ROBOTICS – CHANCES AND CHALLENGES OF A KEY SCIENCE

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Abstract. *Robotics has been named a key science of the 21st century. The means and methods of mechatronics and robotics are spreading to other engineering sciences, and to medical areas, offering huge chances for novel products. The development of robots into intelligent machines touches upon issues such as the self-understanding of humans, upon socio-economic, legal, and ethical isues. It may be good to step back for a moment and reflect on objectives, on chances, and on limitations and controversial aspects to be considered. Examples for applications in medicine, robots in service and edutainment, robots for work in micro- and nano-techniques, and extensions to embedded robotics will be presented.*

Keywords. *Robotics, Mechatronics, Intelligence, Ethics, Legal constraints*

1. Introduction

Robotics is an area where a number of scientific fields meet, and this fact already is a source of attraction for the involved scientists, for users, and the public. Expectations run high and in diverse directions.

The word "robot" itself comes from literature and was created in the twenties by Czech poet, Karel Capek, in one of his plays, a play that ended tragically. In the forties, another writer, Isaac Asimov, made robots the leading figures in his utopian novels. Since these times, robots have been subjects of imagination. The reality of industrial robots only came in the sixties when Joseph F. Engelberger introduced the PUMA robot as a freely programmable, universal, handling device. With it came automation in manufacturing industry, economic issues, and social concern about human labour replaced by machines. The versatility of these robot machines has been increasing, largely due to their continuously increasing ability of information processing. The ultimate goal was the autonomous robot. However, as the application field for robots is widening, and the robot is coming out of the factory halls, new challenges are seen, and even a change of paradigm is taking shape. The robot is expected to be an extended, intelligent tool for the human, it should become a partner instead of being a "competitor" in fulfilling tasks, and there is a developing relation to biological systems. This development is illustrated by terms such as behaviour, emotions, or intelligence, taken out of their biological context and used to describe technical features and properties. For example, the term "intelligent" is being used to describe advanced robot behaviour, maybe still rather as a marketing term, but the idea certainly is to give it more meaning.

It is obvious that there are high expectations as to the future potential of robotics, even euphoric ones and somewhat unrealistically utopic (Moravec, 1988). On the other side, there are sceptical views, seeing robotics as one of the most powerful technologies of the 21st century, together with genetic engineering and nanotech (Joy, 2000), threatening to make humans an endangered species. A more moderate and realistic, but still fascinating approach has been taken by a study group, consisting of experts from engineering, medical, philosophical and legal sciences, discussing the provoking question whether humans could be substituted by robots (Christaller et al., 2001).

The paper will give examples of the actual state of the art by referring to nano-manipulation, a human leg prosthesis, and by looking at developments in the medical area, and into embedded robotics. The paper will present some aspects and results discussed by that study group cited above, it will comment on robot intelligence, on expected benefits of future robot technology, as well as on socio-economic, legal and ethical constraints.

2. About intelligence

As robots of the future are supposed to show some kind of intelligence let us first look at various meanings of that term. A history of intelligence (Stonier, 1992) names a number of different approaches to explain and to categorise intelligence and its aspects. To illustrate the broadness of the issue some of the "definitions" will be summarised.

In *biology*, intelligence is considered to support survival and to further natural selection. It thus, in principle, could be extended from humans and mammals to bacteria or plants as well. In *physics and chemistry* about anything can be retraced to the skilful arrangement of molecules, and certainly the research on the signal transmission between neurons in a brain has been profiting from this attitude.

In *communication theory* there are measures for intelligence based on entropy-related values. In *social sciences* the term "collective intelligence" characterises the performance of knowledge handling structures such as libraries, legal systems, databases, or even the complex behaviour of an ant population. *Artificial Intelligence*, a spring-off from computer science, as it stands now, appears to require some embodiment to make intelligence actually work (Christaller, 1999, Pfeiffer, 2000). The *anthropocentric approach* puts the human into the centre of consideration and regards intelligence as a capability of humans, as the core of their social competence, and as the ability to deal with reasons. Obviously, there is no way to come to a generally accepted definition of intelligence. Probably there is no need either, as there are other terms, such as "information", which has never been defined unanimously, and nevertheless it is the basis for a flourishing science.

The term *robot intelligence* could be justified by its usefulness to characterise some very desirable, human-like features, to be implemented in robots. In particular, a robot that should be useful to humans as a tool or even a partner, should be able to communicate with its human users on a reasonably high level, it should be able to "understand". Certainly, there are various levels of understanding that may have to be defined, giving measures of such an intelligence. This stepwise approach may be less stringent than the classical definition of artificial intelligence using the Turing test (Turing, 1950) but it could be more pragmatic and constructive. Thus, the ability for communication with humans could be the basis of an anthropocentrically oriented robot intelligence.

3. Trends and expected benefits

The leading role of robotics is based on its inherent technology potential and, in particular, its relations to areas beyond technology. In comparison, the direct economic impact of robotics appears to be rather small. As robotics is a multidisciplinary area, expectations are very diverse as well. Subsequently some trends and potential benefits will be outlined for different areas.

3.1. Technology

Robotics can be regarded as a typical and representative part of *Mechatronics*, as a cutting edge technology in this rapidly expanding research field (Schweitzer, 1996). Mechatronics combines in a synergetic way the classical engineering disciplines mechanical and electrical engineering and computer science, leading to new kinds of products. It can be stated that any technical progress in robotics will quickly spread over to products of every day life and may eventually initiate further progress.

Automotive technology for modern cars, for example, in making advanced use of sensors for controlling their dynamics and assisting in safe driving are following ideas from robotics (Hiller et al., 2001). In addition to that, the need for low-priced sensors in mass-produced cars has subsequently spurred the industrialisation of micro technology in a very sustainable way.

Methods of robotics and mechatronics serve, beyond the individual product, as guidelines for the development of complete systems. Thus, the name *system robotics* or *embedded robotics* has been coined, to desribe the integration of sensors, control, actuators and information processing into a system. This can be a car, an automated traffic control system, a military air defence system, medical service and human care systems, or the safety and energy management system of a building. There are already names such as cartronics, or domotronics, characterizing these new fields (Schweitzer, 2003).

A very promising area is *nano-techniques*. Results from physics research are already available, but exploiting and using them on an industrial scale needs highly automated processes, it needs the transfer of technology known from robotics. In addition, this technology will be the basis for novel products in medical techniques, for techno-implants, or for prostheses.

An actual research topic in robotics is the development of *"soft computing"*, i.e. learning algorithms and the interpretation of uncertain data from unstructured environments with methods such as fuzzy logic, neural nets or genetic algorithms.

The spread-over to *smart machine technology*, with self-calibration, self-diagnostics, and self-tuning control loops can already be seen. This will lead to improved safety, reliability, and maintenance procedures for such smart machines, and there the expected economic benefits are obvious (Schweitzer, 1998).

Another important area that is profiting from the advances in robotics is the *control of complex dynamical systems*. Examples are humanoid robots, as well as vehicles, construction machinery, machine tools, or prostheses for limbs and hands. On one side, it is the non-linear, model based, adaptive control that makes novel machine tools with parallel kinematic structures feasible, together with hard real-time operating systems, being used already in mobile robots. On the other side, bio-inspired behavioural control will lead to intelligent mobile robots moving smoothly in unstructured environments. Ideas for such a kind of control architecture are derived from motor control in animals. The relation between robotics and biology, however, goes beyond that and will be considered subsequently.

3.2. Biology and neuro-science

Robotics has a very stimulating co-operation of mutual interest with biological information processing and neuro-science. On one side data processing in biological systems can play a role model for advanced robot systems, and on the other side, the proven methods and tools for modelling in robotics may help to better interpret and understand the rather descriptive input/output models usually being available in biology. Investigations on the walking of stick insects, the navigation of desert ants, the swimming motion of fish, and the flight techniques of bees are being related to mobile robots. This effort may be stimulated by the underlying assumption that the ability to master motions is an evolutionary component of intelligence.

Neuro-science, in particular when related to motor control, is using robotics to verify its models for walking or grasping motions. This will have implications for the better understanding of human motor control and the design of prostheses, technical replacements of sensory organs (techno-implants), and limbs (see chapter on knee prosthesis).
The speculative question arises: will humans eventually be replaced by robots at all (Christaller et al., 2001)? The subsequent consideration might contribute to an answer: Contrary to the passionately discussed potential of controlling human development by genetic engineering, the evolutionary change of humans and human life due to technical developments takes place in a dark spot of our realization. Our ability for information processing, moving around and conquering distance and remoteness, underwater and in space, and overcoming biological deficiencies has dramatically changed just in the past one hundred years. Actually, it will be complemented now by gradually integrating intelligent robots as tools into our life, and by enhancing our life system by "spare part medicine", making use of techno-implants, i.e. artificial sensory organs, technical heart assist systems and prostheses. This development and its consequences is hardly reflected consciously. It can be assumed that humans will make the relevant decisions step by step within an evolutionary process.

3.3. Man-machine relations

Obviously, the relation of man to machine will be the key issue in dealing with intelligent machines. It has become a most complex area with technical, psychological, and socio-economic aspects, and its implications are leading to a change of paradigm in the objectives of robotics and to a new definition of a robot.

3.3.1. Communication and emotional behaviour

The interaction between human and computer is seen today as one of the topics in computer science (Shneidermann, 1998), and these approaches certainly will form an essential part of the communication methods between human and robot as well. In addition to that, safety aspects will be of much more importance, as a misunderstanding or a mistake in the communication can have most serious consequences. Furthermore, the activity and mobility that can be exerted by a robot will allow a wider range of communication modalities. The robot can turn its attention actively to points of interest, it can explore strange situations, and it can actually "bring" information or objects. The observer, seeing a real, moving robot will get different impressions than just by looking at some animated simulation from virtual reality. A nice example is the toy dog from Sony (Fig. 1). It is even supposed to express "emotions", for example by wagging its tail. Emotions may play an important role for man-machine communication, expressing expectations, summarising rational thinking, condensing information and representing it in an easily understandable way. This desire to generate human-like communications may be an argument for building humanoid robots whose body motion could carry "emotional qualities" that might be more easily interpreted by humans.

Figure 1. Aibo, Sony's robo-dog with emotional behaviours, source: www.world.sony.com/robot/get/m_instinct.html.

3.3.2. Allocation of work and authority

Another issue in designing the cooperation between man and machine is the allocation of work and the authority to make decisions when man and machine are jointly solving a task. Our capabilities to use automated machinery for carrying out complex tasks is increasing, and at the same time, we are aware of the limitations in the autonomy with which machines can or should perform these tasks. It therefore appears natural to design machines that can co-operate in an "intelligent" way with their human users, thus extending the range of the human and making best use of the capabilities of the machine. Such *human oriented machinery* will have novel features in their behaviour, related to their interaction with humans. The allocation of work between human and machine is a problem that is being discussed and will influence the way of automation and the design of future machines. We will need machines which can work in an autonomous way up to a certain degree of complexity, and in critical situations or on a higher level of autonomy the necessary *interactions* with the human operator or user have to be facilitated and structured.

The design of a machine and its motion control heavily depends on the *degree of automation*, i.e. how function and authority is allocated to man and machine. There are a number of criteria for allocation, briefly characterised, for example, by the terms *left over, economic, comparison*, and *complementary*. In the *left over* scenario, the degree of automation is as high as is technically feasible and only the tasks that can not be automated are left over for the humans. Following only *economic* criteria means that for each partial task the cheapest solution will be chosen. In the case of *comparison*, a task will be allocated to the one, machine or man, who performs it best. The *complementary* approach assumes that man and machine have basically different capabilities that complement each other. The idea is to combine positive capabilities, the *versatility of man* and the *consistency of the machine*. Thus, the objective is to assist the operator by providing him with an intelligent tool, and not to replace him by an automated machine. At the Institute of Work Psychology of the ETH a concept for the co-ordination of the three areas Man-Technique-Organisation (*MTO-concept,* Ulich, 2001, Grote, 1995) has been derived. A number of projects have already shown the advantages of this approach for *soft automation*, and one example, the user oriented automation of flexible sheet bending, will be briefly presented subsequenetly.

The manufacturing cell for flexible sheet bending was developed at the ETH Center for Integrated Production. The cell consists of a laser cutting machine, press brake, conveyor belts, and a robot. The work has been jointly pursued by the Institutes of Work Psychology, Forming Technology, and Robotics. The robot system for charging the press brake has to fulfil the requirements of the MTO-concept. It has to offer user friendly and application-tuned task level programming for interactive program optimization and error correction, as well as interaction facilities to intervene in decisions on every system level. Thus, for example, the cell can be used for manual manufacturing of single, complex products during daytime, and for fully automated operation during night shift. In this way the expert knowledge and the responsibility of the press brake operator can be maintained and even enhanced. The human worker and the robot are sharing the same work space. This is different from classical industrial applications where, for safety reasons, the robot work space is separated from the human work space, usually by some kind of fence. An idealistic view for that holistic automation approach is shown in Fig. (2).

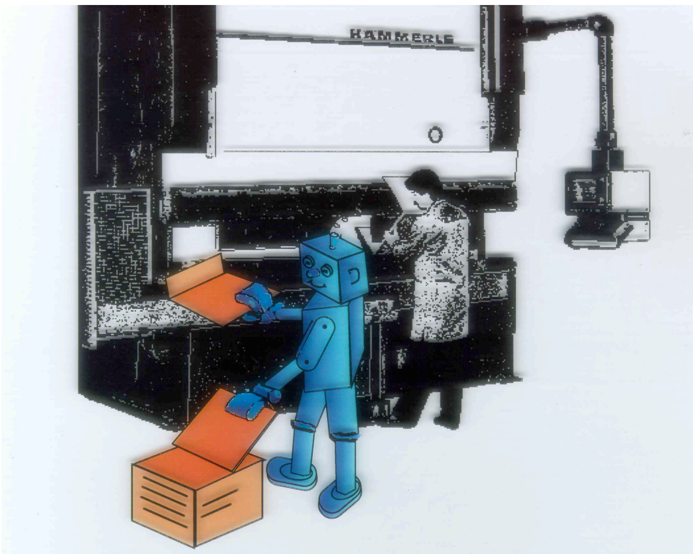

Figure 2. Still utopic scenario of a robot helper assisting a human expert in sheet bending.

Not only the contents of work can be shared between man and machine, the authority, as well. The different levels for the complementary allocation of authority, i.e. who is in control of a process, are shown in Fig. (3). The range spans from full human control (manual mode of operation) to the fully automated process. The examples mentioned in this figure are selfexplaining, and additional examples from robot research have been shown in Schweitzer (1996). Of course, safety is a dominant issue in designing the appropriate man-machine-interaction. It can be improved by making best use of the “intelligence” of the machine.

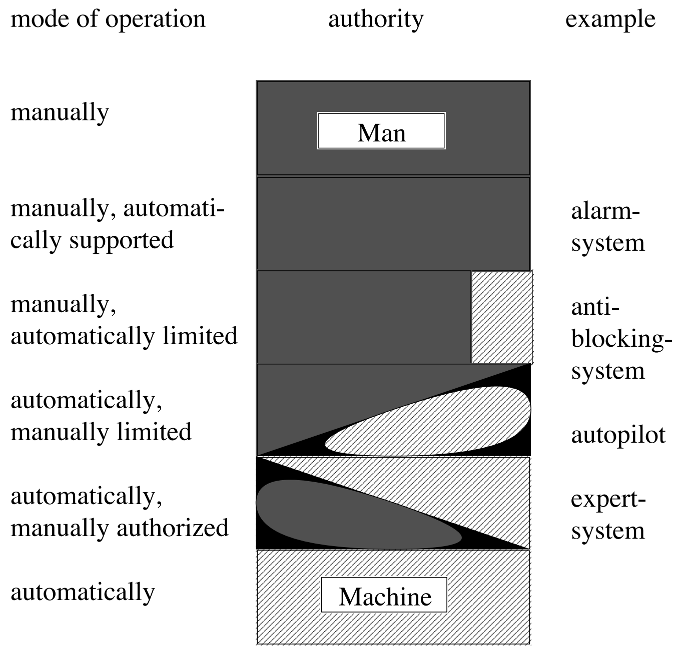

Figure 3. Different levels for the allocation of work authority between man and machine.

3.3.3. A change of paradigm in robotics objectives

Another concern of actual and future robot application is its socio-economic implications. Problems such as job availability for humans and the distribution of income in an "automated" society will have to be discussed. It appears to be most essential to design the relation between robot and human as co-operative and not as competitive. From the part of robotics the change of paradigm, mentioned already in the introduction, might be helpful in such discussions:

> Instead of building machines that can do the work of humans, we should build machines that can do the work which humans cannot do, or do not want to do.

This would extend the overall range of human work, and it would mean that in most applications the robot can be considered to be an intelligent tool. For such a robot with a co-operative behaviour towards the human user the nice term “cobot” has been used recently (Akella, 1999). It is obvious that the classical definition of a robot will not cover these novel features of man-machine-interaction, and therefore a modification is introduced subsequently.

3.3.4. A new definition of a robot

One of the classical definitions for an industrial robot, as characterized in Fig. (4), says

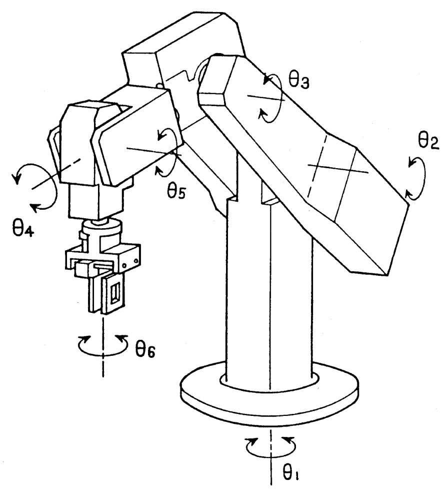

Figure 4. Typical configuration of an industrial robot.

A robot is a freely and re-programmable, multifunctional manipulator with at least three independent axes, for moving materials, parts, tools, or special devices on programmed, variable trajectories in order to fulfil a multitude of various tasks.

This definition was practically adopted by the international ISO-Standard (?). But, in view of the said above, it is understandable that this definition does not meet the expectations and needs of future development. Formerly, there was no discussion about autonomy, mobility or even intelligence of robots. Therefore, other definitions have been suggested which take the relation to humans into account. A recent definition (Christaller et al., 2001) says

Robots are sensumotoric machines for the extension of human mobility. They consist of mechatronic components, sensors and computer-based control functions. The complexity of a robot differs clearly from other machines by the larger number of degrees-of-freedom and the variety and the scope of its behaviours

This modern class of machines is expected to behave in a more ore less intelligent way. The term intelligence is deeply related to human beings. If some elements of this intelligence is transferred to other areas - biological, social, or technical ones, e.g. machine intelligence - it needs special definitions to show the limits and differences. The term *robot intelligence* may be justified by its usefulness to characterise some very desirable, human-like features, to be implemented in robots (see chapter 2).

4. Legal and ethical aspects and challenges

Beyond the technical, ergonomic and socio-economic aspects, basic questions as to the role of machines in human life, leading to legal and ethical issues, have come up.

4.1. Legal challenges

When robots become more and more part of daily life, legal questions of their interactions with humans and their consequences have to be addressed. At the time being, robots are considered machines, and liability is being judged by existing regulations. In Europe, for example, machines are required to have a quality standard that corresponds to the state of the art and is defined by the machine guidelines (Richtlinie fuer Maschinen, 1998), and in addition there is the well known product liability (Richtlinie ueber die Haftung fuer fehlerhafte Produkte, 1999).

The risk potential for robots that move around freely, in the same work space as humans, is much more difficult to classify. Intelligent robots are supposed to be able to learn, and to adapt their behaviour to unstructured and changing environments. As an example we can look at a robot transport assistant, helping an airport passenger to bring his luggage from the conveyor belt to the car or train, or a messenger robot delivering an express parcel within an office building or even across the city (The question whether such services should be automated at all, is a different issue; see chapter 3.2). It is easily conceivable that the exceptional situations during such a robot task can not be completely predicted, that malfunctions can not be excluded, and that the risk of humans being injured by such a robot is immanent. Who would be responsible? Potential addressees are: the owner of the robot, the operator, the producer, the person who has written the learning programm, the teacher who has taught the robot, the injured person himself, or a third party. Certainly, the use of such an "intelligent" robot would require some kind of insurance coverage, and in addition, there will have to be technical means to clarify any critical situation: the robot has to be identifiable, and it will have a memory that is accessible to document the past life of the robot. A detailed study of the legal questions coming up with the use of intelligent robots in various application areas, in particular for medicine, is given by Schweighofer (in Christaller et al., 2001).

4.2. Philosophical and ethical issues

In Christaller et al. (p. 111 ff., 2001), in a chapter on philosophical anthropology, Sturma states that robotics has more consequences for our personal and cultural self-understanding than other technologies. In robots, man appears to meet himself. Variations of such encounters can be found in myths and fictions about the artificial man, which go back to antique Greek times.

Sturma pledges, among others, that the unjustified use of anthropological terms such as 'conscience', 'knowledge', 'way of life', 'intention', 'autonomy', 'behaviour' can lead to a failure of appreciation of basic differences between man and machine and to problematic lines of reasoning. For example, it appears to be rather popular to claim in a cultural pessimism that in future humans might be replaced by robots or computers, be it for the better or the worse (Moravec, 1988, Joy, 1999).

The ideas about what machines could or should do to make them "behave" in a complementary or even similar way to human beings touch upon a broad range of human values. As an example, there are ethical rules such as the famous "Three Laws of Robotics" from Asimov's utopian novels (Asimov, 1985 and 1986). As a reminder, Asimov's three laws run as follows:

1. A robot may not injure a human being, or, through inaction, allow a human being to come to harm.

2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Of course, such rules cannot be implemented technically, even in near future. However, they can be regarded as a contribution to develop *orientational* knowledge in addition to the technology dominated *factual* knowledge that is necessary for actually building robots. The time is ripe for a step towards considerations of this kind, and who else would be able to recognise the implications and to acknowledge at least partially the responsibility if not the involved scientists themselves? Ethical rules would not mean restraints on basic science - once a question has been asked it can not be made unthought and eventually someone will seek an answer to it – but they certainly would put certain constraints on applications. It is quite obvious that intelligent robots can be applied in very sensitive areas, such as medical care, military, or biology, and not everything that can be done should be done. At least, any responsible engineer should develop his or her individual value judgement and be able to make accountable decisions.

5. Applications and examples

Intelligent robots will offer novel chances in various ways and for different areas. The subsequent selection of applications gives some comments on the chances offered:

- Robots for the extension of the human work range are being used in areas such as space (Hirzinger, 1999, and in Christaller et al., 2001, p. 46 ff.), underwater, and the micro- and nano- world. An example will be given below.
- Robots for the alleviation of humans from hard or dangerous work will be used as intelligent tools in complex environments. Examples are machinery for construction work, in tunnelling (Honegger, 1997), sewage channelling and cleaning, waste disposal, de-mining, de-construction of nuclear power-plants.
- Service robots, serving humans for making life easier, will be built for delivery services in office environments (Tschichold, 2001) and hospitals, cleaning, or lawn mowing. An economic profit is difficult to assess, as they are most often directly competing with relatively cheap and still somewhat attractive human labor.
- Edutainment-robots (for education and entertainment) will probably be the first ones to introduce advanced concepts of “intelligence”. They have the advantage that malfunctions usually do not endanger the user and are of no serious economic consequences, and that they are therefore very suitable to try out novel ideas, even in mass production (see Fig. 1). Playing football with robots is just one of the most popular topics in this field. It is typical that computer games are increasingly integrating artificial intelligence into their programmes as demonstrated for example by the game “Republic – The Revolution” (Eidos, 2003).
- Medical techniques are a dominant research area in robotics today. It includes prostheses for limbs and hands, artificial organs for audio and vision sensing, other techno-implants, surgery robot assistants, in particular for endoscopic surgery, robot helping assistants for handicapped, for rehabilitation, or for the aged to enable them to stay in their familiar environment as long as possible. Some examples are given below.
- Embedded robotics is an extension of machine-oriented robotics to systems. Applications range from ‚cartronics’, ‚domotronics’, to medical systems, and to advanced man-machine-interfaces making use of wearable computing equipment. A survey is given in (Schweitzer, 2003).

5.1. Nano-robot as an example for the extension of human work range

Handling of very small particles with nano-precision has been the domain of physicists. Exploiting and using the results on an industrial scale needs automated processes, it needs the transfer of technology known from robotics. Fig. (5) shows the set-up of a nano-robot-system. A stereo vision module and other sensors are used to localise the gripper and the object. This information is transmitted to the vision-based controller for generating automated robot motions. Additionally, the same information is used to create a *virtual reality scene* to allow the operator to observe the situation and to manually interact. (Codourey, 1995, Sato, 1993).

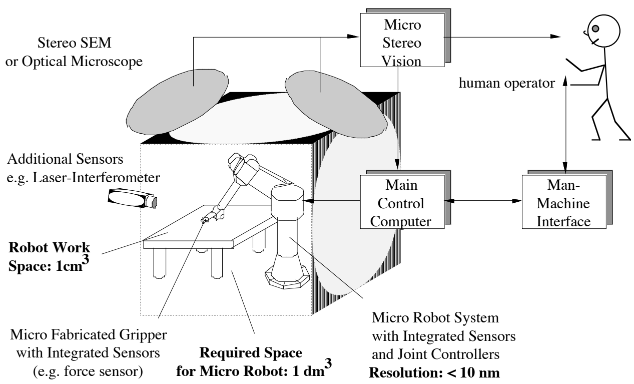

Figure 5. Overview on the ETH nano-robot-system.

5.2 Intelligent control of a leg prosthesis as an example for medical applications

The *above-knee prosthesis*, Fig. (6), shows the direct interaction between man and machine. The prosthesis can be seen as a robot that is, at least partially, replacing human walking functionality. The control of the rather complex motion pattern is based on a finite set of rules. The pre-defined and stored parameters, models, and rules are combined, forming the knowledge base of the system. The soft control is algorithmic and composed of four sub-functions. The first task is gait state identification based on online measurements. Then the gait control computes the damping levels of the knee motion depending on the various gait phases. In order to realise that impedance control, an actuator opens and closes a valve in the hydraulic actuator connected to the knee joint. Thus the energy for controlling the impedance is very small; the major part of the energy for walking is still coming from the motion of the hip. Finally, the gait speed is identified, a parameter which influences both the gait control and the hydraulic control. A laboratory prototype of such a controlled prosthesis was built and evaluated in a rehabilitation clinic, showing a number of distinct advantages over classical prostheses (Zlatnik, 1998). Figure 7 points to a success story. The potential of the novel prosthesis is mainly based on its ability for internal information processing, and, in future, it can still be enhanced by making use of learning algorithms to adapt the prosthesis to the individual gaits of its bearer.

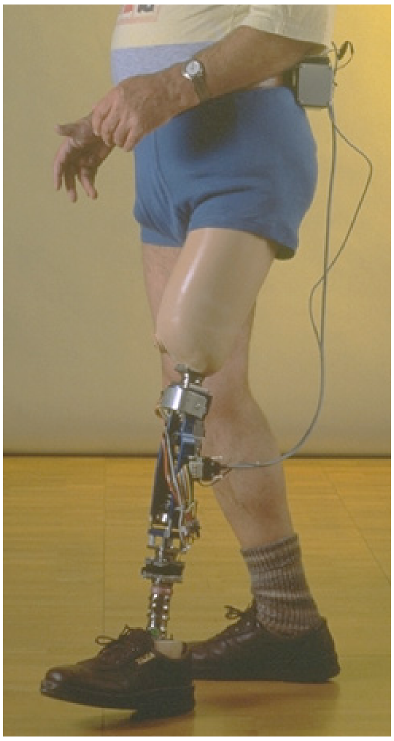

Figure 6. Intelligently controlled above-knee prosthesis in clinical test. The prototype computer is fastened to the belt.

Figure 7. LIFESAVER - Curtis Grimsley used his Otto Bock C-Leg to walk down from the 70th floor of the World Trade Center on Sept. 11. He says the device saved his life (Austen, 2002).

5.3. Medical robot systems

Obviously, in medical robot systems the interaction between man and machine is very close, giving rise to a number of questions, ranging from technical to ethical ones. Medical robots for surgery on the hip, even open heart, and supporting tools for minimal invasive surgery are well known, already, and are under continuous development. Figure 8 shows a *simulated setup for robot assisted surgery*. The KISMET (Kinematic Simulation, Monitoring and Off-Line Programming Environment for Telerobotics) software is under development at Forschungszentrum Karlsruhe since 1986 as a 3D realtime simulation support tool for medical applications. Research on such medical robot systems is being done at the Robotics- and Mechatronics Lab of the DLR. A survey on robots for endoscopic surgery and on neuro-surgery is given in (Christaller, et al., 2001, p. 53 ff. and p. 91 ff.).

One of the most powerful tools for advancing medical techniques actually is the integration of computers. For example, the fundamental target of a Swiss national research program (CO-ME, 2003) is to understand, realise, and demonstrate the potential, which information technology offers for the optimisation of medical interventions in order to improve both the treatment of individual patients and the overall health care for the whole society. The focus of this program is on the development, integration and validation of enabling technologies towards advanced computer aided and image guided systems for medical interventions that support the complete treatment process from therapeutic planning and simulation via intra-operative action to postoperative care, monitoring and documentation

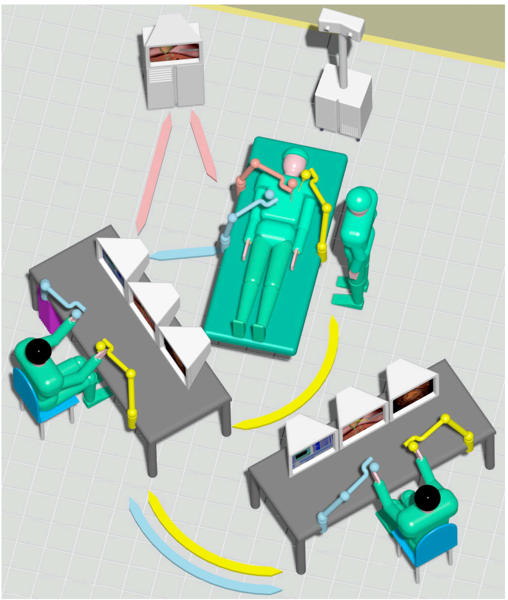

Figure 8. Robot assisted minimal invasive surgery of the future. http://www.robotic.dlr.de/medical/hi/

6. Conclusions

Robotics is a key science of this century. The development of robots into "intelligent" machines and systems will offer chances, however, challenges will have to be overcome. Intelligent robots should be able to communicate with users and work as intelligent tools in a co-operative way in the same work-space. The paper presents some aspects and results discussed by a study group on robotics, consisting of experts from engineering and natural sciences, philosophy, medicine, and legal science on "Perspectives on human ways of acting in future society" (Christaller et al., 2001). It will comment on robot intelligence, on expected benefits of future robot technology, as well as on socio-economic, legal and ethical constraints, and it will give some examples.

Here, "intelligence", and in particular the intelligence of robots, has been defined in a rather anthropocentric way, according to the needs of humans co-operating with such robots and using them as intelligent tools. Subsequently, trends and expected benefits of such intelligent robots are addressed.

Technology related to and growing from robotics has been discussed. It includes areas such as mechatronics, automotive concepts, micro- and nanotechniques, smart machine technology, soft computing, embedded robotics, and dynamics and control of complex, bio-inspired motion systems.

Relations to biology and neuro-science play an important role in defining robotics trends, and in giving an answer to the question: will humans be replaced by robots some day? The arguments converge to the conclusion that humans will make use of advanced robotics tools in an evolutionary way.

The relation between man and machine will be a most important issue. It will require efforts in the technology of communication, and in the discussion of socio-economic, legal and ethical issues.

On one side, communication will make use of the progress of classical tools for communicating with computers. In addition, the non-linguistic communication, the information transfer through motion and gesture, through emotional expressions and the phenomenology of humanoids, will support the information flow between man and machine and lead to some kind of "understanding". Progress will come through edutainment robots.

Socio-economic aspects will come up in allocating work between man and machine. Suggestions are being made for the simultaneous optimization of "Man, Techniques and Organization ". Examples for allocating authority, the decision making, in joint tasks of man and machine are shown.

The classical objective of robotics, to build a robot which can work autonomously and which can do the work of man, is undergoing a change of paradigm: Instead of building machines that can do the work of humans, we should build machines that can do the work which humans cannot do, or do not want to do. A robot definition which considers this trend to intelligent machinery is given.

In such a complex, far reaching and promising area as robotics it is unavoidable that ethical and legal constraints have to be set. Ideas and suggestions are briefly presented, including some philosophical comments on the indiscriminate use of anthropological terms such as 'conscience', 'autonomy', 'behaviour', which can lead to a failure of appreciation of basic differences between man and machine and to problematic lines of reasoning.

A classification of potential applications for intelligent robots and the chances offered by them is listed. The actual state of the art is shown by some examples, referring to nano-manipulation, a human leg prosthesis, and by looking at developments in the medical area.

It appears to be appropriate to leave predictions or prophesies about the far future to visionaries, to poets, and artists. An impressive variety of short summaries are collected for example by Crawford and Edgar, eds. (1997).

7. References

Akella, P. et al., 1999, “Cobots for the automobile assembly line”, Proc. Internat. Conf. on Robotics and Automation ICRA ’99, Detroit, pp. 728-733.

Asimov, I., 1986, “Robot Dreams”, New York, ACE Books.

Asimov, I., Frenkel, K.A., 1985, “Robots - machines in man's imagination”, New York: Harmony Books, Crown Publ. Inc., 240 p.

Austen, J., 2002, “Computerized limbs is next for artificial limbs”, The New York Times, January 3.

Christaller, T., 1999, Cognitive robotics. A new approach to artificial intelligence, Artificial Life and Robotics, 3.

Christaller, T., et al., 2001, “Robotik – Perspektiven für menschliches Handeln in der zukünftigen Gesellschaft”, Wissenschaftsethik und Technikfolgenbeurteilung Band 14, Springer-Verlag Berlin, 280 p.

Codourey, A. et al., 1995, “A Robot System for Automated Handling in Micro-World,” Proc. IROS'95 IEEE/RSJ Internat. Conf. on Intelligent Robots and Systems, Pittsburgh, August 5-9, pp. III.185-190.

CO-ME, 2003, “Computer Aided and Image Guided Medical Interventions”, http://co-me.ch/

Crawford, A., Edgar, R. (eds.), 1997, “Transit Lounge, Wake-up Calls and Travellers’ Tales from the Future”. Craftsman House and G+B Arts International, 192 p.

Eidos Interactive Ltd, 2003, “Republic – The Revolution”, http://www.eidosinteractive.co.uk/gss/republic/

Grote, G. et al., 1995, “Criteria for the complementary allocation of functions in automated work systems and their use in simultaneous engineering projects”, Internat. Journal on Industrial Ergonomics, 16, pp. 367-382.

Hiller, M. et al., 2001, “Development of Mechatronic Automotive Systems”, Proc. IX DINAME, Edited by J. J. de Espíndola, E. M. O. Lopes and F. S. V. Bázan, Florianópolis SC, pp. 5-9.

Hirzinger, G., et al., 1999, “Advances in robotics: The DLR experience”, The Internat. J. on Robotics Research, 18 (11), pp. 1064-1087.

Honegger, M., et al., 1997, “Vision Supported Operation of a Concrete Spraying Robot for Tunnelling Work”. Proc. 4th Ann. Conf. on Mechatronics and Machine Vision in Practice, Toowoomba, Australia, Sept. 23-25, pp. 230-233.

ISO 8373, “Manipulating industrial robots, vocabulary”, International Organization for Standardization, Geneva.

Joy, B., 1999, “Why the future doesn’t need us”, Wired Archive 8.04, http://www.wired.com/wired/archive/8.04/joy.html

Moravec, H., 1988, “Mind children: The future of robot and human intelligence”, Cambridge.

Pfeiffer, R., Scheier, Ch., 2000, “Understanding intelligence”, MIT Press, Cambridge, London, 695 p.

Richtlinie 98/37/EG fuer Maschinen, 1998, AB1 L 207/1998, pp. 1-46.

Richtlinie 99/34EG ueber die Haftung fuer fehlerhafte Produkte, 1999, AB1 L 141/1999, 1985, pp. 20-21.

Sato, T. et al., 1993, “Novel manipulator for micro object handling as interface between micro and human world,” Proc. IROS’93 IEEE /RSJ Internat. Conf. on Intelligent Robots and Systems, Yokohama, July, pp. 1674-1681.

Schweitzer, G., 1996, “Mechatronics for the Design of Human-Oriented Machines”, IEEE/ASME Transactions on Mechatronics, Vol.1, No. 2, pp. 120-126.

Schweitzer, G., 1998, “Magnetic bearings as a component of smart rotating machinery”, Proc. 5th Internat. Conf.on Rotor Dynamics (IFToMM), Darmstadt, Sept. 7-10, pp. 3–15.

Schweitzer, G., 1999, “What do we expect from intelligent robots?”, Proc. IEEE/RSJ Internat. Conf. on Intelligent Robots and Systems IROS’99, Kyongju, Korea, October 17-21.

Schweitzer, G., 2003, “Embedded Robotics – Ideas on the Future of Robotics”, Proc. X DINAME, Internat. Symp. on Dynamic Problems of Mechanics, Edited by P.R.G. Kurka and A.T. Fleury, Ubatuba SP, March 10-14, pp. 13-21.

Shneiderman, B., 1998, “Designing the User Interface – Strategies for Effective Human-Computer Interaction”, 3rd ed., Addison-Wesley.

Stonier, T., 1992, “Beyond information - the natural history of intelligence”, Springer-Verlag, London, 222p.

Tschichold, N. et al., 2001, “The Service Robot MOPS: First Operating Experiences”, Robotics and Autonomous Systems 34, pp. 165-173.

Turing, A., 1950, ”Computing Machinery and Intelligence”, Oxford Univ. Press on behalf of MIND (the Journal of the Mind Assoc.), vol. LIX, no. 236, pp. 433-60.

Ulich, E., 2001, “Arbeitspsychologie”, Stuttgart: Poeschel-Verlag, 5th ed., 754p.

Zlatnik,D., 1998, “Intelligently Controlled Above Knee Prosthesis”, Diss. ETH Zurich No. 12814, 282p.