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Network of Excellence
on Embedded Systems Design

Cluster Progress Report for Year 3

Cluster:

Control for Embedded Systems

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Policy Objective (abstract)

The report summarizes the achievements done during the third 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 objectivesl – 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.

During this year an increased emphasis has been placed on model and tool integration considering control systems tools and related embedded systems tools. There are several reasons for this, including industrial relevance and the fact that several interesting research challenges have to be solved to provide satisfactory solutions. 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 typically handled by different specialists, employing different modeling languages and tools. Approaches to support model integration and management therefore become increasingly important.

The work during the period has focussed on

- further development of the individual tools developed by the cluster partners
- development of a demonstrator platform, the Saint truck, which so far has been used to explore complexity management for automotive embedded systems, limitations of Autosar, and model-based development approaches.
- increased efforts for cross-cluster discussions on model and tool integration. Martin Törnren of the Control for embedded systems cluster took the initiative to raise and discuss the needs of ARTIST2 actions dedicated to synchronization between various platforms, models and tools. Following this initiative, two workshops have been carried out during the 3rd year of ARTIST2 with Martin Törngren as a co-organizer.
- further work on model and tool integation considering in particular how UML and safety models/tools can be connected to control systems models/tools. The work includes both the identification of integration scenarios as well as initial integration case studies.
- Interviews and studies of industrial practices in the area of automotive embedded systems area. This work is motivated to better understand the gap between research and industrial practices, what the industrial challenges are, and provides essential information on important aspects when introducing new methods/technologies in industry.
- 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, except for the planned joint meeting with the HYCON network.

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 objectives for year 3 and 4 were to develop a common framework model in order to facilitate the control and computing codesign, to organization an annual Graduate School on Embedded Control Systems, and to organize a follow-up of the Lund Workshop on Control for Embedded Systems. Both the graduate school and the follow-up to the Lund Workshop were successfully organized. The developed of the common framework is well on its way, although not completed yet.

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 3 were to demonstrate that scheduling algorithms can be made adaptive by means of control schemes, to organize a new industrial workshop along the lines of the workshop organized jointly with the Beyond AUTOSAR activity, and to organiea follow-up research workshop to the Lund Workshop on Control for Embedded Systems. The first objective has partly been achieved through the individual and joint research activities performed within the activity. However, during this year most of the research activity has been focused on real-time techniques for embedded control implementation. The industrial workshop has been pushed into Year 4 due to lack of resources. The follow-up workshop to the Lund workshop was successfully organized in Urbana-Champaigne in May 2007.

Of particular interest to several of the partners involved is the creation of the new STREP proposal ACTORS on feedback-based reservation scheduling that will start in a couple of months. ACTORS, the already existing FP6 FRESCOR project and the ArtistDesign network will provide a good platform for future work in this area, in particular the new Design for Adaptivity activity within ArtistDesign.

Overall: On an overall level the research during Year 3 has continued along the lines of the first two years. The number of publications is high, although the number of joint publications is smaller than during 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. We have also taken the initiative to workshops attached to the IFAC World Congress that will be held in Seoul in July 2008. This we have done both on our own and together with HYCON.

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 applicaton 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 modeling 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 modeling 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 continue 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 modeled 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 continuos-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, specially 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 last year 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. The cooperation with the RT-Components cluster has primarily been within the context of the tools activity.

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

- The partners of cluster have interacted with the partners in HYCON thyrough joint participation.
- The partners of cluster have interacted with the partners in the RUNES and SOCRADES IP projects through joint participation.
- The partner of the cluster has interacted has interacted with the partners in numerous STREP projects. These include ATESST, DYSCAS, 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:
    - o The 3rd Graduate School on Embedded Control Systems, Lund, May 2007
    - o The 2nd International Artist2 Workshop on Control for Embedded Systems, Urbana-Champaigne, May 2007.
    - o An Artist2 poster session at FeBID'07 (Second International Workshop on Feedback Control Implementation and Design in Computing Systems and Networks), Munich. May 2007
    - o An invited session on Tools for Co-Design of Control Systems and Their Real-Time Implementation at the IEEE International Symposium on Computer-Aided Control Systems Design (CACSD), Thursday October 5, 2006, with representatives from industry (e.g. Mathworks) and several academic communities (including AADL).
    - o The KTH/Industry Embedded systems seminar, August 30th, 2007.
    - o Towards a Systematic Approach to Embedded System Design April 20th, 2007 – Workshop at the DATE conference.
    - o Tool Platforms for ES Modelling, Analysis and Validation July 1-2, 2007 - satellite event of CAV 2007, Berlin, Germany.
    - o Tool Exhibition organized by SNART (Swedish National Real-Time Association) (chaired by Anton Cervin of LTH) as part of the Real-Time in Sweden Symposium, Västerås, August 2007.

- Embedded systems colloquium, CTU Prague, Czech Republic, February 1st, 2007
- Summer School – Embedded RTLinux Intro 2007, CTU Prague, June 18th – 22nd, 2007
- Design of Embedded Real-time Systems: a graduate course given within the Artes++ graduate school – with invited speakers from Artist2 affiliated industries, KTH, Autumn 2006
- One week graduate course on Embedded Control, UNED, Madrid, April, 2007

- The partners of the cluster has given numerous keynote addresses, invited sessions, and invited lectures at both academic conferences and in industrial contexts, see the respective activity reports.

3. Overall Assessment and Vision for the Cluster

3.1 Assessment

The integration within the cluster has continued to progress nicely also during this year. The amount of joint research and publications continues to be high, although not as high as during last year. There are several reasons for this. One is just coincidence; several joint publications appeared just at the end of Year 2. These could just as well have been reported as part of this reporting period. Another is due to that we made a very dedicated effort to produce many joint publications last year.

The third reason has to do with the structural problems associated with networks of excellence. Since the amount of money in networks is so small it is necessary, in order to do joint integration-type research, to have basic funding from other sources, not only to support the individual research among the partners, but **also** to explicitly support the joint research. The network of excellence money is too small to match the rather ambitious goals that one normally have. Finding funds that support collaboration between partners in different countries is quite difficult. National funding sources can rarely be used since they normally only may involve partners in the same country. In many cases partners from the same countries that collaborate within a European network end up competing for the same national grants. The alternative then is to find other European projects involving the partners, i.e., IP or STREP projects. However, also here it can in many cases be difficult for partners from the same thematical cluster to be in the same project, the reason being that they will by many proposal reviewers be seen as not being complementary enough. The scope of most EC calls in embedded systems and networked control is so wide, that it normally is enough with a single partner with, e.g. control expertise within the same project. The other partners should have complementary expertise, e.g., on scheduling, component-based design, middleware, security, etc. Hence, it is de facto easier to get money together with others partners, e.g., partners from other Artist2 clusters, than together with partners from the same cluster.

The excellence building within the cluster has also progressed according to plans. The main examples are our graduate schools, the international workshop, and the different presentation at ARTIST2 events given by members of the cluster. The PhD student mobility between the partners in still low. A major reason for this is that by now the different partners know each others work so well that it is no longer necessary to meet physically in order to continue the collaboration.

3.2 Vision and Long Term Goals

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.

Without this cluster the link from ARTIST2 to the control community would be lost. The result would be incorrect or overly restrictive assumptions about the resource requirements of control applications and it would lead to ad hoc based application of control in the design of embedded systems rather than approaches that are firmly based in control theory. This would affect both academia and industry. We view our cluster as a necessary bridge between the control community and the embedded systems community. We also believe that there is room for expanding the cluster within the scope of ARTIST2.

Since this cluster as a whole will be discontinued after the end of Artist2 a main focus for the remaining time will be to summarize the achievements and to disseminate them outside and inside Artist2. However, in spite of the fact that the cluster will be terminated, 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.

3.3 Plans for Year 4

3.3.1 Technical Description

The future technical activities that are necessary in the fields of the cluster have been identified in the roadmaps, surveys, and research agenda that were developed during Year 1. In the same way as during year 2 and 3 the future work in the cluster will follow these research directions. The exact technical topics that will be investigated during the coming year are to a large extent decided by the forces outside the control of the network, i.e., the objectives and directions of the particular research projects that provide the majority of the funding for the work. Hence, the descriptions below should be interpreted more as ambitions than as hard plans.

3.3.1.1 Cluster activity: Control of Real-Time Computing Systems

We will continue our work on modelling and feedback-based control and scheduling of computer systems, with particular emphasis on different types of server systems, on control systems, and on research management in embedded systems. Special focus will be given to multi-tier or cluster server systems, to experimental verification of the results, and to OS and middleware support for feedback scheduling.

In parallel with this we will continue our work on control-based approaches in communication networks. Much of the work will be motivated by the special problems encountered in wireless sensor network systems where several of the partners are involved in European projects, e.g., RUNES and SOCRADES.

An area which will gain increased interest is feedback-based reservation scheduling for soft real-time systems, where new projects have been approved both nationally and within Europe.

3.3.1.2 Cluster activity: Real-Time Techniques in Control System Implementation

Also here we will continue our work along the lines of year 2 and 3, i.e we will work on the relationships between separation of concerns-based design approaches and integration-based design approaches for embedded control systems. This includes both work on implementation-aware control design methods and control-aware real-time implementation techniques. Special emphasis will be given to temporal robustness in control and to improving the understanding of the fundamental trade-offs that exist between sampling rates, input-output latencies, and jitter in control loops, including networked control loops.

We will continue our work on event-triggered feedback control, which potentially can have a strong influence on embedded architectures. We will also continue our work on server-based implementation methods for control systems (e.g., the Control Server Model), on the Control Kernel, and on the definition of a common framework for the interaction between controllers and the underlying OS-middleware-hardware layer.

Additionally we will also continue the development of benchmarks that can be used to evaluate not only competing control design approaches but also competing real-time implementation approaches. During Year 3 a benchmark based on a RC helicopter has been developed by CTU and a truck control benchmark has been added by KTH. During Year 4 we will add more benchmarks.

3.3.1.3 Network activity: Adaptive RT, HRT and Control

The research problems to be tackled during the next 18 months involves both the use of control-techniques in resource scheduling for embedded systems and scheduling techniques and computational models for embedded control applications, i.e. from a technical point of view it combines the two cluster activities above, but now in collaboration with the partners of the ART and RT Components cluster. These two lines are also combined in the form of feedback-based scheduling of embedded control systems. We will continue and strengthen our joint work. SHARK and TrueTime will be promoted as a common platforms for the joint experimental and simulation activities.

3.3.1.4 Platform activity: Design Tools for Embedded Control

During the remaining time of the project we will in particular address

- UML-Simulink transformations, continuing the earlier work on structural and behavioral mappings.
- Safety modeling in the EAST-ADL language, with an industrial case study and implementing a transformation, also further investigating the UML specification and the level of formalily possible.
- An investigation of how requirements can be formalized and integrated with industrial model-based development will be performed in cooperation with Scania.
- Middleware abstractions will be implemented in Truetime in cooperation between KTH and LTH, where scenarios such as load balancing, software download, connecting external devices pose challenges for modeling and verification.
- The design of a reference implementation of the Dyscas middleware will be initiated for the Saint demonstrator (www.dyscas.org).
- Extensions of TrueTime so that it will be able to model and simulate multicore platforms. This will be performed within the new EU/IST FP7 STREP project ACTORS and within an anticipated new national project (pending proposal)
- Extensions of Torsche - version 0.4.0 will be released in September 2007, so that it is ready for distribution with the book by Michael Pinedo: Scheduling: Theory, Algorithms, and Systems (Third Edition) as requested by the author of this widely used book. Currently we are working on extension of our tool towards graph algorithms in order to have better coverage of general optimization and decision problems (e.g. routing in sensor networks, scheduling of TDMA slots in Profinet).
- It is possible that we will also find the time and resources to investigate the connections between systems level modeling and software/hardware component modeling (as manifested by for example Autosar).

3.3.2 Current and Future Milestones

3.3.2.1 Cluster activity: Control of Real-Time Computing Systems

Year1 Milestone:

- Roadmap describing the current state-of-the-art and the important research issues *(Achieved)*

Year2-4 Milestones:

- Progress made on the fundamental underlying issues: decreased requirements on prior knowledge about resource utilization, increased possibilities to use COTS implementation platforms, and enhanced robustness towards load variations (*Achieved to 30 % currently after Year 2)*

  The research performed during Year 2-3 has contributed to the solution of several of the above items. For example, the work on feedback control of Linux scheduling is a step towards being able to utilize COTS implementation platforms, and the work on queueing system models is motivated by the aim to be robust against load variations. (Achieved to 60% after Year 3)

Year 3-4 Milestone:

- Increase our international and industrial visibility. A good means for this is through the organization of and the participation in the FeBID workshops.

  Achieved. We participated at FeBID 2007 in Munich and also organized a special Artist2 poster session there.

Updated Milestones for Year 4:

- Disseminate the total amount of work done within this activity at Artist organized events.
- Continue our presence at workshops and conferences in the area.
- Continue the research performed within control of server systems, in control-based reservation management and feedback-based scheduling, on applying control to communication networks and sensor networks, and dynamically configurable embedded systems.

3.3.2.2 Cluster activity: Real-Time Techniques in Control System Implementation

Year1: Roadmap describing the current state-of-the-art and the important research issues (*Achieved*)
Year2: A common framework of the control parameters that can be influenced by an embedded control system implementation and the real time operating systems criteria that can be adjusted to increase the robustness of the control system (*Achieved to 50%*)
This milestone has not been fully completed yet. Our aim is to complete this during the reminder of 2006.
Year3-4 milestones:

- A common framework model in order to facilitate the control and computing codesign

This has not been finalized yet. An estimate is that it currently is finalized to around 75%. This will be the focus of the work during Year 4.

- Organization of an annual Graduate School on Embedded Control Systems

Achieved.

- Organization of a follow-up of the Lund Workshop on Control for Embedded Systems

Achieved

Updated Milestones for Year 4:

- Finalize and disseminate the common codesign framework model. At least one joint major publication summarizing this work should be generated
- Organization of the Fourth Graduate School on Embedded Control Systems during Spring 2008
- Disseminate the total amount of work done within this activity at Artist organized events.
- Add at least two additional benchmarks to Bridgit.
- Continue the individual and joint research on control and scheduling co-design, OS and kernel support for embedded control, event-based control, wireless networked control, and modeling and analysis of embedded control systems, according to the roadmap developed in Year 1-2.

3.3.2.3 Network activity: Adaptive RT, HRT and Control

Year1: Setting the technical background and assess the needs (Achieved 100%)

Year2: Demonstrate that applications of diverse type can be specified in terms of resource aware tasks (Achieved 80 %)

The work within the activity has focused on two application types only: multimediaapplications and real-time control. Within these two broad application areas, several types ofapplication have, however, been studied. These two application types are also the ones thatare most natural for these techniques.

Update Milestone for Year3:

- Demonstrate that scheduling algorithms can be made adaptive by means of control schemes *(Acheived 50%) This is a quite general milestone that is fulfilled through the joint and individual research performed by the partners.*
- The organization of a new industrial workshop along the lines of the workshop organized jointly with the Beyond AUTOSAR activity
  (Not achieved) Due to lack of time from the key personnel this milestone has been pushed into Year 4.
- The organization of a follow-up research workshop to the Lund Workshop on Control for Embedded Systems held in June 2005. The workshop is currently planned for Jan-Feb 2007
  (Achieved 100%)

Updated Milestones for Year 4:

- The organization of a new industrial workshop along the lines of the workshop organized jointly with the Beyond AUTOSAR activity
- Disseminate the total amount of work done within this activity at Artist organized events.
- Continued joint and individual research along the lines of the roadmaps developed during Year 1-2. This includes research on control of server systems, control-based resource management, and interactions between control, scheduling and networking, including feedback scheduling-based approaches.
- Coordinate and help to disseminate the results generated by the EC projects FRESCOR and ACTORS which both can be seen as continuations of the work done within this network activity.

3.3.2.4 Platform activity: Design Tools for Embedded Control

Existing milestones - Year1-2: Identification of which of the existing tools that will be included in the platform, and specification of their interfaces.

Comment: The tools developed by the cluster have been investigated and compared. Functionalities represented by other discipline's tools have also been investigated. Interfaces have been described at a high level of functionality. Different approaches to model and tool integration have been investigated. The individual tools have been further developed and disseminated. One prototype tool integration platform has been developed.

Exisiting milestone - Year3: Develop the necessary interfaces that allow the individual tools to be used together

- Development of integration scenarios

- Performed several case studies on model and tool integration, involving tools specific to the cluster as well tools typically dealt with by other research communities (clusters)

Comment: Integration scenarios have been developed and are/will be reported in [Shi et al (2007), Törngren et al (2007)]. Several case studies have been initiated and will be continued in the following year, and new ones will start.

Existing milestone - Year4:

Usage of the tools in new co-design based research activities, adoption in industrial case studies.

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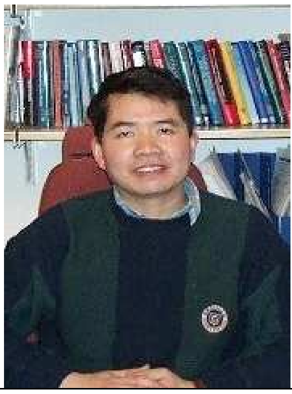	Associate Professor Xiaoming Hu, KTH http:// www.math.kth.se/~hu/
Technical role(s) within Artist2	Technical expert
Research interests	Nonlinear control, motion control, robots.

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	Associate 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.

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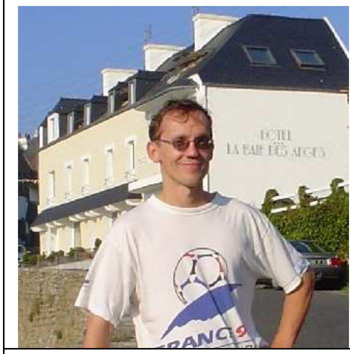
Team Leader for KTH
Activity Leader for “Platform Activity: Design Tools for Embedded Control”

	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

:

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

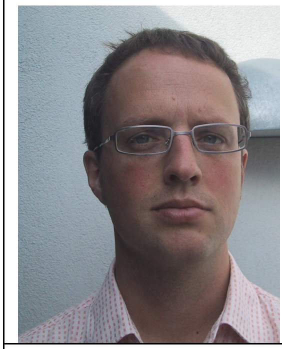
: **Team Leader for UPVLC** **Activity Leader for “Cluster Integration : Real-Time techniques in Control System Implementation”**	
	Professor Alfons Crespo, UPVLC http://www.gii.upv.es/personal/alfons/
Technical role(s) within Artist2	Team leader for UPVLC. Activity Leader for “Cluster Integration : 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

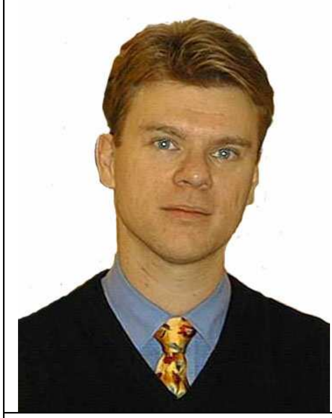
:	
	Professor Vladimir Kucera, CTU http://dce.felk.cvut.cz/kucera/
Technical role(s) within Artist2	Technical expert
Research interests	Linear systems, control theory

4.2 Affiliated Industrial Partners

	Göran Arinder, ABB Automation Technology Products
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 Illinos 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 Illinos 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.

5. Internal Reviewers for this Deliverable

Martin Törngren, KTH