IST-004527 ARTIST2
Network of Excellence
on Embedded Systems Design

Cluster Progress Report for Year 4

Cluster:

Control for Embedded Systems

Cluster Leader:

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http://www.control.lth.se/user/karlerik/

Policy Objective (abstract)

The report summarizes the achievements done during the fourth year by the Control for Embedded Systems cluster. It reports the two cluster integration activities "Control of Real-Time Computing Systems" and "Real-Time Techniques in Control System Implementation", the network activity "Adaptive RT, HRT and Control", and the platform activity "Design Tools for Embedded Systems".

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1. Overview

1.1 High-Level Objectives

Platform: Design Tools for Embedded Control: The long term objectives – as stated in the 1st year deliverable - remains valid, that of achieving a platform consisting of a suite of tools, each tailored for one or several tasks in the development process for resource-constrained embedded control systems. The new and unique feature of the tools is that they take control, computing, and communication aspects into account.

The work during Year 4 has focussed on further developments of the individual tools developed by the cluster partners, development of a new middleware framework for dynamically configurable systems (performed partly within the context of the DySCAS project (www.dyscas.org)), continued efforts for cross-cluster discussions on model and tool integration, organization and participation in open workshops on the topics of model based engineering and models/tools integration, further work on models and tools integration in the context of the EAST-ADL architecture description language and its integration with domain tools for control design (Matlab/Simulink) and safety analysis (HIP-HOPs) and dissemination of results.

Cluster Integration: Control in real-time computing: The overall objective of this activity is to advance the state of the art in applying control methods for uncertainty handling and as a way to provide flexibility and improved performance in embedded computing and communication systems. The application areas include performance control of web server systems, feedback-based reservation management in embedded real-time systems, feedback scheduling of control systems, and control of communication and sensor networks.

The objectives are achieved through the research that has been performed within and between the partners. The planned meetings have all been held and the milestones have been met.

Cluster Integration: Real-Time Techniques in Control System Implementation: The overall objective for this activity was to advance the state of the art in applying real-time system methodology for embedded control system implementation. The milestones for Year 4 have mostly been met. Rather than disseminating the common design framework in a joint publication the work has been concentrating on developing a well-structured course material for the Graduate Course on Embedded Control. A common Wiki has been set up for this purpose and the goal is to have the material available for the coming version of the course to be held during spring 2009 as a part of ArtistDesign. Also, rather than adding two benchmarks to Bridgit only one new benchmark has been added.

Network Integration: Adaptive RT, HRT and Control: The overall purpose of this cross cutting activity is to integrate research among ARTIST2 control and real-time teams on different computational models for embedded control systems and the use of control techniques to provide flexibility in embedded systems. More specifically the objective is to increase the understanding for how the jitter and delay introduced by the operating system on control activities affect the performance of the controlled system, study unified design and implementation approaches for resource-aware embedded control applications, develop reservation-based scheduling methods for control systems and signal processing systems.

The objectives for Year 4 were the organization of an industrial workshop, research dissemination, continued joint and individual research along the lines of the roadmaps developed, and coordination with the ACTORS and FRESCOR projects. These objectives have all been met.

Overall: On an overall level the research during Year 4 has continued along the lines of the first three years. The number of publications is fairly high, although in some of the events not as high as last year. One reason for this is that several partners are involved in new national projects and European projects that still are in ramping up their operation. The mobilities among the partners have increased compared to last year.

The number of events that the cluster have organized or co-organized has been large. A list of the events can be found in Section 2.4.

1.2 Industrial Sectors

Embedded control systems are vital in most industrial application areas, e.g., automotive, avionics, manufacturing, and automation. In many areas it is the quality and performance of the control systems that distinguishes a product or company. Therefore implementation techniques for embedded control systems that are resource-efficient and give good performance are very important. There is still a debate whether control systems best are implemented using time-triggered approaches or whether a more event-based implementation is sufficient. This is something that varies from industry sector to industry sector, and which also depends on the level of safety required and the need for formal guarantees.

The use of feedback-based (adaptive) resource management is of particular interest for soft real-time applications, e.g., multimedia applications within consumer electronics systems. The main applications of control of computer systems can be found at companies like IBM or HP. However, also large users of server technology such as Amazon have in-house application development within this area.

The introduction of multicore platforms also in embedded applications creates new design challenges. A particular problem compared to uniprocessor platforms is the WCET analysis. Due to the shared memory access WCET analysis runs the risk of being very conservative. This will most likely hamper the application of hard real-time techniques based on static analysis. Hence, the market for more dynamic or adaptive resource reservation based on feedback from the true resource utilization and/or the application quality-of-service can be expected to increase in the future.

1.3 Main Research Trends

Controllers are in most cases based on periodic sampling and assume a negligible or constant latency between input and output (sampling and actuation). This is something that in many cases can be difficult or costly to achieve. Time-triggered solutions based on static scheduling are one solution, but are sometimes too inflexible or are incompatible with the rest of the system software. In event-based solutions, pre-emption, blocking, execution time variations and non-deterministic kernels generate sampling jitter and latency jitter. The same holds for event-based network protocols. The problem can be approached in different ways. Robust design can be applied to guarantee a certain level of temporal robustness. Techniques can be used to compensate for the timing variations, either passively based on off-line information about the characteristics of the variations, or actively using measurements. The interaction between control and real-time computing becomes extra important in situations where the computing and communication resources are severely limited, e.g., in embedded control system applications, where separation of concerns-based design principles, with strict interfaces between control and computing, may be unfeasible. Instead it is necessary to take both computing and control aspects into account simultaneously. This requires theory and tools that support codesign. From a pure real-time systems approach it is also desirable to provide more flexible ways of allocating computing resources to different applications or tasks. The area of adaptive or feedback-based resource scheduling is one example of this.

Taking implementation issues and limited resources into account in the control design is covered by the terms resource-aware control and implementation-aware control. The development in this area needs to be matched with the similar developments within the real-time field. It is necessary to create models of computation and scheduling, and system software and hardware, which are tailored to the true needs of control applications. This is covered under the terms of control-aware computing and networking.

Model integration and management constitute key challenges in the design of embedded systems; this is also relevant for embedded control systems. Consider for example the design of an embedded automotive ABS braking system. One obvious concern is that of the core motion control functionality, especially the control logic and algorithms and the dynamic behaviour of the system. However, this is only one out of several aspects. Other aspects include safety, security, network communication, mechanical design, IO, power, etc. These aspects and components are in addition typically handled by different specialists, employing different modelling languages and tools, and moreover belonging to different organizational entities. There is therefore a strong industrial need for solutions that support model and tool integration, as well as model management. There are several related research issues including model transformations and methodology. Some confusion is inevitable in this area since it is approached from so many directions (engineering disciplines, information management, tool specific solutions, standardization etc.). We believe that establishing modelling frameworks that characterize the problem and solution space are very important for the progress of the area.

A relatively new area is control of computer software systems, e.g., large eCommerce servers. These servers are complex dynamic systems with high levels of uncertainty. The need for control arises at several levels, e.g., admission control, delay control, and utilization control. Several new challenges apply. Since the servers are engineering artefacts, first principles do not apply, at least not on the macroscopic level. Several competing modelling formalisms needs to be combined, e.g., continuous-time flow models, queuing models, and various types of event-based models. System stability has an unclear meaning, and the whole issue of how to write controllable and observable software system is still largely unexplored.

2. State of the Integration in Europe

2.1 Brief State of the Art

2.1.1 Control of Real-Time Computing Systems

Feedback-based approaches have always been used in engineering systems. One example is the flow and congestion control mechanisms in the TCP transport protocol. Typical of many applications of this type is that feedback control is used in a more or less ad hoc way without any connections to control theory. During the last few years this situation has changed. Today control theory is beginning to be applied to real-time computing and communication systems in a more structured way. Dynamic models are used to describe how the performance or Quality of Service (QoS) depends on the resources at hand. The models are then analyzed to determine the fundamental performance limitations of the system. Based on the model and the specifications, control design is performed. In some cases the analysis and design is based on optimization. The areas where currently most work is being performed are *control of server systems, control of CPU scheduling*, and *control of communication networks*.

The main example from the first area is large multi-tier eCommerce servers, of the type used by companies like Amazon and Google. Another example is servers in web-hotels. Servers of these types are complex dynamic systems with high levels of uncertainty. The need for control arises at several levels, e.g., admission control, delay control, and utilization control. This type of application imposes several new challenges for the control field. Since the servers are engineering artefacts, first principles do not apply, at least not on the macroscopic level. Several competing modelling formalisms need to be combined, e.g., continuous-time flow models, queuing models, and various types of event-based models. System stability has an unclear meaning, and the whole issue of how to write controllable and observable software systems is still largely unexplored.

In real-time systems with hard timing constraints, e.g., deadlines, it is paramount that all timing constraints are fulfilled. If sufficient information is available about worst-case resource requirements, e.g., worst-case execution times (WCET), then the results from classical schedulability theory can be applied to decide if this is the case or not. Using, e.g., priority-based or deadline-based scheduling strategies, it is then possible to provide a system implementation that guarantees that the timing constraints are fulfilled at all times.

However, in many situations the hard real-time scheduling approach is unpractical. Worst-case numbers are notoriously difficult to derive. In order to be on the safe side, a heuristically chosen safety margin is often added to measurements of “worst-case values”. This may lead to under-utilization of resources. In other cases resource requirements vary greatly over time. The reason for this may be changes in the external load on the system, e.g., large variations in the number of requests to a web server, or mode changes in application tasks. Again, designing the system for the worst case may lead to under-utilization. The above situations are both caused by uncertainty. A major strength of control theory is its ability to manage uncertainty.

In feedback scheduling of CPU resources the allocation of resources is based on a comparison of the actual resource consumption by, e.g., a set of tasks, with the desired resource consumption. The difference is then used for deciding how the resources should be allocated to the different users. The decision mechanism constitutes the actual controller in the feedback scheduling scheme. A key observation here is that feedback scheduling is not suitable for applications that are truly hard in nature. The reason for this is that feedback acts on errors. In the CPU utilization case above this would mean that some tasks temporarily might receive less resources than required, i.e., they could miss deadlines. Feedback scheduling is therefore primarily suited for applications that are soft, i.e., tolerate occasional deadline misses without any catastrophic effects, or that are said to be adaptive. The latter means that missing one or more deadline does not jeopardize correct system behaviour, but only causes performance degradation.

For this type of systems, the goal is typically to meet some QoS requirements. The adaptive class of real-time systems is a suitable description for many practical applications. This includes different types of multimedia applications, and web server systems. It also includes a large class of control applications. Most control systems can tolerate occasional deadline misses. The control performance or Quality of Control (QoC) is also dependent on to which degree the timing requirements are fulfilled. It is only in safety critical control applications, e.g., automotive steer-by-wire applications, that the hard real-time model really is motivated.

Traffic control of communication networks involves issues such as congestion control, routing and admission control. Of particular interest is congestion control and how to control heterogeneous networks consisting of a blend of wired and wireless links.

The research on control of computing systems has increased immensely and gained a large interest during the last years. A large number of applications have been proposed in different areas, e.g., high-performance web, multimedia streaming, real-time databases], web storage systems, network routers, active queue management schemes, processor architectures, and control systems. However, so far most of the work presented in literature has been conducted by scientists working either in the real-time computing or telecommunication fields or in the automatic control field. Unfortunately, this has sometimes led to erroneous models and strange results.

The development within this area during the last year can be described by a steady development rather any revolutionary breakthroughs. An important event was the establishment of the workshop series *Workshop on Feedback Control Implementation and Design in Computing Systems and Networks (FeBID)* that was held last year in Vancouver and this year in Munich. Generally, the research is currently more aimed at studying larger applications, e.g., large multi-tier server systems. Experimental results are also something that continues to be very important.

For a more detailed state-of-the-art overview we refer to the roadmap developed by the cluster during Year 1.

2.1.2 Real-Time Techniques in Control System Implementation

By tradition, the design of embedded control systems is based on the principle of separation of concerns. This separation is based on the assumption that feedback controllers can be modelled and implemented as periodic tasks that have a fixed period, a known worst-case bound on the execution time (WCET), and a hard deadline. The latter implies that it is imperative that the tasks always meet their deadlines, i.e., that the actual execution time (response time) is always less or equal to the deadline, for each invocation of the task. This is in contrast to a soft deadline, which may occasionally be violated. The fixed-period assumption of the simple task model has also been widely adopted by the control community and has resulted in the development of the sampled computer-control theory with its assumption of deterministic, equidistant sampling. The separation of concerns has allowed the control community to focus on the pure control design without having to worry about how the control system eventually is implemented. At the same time, it has allowed the real-time computing community to focus on development of scheduling theory and computational models that guarantee that hard deadlines are met, without any need to understand what impact scheduling has on the stability and performance of the plant under control.

Historically, the separated development of control and scheduling theories for computer-based control systems has produced many useful results and served its purpose well. However, the separation has also had negative effects. The two communities have partly become alienated. This has led to a lack of mutual understanding between the fields. The assumptions of the simple model are also overly restrictive with respect to the characteristics of many control loops. Many control loops are not periodic, or they may switch between a number of different fixed sampling periods. Control loop deadlines are not always hard. On the contrary, many controllers are quite robust to variations in sampling period and response time. Hence, it is arguable whether it is necessary to model them as hard-deadline tasks or not.

From an industrial point of view it can in many cases also be expensive or difficult to pursue a separation-based design approach. Guaranteeing hard deadlines and providing tight bounds on input output latency is costly. It may require the use of computational models which do not match the current state of practice. It requires good worst-case execution time estimates. It often implies that the resource utilization is quite low. Hence, in many industrial application, although the intention is to separate the concerns between control and computing, a complete separation will not be achieved. The effect of this is undesired interactions between the computing system and control system, e.g., jitter and delays, having a negative effect on control performance.

The relationship between computer system design parameters and control performance is quite complex. Scheduling and networking related parameters such as thread periods, deadlines, priorities, protocols, etc., influence the controller task parameters (latencies, jitter, etc) in a complex way. Similarly the controller task parameters influence the control performance parameters (e.g., rise time, overshoot, signal variances, etc) in an equally complex way. Hence, also in applications where a separation of concerns-based design approach is followed, the need is large for analysis tools that help the designer to quantify the relationships above.

The main drawbacks with the separations of concerns are that it does not always utilize the available computing resources in an optimal way, and that it sometimes gives rise to worse control performance than what can be achieved if the design of the control and real-time computing parts are integrated. This is particularly important for embedded control applications with limited computing and communication resources, with demanding performance specifications and high requirements on flexibility. For these types of applications, better performance can be achieved if a codesign approach is adopted where the control system is designed taking the resource constraints into account and where the real-time computing and scheduling is designed with the control performance in mind. The resulting implementation-aware control systems are better suited to meet the requirements of embedded and networked applications.

Of special interest for the work in this activity is temporal robustness in control systems, i.e., robustness towards implementation-level timing uncertainties and implementation-level functional robustness, i.e., tolerance towards implementation platform faults. Increased understanding of which types of temporal guarantees that really are required by a given control application in order to meet desired specifications is needed. Different computational models are more or less well suited for control system implementation. Software component technology and domain-specific languages for control systems are important ingredients in control systems implementation as well as model-based development tools.

Also in this field there has been a steady progress during the year. The push towards using sensor network technology in control applications has increased the need for control system implementation techniques that are temporally robust and resource-efficient. The same holds for the “new” area of cyber-physical systems. In this area, which can be described as just a new name for wireless networked embedded system; integration of control, computing and communication is vital.

For a more detailed state-of-the-art overview we refer to the roadmap developed by the cluster during Year 1.

2.1.3 Design Tools for Embedded Control Systems

Control systems design has traditionally been treated separately from the design of its software and hardware implementation. The increasing use of embedded control in for example distributed, safety critical and mass-produced systems has caused an increasing need for the simultaneous consideration of the control system and its implementation platform during development. To this end, there is a need for both theoretical contributions and supporting tools that assist designers in understanding and analyzing the intricate relationships between the qualities, such as control performance, robustness and cost, and design parameters related to control system and platform design.

There exist numerous types of tools that support co-design, at least partially. One such example is multi-domain modelling languages such as Ptolemy II and Metropolis. In these systems it is possible to model heterogeneous systems consisting of several different models of computation simultaneously. However, the tools are typically weak at representing continuous-time plant dynamics. Another tool category is scheduling simulators that have been extended with support for simulation of continuous dynamics. One such example is RTSIM. These tools typically do not support simulation of networks. A similar category of tools are network simulators, such as ns-2, that have been extended with support for continues-time dynamics. These can be used to simulate networked control loops, but are not well suited for simulation of real-time kernels. Software emulators such as, e.g. Simics, emulate the behaviour of a real-time kernel on the machine instruction level. It is also possible to extend these with support for simple network models. However, again these types of tools are not intended for simulation of the continuous plant dynamics. Hence, there exists a variety of tools from different categories, but few of them can handle all the aspects that are of interest for networked embedded control systems.

The approach taken in the cluster is to focus on Matlab/Simulink as the basic platform. This is the standard analysis, design, and simulation environment for control engineers today. In our Matlab/Simulink tools we have then added support for scheduling, simulation of real-time kernels and networks and control performance analysis.

Model integration and management constitute key challenges in the design of embedded systems. At the workshop on “Tool Integration in System Development” (at the ESEC 2003 conference), one central outcome from the discussions was that available classical results such as the ECMA reference model for case environments (European Computer Manufacturer’s Association. A Reference Model for Frameworks of Computer Assisted Software Engineering Environments) and basic tool-integration mechanisms/middleware services such as CORBA do not really address the essence of the problem. New technologies and frameworks such as ECLIPSE or the OMG’s MDA activities in the area of “model-driven application development” promise to really address the problem in form of (meta-) model-based tool integration but their applicability remains to be proven especially for non standard domains with rather heterogeneous tool landscapes such as embedded systems. Many efforts in the area of tool integration focus on specific inter-relations and on ad-hoc integration of a few views, e.g. integrating safety analysis with architecture design. Another example of this is various co-design efforts. While such efforts can be very useful in a specific setting they provide no solution to the more general problem of model integration. A framework supporting systematic integration, catering for different types of models, relations and integration needs is needed for embedded control systems. An important industrial requirement on solutions is tailorability to suit different needs.

For a more detailed state-of-the-art review we refer to the Tool surveys that we have generated.

2.2 Main Aims for Integration and Building Excellence through Artist2

The main aims for the integration through Artist2 are the following. The first aim is to unite the best European groups in the field and create a strong European research network on control for embedded systems. The second aim is to integrate this network with the other Artist2 clusters, thereby increasing the awareness within the embedded system community of the true computing and communication requirements of networked embedded control applications and of how control techniques can be used in the design of embedded systems to achieve increased robustness and flexibility.

The integration within the cluster has continued to progress nicely also during this third year. The amount of joint research and publications continues to be high. The number of organized events is also large and the interaction with the rest of Artist2, especially with the ART cluster continues to be strong.

2.3 Other Research Teams

The main international research teams within the fields of interests of this cluster are the following for the different subfields:

Control of Web server systems: This field is strongly dominated by US groups, e.g., Univ of Illinois (Abdelzaher, Sha (associated with the cluster), University of Michigan (Tilbury) and IBM (Hellerstein (now with Microsoft)). One of the few European groups active in this area is LUND (Robertsson).

Control-based resource allocation: This is a field where Europe has several strong groups. Scuola Superiore S. Anna and Univ of Pavia (Buttazzo and Lipari) are strong in adaptive resource management. The same hold for Mälardalens högskola (Fohler) and Philips (Steffens). University of Linköping (Hansson) is strong in control-based approaches for database servers. LUND (Årzén/Cervin), UPVLC (Crespo/Albertos) and KTH (Törngren) are strong in feedback scheduling of control systems and QoS approaches in control. Also US groups such as Univ of Virginia (Stankovic, Son), Univ of Illinois (Abdelzaher, Caccamo, Sha) and CMU (Rajkumar) are strong in this area.

Control of Communications Network: Also here Europe has several strong groups. For example, KTH (Johansson), Univ of Patras (Lygeros), and Univ of L'Aquila (Santucci). There are also several strong groups in the US, e.g., Caltech and Berkeley.

Real-Time Control Systems: Here LUND (Årzén/Cervin) is working in implementation-aware real-time control. The same holds for KTH (Törngren), UPVLC (Albertos), CTU (Hanzalek), UPC (Marti), INRIA (Simon), and Univ of Pisa (Bicchi). Univ of York (Bate) is strong on scheduling of control systems. Groups in the US that are strong on real-time control include Univ of Illinois (Spong) and Berkeley (Auslander).

Codesign Tools: Several groups are working on tools for codesign of control and computing issues. These include LUND (Årzén), KTH (Törngren), Univ of Pisa (Lipari), PARADES (Sangiovanni-Vincentelli).

Hybrid Control: Hybrid control is an area with strong relationships to this cluster. The good European groups are all gathered in the HYCON NoE. These include ETH (Morari, Lygeros), Siena (Bemporad), PARADES (Belluchi), EPFL (Henzinger), Verimag (Maler), LUND (Rantzer) and KTH (Johansson). A number of good US groups also exists, e.g., Berkeley (Sastry), Stanford (Tomlin), Univ of Notre Dame (Ansaklis), and UPenn (Pappas).

2.4 Interaction of the Cluster with Other Communities

Similar to previous years the main interaction ¨within Artist2 has been with the ART cluster and the RT-Components cluster. The interaction with the ART cluster has been performed through joint research work, and through joint proposals and projects.

Outside Artist2 the cluster has interacted with a number of other communities. Some examples are given below:

- The partners of the cluster have interacted with the partners in HYCON through joint participation.
- The partners of cluster have interacted with the partners in SOCRADES IP projects through joint participation.
- The partners of the cluster have interacted with the partners in numerous STREP projects. These include ATESST, ACTORS, DYSCAS, CHAT, AEOLUS, and FRESCOR.
- The partners of the cluster have interacted with the respective national research communities.
- The cluster has organized or co-organized a number of workshops and events, both with a research focus and with a dissemination focus. These includes:
  - The Fourth Graduate School on Embedded Control Systems, Stockholm, May 2007.
  - Zdenek Hanzalek was the General Chair for the 20th Euromicro Conference on Real-Time Systems (ECRTS 08) held in Prague, July 2-4, 2008.
  - A one-day workshop on “Embedded Control Systems: From Design to Implementation” was held in association with the IFAC World Congress, Seoul, Korea, 6 July, 2008
  - The cluster was among the presenters at the workshop “Complex Embedded and Networked Control Systems” organized by the HYCON community and held in association with the IFAC World Congress, Seoul, Korea, 5-6 July, 2008
  - The cluster co-organized a workshop on “DataFlow Modeling for Embedded Systems” together with the ART cluster and the ACTORS project that was held in Pisa, 5 May, 2008
  - An invited session on networked embedded control for the CDC 2008 conference was organized together with Albert Benveniste from the RT-Components cluster. The session was accepted and will take place in Cancun in parallel with the final Artist2 review in December 2008.
  - Karl Henrik Johansson and Karl-Erik Årzén co-organized the EU-US’08 workshop held in Stockholm, 16 June 2008. The topic of the workshop was Networked Information and Control Systems.

- A workshop on “Model-based development of automotive embedded systems – The EAST-ADL approach” was co-organized with ATESST, Brussels, 3 March, 2008
- A workshop on harmonization of modeling languages was co-organized with ATESST in Paris, 25 October, 2007. The meeting gathered representatives from the EAST-ADL, AADL, and MARTE communities.
- A KTH/Industry seminar was organized on September 3 to mark the kick-off for the KTH Embedded Systems centre (ICES). Presentations were given among others by representatives from ABB, Ericsson, and Scania and by Edgar Brinksma from the Dutch Embedded Systems Institute.

- The partners of the cluster has given several keynote addresses, invited sessions, and invited lectures, see the respective activity reports.

3. Overall Assessment and Vision for the Cluster

3.1 Assessment for Year 4

The integration within the cluster has continued to progress nicely also during the final year. The amount of joint research and publications continues to be high, although not as high as during last year. The excellence building within the cluster has also progressed according to plans. The main examples are our graduate schools, the workshop organized at the IFAC world congress, the workshop co-organized with the ACTORS project, several internal physical as well telephone meetings, and the different presentation at ARTIST2 events given by members of the cluster. The mobility between the partners has also increased compared to previous year.

3.2 Overall Assessment since the start of the Artist2 NoE

The overall assessment of the work within the cluster within these four years is very good. The total number of individual and joint publications is very high. The partners have in general been very successful in obtaining research grants and projects. The number of events organized or co-organized by the cluster is very high, including four editions of the graduate school on embedded control systems, two international workshops (one in US), two industrial workshops, special sessions at CDC-ECC 2005, IFAC World Congress 2005, CDC 2008 and CACSD 2007, a workshop at the IFAC World Congress 2008, and workshops at DATE and CAV 2007, just to mention a few of them. Additionally, two roadmaps have been produced and the design tools have been developed and extended.

3.3 Vision Beyond the Artist2 NoE

The general vision for the research work that is coordinated within the cluster is summarized in the following two statements:

Development of methods, tools and theory that allow faster and more efficient development of networked embedded control systems that are safer, more flexible, more predictable, have higher degree of resource utilization, and better performance than what is possible today

and

Advance the state of the art in applying control methods for providing flexibility and robustness and manage uncertainty in embedded computing and communication systems.

This cluster as a whole will be discontinued after the end of Artist2. However, in spite of this, a lot of the work will still be continued in the ArtistDesign network, both in the OS and Networks cluster and in the transversal Design for Adaptivity activity. A lot of the work will also continue in the different existing and new IP and STREP projects that the core partners are members, e.g., SOCRADES, FRESCOR, DYSCAS, ACTORS, and ATESST, as well as in different national projects.

There are strong indications that control implementation techniques will continue to be important for the embedded systems community. Control is and will without doubt continue to be one of the largest application areas for embedded system, in particular for ubiquitous networked embedded systems. The current multi-core trend that both makes traditional static implementation techniques more difficult and generates new requirements on programming models and implementation techniques is one sign of this. Another sign is the focus on small ubiquitous networked devices in the form of, e.g., sensor networks, where there are severely limited computing resources, but still a desire to perform as much of the computations (incl. control computations) locally in order to save communication bandwidth and battery power.

The use of feedback to provide performance and robustness in networked embedded computer systems becomes more natural, the more complex and hard to statically analyze the systems are. Since increased complexity and an ever increasing amount of software is one of the most prominent trends in embedded systems today we are convinced that dynamic feedback-based resource management will be increasingly important for the future.

4. Cluster Participants

4.1 Core Partners

: **Cluster Leader** **Team Leader for Lund University** **Activity Leader for "NoE Integration: Adaptive RT, HRT and Control"** **Activity Leader for "Cluster Integration: Control in Real-Time Computing"**	
	Professor Karl-Erik Årzén, Lund University http://www.control.lth.se/user/karlerik/
Technical role(s) within Artist2	Cluster leader. Activity Leader for "NoE Integration: Adaptive RT, HRT and Control". Activity Leader for "Cluster Integration: Control in Real-Time Computing". Technical expert.
Research interests	Integrated control and scheduling, embedded control systems, control of computer systems, codesign tools

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	Associate Professor Anton Cervin, Lund University http://www.control.lth.se/user/anton/
Technical role(s) within Artist2	Provides expertise on feedback scheduling, co-design tool, and integrated control and scheduling.
Research interests	Integrated control and scheduling, embedded control systems, codesign tools

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	Associate Professor Anders Robertsson, Lund University http://www.control.lth.se/user/andersro/
Technical role(s) within Artist2	Provides expertise on embedded control, nonlinear control and control of computer systems.
Research interests	Nonlinear control, control of computer systems

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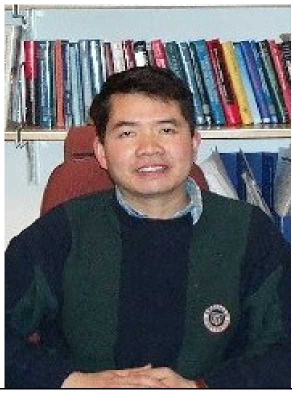	Associate Professor Xiaoming Hu, KTH http:// www.math.kth.se/~hu/
Technical role(s) within Artist2	Technical expert
Research interests	Nonlinear control, motion control, robots.

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	Professor Karl Henrik Johansson, KTH http://www.ee.kth.se/~kallej/
Technical role(s) within Artist2	Technical expert
Research interests	Hybrid control, networked control, control and sensor networks.

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	Associate Professor Mikael Johansson, KTH http://www.ee.kth.se/~mikaelj/
Technical role(s) within Artist2	Technical expert
Research interests	Communication networks, networked control, control and sensor networks.

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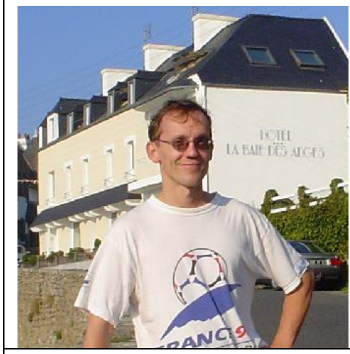
Team Leader for KTH
Activity Leader for “Platform Activity: Design Tools for Embedded Control”

	Professor Martin Törngren, KTH http://www.md.kth.se/~martin/
Technical role(s) within Artist2	Team leader. Activity Leader for Platform Activity: Design Tools for Embedded Control. Technical expert.
Research interests	Embedded control. Model-based development, Co-design Tools

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	Professor Pedro Albertos, UPVLC http://www.aii.upv.es/
Technical role(s) within Artist2	Technical expert
Research interests	Real-Time Control, Digital Control

: **Team Leader for UPVLC** **Activity Leader for "Cluster Integration : Real-Time techniques in Control System Implementation"**	
	Professor Alfons Crespo, UPVLC http://www.gii.upv.es/personal/alfons/
Technical role(s) within Artist2	Team leader for UPVLC. Activity Leader for "Cluster Integration: Real-Time techniques in Control System Implementation". Technical expert
Research interests	Real-time systems, embedded systems, scheduling

: **Team Leader for CTU**	
	Professor Zdenek Hanzalek, CTU http://dce.felk.cvut.cz/hanzalek/
Technical role(s) within Artist2	Team Leader for CTU, Technical expert
Research interests	Real-time systems, embedded systems, scheduling

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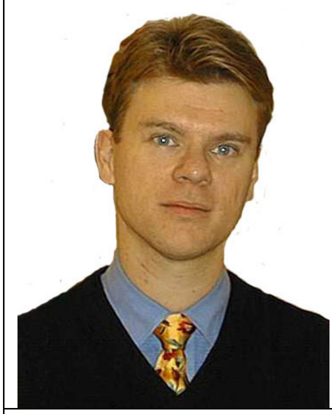
	Professor Vladimir Kucera, CTU http://dce.felk.cvut.cz/kucera/
Technical role(s) within Artist2	Technical expert
Research interests	Linear systems, control theory

4.2 Affiliated Industrial Partners

	Göran Arinder, ABB Automation Technology Products (Retired during 2007. Replaced as Artist contact person by Ulf Hagberg, ABB Automation Technology Products and by Alf Isaksson, ABB Corporate Research)
Technical role(s) within Artist2	Provide examples and feedback from the process automation sector
Research interests	Process automation

	Dr. Johan Eker, Ericsson http://www.ericsson.com/
Technical role(s) within Artist2	Provides input and feedback from the mobile telephone sector
Research interests	Real-Time systems, reservation-based scheduling, control

	Prof. Vladimir Havlena, Honeywell Prague Labs http://www.honeywell.com/sites/cz/en/Honeywell-Technology.htm
Technical role(s) within Artist2	Provides input and feedback from the process automation sector
Research interests	Process control, optimization-based control techniques

	Dr. Jakob Axelsson, Volvo Car Corporation http://www.ida.liu.se/~jakax/
Technical role(s) within Artist2	Provides input and feedback from the automotive sector

Research interests	Systems engineering, real-time systems. safety-critical systems

	Magnus Hellring, Volvo Technology http://www.volvo.com/group/sweden/sv-se/Volvo+Group/our+companies/volvotechnologycorporation/vtecabout/
Technical role(s) within Artist2	Provides input and feedback from the automotive sector
Research interests	Real-time systems, systems engineering

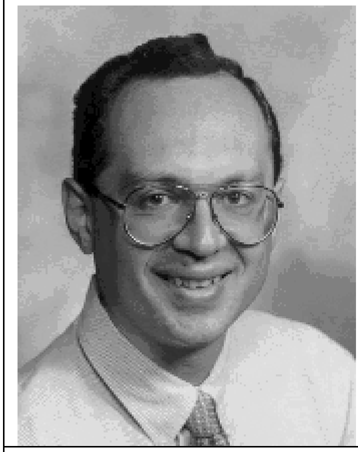
N.A.	Dr Joachim Stroop, dSpace http://www.dspaceinc.com/ww/en/inc/home.cfm
Technical role(s) within Artist2	Provides input and feedback from the tools and automation sector.
Research interests	Code generation tools, simulation tools.

N.A.	Klas Engwall, Maquet Critical Care http://www.maquet.com/
Technical role(s) within Artist2	Provides input and feedback from the medical sector.
Research interests	Medical embedded equipment and systems

4.3 Affiliated Academic Partners

The cluster has no affiliated academic partners.

4.4 Affiliated International Partners

	Professor Tarek Abdelzaher, University of Illinois at Urbana-Champaign http://www.cs.uiuc.edu/homes/zaher/
Technical role(s) within Artist2	Technical expert
Research interests (optional)	Operating systems, networking, sensor networks, distributed systems, and embedded real-time systems.

	Professor Lui Sha, University of Illinois at Urbana-Champaign http://www.cs.uiuc.edu/directory/directory.php?name=sha
Technical role(s) within Artist2	Technical expert.
Research interests	Distributed real-time computing systems, dynamic real-time architecture, QoS driven resource management and security and fault tolerance in networked embedded systems.

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5. Internal Reviewers for this Deliverable

Martin Törngren, KTH and Giorgio Buttazzo, Pisa.