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Mechatronics, robotics and components for automation and control

IFAC milestone report

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Abstract: This paper presents a general overview of the technological fields of mechatronic, robotic, components for automation and control. Five technical areas are considered: component and instruments, mechatronic, robotics, cost oriented automation and human-machine systems. The paper addresses their current key problems and the recent major accomplishments. At last the most promising forecasted development and applications are considered.

Keywords: Component for control; Mechatronic systems; Robotics; Cost oriented automation; Human-machine systems

1 INTRODUCTION

These last years control technologies and applications were more and more concerned with the development of new systems and functions assisting human beings in their daily lives, to improve their safety, security, and comfort. A good example is provided by the transportation industry with the progressive introduction to the market of ADAS (Advanced Driver Assistance Systems) which supports or substitutes driving task of drivers (see Ollero *et al* 2006). Another aspect of the technology evolution during these last years is obviously related with energy saving. It is now more and more accepted by the human community that there will be a breakdown in conventional fossils energetic resources in about 50 years. In addition energy consumption is the major reason for pollutant emissions and green house effect. Solutions for the reduction of energy consumption and pollutant emissions have been addressed by automotive industry and production plants since twenty years.

These technologies advances are highly supported by the development of mechatronic, the miniaturization and the drastic cost reduction of smart sensors and actuators and of course the increased processing capacity. Moreover a better control of the processes including an improvement of the robustness, the reliability and the maintainability of the various components has drastically improved the performances of the systems. In addition the large development of the wireless communication led to the design of wide networked processes. Nevertheless these systems are becoming more and more sophisticated and complex and the performance requirements increase. There is a real need to include this complexity in the control system design but also to address legible and understandable interface for human operators. Thus a better comprehension of the human-machine interaction is needed as well as a better understanding of the human cognitive behaviour in order to design efficient and acceptable systems.

The advances in mechatronics, robotics, cost automation, and human-machine interfaces have been fostered by continued advances in components and technologies for control. They include both software and hardware, ranging from many new embedded specialized software systems for specific applications to sophisticated hardware that does more functions with reduced physical size at lower costs. In addition, various intelligent control based technologies have allowed for more efficient implementation of these components to various mechatronic, robotic and automation systems, as further discussed in the below. For many years control engineers have been using sensors and electronic processing to enhance and/or alter the performance of mechanical systems, in many cases to provide a level of functionality that is not possible without the electronics. It is noted that miniaturization by Micro Electro Mechanical Systems (MEMS) technology and wireless communication technology have brought the state-of-the-art in sensing and actuation to a higher level. The sophistication which has more recently been possible through increasingly powerful processing devices and heightened software skills, combined with modern sensing and actuation technologies, has resulted in an increasing trend towards embedded mechatronic solutions involving a synergetic combination of mechanics, electronics, software and computing. This necessitates a multi-disciplinary understanding of the relevant scientific and engineering principles, and the individual knowledge of the mechatronic engineer must be sufficiently comprehensive to be able to create the innovative combination that makes up mechatronic solutions.

Robotics fields are expanding their research areas rapidly from mechanical and Electrical Engineering to Computer Science. In the beginning, Robotics was initiated as control applications using digital computers such as industrial robots. The main problems were kinematics, dynamics and control. Then many researchers handled robot manipulators as control targets. At the same time computer science people treated Robotics as one of AI fields. Then those two different directions tried to merge each other. But it failed because there were big gaps from the viewpoint of engineering. Control community people looked robots as actual research targets. On the other hand Computer community people looked robots in virtual world, i.e. in computer world. These days control people are using the results of computer science research more and more. For example, they are now using soft computing, image processing, network technology, etc. On the other hand computer science people are paying attentions to real world. For example, AI people work for Robocup, i.e. real robots. Also many computer science people are doing research on human-robot interaction. They have to treat actual robots with human. Those two directions (control and computer) are approaching each other via Robotics, that appears as a very attractive research target. Humanoid robots and Robotic Technology (RT) are of course very good examples of these synergies.

Cost oriented automation systems or affordable automation consider the cost of ownership with respect to the lifecycle of the system: designing, implementing, operating, reconfiguring, maintenance or recycling. Components and instruments could be expensive if lifecycle costs decrease. An example is enterprise integration or networked enterprises as production-systems vertically (supply chain) or horizontally (network) organized. Affordable automation systems mean that these systems are affordable for its owner with respect to the problem he has to be solved. An example is a manufacturing system in a small or medium sized enterprise, when automation increases the productivity and therefore the competitiveness. Another example is automation in buildings to save energy and therefore costs. Low cost automation is therefore a strategy to achieve the same performance with lower costs. The designers of automation systems have a cost-frame within they have to find solutions. This is a challenge to theory and technology of automatic control as the main part of automation.

The analysis of the interaction between Human and machine is a more and more critical issue. Over the last years we notice a trend to higher complexity of technical systems. This development is mainly driven by the advances in micro-electronics. Very powerful computing systems are available even in small embedded applications allowing new forms of interaction like speech control. Furthermore all devices become more and more interlinked to each other by powerful networks. Whereas the wire-based networks like CAN (Controller Area Network), Foundation Field bus or Profinet can be seen as state of the art in technical control systems, the broad range of the new wireless network technologies gains more and more acceptance even in industrial applications. Many of these technologies have matured in the field of consumer goods and are widely accepted by the public. A very good example is mobile phones. Besides the basic function of mobile communication they offer today a broad range of additional functions like a camera, an MP3-player, an organizer or even a GPS navigation system. And as all these functions are based on a very powerful computing platform including an operating system like WIN CE/mobile or SYMBIAN they may also be used in industrial applications.

2 Key problems

2.1 Components and Technologies for Control

A wide-spectrum of key problems in components (sensors, actuators and instruments) and technologies (generic methodologies, techniques, new developments, and subsystems) for advanced control and measurement applications is addressed. Applications include: automotive and other transportation systems, mechatronics, robotics, humanoids, building automation, environmental systems, motion control, factory automation, process control, network measurements, perception systems, healthcare and medical applications, and human assistance. Key problems are concerned with improved performances, quality of services and implementation.

To achieve advanced performance in these control applications, expanded functionalities through improved measurement, actuation, auto-configuration, diagnosis, self-learning, and communication are needed.
To improve the quality of service and performance characterization of requirements, types of provided services, and implementation are necessary.
For implementation, modelling of components and instruments in mechatronic systems, integrated sensor and actuator systems, multi sensor systems, intelligent controllers, virtual instruments, perception devices, and positioning systems, to name a few, are necessary.

Furthermore, recent advances in MEMS (micro electro mechanical systems) and NEMS (nano electro mechanical systems) sensors and actuators allow more compact yet more advanced solutions. Among these components, modules, subsystems, and systems, communication networks and fieldbuses, involving wireless network, automation network instruments, buses and interconnection systems, profiles, interoperability, service and management, need to be addressed.

Finally, system design methods in embedded Oss (Operating Systems), languages, configuration, validation, simulation, hardware/software co-design, dedicated circuits, and system-on-chips (SoCs), as well as data handling techniques in fuzzy logic, neural networks, genetic algorithms, rule-based approaches, data-fusion methods represent the challenges.

2.2 Mechatronic System

Many technical processes and products in the area of aerospace, mechanical and electrical engineering show an increasing integration of mechanics with electronics and information processing. This integration is between the components (hardware) and the information-driven functions (software) and embedded control, resulting in integrated systems called mechatronic systems. Their development involves finding an optimal balance between the basic mechanical structure, sensor and actuator implementation, automatic digital information processing and overall control, and this synergy results in innovative solutions.

The key problems for future developments in mechatronics focus around the multidisciplinary requirements of both engineers and the tools that they use. Research and development (R&D) effort needs to be devoted on every element of mechatronic systems as depicted in Fig. 1.

Integration is at the center of mechatronics disciplines. At the same time, research in mechatronics must address enabling technologies such as embedded computing and sensing/actuation technologies as well as enabling dynamic systems and control methodologies from modeling and identification, control algorithm design and failure detection and monitoring. Though not explicitly identified in Figure 1, modeling is an important R&D item.

Another issue arises because the integrity/ reliability/ availability required of the mechatronic solution is increasingly of general importance (i.e. not only for safety-related applications), and so a vital mechatronic skill is in the area of fault diagnosis and tolerance. Generally the integrity of mechanically-based products and processes can be assured by careful design of critical components, supported by targeted maintenance regimes, which as far as possible avoid dangerous failures. However failure modes for sensors, electronics and software are much more diverse and integrity now has to be provided through functional and analytical redundancy. In the traditional approach, the fault tolerance study is performed after the system has been designed. However it is possible that the fault tolerance could have been achieved easier/better/cheaper had it been taken into account at the very first stage. So, a general theory and/or methodology for handling the synthesis problem for complex multi-disciplinary systems to meet multiple objectives and constraints, including those related to fault tolerance, is needed to maximize the impact of mechatronics.

A final key issue is related to human factors. Early mechatronic products required only limited human interaction, whereas their ever-broadening applicability means that many mechatronics products are now used on daily basis and human factors need to have correspondingly increased importance. In part this again comes back to the skill base of the mechatronic engineer, but also the contribution of the design tools needs careful consideration. This observation also links strongly with many of the ideas identified in human-machine systems (see section 2.5).

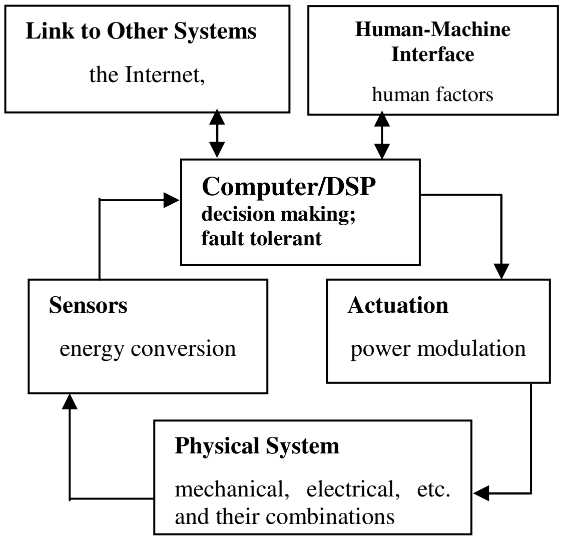

Figure 1: Block Diagram of Mechatronic Systems

2.3 Robotics

The key problems for the future developments of Robotics are related with the design of new generation of humanoid robots as well as the sensing and control aspects taking care of the human robot interfaces.

The future major issues in humanoid robots are related to mechanical design, control and learning. The body mechanism of humanoid robots is important to realize flexible and natural motion like humans. Safety for humans should also be assured. The bipedal movement characterizes humanoid robots. Therefore, one of the major problems in control of humanoid robot is two-legged locomotion. Developing the intelligence of humanoid robots is also a critical and challenging problem.

Sensing in RT means that the properties of the environment are measured and represented inside the RT system. The purpose is to enable the system's decision making, and in turn control the actuation to the environment. With the rapid development of different sensors a much larger amount of data is available to RT systems than before.

Yet another research direction is the distribution of sensors in the environment, and their work in cooperation with the robots, as in intelligence space systems (*Figure 2*) (Lee *et al* 2002).

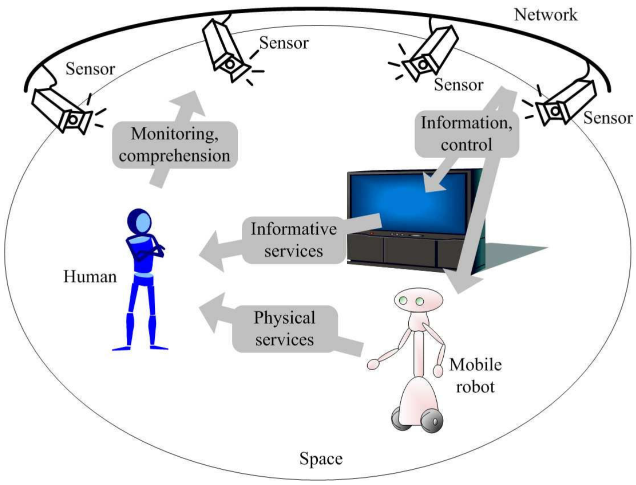

Figure 2: Concept of intelligent spaces.

The cooperation between humans and robots is also very critical. The progress in the development of various service robots brought a growing need for robot architectures and control algorithms for robots that coexist with humans. The essential needs are safety, reliability and adaptability. Research in this line goes from development of algorithms for safe soft interaction to dexterous manipulation, with applications ranging from nursing and home robots, to telemanipulation for medical purposes.

Another line of research is in the mobility of robotic platforms. Motion planning algorithms have reached a fairly mature stage, but there are still large problems in the real time and smooth planning for complex systems. The problem of robot self-localization and environment mapping has also received considerable attention and still continues to be developed.

Finally, since modern control robotic systems are becoming more and more complex, an important part of RT control is distributed control of systems consisting of multiple parts. This has led to the development of several platforms and middleware solutions, and this area is still under active research.

In human-robot interactions, multi-modality is increasingly important. Therefore, human interfaces in RT fields mainly address "recognition" of humans' actions such as voice, face, gesture, intention, behaviour, activity and so on. Recently, spatial human interfaces have been proposed (Niitsuma *et al* 2007). Human's vital information is also a key issue, because it can be utilized not only for commands but also for evaluation of interactions. Another key problem is how to present information from robots to humans. Haptic interfaces and tactile interfaces are widely studied. Haptic interfaces are included in control problems and mechanism problems.

2.4 *Cost Oriented Automation*

Energy saving control in plants and buildings is an emerging area in automatic control; widely used PID controllers are stepwise replaced by more suitable algorithms. Therefore control theoretical insights should become more practical. More applications to be used as references for benchmarking are necessary to make energy savings more visible and to analyze the cost of ownership and societal benefits. A crucial point in building automation is the assessment of the performance of feedback loops. These loops, which frequently use the PID controller, often act as the final interface between the control logic and the energy-using equipment. Monitoring these loops and measuring performance thus holds the potential of catching a large percentage of problems in building systems (Salsbury, 2006).

To reduce or avoid downtime of machines and therefore costs are one of the main problems particularly in manufacturing and mining equipment. Many sophisticated sensors and computerized components are capable of delivering data about the machine's status and performance. When machines are networked and remotely monitored and when their data is modelled and continually analyzed with embedded systems, it is possible to go beyond mere "predictive maintenance" to intelligent "prognostics". The advantage of e-maintenance was discussed by Lee *et al* (2005). This approach is mainly focused to large enterprises (automotive-, aircraft-industry). To make it available and cost effective also for smaller enterprises some specific developments are necessary.

More effort is still necessary to effective control human-robot collaboration for semi-automated assembly and disassembly, and for orthopaedic diagnostics and rehabilitation in health-care (*Figure 3*). Some recent developments like Cobots (*Figure 4*) are promising (Surdilovic *et al*, 2005). Robots cannot come close to matching the abilities or of humans' intelligence. Therefore, new systems which enable the interaction between humans and robots are becoming more and more important. The advantages of using innovative robots can especially be seen in medical or other service-oriented areas as well as in the emerging area of humanoid robots (see section 2.3)

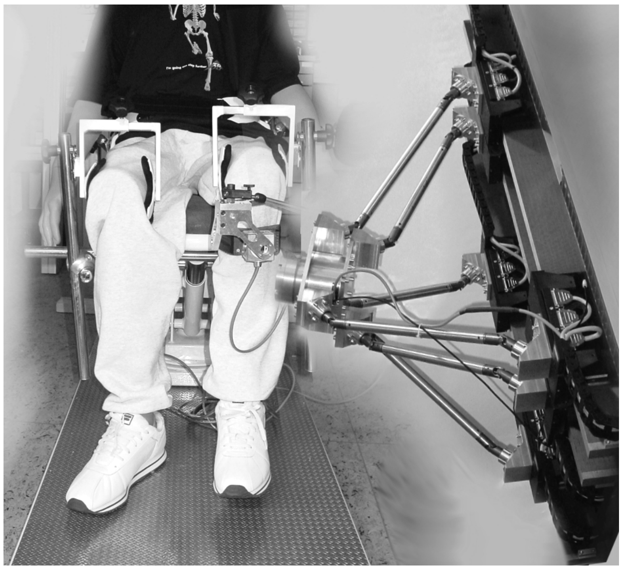

Figure 3: ROBOPED, Patient-Robot-Interface.

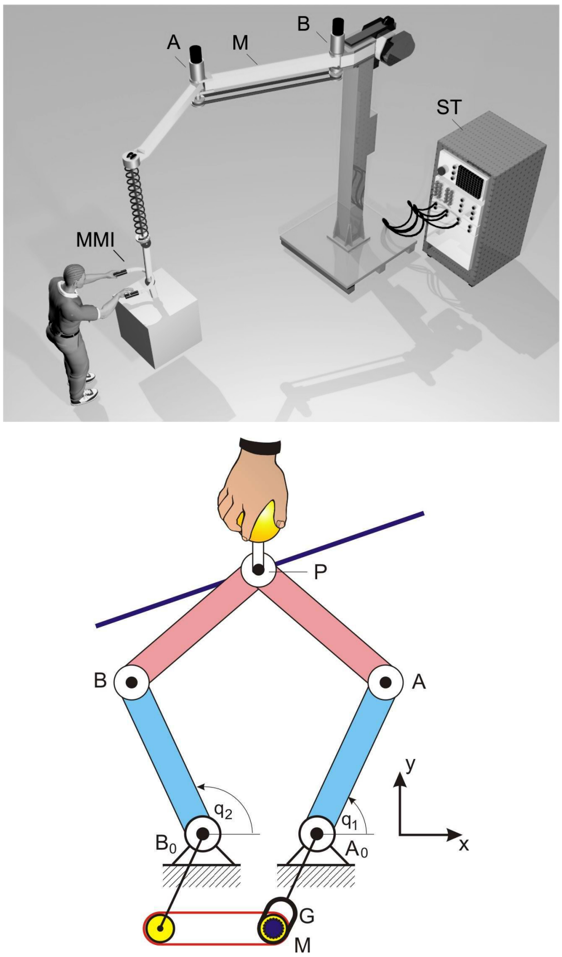

Figure 4: Conceptual Construction of the IPK-Berlin Cobot- Prototype.

2.5 Human-Machine Systems

The capital goods industry is facing a hard competition on a more and more global market. Besides the everlasting cost criteria this leads to additional challenges in the field of new requirements like shorter time-to-market, shorter product life cycles, advanced planning methods and a higher importance of quality and customer satisfaction. Over the last years many improvements in this direction could be made. Virtual planning tools or advanced software engineering tools not only led to more efficient planning and development processes but also improved the quality of the processes. But when it comes to user interfaces we are missing equivalent improvements.

In the last decades a lot of work was done in the high-risk application areas like power-plants or aircrafts. The research work led to a better understanding of the human role in these fields and thus to a very high degree of safety. But in those many low-risk industrial areas there is still a lot of work to be done. And with the increasing complexity and new technological solutions described above this field has to be addressed with a much higher priority.

3 Recent major accomplishments

3.1 Components and Technologies for Control

There have been tremendous advances in components and technologies for control in the last years. Especially, there have been increased activities in the application of intelligent control techniques, including fuzzy logic, neural networks, self-learning models, rule-based approaches, and genetic algorithm to improve the performances of autonomous vehicles, automobiles, service robots, intelligent robots, network robots, and humanoid robots. Furthermore, similar techniques are applied to complex subsystem levels, such as multiple sensors, sensor networks, as well as embedded sensor and actuator applications. This, in an indirectly way shows the complexity of modern components and application problems where simple standalone low-order mathematical model may not adequately address the control issues associated with them. The intelligent control technologies are more successfully addressing the control issues in these complex engineering problems.

We are also beginning to see significant activities and advances in microsensors and microactuators based on the MEMS technologies. The semiconductor fabrication derived MEMS technologies have become a major force in microsensors in recent years. The initial phase in the 1990s was single sensor units, such as crash-detection sensors for airbags and pressures sensors for engines. In the early 2000s the advances shifted towards integrating multiple sensors with CAN and other types of data buses in a PCB module as a cluster. Vehicle dynamic control (VDC) or electronic stability program (ESP) and tire pressure monitoring systems (TPMS) benefited from such sensor clustering technologies. These sensor clusters typically are smaller than a cigarette box. In the most recent years, efforts are given to further shrink the clusters by integrating multiple sensors in the wafer level during silicon fabrication, and by integrating multiple readout Integrated Circuits (ICs) as Systems On Chip (SOCs) in CMOS (Complementary Metal Oxide Semiconductor) foundry. An example of such a multiple sensor unit is shown in *Figure 5*.

Figure 5: A Miniaturized (30 x 30 x 8 mm^3), mountable Printed Circuit Board (PCB-mountable), 3-axis inertial measurement unit (IMU) complete with signal processing MCU and serial communication (the unit has integrated MEMS accelerometers and gyroscope as well as signal readout SOC inside.) The IMU can be used for motion control in automobiles, robots, and other motion systems.

Additionally, there have been steady progresses made in sensor fusion and data fusion technologies, guidance and navigation methods, and efficient field buses. The topic of diagnostics, fault-detection, dependability, and reliability also pose great challenges where we have seen much contribution in recent years.

3.2 Mechatronic System

Many industries over the last decade have made great strides towards mechatronic solutions, some of which link strongly to developments identified in other sections of this article, especially those related to Components and Instruments.

Automotive industry is one of the Key industries where mechatronic systems and components are found (Isermann, 2008). An incomplete application list includes electronic power steering, active steering for automobiles, power train management, traction control, intelligent cruise control and electro-hydraulic brake and last but not least, the combustion engines, with the development of: the common rail injection system for Diesel engines and also the injection systems for gasoline engines.

Data storage is also one of the important areas for the development of mechatronic systems with sophisticated but extremely cost-effective magnetic and optical storage systems based upon sophisticated embedded control highly integrated with the mechanics of the products; specific examples include dual-stage actuation and self servo writing (Devasia, et al., 2007).

Tilting technology in trains enabling higher speeds through curves; active secondary suspensions to give improved ride quality can also be held up as an example (Zamzuri *et al.,* 2007).

Progress is being made towards tackling a number of the key skills issues in mechatronics. Universities have recognised industry's needs for multidisciplinary engineers and are increasingly offering targeted mechatronic undergraduate programs that satisfy some of the multi-disciplinary skills requirements, and through this and other trends there is undoubtedly a greater awareness within industry of the importance of the mechatronic approach than there was (say) 10 years ago.

Design tools are progressively improving in their ability to handle the multi-domain modelling in a usable manner, although truly multi-objective optimisation capabilities remain limited (and where they are provided they are often under-exploited). In general modern design tools are better at providing the full-complexity simulation models than they are the appropriate simplified models needed for control design; even though formal model reduction techniques are available, they need considerable translation for use in a practical design context, in addition to which they are primarily based upon linear(ised) models because non-linear model reduction is still an open research problem. Rapid prototyping hardware tools for testing mecharonic systems are now readily available.

The overall research trends must therefore be towards more systems-oriented design methodologies and software tools that can provide real support for the burgeoning range of mechatronic products and processes, in particular bringing in some of the increasingly critical requirements related to fault tolerance, human factors, etc. Having said so, it should be noted that research on sensing and actuation technologies in particular from the viewpoint of hardware and software integration remain strong in the mechatronics community. Specific examples of such research include smart materials, micro/nano systems (Devasia *et al*., 2007) and sensor networks.

3.3 Robotics

Recent designs of humanoid mechanisms are inspired by the biological ones. Musculo-skeletal models such as flexible spine or bi-articular muscles are utilized for human-like flexible movement (*Figure 6*).

Figure 6: The Honda humanoid robot ASIMO is capable of both walking and running movements.

The conventional biped walking control is based on ZMP (Zero Moment Point). Recently, efficient biped walking is achieved by passive dynamic walking. Running movement (both feet get off the ground at a certain moment) is also realized (Honda 2008). In addition, Humanoid robots have to study new tasks or understand the common sense for coexisting with human, which are difficult to program in advance. One solution to this problem is learning from observation of humans. The function of imitation learning is useful method for teaching or automatic acquisition of the motion patterns.

A large progress has been made in the field of sensor development. The spatial and temporal resolution and the accuracy of sensors are enormous, comparable or even exceeding human sensing abilities, which is an important fact when talking about humanoid robots. As one of the largest research areas in mobile robotics in recent years, the simultaneous localization and mapping problem has been explained in detail and several solutions given. Path planning has seen a large development especially in the work on rapidly exploring dense trees and probabilistic roadmaps.

Not only reaching the level of sensory complexity of humans is aimed by today's research. The computational complexity of the brain is also a very important goal, and with the exponential growth of available computational power, for many it seems possible to reach. Many brain inspired (biological, cognitive, etc) systems and computational models have been accomplished, which aim to transform input sensory data into valuable information and knowledge (such as object recognition, filtering, etc). These systems can achieve quite astonishing results, undoubtedly useful in RT systems.

The research in the robots for nursing has been progressing steadily in recent years, driven by the aging society problems in developed countries, and many actual systems have been presented recently. Advances in manipulation and grasping have also been presented.

The major accomplishment focuses with RT human interface with the therapy animal robot "Paro*" (Figure 7)* (AIST 2008). Paro has many sensors to observe environmental information such as human's voice and touch. By recognizing them, its internal status is modified and it behaves according to interaction histories.

Figure 7: Robotic seal "Paro" showed promising therapeutic results in elder persons.

3.4 Cost Oriented Automation

As it has been discussed in Ollero et al (2006), integrated Product and Process Development as a cost saving strategy has now been introduced in industry. However, as Nnaji (2005) mentioned, lack of information from suppliers and working partners, incompleteness and inconsistency of product information/knowledge within the collaborating group, incapability of processing information/data from other parties due to the problem of interoperability hampers the effective use. Hence, collaborative design tools are needed to improve collaboration among distributed design groups, enhance knowledge sharing, and assist in better decision making.

Networked product development and manufacturing is a future trend in connection with the research on Collaborative Networked Organization (Camarinha-Matos et al, 2007).

Condition based maintenance strategies has been meanwhile implemented. The trend is to merge on-site and remote intensive infotronics technologies in order to recover expected performances as well as to face increasing demands on performance (agility, interoperability, reactivity, configurability, security certification, failure recovery). The trend is going to e-maintenance and e-service (Lee, Iung, Morel et al (2005).

Energy Saving control, particularly Building Automation is far from satisfactory. The trend is going to more effective control algorithm beyond the mostly used PID-Control. The problem is to make more sophisticated control understandable to the practical engineer (Salsbury, 2005, 2006).

Well established automation in Mining and Metal – processing saves energy, improves the security of the workforce, and is more efficient than manual work, therefore enhancing the competitiveness of factories. The trend is to develop low cost tele-operation or tele-manipulation with force feedback, and the maintenance. Sensors with local information processing to minimize the flood of data to be sent to the supervision computer, as well as data fusion processes are saving cost.

Smart Devices (sensors, actuators) with local information processing in connection with data fusion is meanwhile matured (Zayed et al, 2005) regarding cost reduction of components as well as with application in several fields. The trend is now to avoid cabling and introduce wireless connection to save cost.

The importance of automation technology continues to increase in the process industries. The traditional barriers between information, communication and automation technology are, in the operational context, gradually disappearing. The latest technologies, including wireless networks, field bus systems and asset management systems, boost the cost- efficiency of process systems. New application fields like biotechnology and micro technology pose challenges for future theoretical work in the modelling, analysis and design of control systems (Jämsä Jounela, 2007).

3.5 Human-Machine Systems

In the field of more basic oriented research, the valuable work on a better understanding of the human action was continued (see Ollero et al (2006)). This includes the understanding of cognition, situation awareness and decision making. Most of this work is still related to the more high-risk application fields where the error prevention is of very high importance. It is also obvious that the scope of research has broadened by a more socio-technical understanding of today's systems. Good examples can be found in the cooperation of the IFAC technical committees on Human Machine Systems (HMS) and Social Impact of Automation. In the last years the research topics presented during the two major symposia on *Analysis, Design and Evaluation of HMS* and on *Automated Systems Based on Human Skill* were more and more overlapping and of mutual benefit.

Another field of current research is the use of new interaction technologies. Examples are auto stereoscopic displays for a better three-dimensional view of complex situations and data spaces or augmented reality techniques for guiding the people in complex work situations. The use of agent technologies for supporting or supervising the worker in complex situations is also a new and promising field of research. But a lot of work has still to be carried out to prove the design principles and the reliability of agent-based software systems (Pritchett, 2004).

During the IFAC symposium on *Analysis, Design and Evaluation of HMS* in Atlanta 2004 the topic of pervasive computing technologies in industrial application fields has been addressed for the first time (Zuehlke, 2004). All panellists made clear that these technologies will have a deep impact also on how we operate future systems. Especially the new degree of mobility enabled by powerful mobile computers and the various wireless networking technologies will lead to new solutions, new challenges, but also new problems. People can do their work with any device which is best suited for the current situation, they will be connected anytime at any place and they can use their mobile devices for any task. But in industrial use we have to consider the equipment lifecycles. Whereas the machine or process equipment have a design life of about 20 to 30 years, the new nomadic operating devices will be obsolete after 2 to 3 years already. This requires a strict hardware-independent design of the communication software (Thiels *et al*, 2006).

4 Forecast

4.1 Components and Technologies for Control

In the forthcoming years we anticipate much more matured microsensor and microactuator industries, which in turn will give control engineers a wider variety of sensors and actuators at lowered costs. These technological advances will enable more systematic applications of control technologies to more advanced problems in robots, automation systems, and other mechatronic systems, with a greater sensing and actuation degrees of freedom. This will then require increased research efforts in managing and gathering data, data fusion, diagnostics, dependability, and fault tolerance. In addition, we anticipate more embedded software platforms and more standardized data buses. These advances in components and technologies will be then used for automobiles, robots, mechatronic systems, and automation systems as described in the below.

4.2 Mechatronic System

The definition of mechatroncis has been and will remain evolving. Although wireless communication and GPS technologies are not explicitly stated in the scope of the IFAC Technical Committee on mechatronic systems, they are important in modern mechatronic systems. Despite being a relatively new area in terms of real industrial involvement, there has been an enormous increase in the number of products and processes which can now be considered to be mechatronic. The increasing awareness of future products and processes that can be facilitated by the application of mechatronics will continue to grow, and many industrial companies, research organizations and university departments have reorganized to ensure that the maximum exploitation possibilities are realized.

In particular the industrial areas mentioned in section 3.2 will continue to be developed to provide higher mechatronic implementations: automobiles will progressively take up concepts such as steer-by-wire, currently only at the experimental stage; data storage systems will adapt towards new concepts that still require sophisticated control and data processing; the use of mechatronics in trains will progress towards active control of running stability and, possibly, new mechatronic vehicle concepts; mechatronic systems such as wheel chairs and orthosis to help impaired and physically disabled persons are gaining popularity; and so on.

Future systems will see further synergies between mechanics, sensing and actuation, greatly enhanced by embedded electronic “system-on-chip” technologies which will continue to shift the cost-effectiveness balance towards solutions that incorporate advanced electronic processing. A key complementary technology for mechatronic products is MEMS, linked of course to developments in Components and Instruments.

A future possibility is mechatronics of a more hierarchical nature, e.g. high functionality mechatronic systems constructed from a set of mechatronic sub-systems providing distributed processing functions combined with central coordination. These would include smart materials to make up the mechanical structure, sophisticated MEMS sensors, self-diagnosing actuators and complex, centralized information processing capable of adaptation and reconfiguration to maximize performance and reliability at minimum cost. Communication technologies, in particular wireless communication, will play an important role in hierarchical mechatronic systems.

Mechatronics is already an enabling system-level technology that cuts across many industrial sectors, and as the major challenges are tackled and overcome it will become more and more a normal part of the engineering design process, so much so that purely mechanically-based solutions will become the exception. The implications of this trend raise questions about the future role of mechatronics: it is (arguably) a paradigm rather than a science, and as it increasingly becomes accepted as the normal approach to engineering the role of mechatronics training and technical support activities, and indeed of the word itself, need to be developed accordingly.

4.3 Robotics

Considering the technological advances in sensors, computers and actuators, the components of the robot will progress at rapid speed. The future directions should pay more attention to the whole-body motion behavior generation. As described in section 3.3, human mimetic architecture is the most practical solution. Furthermore, safety for humans is an important problem for introducing the humanoid robots in our living environments. Materials, mechanism and control method should be developed for human compliant as well as performance of the robots. Another essential and challenging problem is the intelligence of humanoid robots. Interaction between humans and robots is also investigated.

The complexity of the brain is fairly reached by artificial computational tools, but only in terms of elementary computational units (neurons vs. transistors or logic gates). The complexity of the interconnecting network between the elementary units is still much higher in the brain, which explains its superiority in solving computational problems. In the near future the development of multiple seed processors may lead to a system of much higher network complexity, and in turn allow the implementation of computational models with problem solving abilities much closer to that of the brain.

The need for robot-human coexistence will result in more advanced control for their direct interaction. This will probably be accompanied by a more thorough understanding of human motion and activities. Continued development can be expected in various services and medical applications. Also, robot mobility as one of the major necessities for RT can be expected to grow with still better algorithms being developed and implemented in actual systems. On the other hand, robot systems can be expected to grow more and more complex, which will lead to developments of still better complex system control and network components middleware solutions.

This robot-human coexistence will also be supported by an improved RT-Human interfaces. Each recognition technology such as voice, face, and gesture will be combined to recognize high-level information about humans such as intention, activity while expressiveness of haptic and tactile interfaces should be more sophisticated.

4.4 Cost Oriented Automation

Maintenance is now a very important topic for which a lot of issues and challenges have to be discussed. The most costly and not yet solved problem is the downtime of machines and equipment. Near-zero-downtime would enhance the overall performance of a production system and saving costs. To minimize disturbances, breakdowns, and to observe degradation of parts, e-maintenance and process supervisory control systems are being developed and introduced. The implementation of advanced e-maintenance technologies considers Cost, Reliability, Availability, Maintainability, and Productivity, i.e. the performance, for any equipment and associated applications. It necessitates a holistic approach for integrating views and evaluations, not only of the systems themselves, but also for their mutual interactions and their interactions with the environment.

The main topics of interest of Cost Oriented Automation are the maintenance strategies, the organizational and economical methods and the business models; the Asset and maintenance management; the maintenance related services; the E-maintenance technology and processes; the Diagnostics, prognostics, reasoning and decision support; the condition monitoring sensors, signal analysis and failure analysis; the reliability and statistical approaches; the lifecycle and sustainability issues

4.5 Human-Machine Systems

In the next years we will surely notice a migration of many technologies from the everyday-application into the industrial world. These technologies will have reached a degree of maturity and acceptance that will make their use profitable even in harsh industrial environments. Especially the wireless networking systems will lead to a very high degree of mobility of technical devices as well as the worker. By this, we will not only face technical improvements but also social implications. When a worker can operate systems in front of the process as well as sitting at home on the sofa we have to answer the more social questions about the limits between working and living. And closely linked to this is surely the important field of responsibility for the work and possible failures.

Future human-machine systems will become more and more multimodal. They will accept inputs via speech, gesture, eye focus, touch and many others. And these inputs may overlap in information. As these multimodal channels have a high degree of redundancy the user interface design must cover ad-hoc all possible modal channels. Furthermore, the short lifecycles of the operating hardware, e.g. a smart phone, will require an independency of the communication software from the hardware. This can only be achieved by using abstract, domain-specific communication models to describe the interaction independent from the actual hardware realisation (see *Figure 8*) (Bock *et al*, 2006). We will have to develop such models which must then be implemented in the appropriate engineering tools (Botterweck, 2006). During the 10th IFAC symposium on Analysis, Design and Evaluation of HMS this important topic has been addressed in a first workshop on model-driven user-centric design & engineering.

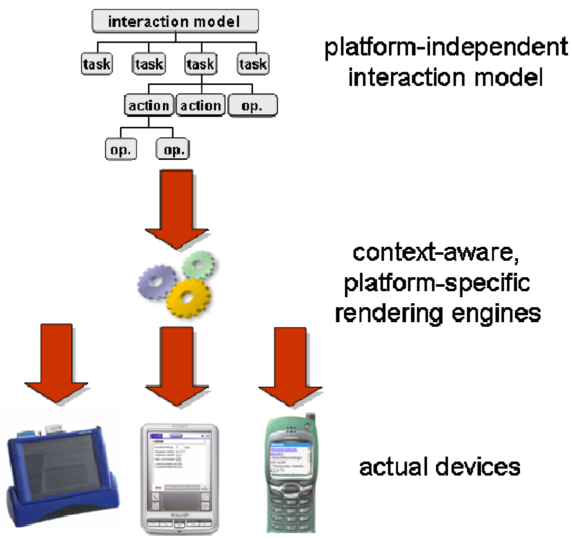

Figure 8: Context-aware and platform-specific renderers creating software for given device platforms using abstract interaction models

5 Conclusions

This milestone paper has presented the current key problems, accomplishments and forecast in control technologies in the field of components and technologies for control, mechatronics, robotics, cost oriented automation and human-machine systems. Several technological trends have been identified. The first one is the development of wireless communication and networking that should improve the range of mobility of the technical devices. The second is the importance of energy saving in the design of the new control system that is becoming a very critical issue within the next years. The third is dealing with the increasing importance of embedded electronic and system on chip technologies and the large development of MEMS in relation with cost reduction.

The leading application fields are obviously transportation systems with a specific focus to automotive that can be considered as a "pushy" domain. In addition application fields like robotics as well as new emerging topics like building automation are also of very high importance.

Finally, the increasing importance of the human-machine interaction and the necessity to take into account the users' understandability and acceptability will be a key issue for the future. It will certainly become one of the important research themes for the next years involving cooperation between control engineers, ergonomics, psychologists, sociologists.

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