ARTIST 2

Network of Excellence

IST-004527 ARTIST2:
Embedded Systems Design

Cluster Progress Report for Year 2

Cluster:

Control for Embedded Systems

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Policy Objective (abstract)

The report summarizes the achievements done during the second 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 main objectives for this period involved tool integration, coordination with other clusters, and further development, coordination, and promotion of individual tools. A tool integration plan would be developed as well as use cases, integration scenarios, and case studies. Further, the other clusters would be invited to join in a refined tool survey.

There is no major deviation from these objectives. The work during the period has focussed on further development of the individual tools developed by the cluster partners, initial work on the integration of these tools, a broader contextual study on how tool integration can be accomplished in a systematic way, and dissemination of the results from the first year of ARTIST2

It should however be noticed that the effort for tool integration is considerable. The survey on approaches towards tool integration has revealed a large number of potential topics for further work and for interactions with other clusters. Interactions with other clusters and affiliated partners have been initiated and some achievements are reported for the work during the second year. Integration scenarios and case studies have been developed. We still believe that a joint tool/platform meeting involving all the clusters should be organised within ARTIST2. The planned meetings have all been held.

Cluster Integration: Control in real-time computing: The overall objective of this activity was 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.

These objectives have been achieved in a nice way through the large amount of research that has been performed within and between the partners. The planned meetings have all been held, except for the follow-up workshop to the successful Lund Workshop on Control for Embedded Systems which have been postponed until early Spring 2007 (this time in Urbana-Champaign)

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 18 months objective was to provide 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. The long term goal is to provide a common framework model in order to facilitate the control and computing co-design. In addition research work should be performed on scheduling and control co-design, development of components for control system applications, and mode change techniques.

The overall objective has also here been achieved nicely through the large amount of research that has been performed and published. The work on a common framework has been started but not completed. Individual research has been performed within several areas of these activities, e.g., scheduling and control co-design. However, the small amount of research funding in Artist2 has not made it possible to follow the plan exactly. The planned meetings have been held except for a joint workshop with HYCON in Stockholm in June that was cancelled by HYCON due to them having an internal large meeting in Lund, also in June.

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 18-month objective was to demonstrate that applications of diverse type can be specified in terms of resource-aware tasks, and scheduling algorithms can be made adaptive by means of control schemes.

The 18 month objective has been well achieved. The work has focused on two application types: multimedia applications and real-time control. Within these two broad application areas, several types of applications have been studied. Several joint research activities have been initiated, especially between the Control and the ART cluster. The RT-Components and the Control cluster have jointly organized an industrial workshop. The planned meetings have all been held. However, instead of having meetings with all three clusters involved the meetings have been with either the Control cluster and the ART cluster, or the Control cluster and the RT-Components cluster.

Overall: On an overall level the research during Year 2 has moved in the direction of joint work and publications, either within the cluster or with other ARTIST2 partners. The partners have co-authored 19 joint publications during this year. This is a good sign of the increased integration that has been achieved. In total an impressing number of publications have been generated and several meetings have been organized. Far more than what could be expected considering the small amount of funding involved for each individual partner. A complete list of publications produced by the Control cluster during Year 2, with downloads available for most of the papers, is available here:
http://www.md.kth.se/RTC/ARTIST2/publications.html

1.2 Industrial Sectors

Embedded control systems are vital in most industrial application areas, e.g., automotive, avionics, manufacturing, and automation. 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.

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. An initial such framework has been proposed by the cluster participants (see http://www

.md.kth.se/RTC/ARTIST2/publications/CACSD06_Chen.pdf)

A 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.

1.4 Internal Reviewers for this Deliverable

Martin Törngren, KTH

Anton Cervin, LUND

2. State of the Integration in Europe

2.1 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 Virginia (Abdelzaher (associated with the cluster)), University of Illinois (Lui Sha (associated with the cluster)), University of Michigan (Tilbury) and IBM (Hellerstein). 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 Virginia (Abdelzaher, Caccamo) 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), Siena (Bemporad), PARADES (Belluchi), 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).

2.2 Interaction of the Cluster with Other Communities

During the first 12 months, the cluster was mainly occupied by the development of two roadmaps. During the second 12 months the orientation of the cluster has changed. Now the main priority is joint research along the lines of the roadmaps, both among the partners within the cluster and with other clusters. The cluster is the leader of the network activity on Adaptive Real-Time, Hard Real-Time and Control together with the RT Components cluster and the Adaptive Real-Time cluster. Here the interaction is very strong with a number of joint research activities, joint organization of a summer school with the ART cluster (First European Laboratory on Real-Time and Control for Embedded Systems in Pisa, June 10-14), and an industrial workshop with the RT-Components cluster (Interaction between control and embedded electronics in automotive industry, Innsbrück, March 23). The interaction with the other ARTIST2 clusters has so far been limited. However, the potential for more interaction is strong, in particular with Testing and Verification (testing and verification of embedded control systems) and Execution Platforms (hardware and OS support for feedback scheduling and resource negotiation). A first joint activity involving these clusters and the Control for embedded systems cluster was the "Scandinavian ARTIST2 Seminar on Embedded Systems Design" – mainly a dissemination event (www.snart.org). However, in general the limited resources have so far hampered this interaction. In addition to the above the cluster has been involved in joint curriculum development with the other clusters.

2.3 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.

3. Overall Technical View

3.1 Brief State of the Art

3.1.1 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 this year in Vancouver and will be held next 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 is very important.

For a more detailed state-of-the-art overview we refer to the roadmap developed by the cluster during Year 1, see http://www.md.kth.se/RTC/ARTIST2/publications.html

3.1.2 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. For a more detailed state-of-the-art overview we refer to the roadmap developed by the cluster during Year 1, see http://www.md.kth.se/RTC/ARTIST2/publications.html

3.1.3 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. For a more detailed state-of-the-art overview we refer to the roadmap developed by the cluster during Year 1, see http://www.md.kth.se/RTC/ARTIST2/publications.html

3.2 Ongoing Work in the Partner Institutions

3.2.1 Lund University

The work in the real-time systems group at the Control department is focused on the research topics of the cluster. Work is being done on implementation techniques for real-time and embedded control systems, feedback-based scheduling applied to control application, temporal robustness, and control performance evaluation. Work is also done on control of web-server systems. Here the work has received considerable attention, exemplified by the invitation to co-chair the next FeBID workshop.

Another important area is co-design tool development. A new version (1.4) of the open source simulation tool TrueTime has recently been released. Over 2000 downloads have been reported of the previous release, several of these from industry. Lund also develops the analysis toolbox Jitterbug for evaluation of control performance subject to timing variations.

3.2.2 KTH

The ARTIST2 node – KTH – includes several departments. At the department for Signals, Sensors and Systems the work is focused on control and communicaton networks. Examples are control over networks, e.g., over sensor networks, control of different types of network-related resources and optimization-based network protocol design. A lot of the work is aimed at wireless sensor networks. They participate in several European projects in this area, e.g., RUNES and SOCRADES.

Inherent limitations of controller performance have in the past been considered exhaustively with respect to bounds on controller resources, such as actuator authority and sensor accuracy. KTH addresses communication bandwidth limitations in this context. These are of primary importance in embedded control systems, where sensor information and control signals are communicated over wired or wireless links. They are particularly interested in coordination problems in mobile robotics, where several robots need to make cooperative decisions and share sensor information in order to optimize behavior.

A continually increasing use of the Internet with its widening set of services increases the demand on the control of the network. In industry, feedback control is a widely recognized method to increase productivity and product quality. The intention of KTH is to explore what control theory has to offer network communication systems. The objective is to improve traffic throughput and to better accomodate different service demands. It has been experimentally observed that Internet traffic exhibits turbulent fluctuations. This causes congestion that results in delays and losses. Their goal is to develop control mechanisms for routers in heterogeneous networks to reduce these fluctuations. The approach is to design control strategies that operate with local information and yet optimize the system power (throughput divided by delay). A fundamental issue in this context is to quantitatively relate the amount and spatial distribution of feedback information to the performance benefits that this information can bring.

At the division of Mechatronics (Machine Design Department) the work is focused on model based development of embedded control systems, including model and tool integration, model management and the development of modelling languages for embedded control systems.

Work is also focused on architectural design of embedded systems. A new research strand is the development of dynamic middleware for automotive systems. Work is also devoted towards methodology supporting model based development and systematic verification of embedded systems.

3.2.3 CTU

Scheduling on FPGAs: To facilitate the FPGA design process CTU works on scheduling algorithms using very universal models, where tasks are constrained by precedence delays and relative deadlines. The precedence relations are given by an oriented graph, where tasks are represented by nodes. Edges in the graph are related either to the minimum time or to the maximum time elapsed between start times of the tasks. The NP-hard problem of finding an optimal schedule satisfying the timing and resource constraints while minimizing makespan, is being solved using several approaches. The first one is based on Integer Linear Programming, the second one is implemented as a Branch and Bound algorithm, the third one on budget-like heuristic algorithm and the fourth one on EDF-like heuristic algorithm.

Queue modeling and waiting time balancing: CTU models systems with queues (urban traffic systems, internet communications) by means of non-linear difference state equations. Further, they use the extended queue model to derive the parameters of the controllers for a simple system with two queues. Secondly, they aim at more complex systems of the same type and structure. CTU would like to include additional practical constraints to the problem (e.g., supervisory systems performing high-level optimization on the model). In order to model the traffic with higher precision (i.e. incorporating logarithmic stream model capturing the output flow as non-monotonic function of the density) they are developing a model based on continuous Petri Nets. In the end, they want to compare both models and evaluate the resulting control performance.

Analytical approach to response-time analysis: The work consists in construction of mixed-integer linear program for solving the problem of response-time analysis for tasks with offsets. After solving the problem, they would like to combine that analysis part with some optimization of real-time system parameters, e.g. the optimization of priorities of the tasks in order to meet deadlines which are not met if the priorities are assigned “randomly” by a designer of the system. Here they could utilize the fact that it is possible to merge the MLP programs for analysis of two or more distinct task to one bigger MLP program and analyze these tasks together and simultaneously find the optimal priority assignment. Other directions of future research can be optimization of some other parameters than the priority, e.g. optimization of power consumption, optimal mapping of tasks to nodes of distributed system, optimization of memory demand of distributed application etc. All these optimizations would profit from the fact that schedulability analysis could be contained in the optimization constraints.

3.2.4 UPVLC

Control Kernel: In an operating system there is a clear understanding about what is the kernel and which services have to be supported. These are common services on top of which application designer have been working for long time. However, when we speak about the basic control services there is not a common understanding about what is, which services have to be included and how is implemented. The UPVLC group is working in the definition of the minimal services provided by a control kernel in order to ensuring control action (CA) delivering at time even if the calculated action for this period has not been updated, data acquisition services at appropriated rate and handling delays, transferences between control structures depending on the system status and external communications.

Kernels for embedded control systems: The design and implementation of a kernel for embedded systems including services for control systems is the goal of this research line. This is supported by the development of a hypervisor which permit to execute several temporal and spatial isolated execution environments (operating system + application) on a processor. It permits to add security and reliability to the control application. A specific control layer provides the control services. The main issues considered in this topic are scheduling policies for control task models and memory management.

Predictors for embedded systems: In practical digital implementation of any controller, delays appear due to transport phenomena, computation of the control input, time-consuming information processing in measurement devices, etc. In order to cope with these delays, a number of algorithms have been reported. A close analysis of these methods show that they all use, in an explicit or implicit manner, prediction of the state in order to generate the control of the system. A common drawback, linked to the internal instability of the prediction, is that they fail to stabilize unstable systems. In this research, we have developed a discrete-time controller based on state feedback using the prediction of the state. The convergence analysis and the temporal analysis (delay effects and variations of the sampling period) have been studied. Considering these results, we are working with the possibility to obtain some scheme in the Smith-Predictor framework that is able to cope with unstable system and easy to implement in an embedded system. This is one of the current results: a new scheme of prediction for discrete time systems.

3.3 Interaction and Building Excellence between Partners

The interaction and excellence building among the partners in the clusters and between the cluster partners and other ARTIST2 partners is very strong. Here follows some examples of activities that have been taking place during Year 2:

- There are several joint research activities among among the partners within the cluster. Examples are joint research work involving KTH and LUND, CTU and LUND, UPVLC and LUND, LUND and Pisa, LUND and Mälardalen/Kaiserslautern, KTH and Mälardalen, LUND and UPC, Ericsson and LUND, KTH and Volvo, and LUND and ABB. Most of these have generated joint publications during this year. For more details see the activity reports.
- The Control cluster partners each year arrange a Graduate Course on Embedded Control. This year it was given 3-7 April in Prague. The course was coordinated by Zdeněk Hanzálek (CTU) (see http://www.artistembedded.org/FP6/ARTIST2Events/Events/EmbeddedControl/Programme.php). The objective of the course was to provide an overview of the main principles and technologies for supporting the development of embedded control systems. The course was aimed at graduate students, PhD students and engineers with some background in control engineering and computer science. The school was divided in 10 courses and 4 laboratories, each of 90 or 120 minutes.
- The session on “Tools for Co-design of Control Systems and their Real-time Implementation” was prepared by Zdenek Hanzalek (CTU), Martin Törngren (KTH) and Karl-Erik Årzén (LUND). The session will be held at the IEEE Conference on Computer Aided Control System Design (CACSD) in Munich, October, 2006. The session consists of one survey presentations (Tools supporting the co-design of control systems and their real-time implementation; current status and future directions) plus five presentations oriented towards specific tools and principles (Model based integration from the Royal Institute of Technology, Jitterbug and TrueTime from Lund University, Sweden, TORSCHE from the Czech Technical University in Prague, the schedulability issues from Valencia, the SAE Architecture Analysis & Design Language from Carnegie Mellon Software Engineering Institute, US Army/AMCOM and Honeywell Labs).

- Presentation of the ARTIST2 project in two workshops organized by EMTECH (IST project, targeted to embedded systems for SMEs in new member states): EMTECH SME Embedded Systems Workshop I, Rožnov pod Radhoštěm, Czech Republic, 22nd-23rd of November 2005 and EMTECH SME Embedded Systems Workshop II, Brno, Czech Republic, 20th of June 2006.
- The control cluster organized the First European Laboratory on Real-Time and Control for Embedded Systems, July 10-14th, 2006: Pisa, Italy jointly with the ART cluster. A report summarizing the event is available on the Year2 Review Material page.
- The workshop **Interaction between control and embedded electronics in automotive industry** was jointly organized by the RT Components and the Control clusters in Innsbrück, March 23. It was co-located with the Beyond AUTOSAR meeting organized by the network activity "Forums with Specific Industrial Sectors" where also the Control cluster participates.
- The ARTIST2 project was presented at the Scandinavian ARTIST2 Day in Stockholm, 21 August 2006 organized by LUND and KTH. Representatives for all clusters were present except for the ART cluster. The aim of the day was to disseminate project information and broaden the industrial interaction with ARTIST2 within the Scandinavian countries.
- Several of the ARTIST2 partners, including Martin Törngren (KTH) from our cluster, have participated in joint curriculum development for embedded systems.
- Several new EU project involving partners from this clusters have been accepted. These include SOCRADES (KTH, ABB), ATESST (CEA, KTH, Volvo), and FRESCO (CTU, UPVLC, Pisa, U Cantabria, U York, TU Kaiserslautern). Also several national projects have been accepted involving several of the partners.
- An invited session involving work from the RUNES and the ARTIST2 projects were held at the CDC-ECC conference in Sevilla in December, 2005.
- Karl-Erik Årzén participated (by invitation) in the Joint EU-US Workshop on Large ICT-Based Infrastructures and Interdependencies: Control, Safety, Security, and Dependability in Wahsington D.C representing ARTIST2.
- A special issue of the Journal "Revista de Automática e Informática Industrial" (in Spanish) about real-time and control systems was published in 2005 with the participation of UPVLC, UPM, U. Cantabria, and UPC.

4. Overall Assessment and Vision for the Cluster

4.1 Assessment

The integration within the cluster has continued to progress nicely also during this year. Compared to the first year the amount of joint research and joint publications has increased drastically. The total number of publications generated is also impressing considering the cluster size and budget. Several of the publications are of very high quality.

The high-level objectives have in almost all cases been met. To exactly follow the plan in a NoE is, however, in general very difficult, due to the special nature of these projects and their reliance on other funding sources. The interaction with the other clusters has developed nicely. Strong interaction points exist, in particular with the ART cluster and the R-T Components cluster. The work on Control for Real-Time Computing is especially important for the cluster, since it essentially is Europe's only dedicated activity in this area.

An important goal for the cluster was to disseminate the two roadmaps produced during Year 1. This has partly been done in the form of one invited conference presentation and one journal article. However, here is still work that remains to be done. The goal is to have the two roadmaps published together during this fall or early spring 2007.

The excellence building within the cluster has also progressed according to plans. The main examples are the two summer schools, the industrial workshop, and the different ARTIST2 presentation days organized by the cluster. The PhD student mobility between the partners in the cluster has decreased compare to Year 1. 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.

The planned follow-up workshop to the Lund Workshop on Control for Embedded Systems has had to be postponed until early spring 2007. This time it will hosted by our international affiliates Tarek Abdelzaher and Lui Sha at Univ of Virginia at Urbana-Champaign. For this event we will invite the top US researchers within the field.

4.2 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.

With respect to spreading excellence our vision is to maintain and perhaps increase the current activity level.

4.3 Future Work and Evolution

4.3.1 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 and which are available on http://www.md.kth.se/RTC/ARTIST2/publications.html The future work in the cluster will follow these research directions. The exact technical topics that will be investigated during the coming 18 months 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.

4.3.1.1 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. Topics that will be investigated are congestion control, control of transmit power in wireless networks, control-based error coding, and optimization-based network protocol design. 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.

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

We will continue our 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 further increase 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 develop one or two common benchmarks or cases that can be used to evaluate not only competing control design approaches but also competing real-time implementation approaches. To begin with the benchmarks will be simulation-based, but eventually or goal is to also derive physical versions of these benchmarks. One possible benchmark is an embedded control system for a RC helicopter.

4.3.1.3 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. A substantial part of this activity will be devoted to interaction with industry, leaving less room for pure the technical work. However we will continue and strengthen our joint work on feedback-scheduling of control tasks, on mechanisms for overrun handling, and on different timing models for embedded control. We will also actively support and pursue new upcoming research topics at the intersection of the different cluster areas. SHARK and TrueTime will be promoted as a common platforms for the joint experimental and simulation activities.

4.3.1.4 Platform activity: Design Tools for Embedded Control

The planned technical work for the coming 18 months includes the following parts

- Further development of partner's individual tools
- Further work on model and tool integration including
  - Development of integration scenarios
  - Development of case studies involving integration of tool functionalities developed by cluster partners
  - Development of case studies providing integration with UML tools
  - Development of case studies providing integration with tools for system safety analysis
- Further dissemination of results

To create a better cross-cluster understanding, and map of tools for embedded systems development, it is our opinion that a joint tool/platform meeting involving all the clusters should be organised within Artist2.

4.3.2 Current and Future Milestones

4.3.2.1 Cluster activity: Control of Real-Time Computing Systems

Year1 Milestone: Roadmap describing the current state-of-the-art and the important research issues *(Achieved)*

The roadmap has been completed and partially disseminated. What remains is to make the entire roadmap more easily available to the general public. We plan to print the two roadmaps together as a single document or report during the fall of 2006.

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)*

The research performed during this year contribute 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.

New 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.**

4.3.2.2 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

Updated Year3-4 milestones:

- **A common framework model in order to facilitate the control and computing co-design**
- **Organization of an annual Graduate School on Embedded Control Systems**
- **Organization of a follow-up of the Lund Workshop on Control for Embedded Systems**

4.3.2.3 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: multimedia applications and real-time control. Within these two broad application areas, several types of application have, however, been studied. These two application types are also the ones that are most natural for these techniques.

Update Milestone for Year3:

- **Demonstrate that scheduling algorithms can be made adaptive by means of control schemes**
- **The organization of a new industrial workshop along the lines of the workshop organized jointly with the Beyond AUTOSAR activity**
- **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**

4.3.2.4 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: As a basis for tool integration, it is important to clarity the relevant usage scenarios, i.e. how the tool integration supports the various design activities. Moreover, systems design is not limited to just the aspects traditionally dealt with by this cluster. Therefore it is important to carry out case studies that illustrate tool integration also considering other relevant aspects. This update of the Year 3 milestone is also supported by the previous 18 month plan..

Existing milestone - Year4: Usage of the tools in new co-design based research activities, adoption in industrial case studies.

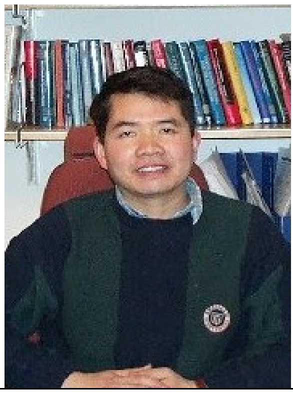
5. Cluster Participants

5.1 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

	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

	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

	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.

	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

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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

5.2 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

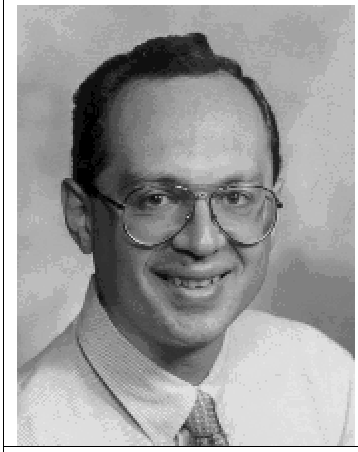
	Dr. Jakob Axelsson, Volvo Car Corporation http://www.ida.liu.se/~jakax/
Technical role(s) within Artist2	Provides input and feedback from the automotive sector
Research interests	Systems engineering, real-time systems. safety-critical systems

	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

5.3 *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.