IST-004527 ARTIST2
Network of Excellence
on Embedded Systems Design

Activity Progress Report for Year 4

JPRA-Cluster Integration

Real-Time Techniques in Control System Implementation

Clusters:

Control for Embedded Systems

Activity Leader:

Professor Alfons Crespo, Universidad Politécnica de Valencia

http://www.gii.upv.es/personal/acrespo/

Policy Objective (abstract)

The overall objective for this activity is to advance the state of the art in applying real-time system methodology for embedded control system implementation. This report summarizes the achievements obtained during the fourth year of the network.

Table of Contents

1. Overview of the Activity

1.1 ARTIST Participants and Roles

Professor Pedro Albertos – UPVLC (Spain)
Role: Provides expertise in control systems.

Professor Alfons Crespo – UPVLC (Spain)
Role: Provides expertise on embedded computing.

Professor Karl-Erik Årzén – LUND (Sweden)
Role: Provides expertise on real-time control.

Ass. Prof. Anton Cervin – LUND (Sweden)
Role: Provides expertise on real-time techniques.

Ass. Prof. Patricia Balbastre – UPVLC (Spain)
Role: Provides expertise on scheduling and real-time techniques

Prof. Martin Törngren – KTH (Sweden)
Role: Provides expertise in development methodology, co-design of control and computer systems.

Ass. Prof. Zdenek Hanzalek – CTU (Czech Republic)
Role: Provides expertise in co-design theory

.

1.2 Affiliated Participants and Roles

Alf Isaksson and Ulf Hagberg – ABB Corporate Research and ABB Automation Technology Products (Sweden)
Role: Provide feedback and input from the industrial automation sector.

Prof. Vladimir Havlena – Honeywell Prague Labs (Czech Republic)
Role: Provide feedback and input from the industrial automation sector.

Dr Jakob Axelsson – Volvo Car Corporation (Sweden)
Role: Provide feedback and input from the automotive sector.

Magnus Hellring – Volvo Technology (Sweden)
Role: Provide feedback and input from the automotive sector.

Joachim Stroop – dSpace (Germany)
Role: Provide feedback and input from the automation sector.

Klas Engwall – Maquet Critical Care (Sweden)
Role: Provide feedback and input from the medical equipment sector

1.3 Starting Date, and Expected Ending Date

The activity started September 1, 2004. This activity should provide techniques to improve the performances of real-time embedded control systems. The activity will run over the entire life-time of Artist2. Part of this work will also continue within the OS and scheduling cluster of ArtistDesign.

1.4 Baseline

Each of the core teams has a long tradition of research within real-time and embedded control. The work that is under development within this cluster is based on the work previously carried out by the partners in integrated control and scheduling methods, temporal robustness in control systems, methods for handling delays and jitter in control loops, component technologies for control systems, domain-specific languages and computational models, implementation-aware control system design, and real-time computing platforms for control applications.

1.5 Problem Tackled in Year 4

During the fourth year the main activity has been joint and individual research projects along the lines of the roadmap and research agenda developed during the first year. The specific research problems investigated are discussed in more depth in Section 2.4.

1.6 Comments From Year 3 Review

The comments were "*This is a quality document. No specific remarks.*" We have therefore continued along the same lines as last year.

2. Summary of Activity Progress

2.1 Previous Work in Year 1

Since this a rather new research area it was decided that the main integration activity during the first year should be the creation of a research roadmap. The aim of the roadmap was to chart the area, provide a common platform for the coming work, and to identify the most important research directions. The roadmap consists of approx 60 pages.

Another important integration activity was the International Workshop in Control for Embedded Systems was held in Lund with 20 participants. The international affiliates Lui Sha and Tarek Abdelzaher participated and gave value input. A separate research agenda for the work within Artist2 was written collectively as the output from the workshop.

A third important integration activity was the Valencia Graduate Course on Embedded Control Systems in April where all the cluster members lectured and the course material was developed jointly.

Additionally, a number of civilities have been performed.

- RTC 2005, a workshop on real-time control and control of real-time computing systems was organized in association with ECRTS 05 at Mallorca.
- An invited session on control over sensor networks and control of sensor network resources (co organized with RUNES) was accepted for the IEEE Conf on Decision and Control and the European Control Conference, Sevilla, Dec 2005.
- An invited session about the research in the cluster was organized at the IFAC World Congress, Prague, July 8.
- The IFAC Summer School on Control, Computing and Communication, Prague, June 27 – July 1 was co-organized by the cluster. A special session on Model Driven Engineering at Euromicro, Porto, August 30 – September 3 was organized by the cluster.
- A number of quality publications have been produced by the members of the cluster during the year. For example, Årzen and Cervin are co-authors of the RTSS 25 year anniversary article “Real-Time Scheduling: A Historical Perspective” (has appeared in the Real-Time Systems journal). Several of the cluster members are also authors of chapters in the recently published “Handbook of Networked and Embedded Control Systems” (Birkhäuser), with Årzén in the editorial board

2.2 Previous Work in Year 2

Achievement: Dissemination of Roadmap Material

The dissemination of the Roadmap on “Real-Time Control Techniques Implementation” has been performed in several conference papers and courses. However, the complete roadmap has yet not been disseminated. The second edition of the Embedded Control Systems Graduate Course held in Prague April 3-7 2006, provided the opportunity to deliver the Roadmap to the community and to extract the main issues in form of lectures. Additionally, several papers have been presented in different workshops and conferences.

Achievement: Scheduling and control co-design techniques

Two main activities have been developed under this main goal:

- Jitter reduction models
- Evaluation of different controller task models.

Jitter reduction models. In order to reduce the jitter in control systems several activities have been carried out:

- Probabilistic analysis of the response time of a control task. The response time probabilistic analysis is focused on calculate the response time distribution of a periodic task without simulating all over the hyperperiod (H). Some preliminary results have shown that the response time distribution in the interval [0,t] with t<H is very close (with a low error) to the response time of the task in [0,H]. This behaviour can be observed for any periodic system. However, the window [0,t] is different for every task set. The future work is focused on two ideas of how to find the parameter t:
  - Using relationships between temporal parameters of tasks (C,D,P). We have developed a method to calculate t that achieves a response time distribution very close to the total distribution with an error less than 0.25% and a reduction factor (t/H) of 74%.
  - Using statistical theory to calculate the size of the sample t that represents the population (H).
- Deadline minimisation. The deadline minimisation is used to strongly reduce jitter of control tasks, in a real-time control application. Task periods are usually set by the system requirements, but deadlines and computation times can be modified in order to improve system performance. Sensitivity analysis in real-time systems is focused on changes in task computation times, using fixed priority analysis. The aim of this work is to provide a sensitivity analysis for task deadlines in the context of dynamic-priority, pre-emptive, uniprocessor scheduling. This work permits to obtain a deadline minimisation method that achieves the maximum reduction. As undertaken in other studies concerning computation times, we also define and calculate the critical scaling factor for task deadlines.

Evaluation of different controller task models. A simulated system consisting of three independent plants with different initial parameters has been used to compare the performance when different methods to reduce the jitter are applied. The system is controlled by a computer with limited computational resources. So, a linear digital controller is designed for each plant. The three plants are implemented as real-time tasks such that the overall control performance is optimised. The methods compared are results of the partner's previous proposals as:

- STM: Typical task's model. Each task controls one pendulum.
- CO_US: Lund model.
- IMF: UPVLC model.
- ICOFU: Hybrid system between CO_US and IMF. Integrated model proposed by Lund and UPV.

Achievement: Control kernel

The control kernel deals with the essential control activities to guarantee the safe behaviour of the complete system. For this purpose, the control software can be arranged in different layers. At the level of the OS, activities to closing the loop and driving the system to a safe position should be included. At the top level, the control system may include several on-line controller options as well as supervising and optimising activities.

The functionalities of the Control kernel can be summarized as follows:

1) Ensuring control action (CA) delivering: the control action has to be delivered in time even if the calculated action for this period has not been updated. In this case, a backup control action or a safe control action based on previous data has to be delivered.

2) Data acquisition of major signals: Data is acquired based on the appropriate rate; delays on data acquisition cannot produce delays in the system. From this point of view, it is considered better a past data than a delayed data and no new control action computation is required (the previous control action computation is still valid.

3) Transfer to new control structure: Control system provides several regulators that can be used in different situations.

4) Communication facilities: Communications with external devices should be fully supported by the control kernel.

The work carried out has been focused in the definition of the parameters to define the platform support and the implementation of the control kernel.

Achievement: Operating system support for embedded systems

The development of specific services in the operating system for embedded control systems is one of the issues to be considered in this activity. These services include:

- Specific scheduling policies related to the proposed task model to minimise the output jitter.
- Control middleware which includes services to support the control kernel concept and functionalities.
- Supervisor to support several execution environments or domains
- Memory management in embedded systems with memory constraints.

Two main results have been obtained:

- XtratuM: It is a supervisor which permits to create different domains spatial and temporal isolated. Currently, a domain is based on control applications based on Partikle and the other one is Linux.
- Partikle: It is a new real-time kernel which includes specific services for control systems. The kernel concept has been implemented as a Control middleware.

Achievement: Developments in Sporadic Event-based control

Normally, controllers are designed assuming equidistant (periodic) sampling. This simplifies the design process greatly, since the sampled plant description becomes a linear time-invariant (LTI) discrete-time system (assuming that the continuous plant was also LTI). However, other sampling schemes could be beneficial. From a computing or network point of view, it makes sense to only sample or control when something significant has occurred in the system. In this work, we have investigated sporadic control of a first-order system, and compared the resulting performance and resource usage with ordinary periodic control and with aperiodic control which has been studied before by Lund. It is found that some performance can be gained even in the case where the sporadic controller is only allowed to sample more seldom than the periodic controller.

Achievement: Optimal on-line scheduling of multiple state feedback controllers

Digital controllers are usually designed as periodic tasks that regularly perform their sampling, computation, and actuation activities. In severely constrained systems, a better approach might be to only control one plant at a time. In this work, we have proposed a nonpreemptive on-line scheduling policy that uses the measured state of each plant when deciding which plant to control. Deriving the scheduling policy is very time-consuming but can be done off-line, using a technique called relaxed dynamic programming. We have also compared the nonpreemive on-line policy against common periodic schemes on a set of real laboratory processes. The results show that the new scheme can give large performance improvements while at the same time allowing the background tasks run when the need for control is small.

Achievement: Scheduling of control calculations on FPGAs

To facilitate the FPGA design process CTU works on scheduling algorithms using very universal model, 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 C_{max}, 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.

Achievement: Time-Delay compensation

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. The area of control of delayed systems has attracted the attention of many researchers in the past few years because delays may be responsible for instabilities in closed-loop control systems. In order to cope with these delays, a number of algorithms have been reported.

The algorithm proposed by UPVLC is a discrete-time controller based on state feedback using the prediction of the state. A convergence analysis shows that the state converges to the origin in spite of uncertainties in the knowledge of the plant parameters, the system delay and even variations of the sampling period. The proposed control scheme also has been satisfactory implemented to control the yaw displacement of a real four-rotor mini-helicopter. The experimental validation has been developed on an embedded system, MaRTE OS, which allows the implementation of minimum real-time systems according to standard POSIX.13 of the IEEE.

After these first results, we considered it would be also interesting to study the possibility to obtain some scheme in the framework Smith Predictor able to cope with unstable system and easy to implement in an embedded system. As a result it has been proposed a new scheme of prediction for discrete time systems, easy to implement, such as it is required by embedded system that allows any control both for stable or unstable systems. In the scheme proposed, the undelayed output of the plant is estimated by combining the outputs of both a finite impulse response (FIR) filter for the process input and a stable filter for the process output. Thus, the estimation is stable even for unstable plants. The proposed structure is analyzed in order to show the stability and robustness to control unstable plants with long delays. Robust performances to reject step load disturbances are also analyzed, and a refinement is introduced to improve the controlled plant robustness against disturbances. The proposed scheme, based on a New Smith Predictor (NSP), has been compared with other recently published works. It can be seen that it has better robustness and control performances to reject load disturbances.

The initially proposed output estimator does not work for non-minimum-phase plants, as the output filter becomes unstable. Thus, for unstable non-minimum-phase plants, the control problem is solved in two steps. First, the system is stabilized and then, a conventional SP is used to design the global control. One very important improvement over the previous methods is that, in any case, the tuning of the controllers is made by considering a free-delay model of the plant. This work has been performed in collaboration between UPVLC and LUND. Pedro Garcia has spent the two summers 2005 and 2006 in the control group at LUND.

2.3 Previous Work in Year 3

Achievement: Operating system and language support for embedded control systems

Embedded Control and Real-Time Java (LUND, ABB)

Lund has in collaboration with ABB and Sun investigated embedded controller implementation for industrial robots using Sun Java Real-Time System (RTS) 2.0. A motion control system and a robotics application have been implemented entirely in real-time Java for an ABB IRB 340 industrial robot, using standard computer hardware, off-the-shelf etherCAT servo drives, and the Sun JAVA RTS 2.0, running on Solaris 10. This new implementation of RTSJ introduces a new real-time garbage collector (RTGC) making it possible to access the heap for critical control applications. That allows a much cleaner system design, as the real-time and non-real-time parts of the application can share the same reference space. The RTGC implementation is based previous work done at LUND.

OS and Control Kernel Implementation (UPVLC)

This activity line is in charge of the implementation of the theoretical developments. The implementation concerns the operating system level (basic functionalities for embedded systems) and a control middleware (Control Kernel). At the operating system level, some services to improve the memory management including an integrated quality of service of CPU and memory have been proposed.

On the other hand, a middleware specially designed for control purposes and interacting with the peripherals (sensors, actuators and communication channels), with the OS, and exchanging information with the control algorithms implemented for different control loops in the application area in the same CPU has been designed and implemented.

This control kernel based on a middleware architecture provides to the control application basic features involving input/output, fault tolerance, relialability, etc.

Achievement: Scheduling and control co-design techniques (UPVLC, LUND)

Adjustment and analysis of periodic task parameters is one of the issues related to Real-Time Control in order to increase the control performance and reduce the system degradation. The parameters considered are

- Deadlines: The deadline minimization permits the reduction of the control task jitter. The aim of this work is to provide a sensitivity analysis for task deadlines in the context of dynamic-priority, pre-emptive, uniprocessor scheduling. The work permits a reduction of the deadline of a set of tasks maintaining system schedulability. Research considering period and deadline reduction in a coordinated way is ongoing.

- Computation: Feasibility tests for hard real-time systems provide information about the schedulability of the task set. However, this information is a yes or a no answer, that is, whether the task set achieves the test or not. From the real-time system design point of view, having more information available would be useful. This work provides methods to determine on-line how much a task can increase its computation time, by maintaining the system feasibility under a dynamic priority scheduling. The extra time can be determined not only in all the task activations, but in n of a window of m invocations.

- Variable execution time of task: The execution times of flexible control systems are affected by variables that originate in external environments, and this leads to a new class of task allocation problems. The use of histograms to analyse the execution distribution and propose methods for these systems based on stochastic processes has been considered. A deep analysis of the real-time tasks with high variability of its execution time has been performed.

Achievement: Automotive Embedded Control (CTU)

CTU has been working on how a multitasking automotive application running under a real-time operating system compliant with an OSEK/VDX standard can be modeled by timed automata. The applications under consideration consist of several non-preemptive tasks and interrupt service routines that can be synchronized by events. A model checking tool is used to verify time and logical properties of the proposed model. Use of this methodology is demonstrated on an automated gearbox case study and the result of the worst-case response time verification is compared with the classical method based on the time-demand analysis. It is shown that the model-checking approach provides less pessimistic results due to a more detailed model and exhaustive state-space exploration.

Further CTU has presented a hybrid Hardware-in-the-Loop (HIL) testing methodology based on both the discrete event system, given by timed automata, and the continuous systems, given by difference equations. The methodology is implemented using an FPGA platform. It guaranties not only the speed enhancement but also the time accuracy and extensibility with no performance loss. Compared to the operating system based platforms, the FPGA platform is able to achieve much faster sampling frequency. The FPGA implementation is generated while using Xilinx System Generator, bit exact toolbox for Matlab/Simulink and UPPAAL.

Achievement: Sporadic Event-based control (LUND)

The work on sporadic event-based control started during Year 2 has been continued by LUND. During Year 3 the focus has been on how delays, jitter and measurement noise effect the event-based approach and how load disturbances and limit cycles can be handled. LUND has also collaborated with Chenyang Liu at Washington Univ, St Louis on how these results can be used in the context of control of client-server systems. The idea is to apply event-based control theory to load control and end-to-end delay control in client-server systems. Viewing the collective workload from the clients as a Wiener process, the server should regulate the workload only when specified limits are exceeded. At the same time, each client should control its own end-to-end delay by a combination of local adaptation and requests to the server.

Achievement: Scheduling of control and signal processing calculations on FPGAs (CTU)

The work on off-line scheduling of control applications on architectures with pipelined processors by CTU presented above has continued also during this year. This work deals with a scheduling technique used to optimize computation speed of iterative algorithms running on architectures that may include pipelined dedicated processors. The problem under consideration is to find an optimal periodic schedule satisfying the timing constraints. Motivated by FPGA (Field-Programmable Gate Array) architecture we formulate a problem of cyclic scheduling on one dedicated processor where tasks are constrained by the precedence delays. Further we generalize this result to the set of dedicated processors. We also show how the set of constraints in both problems can be extended by start time related deadlines, multiprocessor tasks, changeover times and minimization of data transfers. We prove that this problem is NP–hard by reduction of Bratley’s scheduling problem 1|rj,dj|Cmax and we suggest a solution based on ILP (Integer Linear Programming) that allows one to minimize the completion time. Besides this, we suggest elimination of redundant constraints and binary variables in integer linear programming model which leads to a speedup of the scheduling algorithm. The experimental results are shown on an application of recursive least square filter and other control engineering benchmarks.

Further we extend this approach to iterative algorithms with matrix operations or nested loops. The method is demonstrated on an implementation of the Finite Interval Constant Modulus Algorithm. It is an equalization algorithm with QR-decomposition which is suitable for modern communication systems (4G and behind). Traditional approaches to the scheduling of nested loops lead to a relatively large code, which is unsuitable for FPGA implementation. Our methodology models both, iterative loops and imperfectly nested loops, by means of the system of linear inequalities. Moreover, memory access is considered as an additional resource constraint. Since the solutions of ILP formulated problems are known to be computationally intensive, an important part of this work is devoted to the reduction of the problem size. This method is also demonstrated on a synthesis of LQ controller.

Achievement: Time-Delay compensation (UPVLC, KTH, LUND)

The work on control of systems with delays started in Year 2 was continued by UPVLC. Control of systems with delays, by considering the option of stable/unstable and minimum/non-minimum-phase processes, is a challenging one and very relevant for networked embedded systems. Most of the existing solutions do not cover all the situations and, in any case, they lead to complex controllers. Simple controllers, easy to design and tune, are very important in the process industry. In this activity line, some control schemes have been proposed. Internal stability and robust stability analysis for these control structures have been studied. On the other hand, the study has been completed when scarce irregular measurements with time varying delays are present in the system. A model based predictor that takes into account the past measured outputs is used.]. KTH has utilized the jitter margin result developed by Lund in order to derive new simple tuning rules for PID controller subject to input-output latency.

Achievement: New results in Wireless Embedded Control and Automation (KTH, LUND, ABB, CTU)

Wireless networked control and estimation poses a multitude of new theoretical challenges caused by the unreliable and time-varying communication properties. KTH and Lund have been investigating the implications of this within the EU FP6 IP RUNES led by Ericsson and KTH and ABB are investigating these issues within the EU FP6 SOCRADES project. During the year KTH have done work on estimation over wireless sensor networks, predictive control over sensor networks], and distributed consensus. Lund has worked on localization and navigation techniques for mobile robots over sensor networks.

CTU and KTH have proposed an algorithm for optimal real-time routing in multi-hop communication networks for multi-source/multi-sink connection. The algorithm deals with various capacity constraints in terms of communication limits and real-time constraints expressed as deadline for each particular flow of data. The objective is to find the optimal routing in terms of energy consumption. The algorithm is based on a data flow model leading to Linear Programming formulation and therefore it ensures polynomial-time complexity. An extension handling simultaneous real-time and non real-time routing is added. We have shown an example of data collection from 100 nodes and performance experiments illustrating time complexity in dependence on the number of nodes.

Achievement: Embedded Control System Implementation Case Studies (CTU)

As case studies a number of challenging embedded control systems have been implemented. First, an open project, dealing with autopilot design for autonomous Unmanned Aerial Vehicles has been realized. Networked hierarchical distributed control system is used. Control algorithms, based on PI, LQG and SDRE approaches, focused on rotorcraft UAVs have been proposed, including a complex hierarchical autopilot design. Real data, measured during test-flights of an experimental UAV, have been presented and evaluated.

The second case study is an embedded control system for a biped walking robot, including hardware, basic software and control design. Primary goal achieved is a static walking with non-instantaneous double support phase and fixed trajectory in joint coordinates. The robot with two legs and no superior body is capable to walk with fixed, manually created, static trajectory using simple SISO proportional controller, yet it is extendable to use MIMO controllers, flexible trajectory, and dynamic gait. Distributed servo motor control over a CAN field bus is used. We solved interesting problems in the area of construction and kinematics, motor current cascaded control and field bus timing. The project is open with full documentation available.

2.4 Final Results

In many cases the technical achievements for Year 4 are continuations of work presented and described among the results of Year 3, i.e., in the previous section. Rather than repeating the same information we in those cases refer to the corresponding parts of the Year 3 section.

2.4.1 Technical Achievements

Achievement: Sporadic Event-Based Control of First-Order Systems (LUND)

Normally, controllers are designed assuming equidistant (periodic) sampling. This simplifies the design process greatly, since the sampled plant description becomes a linear time-invariant (LTI) discrete-time system. From a computing or network point of view, it makes sense to only sample or control when something significant has occurred in the system. In this line of work, we have continued our previous investigation of sporadic control of first-order stochastic systems. Firstly, we have analyzed how delay, jitter and measurement noise affect the performance of the control loops [21]. It is shown that the advantage of sporadic control over periodic control remains also in these cases. Secondly, we have looked into scheduling of multiple sporadic controllers on a shared communication medium, considering TDMA, FDMA and CSMA medium access methods [22]. It is shown that the combination of CSMA and event-triggered control gives the best performance.

Achievement: Limit Cycles in Event-Triggered Control Systems (LUND)

For higher-order system, the analysis of event-triggered control systems is more complicated. In this work, we have analyzed a certain control structure, involving a linear process, a threshold event detector, and a linear control signal generator. For a given constant disturbance acting on the system, it is possible to characterize the resulting limit cycle period (which corresponds to a certain resource utilization factor for the computing platform) [23]. We have also investigated how to introduce integral action in such a control system.

Achievement: Practical Implementation of an Event-Based PI Controller (LUND)

Traditional Linear Time Invariant (LTI) control design assumes that measurements are available at regular intervals and have the same kind of disturbance characteristics at all times. A common practical case that violates this assumption is the use of encoders that give quantized position measurements; when movement is slow, the quantization noise is far from LTI. In this work, we compare the implementation of a standard LTI controller and an event-based controller for a moving cart with quantized position measurements [24]. It turns out that with a bit of extra implementation work, the impact of quantization noise is drastically reduced. The controller is implemented in a small microcontroller and tested on the moving cart process.

Achievement: Suboptimal State Estimators for Systems with Event-Triggered Measurements (LUND, KTH)

In event-triggered control systems, a key question is how to generate process state estimates from intermittent observations. An optimal Bayessian observer requires on-line solution of nonlinear partial differential equations and is not feasible to implement except for very simple systems. In this line of work, we have developed suboptimal observers that combine standard Kalman filtering with nonlinear observers for set-bounded uncertainties [25]. The event-based characteristics of the measurements are modelled as uncertainty sets. In each time step, the uncertainty sets and the regular noise descriptions are combined and simplified, keeping the complexity bounded.

The work on event-based control was especially mentioned in the RQ-08 Quality Review of Research at Lund University performed during 2008. Toivo Henningsson will present his Licentiate thesis (Swedish half-way PhD thesis) on event-triggered estimation and control on November 28, 2008.

At KTH the work on event-based control has been focused on optimal stopping conditions for event-based estimation and control [10].

In relation to event-triggered control, Anton Cervin at LUND, Maben Rabi at KTH and Prof. Maurice Heemels at Eindhoven University of Technology put together an invited session proposal for the European Control Conference 2009, to be held in Budapest, Hungary. Among the invited authors are ARTIST members (Enrico Bini, Pisa) and ARTIST affiliates (Pau Marti and Manel Velasco, UPC). The other invited authors are from University of Notre Dame, University of Maryland, and University of California at Los Angeles.

Achievement: Time-Delay compensation (UPVLC, KTH, LUND)

The work on control of systems with delays started in Year 2 and 3 was continued by UPVLC and LUND. A new dead-time compensation scheme to control stable, integrative or unstable time-delay systems has been developed [8,38]. The approach has also been combined with a multi-rate observer scheme in order to control time-varying delay systems with measurement data loss, arising in, e.g., networked control [39]. The Universidad Nacional a Distancia (UNED), Spain and Universidad de Almeria, Spain are collaborating with UPVLC to integrate the controllers developed for analysis of time-delay systems with dead-time compensators in a Java-based tool. The work at KTH utilizing the the jitter margin result developed by Lund in order to derive new simple tuning rules for PID controller subject to input-output latency has resulted in [11].

Achievement: Operating system and language support for embedded control systems (UPVLC)

Control Kernel

In the framework of coordinated control systems, the concept of a control kernel, similar to the OS kernel, arises. The idea behind the control kernel is to determine the minimum controller code that must execute for any control task instantiation to ensure a safe operation of the controlled system, accepting the degrading of some performance and even the evolution to a safe shut-down.

The goal is to provide embedded systems with a high level of intelligence by means of the interaction with the environment and the communication among all components forming a solution based on embedded systems. This new level of intelligence must be compatible with fulfilling real-time restrictions of all control tasks.

This control kernel framework requires the design and implementation of efficient middleware for control purposes. An efficient implementation of this middleware has been completed. It was experimented in small control systems. Recently, it has been used as core of the biped robot control developed in the UPV labs. UPVLC collaborates with CUJAE (Instituto Superior

Politécnico José Antonio Echeverría) from La Habana (Cuba) in the implementation of the Control Kernel.

The control kernel work is published in [3,4,6].

Operating System Support

UPVLC continues the development of the PartiKle RTOS and the associated Xtratum hypervisor. The previous work on the PartiKLe real-time operating systems has been implemented on x86 processors. This development have also been ported to other architectures (ARM) to cover a widely range of platforms.

Hypervisor XtratuM is being redesigned to add security functions and is being ported to Sparc V8 processors. The Java port of PartiKle is done together with The Universidad de Colima (México). UPVLC also collaborates with The University of Lanzhou (China) on PartiKle and Xtratum.

Achievement: Scheduling and control co-design techniques (UPVLC)

This work is focused on finding the feasibility region of deadlines and periods (called D-P feasibility region) for a single task in the context of dynamic, uniprocessor scheduling of hard real-time systems. This works permits to choose the optimal deadline and period pairs that best fit application requirements. We provide an exact and an approximated algorithm to calculate this region [1]. We also show that the approximated solution is very close to the exact one and it takes considerably less time.

Achievement: Control of networked systems (UPVLC)

Heterogeneity in current systems, composed by networked multiple components with diverse characteristics, suggests the development of distributed control systems where the different control functions can be implemented at different levels. Whenever these configurations include elements with mobility (robots, vehicles…), the ability to obtain and process information, as well as to produce control actions, varies with time. Furthermore, the available resources from each element to perform assigned activities might be, at each moment, variable and limited. In this sense, there is a need to define a structure of hierarchical control, in order to assure that the actions with the maximum priority are executed at the local level and those other actions with lower priorities (coordination, optional duties, refinement), are assigned and executed at higher levels.

The challenge is the development of a modular control methodology design assuring performance maximization and stability, adaptability to the changing availability of resources within an interactive environment, and an autonomous and secure operation [5,7].

Particularly, the following aspects are considered:

- Interaction models in cyber-physical systems.
- Hardware – Software codesign under constraints.
- Middleware for the support of sensing and control.
- Development of robots with a specific sensorial capacity.
- Processor scheduling oriented to the execution of control tasks with a changing load.

Achievement: New results in Wireless Embedded Control and Automation (KTH, ABB, LUND, CTU)

The work on optimal flow routing in multi-hop sensor networks involving KTH and CTU reported last year has resulted in the joint publication [40]. The work in Lund on distributed estimation, localization and navigation techniques for mobile robots over sensor networks has also continued and led to the publications [26, 27] and the PhD thesis [28]. During the year KTH has been working on consensus algorithms for distributed control problems [9], hybrid model-predictive wireless networked control [12], state estimation [15, 19, 20], localization [16], optimal routing [17], outage compensation [18], and applications [14].

Achievement: Scheduling of control and signal processing calculations on FPGAs (CTU)

In this topic we followed the same objective as in previous years: to schedule the applications on the FPGA resources while minimizing the schedule length that resulted in several publications [29, 30, 34, 37]. This year we tackled larger problems while focusing on heuristic algorithms. We have implemented our own heuristics and evaluated their performance. The best one, inspired by so called Interval Modulo Scheduling, has very modest deviation from the optimal solution (less than 5%) while evaluated on small instances solvable by an ILP (up to 30 tasks). When written in C#, the heuristic was able to solve instances with 400 tasks in several minutes. Further we extended our model by additional resources in order to model availability of memory, buffers and registers whose time occupation is not known apriori.

Achievement: Automotive Embedded Control (CTU)

The work on verification of multi-tasking applications that was initiated during Year 3 has continued and led to the publications [31, 33, 36]. The work on a hybrid Hardware-in-the-Loop (HIL) tester tool has also continued. The work has focused on the implementation of a discrete event system, specifically timed automata into FPGA, and we have linked them with continuous systems implemented as filters in fixed point arithmetic. The paper [32] shows a methodology, which employs widely used tools (Matlab, UPPAAL) as a user interface, and which implements the FPGA based tester tool.

2.4.2 Individual Publications Resulting from these Achievements

UPVLC

[1] Patricia Balbastre, Ismael Ripoll, Alfons Crespo “Minimum Deadline Calculation for Periodic Real-Time Tasks in Dynamic Priority Systems”, IEEE Transactions on Computers, January 2008 (Vol. 57, No. 1) pp. 96-109

[2] A. Marchand, P. Balbastre, I. Ripoll, and A. Crespo, “Providing Memory QoS Guarantees for Real-Time Applications”, 14th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA 2008) Kaohsiung, Taiwan. August. 2008

[3] A. Fernández, M. Vallés, A. Crespo, P. Albertos , J. Simó. “Middleware for Control Kernel Implementation in Embedded Control Systems”, 17th IFAC World Congress. Seoul, Korea. July 6-11. 2008

[4] Adel Fernández Prieto, Marina Vallés, Alfons Crespo Llorente, Pedro Albertos Pérez, José Simó, Orestes Llanes-Santiago, “Implementation of the Control Kernel Middleware.” Workshop on Sensor Networks and Applications. Gramado, Brazil. September. 2008.

[5] V. Nicolau, M. Albero, J.F. Blanes, J.E. Simó. “Biped Robot Monitoring using a C.A.N. – WiFi Bridge”. 7th IFAC International Conference on Field buses and Networks in Industrial and Embedded Systems (FeT2007). Toulouse November 2007.

[6] R. Simarro, J. Coronel, J. Simó, J.F. Blanes, “Hierarchical and Distributed Embedded Control Kernel”, 17th IFAC World Congress. Seoul, Korea. July 6-11. 2008

[7] J.L. Posadas, J.L. Poza, J.E. Simó, G.Benet, F. Blanes, “Agent-based distributed architecture for mobile robot control”, Engineering Applications of Artificial Intelligence - ISSN: 0952-1976 (Journal). Date: 2008

[8] P. Garcia and P. Albertos., “A new dead-time compensator to control stable and integrating processes with long dead-time”. Automatica, Vol. 44, pp 1062-1071, April 2008.

KTH

[9] Björn Johansson, Tamas Keviczky, Karl H. Johansson and Mikael Johansson, Methods and Consensus Algorithms for Solving Separable Distributed Control Problems, Proceedings IEEE Conference on Decision and Control, December 2008. Submitted.

[10] Maben Rabi, Karl H. Johansson and Mikael Johansson, Optimal Stopping for Event-triggered sensing and actuation, Proceedings IEEE Conference on Decision and Control, December 2008. Submitted.

[11] Lasse M. Eriksson and Mikael Johansson, Simple PID tuning rules for varying time-delay systems, *Proceedings IEEE Conference on Decision and Control*, New Orleans, LA, pp. 1801-1807, December 2007.

[12] A. Bemporad, S. Di Cairano, E. Henriksson, and K. H. Johansson, Hybrid model predictive control based on wireless sensor feedback: an experimental study. In journal submission.

[13] Emmanuel Witrant, Pan Gun Park, Mikael Johansson, Carlo Fischione and Karl Henrik Johansson, Control over wireless multi-hop networks, Proc. of the IEEE Conf. on Control Applications, October 2007.

[14] E. Witrant, A. D’Innocenzo, G. Sandou, F. Santucci, M. D. Di Benedetto, C. Fischione, A. J. Isaksson, K. H. Johansson, S.-I. Niculescu, S. Olaru, L. Pomante, C. Rinaldi, E. Serra. and S. Tennina, Wireless ventilation control for large-scale systems: the mining industrial case. In journal submission.

[15] S. Di Cairano, K. H. Johansson, A. Bemporad, and R. Murray, Discrete and hybrid stochastic state estimation algorithms for networked control systems. In M. Egerstedt and B. Mishra, Ed., Hybrid Systems: Computation and Control, Lecture Notes in Computer Science. Springer-Verlag, 2008.

[16] J. Araujo, H. Sandberg, and K. H. Johansson, Experimental validation of a localization system based on a heterogeneous sensor network, IEEE ACC, Saint Louis, St. Louis, MO, USA, 2009. Submitted.

[17] L. Shi, K. H. Johansson, and R. M. Murray, Optimal sensor hop selection: sensor energy minimization and network lifetime maximization with guaranteed system performance, IEEE CDC, Cancun, Mexico, 2008. To appear.

[18] E. Henriksson, H. Sandberg, and K. H. Johansson, Predictive compensation for communication outages in networked control systems, IEEE CDC, Cancun, Mexico, 2008. To appear.

[19] H. Sandberg, M. Rabi, M. Skoglund, and Karl H. Johansson, *Estimation over heterogeneous sensor networks,* IEEE CDC, Cancun, Mexico, 2008. To appear.

[20] L. Shi, K. H. Johansson, and R. M. Murray, Estimation over wireless sensor networks: tradeoff between communication, computation and estimation qualities, IFAC World Congress, Seoul, Korea, 2008.

LUND

[21] Anton Cervin, Erik Johannesson: "Sporadic Control of Scalar Systems with Delay, Jitter and Measurement Noise". In Proc.17th IFAC World Congress, Seoul, Korea, July 2008.

[22] Anton Cervin, Toivo Henningsson: "Scheduling of Event-Triggered Controllers on a Shared Network." In Artist2 invited session at Proc. 47th IEEE Conference on Decision and Control, Cancun, Mexico, December 2008. To appear.

[23] Anton Cervin, Karl Johan Åström: "On Limit Cycles in Event-Based Control Systems." In Proc. 46th IEEE Conference on Decision and Control, New Orleans, LA, December 2007.

[24] Toivo Henningsson: "Comparison of LTI and Event-Based Control for a Moving Cart with Quantized Position Measurements". In submission to the European Control Conference, 2009.

[25] Toivo Henningsson: "Recursive State Estimation for Linear Systems with Mixed Stochastic and Set-Bounded Disturbances." In Proc. 47th IEEE Conference on Decision and Control, Cancun, Mexico, December 2008. To appear.

[26] Peter Alriksson, Anders Rantzer, "Experimental Evaluation of a Distributed Kalman Filter Algorithm", In Proceedings of the 46th IEEE Conference on Decision and Control, New Orleans, LA, December 2007.

[27] Peter Alriksson, Anders Rantzer, "Model Based Information Fusion in Sensor Networks", In Proceedings of the 17th IFAC World Congress, Seoul, Korea, July 2008.

[28] Peter Alriksson, "State Estimation for Distributed and Hybrid Systems", PhD thesis ISRN LUTFD2/TFRT--1084--SE, Department of Automatic Control, Lund University, Sweden, September 2008.

CTU

[29] Šůcha, P., Hanzálek, Z.: Deadline Constrained Cyclic Scheduling on Pipelined Dedicated Processors Considering Multiprocessor Tasks and Changeover Times. Mathematical and Computer Modelling. 2008, vol. 47, no. 9-10, p. 925-942.

[30] Šůcha, P., Hanzálek, Z.: Scheduling of a LQ Control Algorithm for Efficient FPGA Implementation, 17th IFAC WORLD CONGRESS, JULY 6-11, 2008, Seoul.

[31] Waszniowski, L., Hanzálek, Z.: Formal Verification of Multitasking Applications Based on Timed Automata Model. Real-Time Systems. 2008, vol. 38, no. 1, p. 39-65. ISSN 0922-6443.

[32] Krákora, J.,Hanzálek, Z.: FPGA based tester tool for hybrid real-time systems Microprocessors and Microsystems, Elsevier, article in press, doi:10.1016/j.micpro.2008.07.003

[33] Jan Krákora: Using Timed Automata for Verification, Testing and Scheduling in Distributed Systems, PhD thesis, Department of Control Engineering, Czech Technical University in Prague, Czech Republic, 2008.

[34] Kelbel, J. - Hanzálek, Z.: Constraint Programming Search Procedure for Earliness/Tardiness Job Shop Scheduling Problem. In Proceedings of the 26th Workshop of the UK Planning and Scheduling Special Interest Group. Praha: UK MFF, December 2007, p. 67-70. ISSN 1368-5708.

[35] Peca, M. - Sojka, M. - Hanzálek, Z.: Spejbl - The Biped Walking Robot. In Preprints 7th IFAC International Conference on Fieldbuses and networks in industrial and embedded systems. Toulouse: Universite Toulouse, November 2007, p. 63-70.

[36] Krákora, J. - Hanzálek, Z.: Optimization of Applications for FPGAs with PowerPC Processor Using Priced Timed Automata. In IEEE International Symposium on Industrial Electronics – ISIE 2008. Cambridge: Anglia Ruskin University, 2008, ISBN 978-1-4244-1666-0.

[37] Kelbel, J. - Hanzálek, Z.: Feeder Setup Optimization in SMT Assembly. In Proceedings of the 21st International FLAIRS Conference. Menlo Park, California: AAAI Press, 2008, p. 575-576. ISBN 978-1-57735-365-2.

2.4.3 Interaction and Building Excellence between Partners

Integration and excellence building among the partners have been implemented in several different ways. The following is a list of the major collaborations between partners in the Control in Real-Time Computing activity which has contributed to creation of excellence between partners.

- All partners have jointly organized and participated in our Embedded Control Graduate School. This year we had 34 participants, mainly European PhD students but also industrial participants from Scania and Hyundai Heavy Industries, The feedback from the students was again very positive. In addition to presentation by the core cluster members, industrial presentations were given from Scania, ABB, Ericsson, and Swedish Space Corporation. A separate report is available with conclusions and evaluation.
- All partners have participated in the workshop “Embedded Control Systems: From Design to Implementation” organized by the cluster in association with the IFAC World Congress, Seoul, Korea, 6 July, 2008.
- The partners interact through the Bridgit embedded control benchmark repository. This year the interaction has primarily involved LUND and CTU. The helicopter project provided by CTU has been used in a project course at LUND during Spring 2008.
- CTU and KTH also collaborate on wireless networking. ABB and KTH collaborate on wireless automation within SOCRADES.
- UPVLC and Lund collaborate on compensation for time delays. This has resulted in one joint publication.
- The development of a common framework for control and scheduling co-design is something that unites, in particular, Lund and UPVLC. However, UPVLC and CTU also work on these issues within the FRESCOR context.
- ABB and Lund have a long history of collaboration on embedded control in industrial robotics. During this year this has resulted in a new FP7 project ROSETTA that has been accepted.
- Lund and KTH are both working on event-based control and are currently co-organizing a joint invited session on this.

2.4.4 Joint Publications Resulting from these Achievements

[38] J.L. Guzman, P. Garcia, T. Hägglund, S. Dormido, P. Albertos, M. Berenguel. "Interactive tool for analysis of time-delay systems with dead-time compensators", *Control Engineering Practice,* **16:7**, pp. 824-835, 2008.

[39] Angel Cuenca, Pedro Garcia, Karl-Erik Årzén, Pedro Albertos, "A Predictor-Observer for a Networked Control Systems with Time-Varying Delays and Non-Uniform Sampling", In preparation for submission to European Control Conference, 2009.

[40] Jiri Trdlicka, Zdenek Hanzalek, Mikael Johansson: Optimal Flow Routing in Multi-hop Sensor Networks with Real-Time Constraints through Linear Programming. 12th IEEE Conference on Emerging Technologies and Factory Automation, September 25-28, 2007 Patras.

2.4.5 Keynotes, Workshops, Tutorials

The members of this activity given four keynotes or plenary addresses, organized one tutorial session, organized one international workshop, one national workshop, and four summer school or graduate courses.

Keynote: P. Albertos (UPVLC) "New Control Challenges in the Design of Embedded Control Systems." **Location:** Plenary session in IEEE Multi-conference on Systems and Control, Singapore, October 1-3, 2007

Keynote: Karl Henrik Johansson (KTH)
Location: 6th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Berlin, Germany, March 31-April 4, 2008

Invited Lecture: Karl Henrik Johansson (KTH)
Location: Tutorial Session on Communication Challenges in Networked Control Systems, American Control Conference, Seattle, USA, 2008

Workshop: "Embedded Control Systems: From Design to Implementation", All cluster members.
Location: In association with the IFAC World Congress, Seoul, Korea, 6 July, 2008

Workshop: DataFlow Modeling for Embedded Systems, LUND and Ericsson together with members from the ART cluster.
Location: Pisa, 5 May, 2008

Workshop: ACCESS Industrial Workshop, 13 March, 2008, KTH 150 participants. Several speakers and participants from Artist2

Workshop: EU-US Workshop, 16 June 2008, at KTH, Stockholm. The aim of the workshop was to gather key researchers from academia and industry to discuss research challenges and emerging industrial trends on next generation networked embedded systems. About 50 participants. Several speakers and participants from Artist2.

Workshop: Feednetback Workshop on Networked Control, 25 Sep 2008, KTH. 40 participants from KTH, UNIPD, Seville, Grenoble.

Workshop: "Embedded Control Systems: From Design to Implementation", in association with the IFAC World Congress, Seoul, Korea, 6 July, 2008. All cluster members.

Summer School: Fourth Artist2 Graduate School on Embedded Control Systems. All cluster members
Location: KTH, May, 2008

Summer School Participation: Four lectures at the ARTIST2 Summer School in Autrans 8-12 September, 2008 were initiated and/or given by the cluster. The presentations were a keynote by Karl Johan Åström, Lund and three presentations by Karl-Erik Årzén and Pedro Albertos, Tarek Abdelzaher (UIUC), and Steve Vestal (Honeywell).

3. Milestones, and Future Evolution Beyond the NoE

3.1 Milestones

The milestones for year 4 as defined in the previous activity report were as follows.

- Finalize and disseminate the common codesign framework model. At least one joint major publication summarizing this work should be generated. *Partly achieved. Dissemination at workshops and conferences achieved. Rather than writing a joint publication the aim has shifted to instead focus on developing joint course material for the graduate school organized for this. A common Wiki has been set up for this purpose and the goal is to have this available before the next edition of the course in spring 2009 within ArtistDesign*
- Organization of the Fourth Graduate School on Embedded Control Systems during Spring 2008. *Achieved.*
- Disseminate the total amount of work done within this activity at Artist organized events. *Achieved.*
- Add at least two additional benchmarks to Bridgit. *Partly achieved. Only one additional benchmark has so far been added.*
- 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. *Achieved*.

3.2 Indicators for Integration

The work within this activity ends the current year. The part focused on integrated control design and scheduling will continue within the Operating Systems and Networks cluster in ArtistDesign where Lund is a core partner and UPVLC and CTU are affiliated partners. In this cluster also SSA/Pisa, Aveiro, and UPC have similar interests. The work performed by the control group at KTH will most likely not be continued within ArtistDesign. However, the work and the collaborations will continue anyway within the context of other national and European projects.

There are also other connections between the partners that will ensure that the networking continues. For example, Anton Cervin of Lund has been invited to give a course on event-based control at UPVLC in summer 2009. The successful annual graduate course on embedded control will also continue, now within the scope of ArtistDesign and with contributions from additional partners.

There are two indicators for integration:

- A successful continuation and further development of the graduate course. This includes further course material development.
- Continued joint work (publications, project proposals, etc) on integrated control and scheduling with the partners in the Operating Systems and Networks cluster in ArtistDesign.

3.3 Main Funding

The partners have a good funding situation for the coming years. The main sources are:

- Nationally funded projects. These include
  - Lund: The large 10 year VR Linneaus center “LCCC – Controlling Complex Engineering Systems”. The VINNOVA project “Feedback Based Resource Management and Code Generation for Soft Real-Time Systems”. The VR projects “Control of Server Systems” and “Periodic and Event-Based Control over Networks”.
  - KTH: The large 10 year VR Linneaus center ACCESS. The VINNOVA projects reSENSE, WISA II, NECS and SERAN. The VR projects Wireless Control and CoopNets. The Rembrant project together with Scania and Chalmers. The SSF projects NEC and IDIOM. KTH has also created ICES – Innovative Centre for Embedded Systems where among others ABB, Ericsson, Scania, and Enea participate.
  - UPVLC: SIDIRELI: Sistemas distribuidos con recursos limitados. Núcleo de control y coordinación funded by the Ministerio de Ciencia y Tecnología. RT-Model: Plataformas de tiempo real para diseño de sistemas empotrados basado en modelos funded by the Ministerio de Ciencia y Tecnología.
  - CTU: Centre for Applied Cybernetics (CAK) funded by the Ministry of Education of the Czech Republic. Modular FLY-BY-WIRE Control System for Light Aircraft (Aero) funded by the Ministry of Industry and Trade of the Czech Republic.
- European projects. The European projects where the partners participate are the following: ArtistDesign (Lund, KTH, UPVLV (affiliated), CTU (affiliated)), SOCRADES (KTH, ABB), WIDE (KTH, Honeywell), FeedNetBack (KTH), ACTORS (Lund), CHAT (Lund), AEOLUS (Lund), DIAdvisor (Lund), ATESST II (KTH, Volvo Cars, Volvo Technology), DySCAS (KTH, Enea, Volvo Technology), ROSETTA (Lund), Euro-NF (KTH), VIKING (KTH), TECOM/ITEA-2 (UPVLC). Part of these projects as are projects that have been accepted but not yet started. KTH is also a member of the ARTEMIS proposal CESAR - Cost-Efficient Methods and Processes for Safety Relevant ES coordinated by Airbus.

3.4 Future Evolution Beyond the Artist2 NoE

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

4. Internal Reviewers for this Deliverable

Gerhard Fohler, TUKL
Zdenek Hanzalek, CTU