisions and other unsafe situations. In 2007, DARPA Urban Challenge features autonomous ground vehicles conducting simulated military supply missions in a mock urban area. It will forcus on autonomous vehicles that can navigate and operate in traffic, a far more complex challenge for a ’robotic’ driver.

- Part of the ROBOCUP rules is the Walking-Across-Rough-Terrain-challenge. The rough terrain is a rectangular of hexagons, each of which has a side length of 4 cm and is of different height. The length of the longer side of the rough terrain is about 1.5m; the length of the shorter side is around 1m. The height of the hexagonal tiles varies between 9mm and 24mm. Small-sized legged robots start in fromt of one long sides and have to walk across the terrain without falling. The time needed to cross the terrain is the measure of performance.

- The *RoboCupRescue - Robot League* competition is an international evaluation conference for the RoboCupRescue Robotics and Infrastructure Project research. A team of multiple (autonomous or tele-operated) robots moves inside a testbed, divided in 3 regions of increasing difficulty levels, searching for victims and building maps of the surrounding environment, to be transmitted and/or brought back by the robot(s) to the human operators.

  The objective for each robot in the competition, and the incentive to traverse every corner of each arena, is to find simulated victims. Each simulated victim is a clothed mannequin emitting body heat and other signs of life, including motion (shifting, waving), sound (moaning, yelling, tapping), and/or carbon dioxide to simulate breathing. Particular combinations of these sensor signatures imply the victims state: unconscious, semi-conscious, or aware.

It requires robots to demonstrate their capabilities in mobility, sensory perception, planning, mapping, and practical operator interfaces, while searching for simulated victims in unstructured environments.

6.8 Benchmarks

Several benchmarks are interesting testbeds for household robots:

- The *Robotcup Soccer* offers test scenarios for various abilities of household robots. Though concerned with robots playing soccer, it serves to test design principles of autonomous agents, multi-agent collaboration, strategy acquisition, real-time reasoning, robotics, and sensor-fusion, which all apply to robots acting in the household domain. The final goal is to have a team of fully autonomous humanoid robot soccer players that win the soccer game, complying with the official rule of the FIFA, against the winner of the most recent World Cup.

  Robocup is structured in several leagues, of which the Humaoid League is of particular importance. Humanoid robots show basic skills of soccer players, such as shooting a ball, or defending a goal. This benchmark could become an important testbed for humaoid robots.

- *Cleaning Robots contest*: the first international cleaning robot contest took place in 2002 and consisted of several disciplines: The goal of the floor cleaning category was to clean within 10 minutes 5x5m room as good as possible. The floor was covered with sugar. The scoring was based on the area cleaned (number of cleaned tiles 50x50cm).

- *Grasping Database:* A dataset of sensor readings of a humanoid robot during grasping tasks is part of the Radish repository (see http://radish.sourceforge.net). It was collected from the NASA Robonaut during human teleoperation. Robonaut was teleoperated to perform 45 grasp trials of a vertically oriented wrench. The wrench was placed at 9 different locations in the robot workspace with 5 trials to each location. The provided data contains readings from various force and tactile sensors on the arm and hand on Robonaut used grasping.

6.9 Scientific challenges

In order to advance beyond the obstacles in outdoor robotics, science has to cover four main areas in the future: sensor technologies, cognition, navigation and execution.
Sensor technology has to provide robust, reliable and failsafe perceiving units. So research has to be done towards intelligent sensors, capable of auto-diagnosis and fault-correction. Robustness has to be increased in order to face changing weather conditions and environmental peculiarities.
Cognitive methods and techniques have to be developed that can deal with highly unstructured environments and complex task domains. *Models* and concepts for describing, assessing and interpreting the environment of the outdoor robotic system have to be designed and tested by example applications. Once these models are available in sufficient details, *intelligent reasoning* can be applied on the descriptions of the environment, leading to means of decision support or *decision making* systems. Safety confirmations have to be enforced throughout all levels of system design and implementations, especially in automobile robots that operate in human populated environments.

Precise *navigation without artificial landmarks* is still another open problem to be solved. This involves *self-localisation* from noisy and potentially incomplete sensor data, the construction of (three-dimensional) *models of the near and far environment* of the autonomous robot and the development of high-resolition *maps with specific focus on natural landmarks* suitable for easy and robust detection in sensory data.

Execution and control methods are the last future challenges. They have to take into account rough and unstructured domains of operations, as well as impacts from the environment on the proper execution of movement or manipulation movements, induced for example by weather conditions or underwater currents.

6.10 Future research acitivities

Considering the development of vehicles being capable of driving fully autonomously, the DARPA Challenge demonstration has shown impressively that much effort is needed further on. While technologies for semi-autonomous driving increase the safety in special traffic situations, research of autonomous vehicles could lead to intelligent driving assistant systems which improve safety importantly, because these systems should have an understanding of the actual scene and are therefore able to react and assist accordingly. Many fundamental research is needed although research in autonomous vehicles started in the 1980s. But in the early days research was mainly concentrated in driving under well defined conditions like constant daylight and well structured highways. Therefore the next steps should lead to an improvement of technologies dealing with road surface and lane detection, detection and evaluation of traffic signs, obstacle detection to mention a few. Efforts have to be made to improve person detection and the detection of other traffic participants in order to understand their intentions and to be able to react accordingly. Progress has to be made to enable driving on lesser structured lanes likes inner-city streets or also country lanes. Last not least it is desirable to be able to drive in disadvantageous weather conditions like rain, fog or snow and even at night.

The following key factors of the area of outdoor and field service robots can such be distinguished:

- Modular and expandable build up systems
- Intuitive (standardized) interaction with humans
- Easy programming methods
- Standardized (world wide) knowledge base
- Vast perceptive and cognitive abilities

The development will be based on the identified enabling technologies. The most important factors will be:

- Cognitive components enabling intelligent interaction with the human
- Power systems for long duration outdoor performance
- Highly developed mechanical component
- Intelligent control for difficult tasks in service and field applications

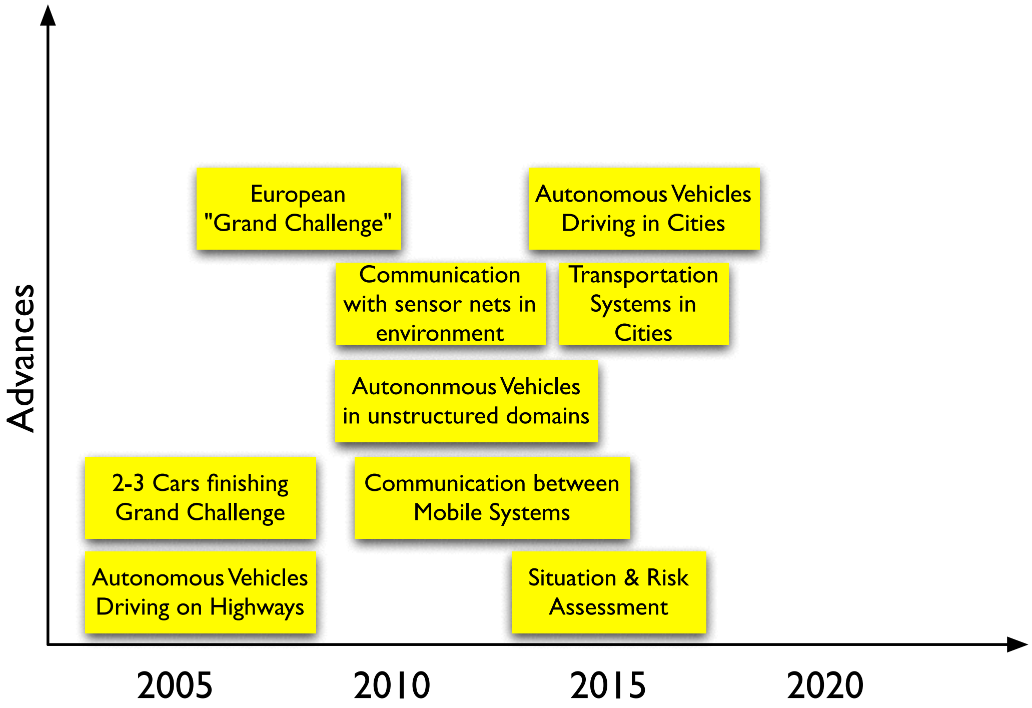


Figure 11: Approximate timeline for the future development of outdoor robotics

For intelligent vehicles, one aspect which has to be considered with respect to an efficient use of the traffic infrastructure is the communication among traffic participants. Multi-agent approaches could be inspected to optimize traffic flows. Driver assistance systems will require new types of human-machine-interfaces. Ideally the future driver assistance system will not be recognized by the driver but just acting safely.

Summarizing, the following key areas are central for the development of intelligent vehicles and outdoor robtotics in the next 20 years:

- Improved sensor technology and 3D-vision
- Advanced methods for sensor data analysis (detection and tracking)
- Cognitive methods for scene understanding, interpretation and assessment
- Reasoning methods on the environmental influences and own abilities
- Decision making and intelligent behaviour
- Localisation and Navigation
- New system concepts for intelligent vehicles
- Human-Machine-Interface for driver assistance systems

The development is forecast to reach several steps at the times specified by figure 11.

7 Health care and life quality

7.1 Introduction

In the last years, all industrialized societies are facing similar problems centered on the issue of aging: The excess of births over deaths has disappeared, leading to degenerated age pyramids. The share of people of age less than 30 is continually decreasing while the amount of elderly people rises. Elderly people tend to have more diseases and require more medical treatments than the younger. Therefore the number of medical treatments, especially surgetical operations, are increasing, while the number of young and well trained health professionals is about to drop. One possible solution to this problem is to provide the medical and nursing staff with robotic aids that allow them to accomplish their tasks in more time efficient manners. Another problem related to aging societies are the increased costs in the health care systems faced by the industrial countries. Again, new efficient techniques, partially applying mechanical and robotic aids can help to reduce the costs and ensure the survival of public health care systems. The main scientific challenges are identified in the field of assistive technologies to support elderly and handicapped persons in their home environment; in surgery and in rehabilitation. Further development of medical and surgical robotics is one of the key trends to track for Europes scientific community in order to address the societal changes in the next few decades.

7.2 Economical and societal driving forces

According to the National Health Interview Survey (NHIS) 1990 results, more than 13.1 millions American people (about 5.3% of total population) use assistive technology (AT) devices to compensate their physical disabilities. In todays aging societies this portion is likely to increase even more. Potential benefit of AT in improving functional self dependency of disabled patients, well known in rehabilitation practice, has been reported in a number of legislative acts in different countries. Medical robotics are likely to address another factor of aging societies: They might fulfill the prophecy of increasing quality of medical treatment by contributing their high positioning accuracy and precision while helping to reduce costs in health care systems with their speed and repetitive abilities. Medical technology established another focus in medical robotics: the training of surgeons and the computer aided surgical planning. VR/AR techniques in training systems enable prospective surgeons to repeatedly train surgery missions in a realistic environment, enabling them to improve their skills and the quality of treatment. Preoperative planning by the use of accurate anatomical and biomechanical models allows simulating incisions, predicting the outcome and determining the best operational strategy. This will result in a reduced risk for the patient, higher quality in surgical treatment and more effective interventions. Intraoperatively, new assistive technologies for navigation and AR techniques are emerging to support the surgeon. Their main advantages are lower costs in comparison with autonomous systems.

7.3 Objectives

According to the National Health Interview Survey (NHIS) 1990 results, more than 13.1 millions American people (about 5.3

7.4 State of the Art

The application of robotics in rehabilitation, in particular in the assistance to disabled and elderly people, has been investigated in the last decades by many research groups, especially as an answer to a growing social need. A variety of solutions is thus available, at different levels of technological complexity. Some examples for assistive technologies can be seen in 12 and 13.

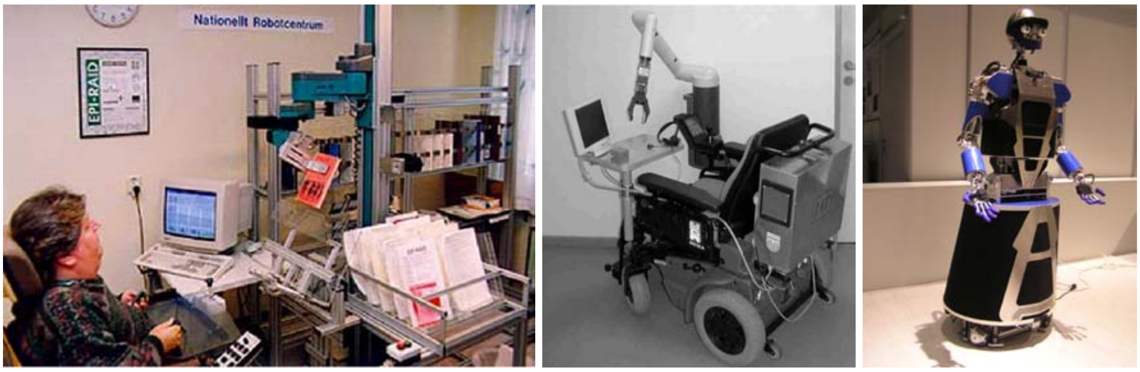


Figure 12: (left) RAID system (EU); (middle) Assistive Robotic Manipulator ARM (Netherland); (right) personal robot ARMAR (Germany)

Figure 13: (left) NurseBot (USA); (middle) Care-O-Bot (Germany); (right) CareMedia (USA)

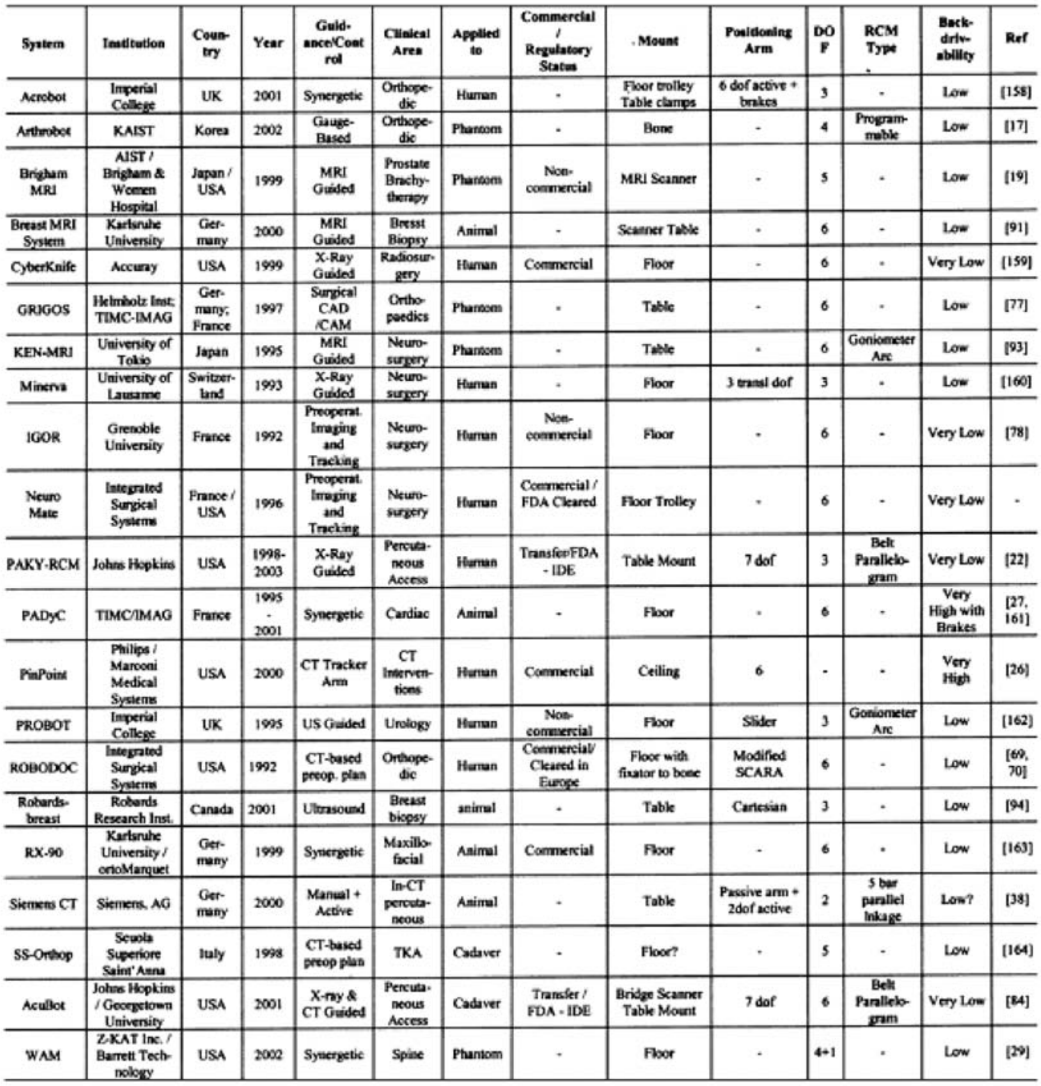
Rehabilitation robots have been developed as a therapeutic tool to help retrain voluntary movement control for individuals who have sustained a local or central nervous system injury. As examples for upper extremity rehabilitation devices, one could mention the GENTLE/s manipulator developed at the University of Reading (UK) and the ARMguide as well as the manipulandum at the Rehabilitation Institute of Chicago. In addition, robots used for lower limb rehabilitation include the Lokomat from Hocoma AG, Volketswil (Switzerland), the AutoAmbulator from HealthSouth, Birmingham, Alabama (USA), and a variety of experimental devices such as those at the University of Tsukuba (Japan) and the University of California at Los Angeles (USA). Though slightly different in design, all share common elements: exoskeletons with robotic linkages that attach to the patients legs, a treadmill and a mechanism that provides weight and balance support. Artificial robotic limbs are currently in their infancy. There are some prototypes of prosthetic limbs available that respond to neuromuscular signals. As an example for the hand one could mention the Fluid Hand P4 which was developed at the Forschungszentrum Karlsruhe (Germany). The Berlin Heart AG has developed a commercial available artificial vital implantable left ventricle assist device (Incor). This device is designed to take over the work of the left ventricle on a permanent basis. Naturally, it is also used in the Bridge to Transplant and Bridge to Recovery programs.

Figure 14: Rehabilitation robotics (left) LokoMat (Hocoma AG, Switzerland); (right) prosthetic arm controlled by the monkeys brain signals (University of Pittsburgh)

[h]
The possibility of replacing human senses by artificial sensors can be shown by the development of artificial human vision (AHV). Currently there is only one commercially system available which is based on the cortical surface stimulation developed at Dobelle Institute Zurich (Switzerland).

Figure 15: Commercially available surgical robots (left) daVinci (Intuitive Surgical Inc.), (right) AESOP (Computer Motion Inc.)

Robots are also applied to directly assist a surgeon. Several robots for this field of application have been developed. ROBODOC was designed by IBM together with the University of California. Since 1992 thousands of total hip replacements have been performed with this tool around Europe. While every precise during execution, ROBODOC has not been FDA approved and is recently suspected to cause severe long-run damages to patients. A similar system, the CASPAR robot for hip a knee replacement and craniofacial surgery has been developed by Ortho-Maquet in Germany and was afterwards sold by URS Ortho. However, both companies are insolvent today and systems must not be used in clinical environment any longer. The AESOP system for minimally invasive surgery was the first product that got FDA approved for clinical use in the US in 1994. Its speech control is until now one of the most intuitive handling concept. The product is sold by Intuitive Surgical Inc., as well as the telemanipulator Da Vinci.



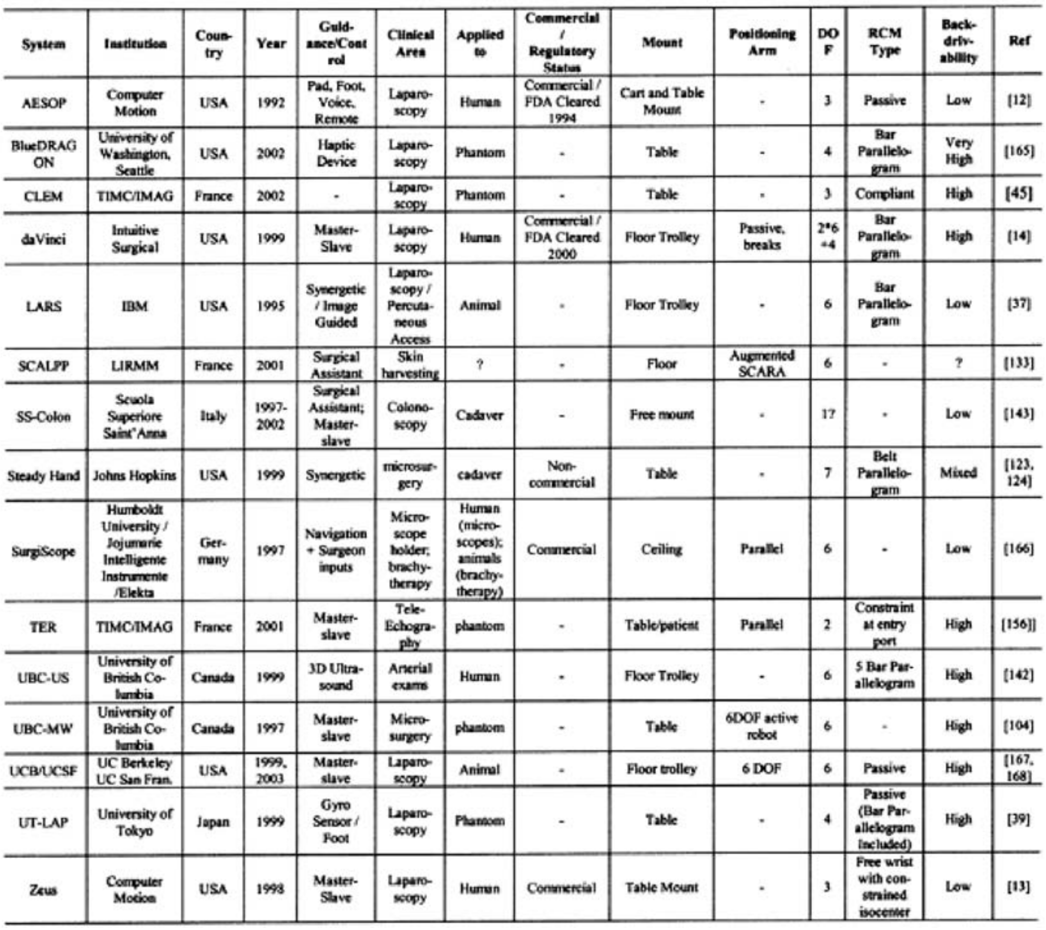
System	Institution	Country	Year	Guidance/Control	Clinical Area	Applied to	Commercial / Regulatory Status	Mount	Positioning Arm	DOF	RCM Type	Backdrivability	Ref
Acrobot	Imperial College	UK	2001	Synergetic	Orthopedic	Human	-	Floor trolley Table clamps	6 dof active + brakes	3	-	Low	[158]
Arthrobot	KAIST	Korea	2002	Gauge-Based	Orthopedic	Phantom	-	Bone	-	4	Programmable	Low	[17]
Brigham MRI	AIST / Brigham & Women Hospital	Japan / USA	1999	MRI Guided	Prostate Brachytherapy	Phantom	Non-commercial	MRI Scanner	-	5	-	Low	[19]
Breast MRI System	Karlsruhe University	Germany	2000	MRI Guided	Bresst Biopsy	Animal	-	Scanner Table	-	6	-	Low	[91]
CyberKnife	Accuray	USA	1999	X-Ray Guided	Radiosurgery	Human	Commercial	Floor	-	6	-	Very Low	[159]
GRIGOS	Helmholz Inst; TIMC-IMAG	Germany; France	1997	Surgical CAD /CAM	Orthopaedics	Phantom	-	Table	-	6	-	Low	[77]
KEN-MRI	University of Tokio	Japan	1995	MRI Guided	Neurosurgery	Phantom	-	Table	-	6	Goniometer Arc	Low	[93]
Minerva	University of Lausanne	Switzerland	1993	X-Ray Guided	Neurosurgery	Human	-	Floor	3 transl dof	3	-	Low	[160]
IGOR	Grenoble University	France	1992	Preoperat. Imaging and Tracking	Neurosurgery	Human	Non-commercial	Floor	-	6	-	Very Low	[78]
Neuro Mate	Integrated Surgical Systems	France / USA	1996	Preoperat. Imaging and Tracking	Neurosurgery	Human	Commercial / FDA Cleared	Floor Trolley	-	6	-	Very Low	-
PAKY-RCM	Johns Hopkins	USA	1998-2003	X-Ray Guided	Percutaneous Access	Human	Transfer/FDA - IDE	Table Mount	7 dof	3	Belt Parallelogram	Very Low	[22]
PADyC	TIMC/IMAG	France	1995 - 2001	Synergetic	Cardiac	Animal	-	Floor	-	6	-	Very High with Brakes	[27, 161]
PinPoint	Philips / Marconi Medical Systems	USA	2000	CT Tracker Arm	CT Interventions	Human	Commercial	Ceiling	6	-	-	Very High	[26]
PROBOT	Imperial College	UK	1995	US Guided	Urology	Human	Non-commercial	Floor	Slider	3	Goniometer Arc	Low	[162]
ROBODOC	Integrated Surgical Systems	USA	1992	CT-based preop. plan	Orthopedic	Human	Commercial/ Cleared in Europe	Floor with fixator to bone	Modified SCARA	6	-	Low	[69, 70]
Robards-breast	Robards Research Inst.	Canada	2001	Ultrasound	Breast biopsy	animal	-	Table	Cartesian	3	-	Low	[94]
RX-90	Karlsruhe University / ortoMarquet	Germany	1999	Synergetic	Maxillofacial	Animal	Commercial	Floor	-	6	-	Low	[163]
Siemens CT	Siemens, AG	Germany	2000	Manual + Active	In-CT percutaneous	Animal	-	Table	Passive arm + 2dof active	2	5 bar parallel lnkage	Low?	[38]
SS-Orthop	Scuola Superiore Saint'Anna	Italy	1998	CT-based preop plan	TKA	Cadaver	-	Floor?	-	5	-	Low	[164]
AcuBot	Johns Hopkins / Georgetown University	USA	2001	X-ray & CT Guided	Percutaneous Access	Cadaver	Transfer / FDA - IDE	Bridge Scanner Table Mount	7 dof	6	Belt Parallelogram	Very Low	[84]
WAM	Z-KAT Inc. / Barrett Technology	USA	2002	Synergetic	Spine	Phantom	-	Floor	-	4+1	-	Low	[29]

Figure 16: Overview of surgical robot systems [TS03]

Research in the field of medical robotics is driven by groups at John-Hopkins-University, Baltimore, at Imperial College, London, at Scuola Superiore SantAnna in Pisa, the Fridericiana University in Karlsruhe and other European groups.

7.5 Bottlenecks to progress

Recent research results, as shown above, have already revealed a promising development of assistive robots in the health care domain. Those systems may indeed help disabled or elderly people to live a more self-determined life and to better cope with their handicaps. Surgical robots and robotical assistive devices may lead to more precise interventions to the benefit of the patients and sophisticated prostheses and rehabilitation techniques may give back a lot of life quality to people that have lost part of their body through an accident or disease. The acceptance of those technical assistive devices in the society is, however, relatively low. Most people are afraid of a world dominated by robots, afraid



System	Institution	Country	Year	Guidance/Control	Clinical Area	Applied to	Commercial / Regulatory Status	Mount	Positioning Arm	DOF	RCM Type	Back-drivability	Ref
AESOP	Computer Motion	USA	1992	Pad, Foot, Voice, Remote	Laparoscopy	Human	Commercial / FDA Cleared 1994	Cart and Table Mount	-	3	Passive	Low	[12]
BlueDRAGON	University of Washington, Seattle	USA	2002	Haptic Device	Laparoscopy	Phantom	-	Table	-	4	Bar Parallelogram	Very High	[165]
CLEM	TIMC/IMAG	France	2002	-	Laparoscopy	Phantom	-	Table	-	3	Compliant	High	[45]
daVinci	Intuitive Surgical	USA	1999	Master-Slave	Laparoscopy	Human	Commercial / FDA Cleared 2000	Floor Trolley	Passive, breaks	2*6+4	Bar Parallelogram	High	[14]
LARS	IBM	USA	1995	Synergetic / Image Guided	Laparoscopy / Percutaneous Access	Animal	-	Floor Trolley	-	6	Bar Parallelogram	Low	[37]
SCALPP	LIRMM	France	2001	Surgical Assistant	Skin harvesting	?	-	Floor	Augmented SCARA	6	-	?	[133]
SS-Colon	Scuola Superiore Saint'Anna	Italy	1997-2002	Surgical Assistant; Master-slave	Colonoscopy	Cadaver	-	Free mount	-	17	-	Low	[143]
Steady Hand	Johns Hopkins	USA	1999	Synergetic	microsurgery	cadaver	Non-commercial	Table	-	7	Belt Parallelogram	Mixed	[123, 124]
SurgiScope	Humboldt University / Jojumarie Intelligente Instrumente /Elekta	Germany	1997	Navigation + Surgeon inputs	Microscope holder; brachytherapy	Human (microscopes); animals (brachytherapy)	Commercial	Ceiling	Parallel	6	-	Low	[166]
TER	TIMC/IMAG	France	2001	Master-slave	Tele-Echography	phantom	-	Table/patient	Parallel	2	Constraint at entry port	High	[156]]
UBC-US	University of British Columbia	Canada	1999	3D Ultrasound	Arterial exams	Human	-	Floor Trolley	-	6	5 Bar Parallelogram	High	[142]
UBC-MW	University of British Columbia	Canada	1997	Master-slave	Microsurgery	phantom	-	Table	6DOF active robot	6	-	High	[104]
UCB/UCSF	UC Berkeley UC San Fran.	USA	1999, 2003	Master-slave	Laparoscopy	Animal	-	Floor trolley	6 DOF	6	Passive	High	[167, 168]
UT-LAP	University of Tokyo	Japan	1999	Gyro Sensor / Foot	Laparoscopy	Phantom	-	Table	-	4	Passive (Bar Parallelogram Included)	High	[39]
Zeus	Computer Motion	USA	1998	Master-Slave	Laparoscopy	Human	Commercial	Table Mount	-	3	Free wrist with constrained isocenter	Low	[13]

Figure 17: Overview of surgical assistant systems [TS03]

of not being able to understand the technical matters and finally of being at the robots mercy. These anxieties have increased after press reports of surgical robots that had caused severe harm to patients. Another reason for the low acceptance are ethical objections, in particular against prosthetic devices that include direct machine-brain-interfaces.

In order to respond to these reservations and to improve the acceptance, efforts have to be made to develop more reliable, more intelligent and more unobtrusive robots that integrate seamlessly with the environment.

While some of the objections against robots in the health care domain are actually unfounded, others are not. Many robot systems definitely lack reliability, which currently impedes further development and broader application. This issue has to be addressed thoroughly having in mind that reliability is not only a matter of safety but is also related to maintenance costs. In the domain of surgical robots the price/performance ratio is rather dissatisfactory due to high development costs combined with a still relatively low benefit for patients and clinics. In view of the bad reputation of surgical robots in the public and unsolved questions concerning liability many manufacturers have stopped their development activities.

7.6 Technological driving forces

Several technological developments that could possibly push forward medical and health care automation can be identified: *Favorable production technologies* are likely to pave the way to widespread monitoring of out-patients. Only mass-produced articles can be cheap enough to be applied in sufficient magnitude to establish remote monitoring and remote diagnosis of patients. New *communication technologies*, especially wireless connections have to be employed in order to transfer the data from the distributed sensing units.

Sensor technologies are expected to improve medical imaging systems. *Information technologies* will drive further development of downstream data processing and data management.

Mechatronic technologies are likely to introduce completely new treatment methods not possible with todays hardware. *Nanotechnologies* will introduce intra-vascular robotics, enabling non-invasive surgery and minimizing unnecessary damage of tissue.

7.7 Scientific challenges

Aiming at autonomous home care systems some major challenges have to be overcome. In general the systems must be conceptually suitable for technically untrained people, they must be particularly reliable and be adaptable to the specific needs of people in need of care.

The most demanding challenge concerning personal health monitoring systems at home is the development of appropriate sensors. While in intensive care units many different measurement techniques exist for various vital parameters, new sensors must meet the specific requirements of home environments and eventually of long lasting use.

For parameters that are only measurable invasively today, non-invasive alternatives must be found. Invasive sensors usually bring along a high risk of infection, are difficult to handle by non-professionals and must be checked regularly. If non-invasive measurements are not possible, autonomous sensors that may be implanted subcutaneously could be considered.

Depending on the persons health sensors should be as unobtrusive as possible in order to allow for a normal life. Major challenges include miniaturization of sensors and of their energy supply. Regarding their long term use biocompatibility is of particular interest, i.e. sensors may not have toxic or injurious effects on the body in any way.

Finally health monitoring sensors must reliably integrate into the home environment which includes problems such as electromagnetic compatibility (EMC) in view of cell phones, household appliances etc.

Assistive robots must be able to perceive their environment and to communicate with people in a natural way. As households are usually dynamic environments it is not sufficient to equip the robot with predefined maps, it must rather continuously create and update its environment model. Well-known problems of vision and cognition are typical challenges concerning this issue.

Communication may be possible through various ways including speech, gesture and facial play. While the automatic recognition of speech or gesture is still a demanding task, the eventually reduced ability of ill or disabled people to articulate or to gesticulate must be taken into particular consideration. Also, concerning reliability and safety, some people may not be able to react in the case of malfunction of the robot, for example by pressing the emergency stop button.

In remote diagnosis, the key scientific challenges are to build systems that offer adequate human interfaces so that the patient, possibly visually or acoustically impaired, can ensure proper handling and correct data. Minimizing the risk of infections is another challenge to be addressed by further research.

In surgical robotics, intelligent instruments are a big challenge. Augmenting the abilities of the human surgeon, new micro-endoscopes and hand-held mechatronic tools are required in order to enhance the quality of treatment and shorten surgical interventions. Keyhole surgery requires new methods for pre-operational planning and intra-operational navigation and control mechanisms.

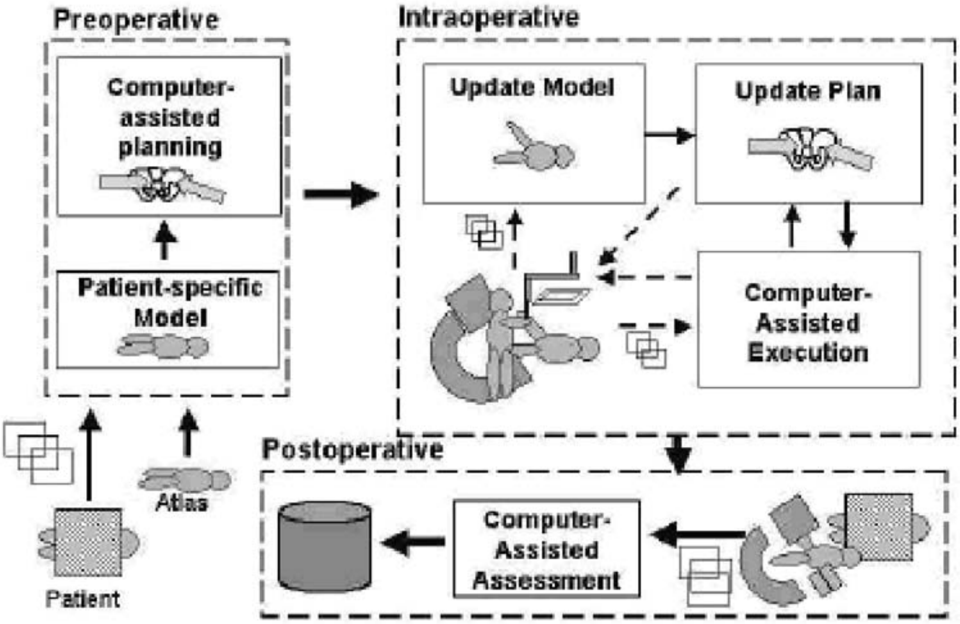


Figure 18: Information flow [TS03]

One possible separation of a computer-assisted robotic surgery system is depicted in figure 1. Three different parts can be identified: preoperative, intraoperative and postoperative.
To generate a computer model of the individual patient it is necessary to acquire 2D or 3D medical images, e.g. of a computer-tomograph. Using this models the surgical procedure can be planned. To improve quality of planning, data from different tomographic sources can be combined using cross-modality registration. This field is still subject of intense research.
Preoperative interventional systems include planning and surgical simulation and training. One objective is the generation of surgical simulators on a patient-specific basis so that the surgeon can simulate the intervention with the real patient data and therefore prepare for possible intraoperative difficulties. The most important technological needs for the construction of such a system are modelling, imaging and simulation of soft tissue, deformable registration, automatically segmentation of medical images and real-time, high fidelity interactions with deformable tissue through a haptic interface.
The transfer of the planning data into the operation room is done using real time registration algorithms and information from an intraoperative tracking system. The main difficulties are the precise localization of instruments with reference to preoperative or intraoperative imaging, hand-eye coordination, accurate path following and real time integration and updating of intraoperative data.
Using robot technologies it is possible to improve the accuracy, e.g. compensation for surgeons hand tremor and motion/force scaling. Soft-tissue interventions demand methods for real time registration and the simulation of topological changes like cutting and suturing. Passive assistance can be generated using augmented reality systems for visualization and interaction with the system.

The crucial question in developing rehabilitation robotics and intelligent prosthesis is the development and design of human-machine-interfaces especially the direct coupling of the human neuromuscular system and the artificial electronic devices. At the physical level, sensors need to be improved; at higher levels, there is a need to find more robust techniques to interpret a patients intentions. Substantial engineering is needed to ensure reliability and safety and to reduce costs of rehabilitation robots and prosthesis. Advances in component technologies, particularly reduction of size, weight and power consumption, are also needed. Numerous technological problems need to be solved, particularly sensor and control interfaces to the nervous system and miniaturization of actuators and batteries, before practical devices can be realized.

7.8 Future research acitivities

In order to realize the vision of next generation health care systems including health monitoring at home, computer assisted surgery as well as the use of robotic technologies for rehabilitation and assistive devices one has to deal with the following research topics in the near future:

- Sensor technology:
  - New sensors for the acquisition of vital health parameters
  - Robust, lightweight and biocompatible materials
  - Integration of sensors in order to make their usage easy and comfortable. This means to miniaturize the sensors, make them comfortably portable or even integrate them into clothes.
  - Non-invasive measurement techniques for parameters that are usually acquired invasively today.
- Human-Robot-Interface:
  - Improvement of the cognitive abilities of the robot so that it can safely navigate through indoor environments.
  - Interfaces for close interaction between humans and robots. This includes visual, acoustic and haptic interfaces.
  - Enhancement of recognition of speech, gestures and facial play to adapt to the specific abilities of impaired persons.
  - Intelligent human-machine interfaces that solve ambiguities and offer a user-friendly dialog.
  - Direct interfaces to the human nervous system
- Robot Technology:
  - Intelligent mechanical solutions of assistive robots, e.g. to support walking or climbing stairs, must be researched.
  - Mechatronic components
  - Light and robust materials for prosthesis design
  - Small and powerful intra-corporal energy supplies
- Algorithms:

- Intraoperative 3D imaging
- Determination of physiological tissue properties
- Augmented reality techniques
- Robust non-line-of-sight tracking and surgical skill modelling
- Real-time forward and inverse biomechanical modeling techniques
- 4D patient models
- Prediction of surgical outcome based on patient-specific simulation.
- Much better understanding of the human neuromuscular system
- Control algorithms that are robust to uncertainties in sensor data and inferred user intentions
- Appropriate communication standards for data transfer between sensors, local monitoring computer and the attending medical doctor have to be defined.

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