Control systems related research in Framework Programme 7 (2007-2013)

Recommendations for a research agenda in Europe

DRAFT   DECEMBER 10, 2005

Based on brainstorming and consultation meetings organised by the European Commission in Brussels, February and May 2005

Publication sponsored by the HYCON Network of Excellence

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PREAMBLE < *to be improved* >

The purpose of this report is to present to policy makers, European Commission and national governments as well as research leaders in industry and academia the current and future needs and priorities for research in the field of control theory, design and engineering and the associated sectors of the economy and novel applications which depend on control. Examples include transport (car, ship or train stabilisation), , communications (quality of service and server stabillty), space (accurate satellite operations), as well as environment, manufacturing, health care,.security and large scale infrastructures protection

Control systems (*from small or tiny embedded to larger ones and also non embedded*) are now a major driver for economic growth and competitiveness. Hence, control is emerging as a strong pervasive discipline and makes a clear case for a dedicated funding strategy covering the period of FP7 from 2007 to 2013. The report also demonstrates the decisive role of control in designing, building and operating the future intelligent and networked systems which will exhibit highest performance and robustness under uncertainties and limited resources.

The control area needs to be reflected 1) as an underpinning scientific substrate and an enabling technology in the EC Framework Programme and 2) as essential enabling technology of a number of other priority areas such as robotics, manufacturing, cognitive and complex systems and the application sectors mentioned above. Control uses developments in embedded and real time systems which are necessary for its implementation.

This dual aim will ensure that advances beyond the state of the art are achieved and taken up in Europe within shorter time horizons than today.

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ACKNOWLEDGMENT

Unit G3 of the European Commission IST Programme on Embedded systems would like to thank the participants of the brainstorming meeting of February 2005 that set the basis for this report and led to the follow up consultation meeting: Dario Floreano, Morari, Lennart Ljung, John Lygeros, Ricardo Sanz, Reinhard Wilhelm and also Ron Patton for his dedication under very tight time constraints and some unforeseen obligations in the UK.

Furthermore a great thanks is due to all research and industry experts who participated in the consultation meeting of May 2005 and provided additional material, comments and remarks after the first version of this report was circulated. In particular we acknowledge the technical contributions and editorial work done by John Lygeros, Alf Isaksson, Samir Bennani, Marek Makowski, Nick Karcanias, Michel Kinnaert, Francoise Lamnabhi-Lagarrigue Thomas Parisini, Claudio Bonivento and Lorenzo Marconi for compiling a focused report on control R&D challenges, Stefano Stramigioli for presenting inputs from the Benelux control groups, Karl-Eric Arzen and Karl Astrom for making available the report and notes from the recent Lund workshop on real time control, June 13-15, 2005 and Manfred Morari and Marika Di Benedetto also for their effort to enrich the report with relevant market figures.

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EXECUTIVE SUMMARY

This report is the result of a brainstorming meeting held at Brussels on the 10th & 11th May, 2005. It shows how Control is emerging as a strong pervasive discipline and makes a clear case for a dedicated funding strategy covering the period of the seventh Framework Programme from 2007 to 2013. On the 6th of April 2005 to the Council, the Commission proposed that a budget of 73 B€ be allocated to R&D over a period of seven years, extending from 2007 to 2013 and organized as the seventh Framework Programme, FP7. The Commission's proposal allocates a major share to Information and Communication Technologies (ICT) with 12 B€, i.e. an annual funding close to 1.8 B€. At the April 6th 2005 meeting the Commission proposed an activity (Pillar) on Embedded Systems Computing and Control for FP7 (2007-2013), under the Information and Communication Technologies Programme.

R & D leaders in Control and related disciplines from both industry and academic institutions across the EU have been aware for some time of the strong developments in Control and the potential benefits Control offers to modern technological and business systems. Currently, in FP6 (and in earlier programmes) European research in Control is (and has been) funded through fragmented application areas of manufacturing, robotics and embedded systems. The steady increase in complexity of modern systems and infrastructures has placed strong demands on the requirements for Control Systems Technologies and underpining methodologies. New advances in computing technology, advanced developments in human-in-the-loop technology, new microelectronics and intelligent embedded devices (MEMS, self-validating sensor and architectures) have facilitated the development of powerful scientific and engineering methods in control. These control technologies, concepts and methodologies go significantly beyond the scope of traditional or classical solutions and now have the capabilities to address new challenges arising from large-scale networking, distributed service provision, life-cycle variability of processes and sophisticated safety-critical applications. The synergy with Computing and Embedded Systems is now very clear and it is the case that most embedded systems, particular at higher abstraction levels actually are control systems or involve control systems.

Stimulated by these findings the brainstorming meeting was held to identify very innovative research and development challenges, objectives and research directions in Control and thereby to establish a rich multi-disciplinary strategy for funding this activity as a dedicated area in this proposed Pillar of FP7. The meeting confirmed that a dedicated funding domain for Control will facilitate developments of research going across disciplines and that have societal and technological significance. Members of the meeting confirmed that control systems are now a major driver for economic growth for advanced automation, transportation, the advanced role of the human operator, healthcare, biomedical research, environmental protection and manufacturing, energy sector, business processes and enterprise activities and new sectors (internet,.). Novel and attractive concepts were presented that focused on both current and future application domains and pointed to the need to maintain competitiveness for products, process and services in Europe.

Recommendations:

The following areas were idenified as targets for further research in control:

- Human in the loop/human as a plant systems.
- Complex distributed systems and improved performance in uncertain environments.

The following research challenges were identified as key to making an impact in these areas:

- Modeling, monitoring and decision support for humans in the loop.
- Bio-mimetic and bio-inspired systems, human machine symbiosis.
- Fault tolerant, self adaptating, learning systems.
- Distributed, coordinated, heterogeneous control.
- Data fusion and information integration.
- Robust contol of large-scale, distributed, networked systems.

INTRODUCTION

Europe, including the new member states, has a long and successful tradition in fundamental and/or basic research including developments in control systems. European developments in **Control Systems Science** (or “Control”) have been extensive for more than five decades and the infrastructure, academic resources and application fields for control related technology, are very rich. However, the wealth and breadth of knowledge of control systems theory and technology have not been fully utilised. This document outlines the reasons why this is so and why even today several industries are losing their basic knowledge and expertise in domains like Control, with a severe impact on their long term competitiveness.

Europe is still undergoing a transformation into a dynamic knowledge-based economy (Lisbon, 2000) involving the growth in **complexity** of all areas of technology and business. FP6 strengthened the content of applied research with a focus on short-term economic success. One can refer to a similar exercise held before the launch of FP6 to see the changes in focus and direction that are emerging (Gray, 2000). This choice was important to keep the European economy competitive and indeed there is evidence that research themes of FP6 have been hot topics for several non-European nations (Murray, 2003). For Control this has meant that FP6 has been able to support high level research into the development of control systems concepts, as long as the research is focussed on an end–user domain. However, taking technology as a whole, this approach is not ideal. Simple facts relating to insufficient reliability, e.g. mobile phones that have to be withdrawn from the market and cars that are called back to dealers, etc, indicate that Lisbon’s goals (i.e. mainly driven by application) may not be reachable simply by strengthening the application of the research. More failures with yet not forseen consequences are likely to occur and Control is not immune from these problems. The challenges for achieving **greater security, quality, availability and reliability** are very real when we are faced with the rapid developments and demands of new complex systems and the changing role of human-system intervention. One must also bear in mind the changes that have taken place globally since 11th September 2001, heightening the enhanced demand for high security and system availability.

The brainstorming meeting held on the 10th & 11th May, 2005 sought ways in which Control research can be expected to contribute to future technology and business developments in Europe, in keeping with world-wide trends and demands. The essential idea is to strengthen the collaboration between and synergy of **system theory** and **automatic control** with new **multi-disciplinary research in cognitive science**, **autonomous systems, pervasive and distributed and bio-inspired computing, complex systems, fault-tolerance and autonomy**. The aim of the meeting was to identify adventurous and very innovative research and development challenges, objectives and research directions in Control and thereby establish a strategy for funding this activity in FP7 during 2007 to 2013.

The participants of this meeting included 19 academic leaders holding senior positions in European research institutions and 11 corporate and engineering management representatives from major European IT, communications, transportation, space and process industries. The participants represented a good cross-section of the established control systems community together with a wide spectrum of other disciplines interested in the development use of control systems such as Bio-Technology, software engineering, modeling, artificial intelligence (AI), autonomous systems, defence and security. The partners included several representatives of the International Federation of Automatic Control (IFAC) including the current and immediate past Presidents and the President of the European Control Association (EUCA).

Members of the meeting confirmed that control systems have been a major driver for economic growth for advanced automation, aerospace & transportation, healthcare, communication, environmental protection and manufacturing and new sectors (internet, etc). Novel and attractive concepts were presented that focused on both current and future application domains and pointed to the need to maintain competitiveness for products, process and services in Europe.

To get an idea of European competitiveness the essential parameters in R & D are summarised as follows [for 2003, prior to EU enlargement] (source: European Commission):

Criterion of R & D Competitiveness	**EU-25**	**USA**	**JAPAN**
R & D Intensity (% of GDP)	*1.97*	*2.59*	*3.12*
Researchers per thousand labour force (FTE)	*5.5*	*9.0*	*9.7*
Share of world scientific publications (%)	*38.3*	*31.1*	*9.6*
Scientific publications per million population	*639*	*809*	*569*
High-tech exports as share of total manufacturing exports	*19.7*	*28.5*	*26.5*
Share of world high-tech exports (%. 2002 figures)	*16.7*	*20.0*	*10.0*

Table 1: R&D Competitiveness Parameters

The data in Table 1 a show Europe's position in R & D expressed in terms of percentage the GDP, compared with the USA and Japan.

Figures illustrating the economic impact of control technologies are listed in the appendix. We get a better indication of the developing strength of control activity in European industry by examining the work of 17 of the top 25 European companies: Several of them have either control business sections and most of them recognise the importance of Control. Examples (far from exhaustive)are as follows:

ABB is a major supplier of automation and control systems to both process and power industiries.has a separate business unit for process automation and control.
Alcatel is a major player in servers and space systems, control for stability of satellite systems.
ALSTOM is a supplier of automation and control systems.
BAE Systems is a major player in aircraft, design, stability and navigation as well as in air traffic control/management systems and defence electronics, sensor networks.
BMW is a major player in the use of Control for vehicle dynamics, stability, electronics and transport safety (ABS, ESP, X-by wire, etc).
Bosch uses advanced control and diagnostics in next generation car electronics.
DaimlerChrysler control plays major role in car electronics and trasport safety (ABS, ESP).
EADS is a major player in the field of aerospace stability, navigation, air traffic control & management systems.
Ericsson has radio link control, base station and servers systems, space systems.
Alenia Spazio Finmeccanica is strong among others in aerospace control systems.
Nokia has radio link control and base station control.
Philips has control of medical systems and adaptive control in multimedia systems.
Renault control plays a major role in car electronics and transport, involving control and safety systems (ABS, ESP).
Schneider Electric has a separate business unit for process automation systems.
Siemens has automation and controls business unit, power systems and drives.
SNECMA has a separate business unit for control systems of engines and turbines for aerospace systems.
Volkswagen is a major player in car electronics and trasport safety (ABS, ESP) involving control.

The steady increase in complexity of modern systems and infrastructures has placed strong demands on the requirements for Control Systems Technologies. New advances in computing technology, microelectronics and intelligent devices (MEMS, self-validating sensor and architectures) have facilitated the development of powerful scientific and engineering methods in control. Almost all embedded systems now involve Control particularly at the high levels of embedding. Control technologies go significantly beyond the scope of traditional or classical solutions and now have the capabilities to address new challenges arising from large-scale networking, distributed service provision and sophisticated safety-critical applications.

The trends and demands for Control R & D are developing on World-wide scale and Europe needs to retain a strong and leading position in the relevant technologies. The brainstorming meeting sought ways in which Control research can be expected to contribute much further to future technology and business developments in Europe. In the light of the increasing complexity of technological and business systems, we propose to strengthen the collaboration of system theory and automatic control with new multi-disciplinary research in cognitive science, autonomous systems, pervasive, distributed and bio-inspired computing, complex systems, fault-tolerance and autonomy. Prior to identifying the most important research and directions and R & D strategies, it is necessary first to outline the Research Vision by answering the following questions:

What is the status of current Research in Control?

How can Research in Control be Advanced?

To help to answer this questions in a focused way, the brainstorming meeting confirmed that the research domains originally suggested at the February 23rd meeting should be re-grouped as follows:

System-human symbiosis: Human in-the-loop/Human as a plant. This topic has two distinct aspects, the control within humans and the human intervention as part of the control loop. The former could be important for eg. autonomy for ageing population (AAL-Ambient Assisted living), whereas the second could influence applications in eg. automated drug delivery, biomedical and health research the operator's role in a process industry. A special section has been included summarising the ensuing discussion.

Pro-active evolvable control: Complex distributed systems and improved system performance in uncertain environments. Special Control techniques can be applied to a wide range of large-scale and complex distributed systems to help reduce the effects of uncertainty (arising e.g from the environment). Good examples of applications of complex systems include energy distribution, transportation (UAVs), telecommunications, environmental monitoring, epidemic management, and some process industries. (e.g.pulp and paper mill).

The report concludes by outlining the most interesting domains for potentially strategic objectives of an ICT R&D programme in FP7, in terms of the domains outlined above.

THE VISION FOR EUROPEAN RESEARCH IN CONTROL

What is the status of current research in Control?

Historical Perspective

According to Aström (1999) “Control systems are all around us - in our cars, airplanes and aerospace systems, power generators, even in our CD players. They are widely used and hugely successful. But control systems seldom get public attention, except when one of them fails and disaster strikes. They typically remain hidden, tucked deep inside the hardware.” The underlying principle here is that the system to be controlled has already been designed before the controlling mechanism or controller has been developed. Control has traditionally been viewed as the final or “add on” stage of the design process for a system that has been constructed and this is the main reason why it is “hidden” as a technology. We can refer to this as the “fixed system structure” assumption of Control that has been valid as long as feedback systems remained in a relatively simple status and requiring “point to point” feedback control loop closure. The reality is that modern technological systems are more complex and heterogeneous in terms of the required design tools and technologies. Until recently Control has tended to not contribute in a heterogeneous way to overall system design, development and construction and for several decades has missed out on these “pervasive” system developments. The contributors of this brainstorming workshop explain how this has happened and in this document show how and why Control can emerge as an important pervasive and facilitating systems engineering discipline.

Down through history and even as far back as the Roman civilization feedback control has been used through mechanical mechanisms and automata. Much later, the fly-ball governor invented by James Watt in 1788 for the steam engine was a king pin in the development of machines in the industrial revolution The fly-ball governor as a mechanism of speed regulation is well known and the stability of this ingenious device was analysed by Clerk Maxwell in 1868 (Bennett, 1979).

The actual concept of feedback (in modern technology) was not re-discovered until “regenerative feedback” mechanisms were developed for radio systems in 1913. However, the basic principle of negative feedback control was conceived by Black in 1927 through the development of the analogue feedback amplifier (Bennett, 1989). The idea of feedback and what it could achieve soon caught on and by the early 1940s Norbert Wiener in the USA led the world into the new field of Cybernetics (Wiener, 1948). In 1940 Wiener developed automatic range finder servomechanisms for anti-aircraft guns able to predict the trajectory of an airplane by taking into account the elements of past trajectories and this was repeated shortly afterwards by the Soviet scientists. During the course of their work Wiener and his colleagues were struck by two astonishing facts: the seemingly "intelligent" behaviour of the machines and the "diseases" that could affect them. The machines appeared to be "intelligent" as they dealt with "experience" (the recording of past events) and could predict the future. There was also a strange defect in performance: if one tried to reduce the friction, the system entered into a series of uncontrollable oscillations, we of course know of today as “limit cycles”. In the 1950s the study of the link between living organisms and machines led to the important concepts of memory and pattern recognition, of adaptive phenomena and learning, and new advances in bionics (attempting to build electronic machines that imitate the functions of certain organs of living beings): artificial intelligence and industrial robots. A further phase of research focused on a return from the machine to the living organism and this accelerated progress in neurology, perception, mechanisms of vision, etc. In the 1960s there was an extension of cybernetics and system theory to industry, society, and ecology.

Historically, cybernetics was the discipline of “building artificial minds” following the principles of artificial intelligence, dynamical systems theory, etc. However, five decades ago these disciplines separated. The “dynamical systems theory” part came to be known as “Control” and remained focused on dynamical systems, their stability, feedback design and applications to industrial, space, vehicle and military systems. The field of cybernetics continued to encompass artificial intelligence, automata, learning systems etc and slowly became an intersecting part of the two disciplines of Computer Science and Cognitive Science.

Control became an independent discipline at the interface of theory, applications & computation. In the wider context of technological development (outside of the field of Control) systems have continued to become ever more complex, deeply embedded and inter-connected and more demanding in terms of safety, reliability, availability and the roles of involvement of the human operator. During the 1970s the concept of "plant wide" Control developed as a high level aspect of control of a multi-level process system or enterprise. A certain amount of research and development at this "large-scale" level was carried out for the chemical and process industries and also for business systems (Singh and Titli, 1978). However, most of the research and development of Control has been done at lower levels (e.g. for control of single process loops – point to point control, flight control systems, autopilots for aircraft and missile systems). The list of applications of local control is endless.

Since the 1970s the "**Information Rich**" world has driven the development of a whole variety of real-time, distributed, pervasive and ubiquitous software and engineering tools and have also been a fundamental basis for the development of Computer Science as a field in its own right. Ideally, what is required is a control technology that is an integral part of or a tool for all embedded levels of process design and fitting well together with the Computing and Cognitive Sciences (Murray, 2003).

The reality is that for more than 5 decades Control has existed in a "force-field" based on the formulaic/systems theory approach underlying the idea of modelling and design, mostly at the local control level. The problem is that the fields of applications and computation have developed rapidly becoming complex, whilst Control itself has remained as a largely theoretical and hidden discipline. Control has contributed key methods for model-based decision-making support in almost all areas of applications, including industry, policy-making, finance, environment, medicine (Wierzbicki, Makowski, Wessels, 2000).

It is interesting to note that since Black's famous feedback innovation in 1927 the analogue feedback amplifier has always been designed in a "pervasive" manner using feedback control principles. By this we mean that the feedback was used at the beginning of the amplifier design; it was a part of the design and not used after the system was designed). In traditional terms there are few examples where these principles form a pervasive part of total system design, the usual tradition follows Åström's observation about *feedback control.*

Summary of the State of the Art in Control

To a significant degree Control *has* retained the fixed system structure (fixed point-to-point feedback loops, etc), designed and developed once the system to be controlled has itself been designed. Whilst other tools have been evolving rapidly according to the requirements of modern complex systems it has become clear that Control could not develop in the restricted scenario it found itself in.

The first 5 years of this decade have shown us that the world can change very quickly. We have seen the bursting of the IT "bubble" and disasters and severe threats to security have occurred. What we are facing is a new world of applications being created by societal expectations that have an impact on: energy distribution/utilities, health, communications, military requirements, manufacturing, transportation, business systems and even in the economy itself. Societal drivers that underlie all of the above are security (security of data, safety-critical systems, safe transportation) and quality (quality of health care, quality of manufacturing, etc.), reliability and availability and a demand for improved economy. In the light of these drivers Control requires greater *decision support*, more advanced *uncertainty management* (e.g. for complex systems) and *key skills* for meeting societal challenges. The realisation of these challenges is developing at a research level in academic institutions and in the asset management of leading industrial organisations. One of the biggest challenges is for this awareness to spread far enough into industrial enterprises, business systems and healthcare etc, and become a widespread part of asset management strategy for funding organisations.

During the last 20 years, the advent of ever-increasing computer technology has facilitated the development of applications of Control that hitherto were considered impossible. Many tools are available, and Control now seeks to deal with problems of the “Information-Rich World” (Murray, 2003). Examples of some of these information-rich areas are:

- Integration of design / operations of technological processes;
- Power generation & distribution systems under market de-regulation;
- Control of communication/ traffic networks, ad hoc networks;
- Networks of systems: systems of embedded systems,
- Business processes and Supply Chains
- Re-engineering of Technological and Business Processes
- Databases and Information Systems
- Life-cycle Management, Business Merging and Asset Management

These areas are rich, as far as challenges are concerned. They do not suffer from the “fixed system structure assumption” and are beginning to have a significant impact on technology, economy etc and are actually characterised by different forms of complexity. Complex Systems emerge in many disciplines and domains and have many interpretations, implications and problems associated with them. An interesting characteristic of complexity is that higher levels of complexity tend to result in increased involvement of the human operator. One must bear in mind that 40 years’ ago the opposite was true as increased factory and industry automation steadily removed some levels of operator intervention. It was thought at that time that factory automation would lead to less operator intervention and this concept went hand in hand with the drive to cut operator costs as company overhead costs soared higher. We are learning that this philosophy was not entirely correct and that aspects of “human in the loop” are becoming increasingly important. The main issue is one of how the human is best used “in the loop”. Humans have skills (e.g. the ability to abstract from information) that are still difficult to replicate via machine learning. But the essential challenge is to understand how the human interacts with machines and systems and hence how the role of the human operator can be enhanced in terms of safety, security, quality and efficiency. Humans are difficult to model and their interaction with the plant, process or vehicle induces additional complexity and uncertainty. We are entering a totally different world. Engineering systems have relatively little flexibility, it is almost hopeless to develop a good model of a human system that is widely useable. Engineering systems use finite state machines etc, what do we use to model humans? Whatever you do with the model of the human you have to do adaptively. So the modelling of the human (as an intervention) in the Control loop remains a very significant challenge! On the other hand humans are good at abstracting information and choosing the right action to be taken, i.e. information-gathering and abstracting information. So, the human in the loop problem is a very important research issue. We certainly know that humans are poor at summarizing information.

The distinguishing features of the above problem areas is their systemic nature and the close link between operations, design, business/economy/society aspects on one side and modelling, system structure and properties, measurement-information and control-management structures as well as the selection/design of information and management organisational structures. Each of the above technology areas has its own ICT requirements and the issue of integration is central. These application fields (and others) are clearly interdisciplinary, contain a number a generic, complex nature type problems, the solution of which underpin the development of future methodologies and associated technologies for the application areas.

The picture is emerging that for Control the wheel has almost turned a full circle since the early 1940s. Control is now beginning once again to embrace the fields of artificial and distributed intelligence, pervasive and ubiquitous sensing and computing, embedded systems and with the ever-increasing role of the human in the loop. As systems increase in complexity this is becoming more important as more “pervasive” system tools become available. In recent years Automatic Control has been branching out in the directions of

Software Engineering and Cognitive Science, giving rise to a discipline that can now be called “Embedded Cognitive Control”, as shown in Fig. 1.

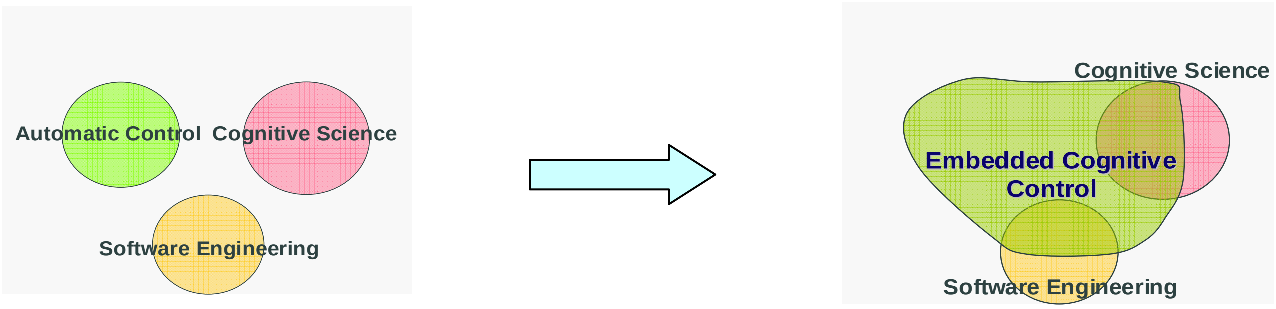


Fig. 1: Example of key disciplines of (Embedded) Cognitive Control

The concept of embedded cognitive seems to imply a return once again to cybernetics. Also because of the extensive developments in all the technologies concerned Control is now able to achieve some of the dreams and aspiration of Norbert Wiener. Control is becoming a facilitating domain of expertise providing the “nuts and bolts” for constructing powerful intelligent devices and systems. However, one could also ask what is the layer between “Cognitive Science” and “Embedded Cognitive Control”? What are the emerging tools that will bolt these disciplines together? The answers to these questions are becoming more apparent as Control itself becomes more multi-disciplinary. Cognition and Control are multi-polar and not bi-polar, we need to open up and see challenging new paradigms and establish links with other disciplines (Cognitive Science and Computer Science). This “integrative” thinking became a formal issue in the mid-1990s (Karcanias, 1995).

Much of the challenge that Control has faced since its birth is the need to overcome uncertainty. Control has a natural potential for rejecting disturbance, noise and “uncertain” system signals. However, a control system must be properly designed to achieve the best of this “disturbance rejection” and minimization of unwanted signals. The traditional designs are based on knowledge of the process characteristics e.g. the way the process system behaves, how it operates, and in general its operating “behaviour” in terms of quality of operation, stability, etc. The basic challenge of uncertainty in relation to problems of Control lies in the principle that knowledge (often expressed in terms of a mathematical model) of the system to be controlled is not known precisely. For 25 years the Control literature has been dominated by papers dealing with *robust design for control systems*, making dynamical systems behave in a repeatable, stable and predictable way when the system undergoes changes in operation or in its working parameters, and when the modelling of the system is imprecise (Maciejowski, 1989).

The uncertainty paradigm is here to stay as models and modelling cannot be avoided in Control, but as systems have become more complex in structure the tendency is for the uncertainty issues to move from the lower to the higher levels of Control, making Control become less “hidden” and more pervasive in the overall heterogeneous system. However, as systems become increasingly more distributed and complex the traditional view of uncertainty (in terms of modelling error, unknown or stochastic disturbance, etc) becomes inadequate and future research will teach us more about appropriate modelling methods. In particular, new methods are needed for proper treatment of irreducible uncertainty and shocks (rare events with catastrophic impacts affecting large communities).

An overall challenge for uncertainty is to know how it can be best managed. We can consider that uncertainty comes from the outer environment through imperfect perception, from the inner environment or even from the knowledge used to perform control or the controller itself. The reality is that modern complex technological enterprises involve uncertainty in these more subtle ways. For example, complex inter-connected systems can have uncertain inter-connections between processes or subsystems with each subsystem representing a process in its own right. Shocks are natural phenomena for uncertain systems, e.g. jumping loads in service, failures of networks, and other unforeseen events, like floods, earthquakes or economic breakdowns; large, or series of small, shocks may lead to failures of a system.

The classical and current terminology is now inadequate as Control moves further into the realm of autonomy and is faced with more ane more system complexity and the need to deal with security. Terms such as: control, computers, communications and components are converging in the sense of the wider field that Control itself must encompass.

How can Research in Control be Advanced?

The current state of the art shows us that as a consequence of increased system complexity and demands for higher security, new paradigms must emerge to enlarge the domains where Control can be relevant. New paradigms will continue to challenge the fixed system structure assumption of Control. These paradigms force us to reconsider some of the fundamentals (viewing Control as the final design stage on a formed system) and create the need for new developments where Control provides the concept and tools intervening in the overall design process, even at stages where the system is not fixed but may vary, and may undergo some process of evolution.

It has become clear that Control should not build on past successes but must look towards societal needs. Control must have more expectations than it has done in the past, as systems become even more complex and gain more constraints. It is a simple fact that more measurements and data require more computing power, more actuators (with higher intelligence), and these in turn give rise to even more complexity. Then you get into the idea of “systems of systems” and at each system level you have embedded elements operating under appropriate control. Each of the system levels has to be designed and developed using control, so the pervasive idea of Control is very much with us and provides a strong way of going forward in Control research. This concept also fits synergisticly with the “Embedded Systems” and “Computing” elements of the proposed ICT Pillar in FP7.

From an international perspective, in 2003 the Technical Board of the International Federation of Automatic Control (IFAC) held a Workshop/Panel Session in Rotterdam to identify trends and emerging areas within Control. The goal of this IFAC Workshop/ Panel was to (Masten, 2003):

- Identify emerging trends within the control system and automation field
- Forecast tomorrow’s most significant applications which will achieve higher performance, increased efficiency, lower cost, or other benefits
- Highlight the likely control methodologies and implementations that will enable such future improvements.

In keeping with the IFAC goal to “promote (in both theory and applications) science and technology of control in all systems, whether engineering, physical, biological, social or economic” the IFAC “Emerging Issues” Workshop/Panel session led, after receiving more than 50 topic suggestions and after extensive consultation, to a strong realisation that the following topics are important emerging trends for the future of Control (here we re-group these topics into a format that is suitable for this presentation):

1. Distributed, Integrated and Embedded Control
2. Autonomous Systems
3. Hybrid / Discrete Event Systems / Networks
4. Collaborative Control

By exploring these IFAC “Emerging Issues” we can see that there is a growing awareness worldwide that places Control in an even more important role at the very centre of the development of secure, reliable, cost effective and available systems. The domain of “Control” must be extended to deal with other issues that may be related to devices in soft, complex systems, embedded systems, integration, robotics, cognition and communication. To achieve this extension and developments there is a strong requirement for well funded and focused multi-disciplinary research. The goal of the brain storming meeting was to drive the discussion towards a specification and proposal of the main focuses that are required for successful development of

Control Research through 2007 to 2013 and beyond. Hence, to achieve this goal we first explore the challenges and issues that arise from the IFAC emerging issues as follows (Marsten, 2003):

Distributed, Integrated and Embedded Control

Control is already taking a central role in the world of "disappearing electronics". For example, for several years sensor networks have been at the forefront of the interest of the research community in emerging fields of medical technologies, health care, consumer products, instruments, communication technologies, environmental monitoring, weather stations (Chakrabarty & SIyengar, 2001; Sinopoli, Sharp, Schenato, Schaffert & Sastry, 2003; Chong & Kumar, 2003).

Networks are also important for advanced vehicle control (e.g. X-by wire cars and fly-by-wire aircraft with integrated avionics), renewable and sustainable energy, advanced flexible manufacturing, etc, as illustrated by Fig. 2. The convergence of internet, wireless communications, and information technologies with techniques for miniaturization has placed sensor technology at the threshold of a period of major growth. The technology evolution that makes the sensing, computing, communications and actuating devices increasingly smaller (e.g. using MEMs technology), that makes them consume less and less power, that makes them increasingly inexpensive whilst more and more intelligent, will facilitate the extension of the functionality of these devices from pure monitoring to fully fledged control (Shapiro, 2005). Microsystem- and nano-technologies can decrease the size, weight and cost of sensors and sensor arrays by orders of magnitude, and increase their spatial and temporal resolution and accuracy. Large numbers of sensors may be integrated and embedded into systems to improve the performance and lifetime, and decrease the life-cycle costs. Along with advanced and pervasive computing these technologies are already having a vital impact on the ways in which control and perception components can together facilitate embedded systems technology.

The networked control system is an important example of the integration of these technologies as a special case of a distributed hierchical system of cooperating controllers and elements which are linked either via hard-wired or wireless technologies. Together these cooperating objects act in “synergism” performing certain complex goals and tasks under supervision and sometimes with autonomy. In the general sense, a networked control system has fixed wired databus interconnections. This structure is hard to maintain and inflexible in the sense that it cannot easily be reconfigured or restructured subsequent to local, or inter-connection faults. When faults occur it is natural for system recovery to be effective using redundant elements of the failed elements. Using wireless technology embedded network control systems beging to take on a new dimension of pervasive design, flexibility and maintenability (Hill, Culler & Mica, 2002).

Fig. 2 Examples of network Pervasive Embedded Control systems (courtesy K Arzen)

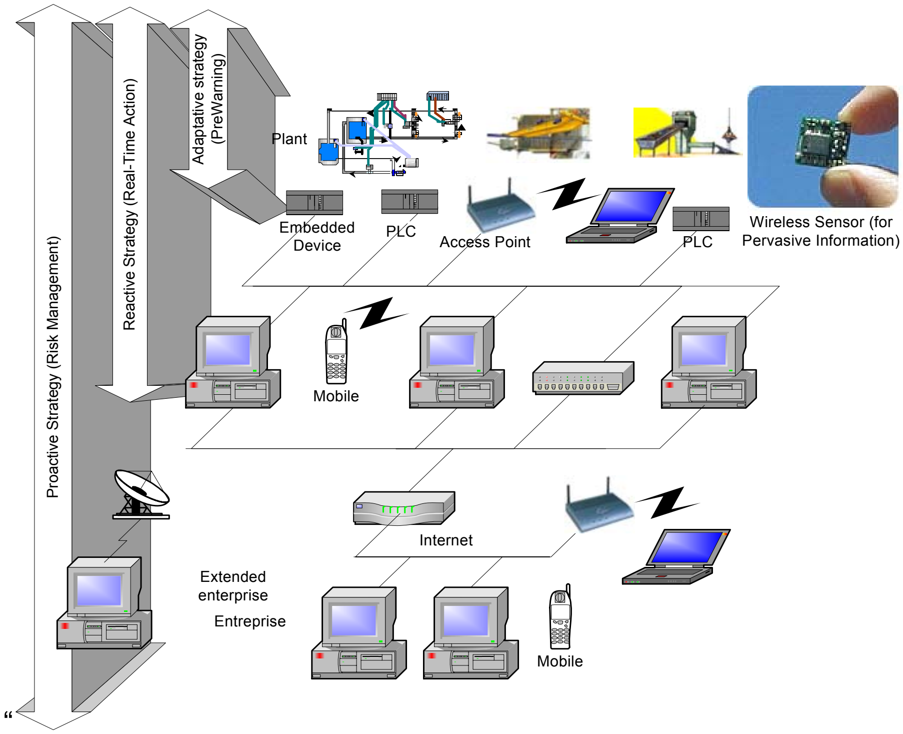


Fig. 3: A Typical Distributed Network System with Extended Enterprises

Fig. 3 illustrates the general case of a distributed network system with extended enterprises and wireless as well as wired plant and subsystem inter-connections, making use of the wireless sensor as a “pervasive information device”. In general, distributed networks are considered an imporant innovation, but there are some challenges: A distributed network can be considered vulnerability to malicious attack and this can be translated into a very large security challenge. Another significant challenge is the large robustness issue (when compared with point to point and more classical control systems). There are also legal issues; medical records should be ultimately secure. Europe has a particular openess to this problem that is not commonly found elsewhere, as legal issues tend to take over (see papers at AMCA 2005, Monte Verità, Switzerland {*www.amca2005.unibe.ch/kas/*}. We have an opportunity in FP7 to capitalise on this good

Finally, when using wireless networks the stability of such systems is difficult to determine and indeed Control technology is not even as yet in a position to provide solutions to guarantee the stability of such networks (due to unknown/uncertain time-delays, etc). These are all issues of complexity that require multi-sectorial solutions.

Large scale complex systems with different embedded levels of “human-technology-environment” interactions operate under irreducible (inherent) uncertainties and shocks with possible catastrophic impacts affecting large communities and/or areas. In particular systems requiring advanced methods for catastrophic risk management typically have heavy-tail probability distributions that are not unimodal, therefore standard solutions (based on a flexible trade-off between anticipative and adaptive mechanisms, multiple performance measures, risks and constraints) are not adequate. Such systems require new concepts and corresponding methods for robust control that is not only efficient for most cases but also sensitive to rare catastrophic events. Moreover, such systems are not only present in industry, but also in infrastructure, environment, finance, policy making, etc., (Hordijk, Ermoliev, Makowski, 2005).

Modeling large and/or complex systems requires adequate modeling methods and technology for supporting and documenting the whole modeling cycle, in which interdisciplinary teams distributed in distant locations are involved. This is especially important for systems, which operate on large amount of data, and/or on several interrelated models (e.g. models that are composed of submodels developed separately, or models whose results are used as parameters in other models) and thus require accountability of modeling work (Makowski, 2005).

Along with robustness there is an accompanying challenge of how to make the networked system fault-tolerant {see 1st Workshop on Networked Control Systems and Fault-Tolerant Control, Corsica, Oct. 6-8, 2005; {*http://www.strep-necst.org/*}. Networked systems comprise massive levels of redundant network pathways and this is a concept that has not been availble in classical point to point control. However, the “plug and play” aspect of the wireless connected network is almost essential to realise the redundancy and provide suitable fault-tolerance via reconfiguration. The “plug and play” concept is a simple way of describing the flexibility, redundancy, fault-tolerance and scalability that can be achieved using this technology. Wireless communication can also be important to keep down cabling and maintenance costs. Whilst wireless technology is desirable the challenge of security adds more complexity to the system. There is therefore a “circular argument” that must be investigated and linked to high priority actions in future collaborative research. Further challenges of the use of wireless network systems are:

- Management of communications in wireless sensor actuator networks
- Filtering and sensor fusion
- Control protocols

Wireless communications networks also provide new possibilities for health-care of the elderly, transportation, detecting toxic agents, monitoring the security of civil and engineering infrastructures, and industrial automation. New sensor networks will permit more effective weather forecasting, called “nowcasting” (Chakrabarty *et al*, 2002). In all of these new applications Control will play an increasing role in dealing with complexity and autonomy.

Traditionally, the control of distributed networks has been tackled using point to point control principles, along with large scale systems techniques (abstraction, aggregation, constrained optimization etc) (Singh & Titli, 1978). However, this approach does not take into account the complex synergism that exists between the cooperating objects, elements or agents. These cooperating systems or agents are inevitably complex both in terms of the large numbers of components and elements and in terms of complex system behaviour.

New heterogeneous computing and control paradigms are emerging that may facilitate a powerful realisation of networked control, with features of fault-tolerance and autonomy. Networked embedded control systems have two important system analysis and design requirements:

(i) temporally robust control, and
(ii) aperiodic/event-based control,

The aperiodic event-based aspects link in with the "hybrid / Discrete Event Systems / Networks" issues. The analysis and design of classical point to point control usually assumes that the computer sampling of the system is deterministic (periodic) sampling, with the occasional use of integer-related multi-rate sampling. For classical control the input output latencies are usually assumed negligible or constant. Unlike classical point to point control, networked control systems suffer from:

- Sampling jitter
- Input-output latency jitter
- Lost communication data packets

The problem of robustness to uncertainty is also different for embedded networked control systems. Whilst there is a large amount of theory available for handling robustness to uncertainty of classical control systems, there is very little theory available for implementation-related uncertainties & faults in networked control systems. The robustness problem becomes one of temporal robustness and the control system designs must satisfy temporal performance requirements. These are very new issues in control theory.

An innovative step forward in networked distributed systems will be the development of combined Control, Computing & Communication (C^3) as an important way forward. It will be necessary to develop Control models of computing systems and investigate controllable software (and software processes). Often software is touted as the essential technology to make distributed systems operate correctly. However, advances in design methods facilitate the synthesis of software (all or in part) from functional specifications. Control algorithms are at the core of the functionality of the systems in question. Hence the performance, quality, reliability and added value of these networks will depend critically on our capability of guaranteeing properties for their operations. When the wheel really has turned full circle Control will be the essential "soft" technology behind the new functionality of these distributed systems that will be immersed in manufacturing plants, homes, automobiles, hospitals and fields. Control will also be essential to make them work correctly in the face of uncertainty of their behaviour as the nodes of the system may die or degrade their performance for a variety of reasons (power shortage, defects, attacks, hostile environments) and to make them respond to human operations and demands. Indeed, complex control is "the greatest software that could ever be built" (Åström, 2001) but the key issues are: How to set up networked systems consisting of hundreds and thousands of sensors and actuators, where nodes communicate wirelessly, perform reliably, stably and safely, and take into consideration energy constraints? How to co-ordinate the control actions in such networks for optimal performance. Multi-disciplinary research co-operation is needed by researchers in control engineering, computer science (operating systems, distributed computing, security), electronics (MEMS/NEMS devices), and wireless communication ("picoradio", scheduling, routing).

Challenges from Embedded Systems: A Starting point to find control challenges is the design flow of embedded systems using the so-called "V- model" with additional loops for validation etc. The goal is to investigate model-based design methodologies incorporating control algorithms and perform a validation of them. This leads to several open and emerging R&D problem/challenges. Among them is correct design and validation of the control systems, fast prototyping, better methods and tools for design, integration, V&V, testing, deployment and new models for validation, integration and execution of control algorithms. The underlying assumption is that Control systems bridge Physics and real-time/ real world implementation topics.

One other challenge is the need to develop tools and methods for re-design and re-use of control systems. In the implementation area of control systems platform selection and timing validation seem to be open for new R&D work.

Inspiration from Biology: Biological and natural systems are rich with examples of large schemes of inter-connected networks of co-operating agents and yet the “control technologies” that are evidently in use in nature are not based on the use of system input-output models. These natural “control systems” completely obviate any consideration of fixed system structure limitations. They perform very complex control tasks with adaption, autonomy, self-healing and recovery. These systems work in a synergistic way. For example the “pacemaking activity” of the human gastro-intestinal tract generates the very complex neuro-muscular electrical activity that “programmes” the mechanical peristalsis activity of this complex inter-connected sequence of organs. This complex behaviour is under autonomous control through two sides of the central nervous system. It turns out that the behaviour of this complex system can be modelled using massive arrays of non-linear coupled oscillators. Different parts of the human body are subject to bio-rhythms at different scales from cells to organs. These rhythms are usually not constant and very interrelated, but even more important, these relations and dynamical changes are different for each person. The understanding of these cycle and their interrelations, could give an enormous insight to the understanding of many phenomenon taking place in the human body. Even more important, once these phenomena and their interrelations would be understood, it would be possible to influence them by control.

There are numerous further examples of complex biocontrol systems which in some cases we cannot even begin to understand or model. We can, however obtain powerful inspiration from biocontrol problems and mechanisms in nature. The exchange of models between researchers is imperative and new websites e.g. BioModels {www.ebi.ac.uk/biomodels} show that this activity is increasing worldwide.

Bio-inspired, control paradigms can be based on bio-creature models. Insects such as a small fly have 10 special sensors for flying and navigation, fault identification, control and obstacle avoidance in contrast to a modern aeroplane which is equipped with completely different set of sensors and avionics. Based on the bio-examples control systems designers can learn a lot about smart sensing control and actuation while building man made systems. This inspiration can lead to great insight into new flight mechanism for rotocraft, etc.

We should try to understand biocontrol systems as a part of our effort to develop new paradigms and take Control into a more powerful pervasive dimension. The Nature publication “In Pursuit of Systems” (Nature, 5th May 2005) poses the question: What is the difference between a live cat and a dead cat?”. One scientific answer is ‘systems biology’. A dead cat is a collection of its component parts whilst a live cat is the emergent behaviour of the system incorporating those parts. Emergent behaviour has become an interesting topic in Computer Science, for example when considering the complex behavioural interactions between intelligent mulit-agents. We certainly need to accept that emergent behaviour can provide useful clues and ideas for furture research in inter-connected, cooperative distributed control, systems. In a further observation (Nature 2005) “Properties such as robustness and evolvability, essential characteristics of life, then emerge from the topology of biological networks, independent of the constituents from which they are built.” However, an aspect that could present considerable challenge is that undesirable emergent behaviour could certainly contribute to system unreliability.

There is certainly a vast distance to go before we can fully encompass Biological systems using a scientific description. So how is systems biology already moving us towards the fullest possible description of a live cat? By focusing on the behaviour of individual proteins and other biomolecules, much of what gives life its unique properties can be missed. To a systems biologist, the network of interactions formed by these components is more important than the molecules themselves. Properties such as robustness and evolvability, essential characteristics of life, then emerge from the topology of biological networks, independent of the constituents from which they are built. Such a holistic view may sound dangerously soft-edged. The wealth of experimental data emerging from systems biology would be uninterpretable without detailed models against which they can be compared. Advances in modelling and simulation are thus no less important than data collection. Every discipline generates community infrastructures and systems biology is no exception.

This is the subject of *Bio-inspiration for Complex Systems and Control*. Systems-biology institutes and department initiatives have been springing up across the globe, especially during this decade. New journals have been launched, including the IEEE Systems Biology and Nature Publishing Group's Molecular Systems Biology. The IEEE Control Systems Society has also established a Technical Committee on Biosystems and Control (*http://www. ieeecss.org/TAB/Technical/biosystems/*). A very useful special issue on this topic appeared in the IEEE Control Systems Magazine (Gosh & He, 2001).

On the basis of this discussion we can summarise the emergent issues for networked systems in a distributed and embedded Control system environment can be stated as:

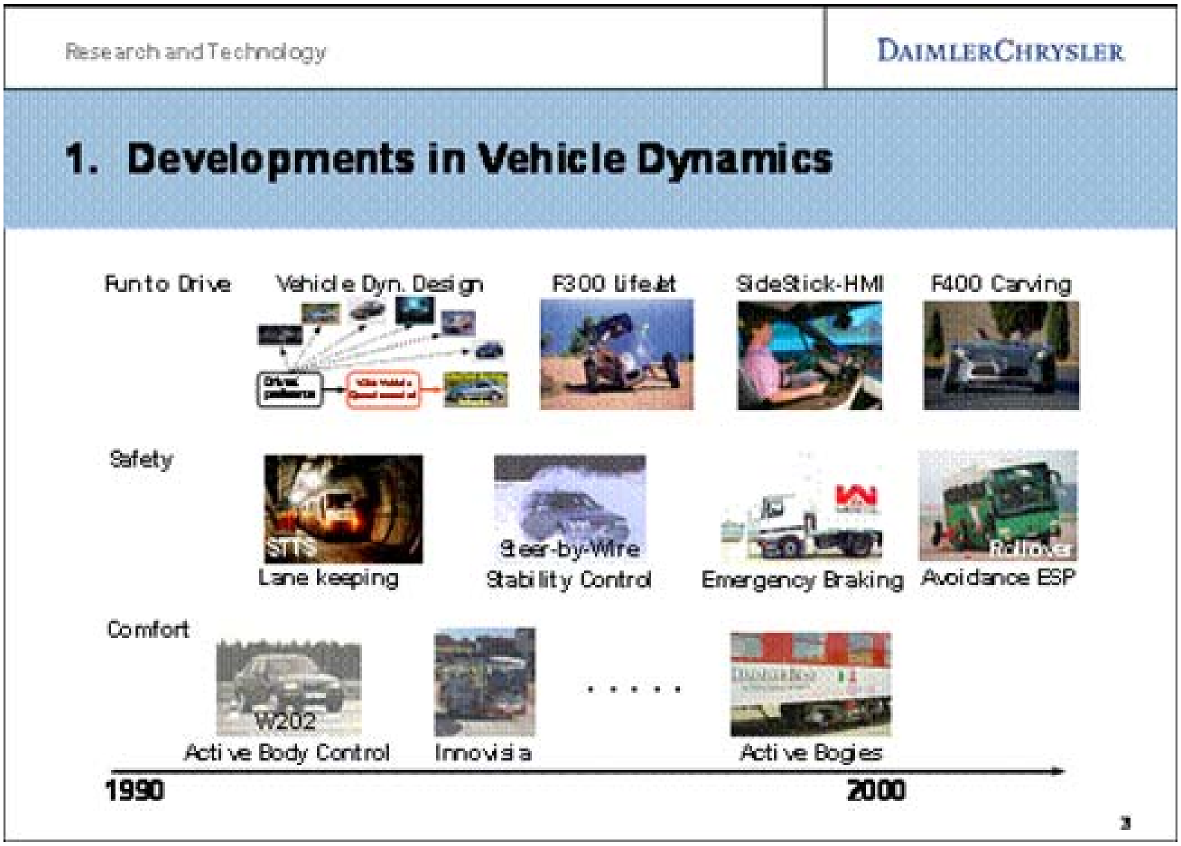
1. To develop new computational paradigms for data fusion, automatic monitoring, fault diagnosis and detection, multi-target tracking
2. To develop new coordination and control principles for large-scale, wireless sensor and actuator networks.
3. To look into Biology for inspiration!

Autonomous Systems

Today's automotive industry offers numerous innovations including driver assistance (ABS, ESP, Distance Detection), suspension control (passive), self-diagnostics, improved comfort (climate control, lighting, seats, entertainment), and more precise engine and driveline control. Emerging developments include drive-by-wire, brake-by-wire, parking assistance, collision warning, pedestrian detection, active suspension control, noise & vibration control, and a host of telematics (navigation, on-board e-services, etc.). Fig. 4a shows some of these developments.

Further on-going developments will improve vehicle safety and, when coupled with infrastructure improvements, will yield *intelligent traffic control*. Such vehicles will plan their own operations, as well as control the vehicle, to achieve these goals and develop alternate strategies when failures or unexpected hindrances are encountered. According to Schoenwald (2000), "AUVs have generated much interest in recent years due to their great promise for performing repetitive, dangerous, or information-gathering tasks in hazardous or remote environments." The autonomous sytems concept is being extended to other applications such as unmanned factories and processing plants, based largely on the *Autonomous Control of Networked Systems*.

To make future European Space Systems & Missions possible it is necessary to develop Control Systems to accomodate fully autononous intelligent self-repairing space systems able to reason and reconfigure reactivley in remote hostile environments. Figure 4b. summarises the European Space Agency's Space Control System Technology roadmap for the next two decades.



Research and Technology

DaimlerChrysler

1. Developments in Vehicle Dynamics

Fun to Drive

Vehicle Dyn. Design

F300 Life Jet

SideStick-HMI

F400 Carving

Safety

STTS

Lane keeping

Steer-by-Wire

Stability Control

Emergency Braking

Rollover

Avoidance ESP

Comfort

W202

Active Body Control

Innovisia

. . . . .

Active Bogies

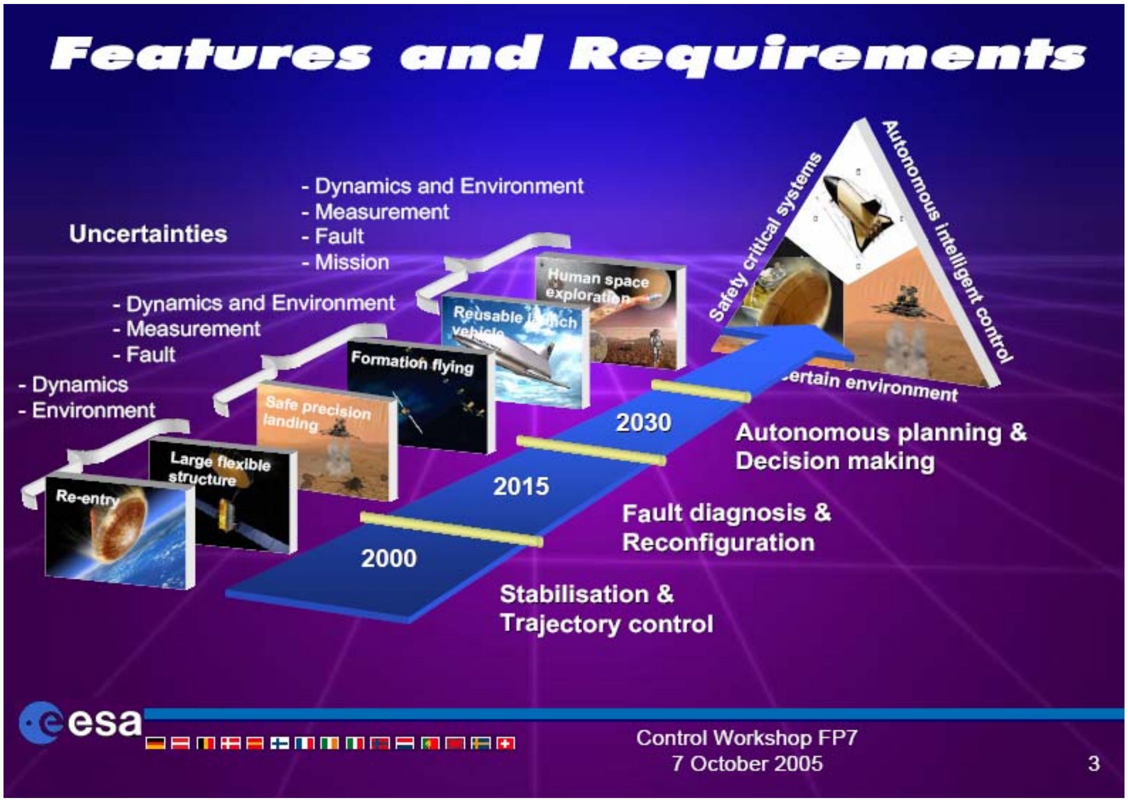
1990

2000

3

Fig. 4a: Developments in Vehicle Dynamics (Courtesy Daimler Chrysler)

Highly sophispticated complex systems have to be innovated, designed and tested to make the space adventure possible. Future European space systems will rely on the development of advanced health management systems with integrated overal fault detection and reconfiguration functions enabling critical safe high perfromance operation under the most unforeseen circumstances. Highly Robust Control Space Systems are the intrinsic control system elements at the heart of the overall Space System and rely on powerfull theoretically well founded tools to guarantee the desired performance properties with respect to never before encountered phyisical conditions. Multi-vehicle coordinated formation flight such as Darwin, safe precision entry, descent and landing systems, autonomous rendezvous and docking systems, etc. are key elements in the ESA's Cosmic Vision and European Programme for the Exploration of the Solar System (AURORA) and will have to rely on the development of novel control system technologies. Additionally, future European space transportation systems will have to respond to more demanding needs such as reusability, multi-mission, etc. on a regular and economically viable basis. Novel guidance, navigation and control technologies will dictate the operational performance of the system, for safety and flexibility reasons health management and reconfiguration systems will be an integral part of the system avionics to assist in safe operation of the system's mission. The entire space enterprise is based at continuously reducing the risks to mission safety at a reduced development and operational cost. Novel control system technologies will also change the way the space systems are operated. Intelligent and autonomous health management and reconfigurable control systems will be effictive in reducing manpower while increasing turn around time making the space enterprise more efficient and economically manageable.



Features and Requirements

Uncertainties

- Dynamics
- Environment

- Dynamics and Environment
- Measurement
- Fault

- Dynamics and Environment
- Measurement
- Fault
- Mission

2000 Stabilisation & Trajectory control

2015 Fault diagnosis & Reconfiguration

2030 Autonomous planning & Decision making

Control Workshop FP7
7 October 2005

3

Fig. 4b: Space Control System Technology Roadmap (Courtesy ESA)

Hybrid/Discrete Event Systems/Networks

Continuous (and discrete) Time systems and Discrete Event systems have essentially been developed independently of each other. However, both phenomena frequently appear in the same process. For example, radar processing requires dynamic estimation of whether or not a target is present, what type of target, whether or not it is manoeuvring, forecasted track movements, etc. Typical solutions are "sequential" which involves detection, then classification, estimation, etc. Such approaches are clearly sub-optimal. Combined solutions for such Hybrid systems will no doubt develop in the future. New controllers will be driven by the need for higher performance from such systems, as well as the need to make better use of resources and an increased use of embedded/integrated systems. Theoretical developments are already being addressed and, as proven performance improves and reliability & autonomy increase, the number of applications will grow. Controllers for such systems will probably be more complex than earlier solutions, and development of such methods will require a merging of heretofore different fields and different designer approaches (sometimes even with different methods and solution languages).

Collaborative Control

As outlined above, distributed systems typically comprise numerous lower-level sub-systems with their individual control tasks and responsibilities. Collaboration among such interrelated systems is clearly essential in order to benefit from the respective strengths of the several "partners" or cooperating agents. Collaborative control encapsulates three system types.

Machine-Machine**:** This type also belongs to the emerging issue of Distributed, Integrated and Embedded Systems, outlined above. Cooperation of smart robotic teams (including micro- and nano- as well as "routine" robots) will improve as new collaborative control techniques are developed; as faults, errors, and interactions are better managed; and as protocols for fault-tolerant operation are developed. This is a rapidly developing field (Shapiro, 2005) that requires the devlopment of more advanced control systems paradigms for dealing with complexity, complex and uncertain/emerging behaviour, uncertainty management, the use of multi-agent techniques, etc. The system of cooperating agents, inter-connected robots or machines is essentially a distributed networked system with both local and global constraints and in which at least partial autonomy is an important development. This subject also includes the inter-connection of systems via the internet as cooperating objects in a similar way to the wireless network outlined above as illustrated in Fig. 3.

Human-Machine: This collaborative system type has several aspects:

a) Human (intervention) in the loop.
b) Control ON, attached TO, or WITHIN humans

Human (intervention) in the loop:

At this stage the session focussed on the emergent issues surrounding the human (intervention) in the control-loop. This subject can involve autonomy for an ageing population (AAL-Ambient Assisted living) and there was some discussion on this subject from the standpoint of complexity and autonomy (see end of section).

The remaining discussion and presentations on this topic focussed on the role of the human operator in a process system or vehicle (aircraft etc). Post mortem investigations report that most industrial accidents are due to human error with many having their origin in the lack of effective control system interfaces for human supervision of embedded sensors (Korzyk & Yurcik, 2002). Systems operate for something like 99% of the time error-free and then suddenly something happens. We need to keep human operators alert and elevate their decision-making so that they are "busy", dealing with several more aspects of the running of a plant, to a more interesting level. This may involve more appropriate excercuses for operators. There is a growing need for more sophisticated human interface facilities based on human usability and human performance design. Several safety-critical systems have one or more humans in the loop, e.g., Air Traffic Management Systems, Transportation Systems, Industrial Control, etc. Humans are very difficult to model!

The "human self" can be represented much more in terms of reasoning, as a cognitive agent and as a "digital system" (as a part of the embedded computing structure of the system, etc). The human self can even be regarded as an "executable" system. It is apparent that as systems increase in complexity these emerging issues and concepts involving the role of the human operator become more and more important. In some aspects humans will be dominant in the sense that there are some abilities that cannot be replaced by an automaed system (e.g., in the analysis of many decision situations, where a comprehensive analysis of diversified elements is not possible to be formalized). In other situations humans may want to keep decision-making sovereignty while using a decision support system for analysing the problem. On the other hand in some situations a dynamic and/or complexity of system may require automatic control. An important challenge would be to have a better picture of what it is about human behaviour that can be understood/improved upon. Indeed an important emerging aspect is to define the boundary between the control approach and the human in the loop.

Computational game-theory *vis a vis* the human in the loop is another important tool. Whatever we try to do with Humans in the loop we cannot avoid complexity at some stage in the analysis and/or design. Yet the behaviour of the overall system depends critically on human actions. This leads to the idea of Error Evolution Control which considers that humans do make mistakes in their situation awareness, which may lead to catastrophic situations. Automation should help in preventing errors from propagating so that catastrophic situations are avoided. The *Three-mile Island scenario*, whilst not a catastrophe in itself was nevertheless an undesirable event comprising error and fault propagation in a nuclear plant to the extent that the human operators were rendered incapable of intervention. Fortunately, the control rods were withdrawn quickly enough to obviate a total disasater on a large scale. To prevent these undesirable scenarios emerging research involves recovery methods to try to understand if an error has occurred, identify these situations and act accordingly. Methods are emerging for the design of estimation algorithms with guaranteed performances for assisting human operators in:

- Error detection
- Error propagation avoidance
- Error recovery in prescribed time-horizon.

Situation awareness plays an essential role in identification and correction of faults and this can be used in conjunction with extensive work from within the Control and AI communities on the development of robust methods for fault diagnosis using both model-based and data-driven methods (Patton *et al* , 2000). The goal is to develop methodologies to design algorithms with guaranteed performances for assisting human operators in error/fault detection and fault isolation, etc when the faults are considered incipient (hard to detect).

The following are considered further motivating issues for "human in the loop as a plant":

- Better (or enhanced) support for the operators
- Alarm handling
- Predictive maintenance
- Decision support
- Ease of tuning

Enhanced operator support should be provided by:

- Identifying the operator and her/his work situation
- Taking into account whether the operator is a layman or a professional
- Weighing up the degree of Control *vs* supervision
- Supporting identified tasks
- Using improved graphics (e.g. 3-D visualisation of control target)
- Regaining overview from old control panels

Fig. 5: Enhanced display facilities that can be further developed (courtesy ABB)

Alarms and alarm signals form the essential feedback mechanism to the human operator. Effective alarm handling has been an emerging field for research as there is a growing awareness that alarms can be used in a much better way in order to optimise the human operator's capabilities in the system loop. This does mean that there are times when some alarms need to be hidden whilst others are active. This involves a systematic way of introducing alarm levels with some intelligent (possibly model-based) reasoning around the alarms. The intelligence may incorporate root cause analysis and the “plug and play” aspects discussed above.

The purpose of predictive maintenance is to predict requited schedules of maintenance by using sensitive measures of changes and faults in the system. The idea is to:

- Give greater plant availability and economy,
- Estimate residual lifetime of plant,
- Calculate accumulated wear (e.g. for mechanical/mechatronic systems),
- Detect incipient (hard to detect) faults

Predictive maintenance generally requires the use of plant models. Not just any models can be used, they have to have specific properties to facilitate sharp discriminiation between modelling uncertainty and fault effects. Sometimes instead of explicit models we can use data-driven methods (neural networks, fuzzy reasoning, neuro-fuzzy schemes). Both approches require a lot of investment in terms of modelling, identification, neural network training etc. The greatest challenge is how the above can be achieved when no business wishes to spend time developing detailed models! Indeed, for many industrial concerns this expertise is not a part of the companies management asset. How do we change this culture? As indeed, if we don’t we cannot easily move on and solve some of these complex problems.

Turning to Decision Support, this uses plant-wide (eventually enter-prise wide) dynamic models for state estimation, on-line operation, “what if” simulation, etc. This needs faster commissioning of on-line model-tuning, better visualization of the plant. Chemical plants have slow dynamics but the information is needed more quickly. Some important visualizations can be developed and the concept of “Augmented Reality” could be important. Ease of tuning is also an important issue. Most trained users/systems engineers can handle very few tuning parameters (Isaksson) and new work could involve a revival of adaptive control methods, involving “intelligent tuning” techniques.

Control ON, attached TO or WITHIN humans:

The essential technologies of these topics are:

Bio-inspired Robotics

Natural Computation

Synthetic Biology

An example of control operating ON the human body is surgery and rehabilitation, as shown in Fig. 6a.

Control attached TO the body is essential in applications such as prosthetics and augmentation. Research at Duke University {http://www.dukenews.duke.edu} is part of a rapidly developing field involving Neuro-prosthetics enabling monkeys to reach certain goals. The research involves neuro-control and neuro-prosthetics and sensors that measure arrays of activities in the brain are used to control an arm etc. The main challenges arising from this research are:

How to interpret the nerve signals?
How to provide the feedback for control?
How to develop adaptive control schemes?

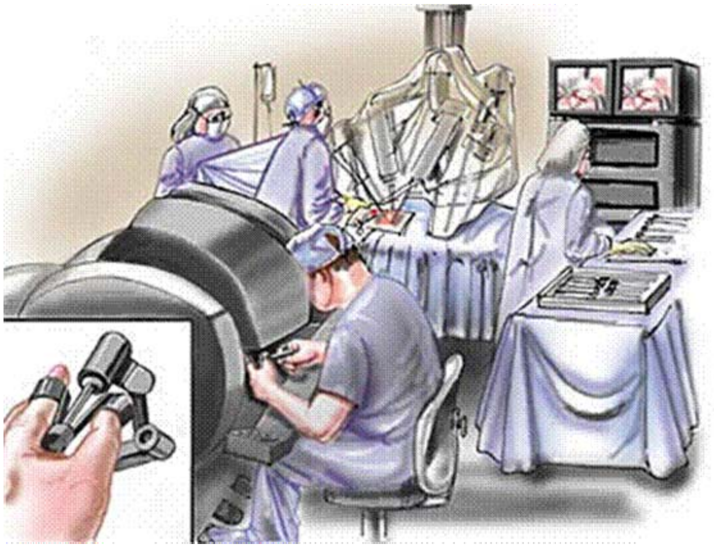


Fig. 6a Surgical Robots

Fig. 6b Rehabilitation Devices
(Automatic Control Lab, ETH, Zurich)

Fig. 6: Precision, degrees of freedom; human system identification & tracking; Portability

Control living WITHIN the body can be envisioned in applications such as monitoring, drug delivery, and repair. This involves mechanisms to stimulate muscles (MIT, Reading University Cybernetics). A Microrobot example at ETH, Zurich uses a small device moving in the body. This microtechnology uses magentic fields and will require intelligent control in the future. Other interesting futuristic applications include: Smart drug delivery, environment-sensitive drug delivery, Visual Fatigue Sensor (EPFL). In this latter example information is gathered, sent back to the human to indicate stress, fatigue levels in eyes muscles etc. This is an important example of *Life Style Monitoring*. An interesting challenge will be to determine if PID control is possible for these novel smart sensor technologies. In the future, this field of research will involve more and more Control.

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<u>Example; Symbiosis: pilot/machine</u>
http://www.primidi.com/2004/04/01.html
The "Solar Impulse" plane as a future concept. This is an aircraft with one pilot and with large very flexible wings (larger than Boeing 747) for solar power, producing zero pollution to the atmosphere and involving "symbiosis between pilot and machine". A number of parameters are monitored, cognitive stress etc. The human pilot has an important role "in the loop" (see Fig. 7b).

Fig. 7a The "Solar Impulse 2009" (Bertrand Picard)

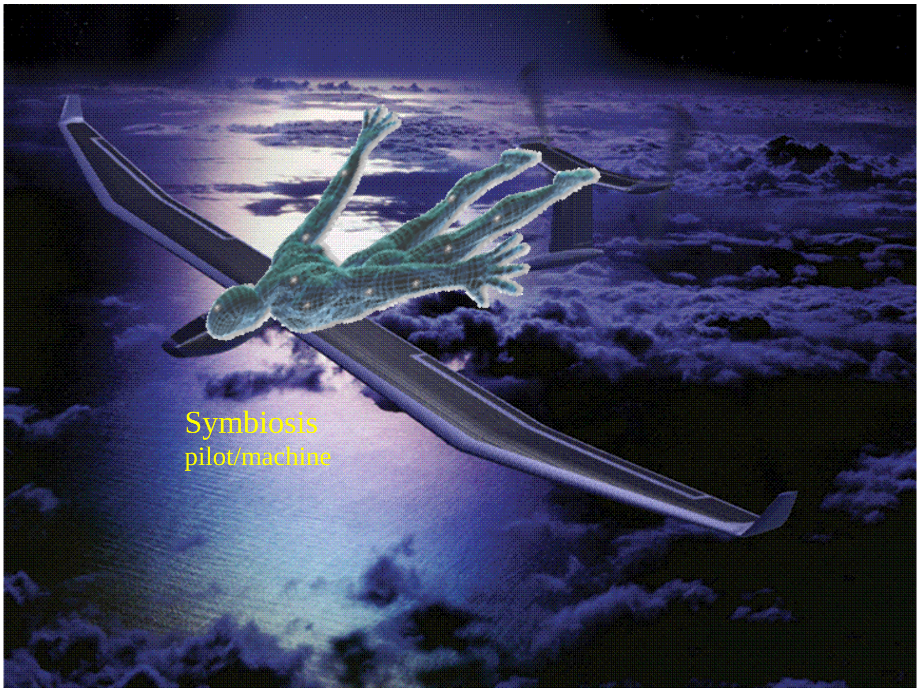

Fig. 7b: Symbiosis: Pilot & Machine

***Human-Human*:** Human "team" performance will improve as enterprise software integrates and aids team decisions, as new methods (e.g. internet-conferencing) improve team coordination (even when remotely located with different databases, culture, or knowledge disciplines), and as task optimization methods enable multiple workers to share work and reduce local overloads.

A STRATEGY FOR EUROPEAN RESEARCH IN CONTROL IN FP7

The most interesting domains

From the presentations at the btainstorming meeting and the discussions It is clear that Control is a discipline that like Pheonix is "rising our of the ashes" of its past history to become an important key player in the development of advanced information rich technologies. New activities in advanced control face the challenge of the complexity (characterized by size, structure, irreducible uncertainty, risk, diversified performance measures, etc) of modern engineering and business systems and enterprises, spanning bio-technology, information technology, space and aeronautics, vehicle systems, process and manufacturing systems, life sciences, the economy, etc.

New conceptual methods and tools have been identified that are required to take up this multi-disciplinary challenge. Systems theory, automatic control, the understanding of the dynamics of complex interconnected systems, their reliability and robustness against unexpected attacks, the role of the "human in the loop", etc. are not only of importance for the themes of the FP7, but they are also fundamental for the traditional European industries, exemplified by process industry (metal production, pulp and paper, chemical, petrochemical etc), electrical power and gas networks, telecommunication, machinery, airplanes, robotics, etc. Many of these industrial exemplars have made a significant contribution to Europe's wealth and to the employment of skilled operators, engineers, technicians and researchers.

To help to arrive at a suitable list of objectives for a programme on Control in the Computing, Embedded Systems and Control Pillar of FP7 the following keywords were used:

Keywords:
Embedded control systems, self-aware control systems, symbiotic control, behavioural distributed control systems, high performance control systems, cooperating/coordinated control systems, cognitive control systems, executive control systems, bio-control, pervasive/ubiquitous computing and control, proactive (distributed) control, autonomous control systems, cooperating objects, robust autonomy, autonomous control systems, scalable control, reflexivity, temporal and spatial robust control, evolutionary systems.

High Level Objectives:

The emerging issues and challenges for Control outlined above encapsulate the main points of the brainstroming meeting discussion. The discussion of emerging issues and challenges, and the above keywords helped the partners of the meeting to formulate the following list of high level objectives that could be used as a basis for funding negotiations for Control in FP7:

- 100% system availability
- Advanced control in efficient and safe management of complex systems in industry, policy-making, environment
- Decision-support for human operator in the control loop
- Control of evolutionary complex processes
- 10 times more complex systems at 10% of today's effort
- Control of cooperating objects
- Control of Bio-technical systems
- Bio-inspired control systems for multi-agents
- Integrated control for 100% vehicle safety even in uncertain environments

Outline of Research Grand Challenges for Control in FP7 and beyond:

The partners of the brainstorming meeting agreed that the most likely research domains to fit these objectives and be of high importance for Control research in Europe are as follows:

1. Human in-the-loop/Human as a plant: System-human symbiosis

Societal and Economic Impact

- Reduce personal and societal consequences of disabilities
- Extend/augment quality of life of an ageing society
- Improve lifestyle (nutrition, movement, sleep) by generating awareness
- Personalise treatment
- Improve role, peformance and working conditions of the human operator in Control loop.

Scientific and Technological Interest:

- Develop new ways of modelling the “human in the loop”
- Better development of Predictive Maintenance strategies
- Develop enhanced Decison-Support
- New sensor technologies required for human monitoring
- Symbiosis between biological and artificial systems must be exploited
- New control strategies must be developed for
- On the body, Attached to the body and Live within the body aspects of human in the loop systems.

2. Complex distributed systems and improved system performance in uncertain environments.

Societal and Economic Impact:

- Enhance the security of safety-critical systems
- Improve standards of health care, consumer products, instruments, communication technologies, environmental monitoring, weather stations advanced vehicle control, renewable and sustainable energy and advanced flexible manufacturing, through developments in control of distributed and wireless networks
- Enhance the availability of distributed networked systems
- Integrated Control for enhanced vehicle safety

Scientific and Technological Interest

- Develop new computational paradigms for Control, data fusion, automatic monitoring, fault diagnosis and detection, multi-target tracking and fault-tolerance in autonomous and/or distributed systems
- Develop new strategies for integrated/heterogeneous Control
- Develop new multi-disciplinary coordination and control principles for large-scale, wireless sensor and actuator networks, including combined Control,
- Computing and Communication (C^3) strategies.
- Investigate inspiration from Biology.

- Develop novel methods and tools for robust control of large-scale distributed and networked systems, especially those operating under irreducible uncertainty and exposed to catastrophic risks.

CONCLUSION

As a conclusion it seems that the real challenge from FP6 to FP7 will be to stress fundamental research to achieve long term goals broader than the framework itself in order to address long term competitiveness and the increasing complexity of systems which will become relevant in the future, like bio-systems. The participants propose to strengthen the collaboration of systems theory and automatic control with applied research fields in a truly multi-disciplinary manner. System and Control theory is the science “par excellence” which provides the right theory and tools available in order to study complex heterogeneous systems, and this is the real challenge in engineering. This should not be misunderstood as pure mathematical abstraction, but rather with the real modeling and control of complex physical systems like for example bio-systems. For these reasons, the significance of control for a modern economy is undisputed.

Europe has excellent academic resources in these fields, as well as important industries. The new aspects are the size and complexity of the systems in biology, information technology, aeronautics, life sciences, economy, etc. Therefore, new conceptual methods and tools are required to take up this challenge. System theory, automatic control, the understanding of the dynamics of complex interconnected systems, their reliability and obustness against unexpected attacks, etc. is not only of importance for the themes of the FP7, but they are also fundamental for the traditional European industries, summarized by metal, chemical, pulp and paper, power networks, telecommunication, machinery, airplanes, robotics, etc. According to the knowledge of the contributor, the latter ones are still responsible for Europe’s wealth, as well as for the employment of skilled personal, engineers and researchers.

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APPENDIX: ECONOMIC IMPACT OF CONTROL TECHNOLOGIES

Table 2 gives an estimate of the economic impact of control in a number of industrial sectors. The table summarizes the situation in the U.S. for a number of applications areas and for a number of years; figures are given in millions of dollars and the examples in parentheses are not all-inclusive of the applications.

Application	1972	1973	1976	1980	1990
Motor control (speed position)	90,3	100,5	112	150	250
Numerical control	43,3	47,3	76	100	170
Thickness control (steel, paper)	45,4	57,8	99	180	240
Process control (oil, chemical)	318,5	357,2	449	700	2000
Pollution monitoring and control	14,0	17,0	26	75	3000
Nuclear control	9,3	11,1	19	25	60

Table 2: Economic impact of control in various industrial sectors

We stress that the industries listed in Table 2 are all traditional application areas for control theory. Impact can be even more dramatic in less traditional areas, simply because the potential for growth and the potential for impact of control theory are greater; the marked in just one such area, wireless sensor and actuator networks, was $150 million in sales in 2003 and is expected to grow to $7 billion in sales by 2010.