ARTIST 2

Network of Excellence

IST-004527 ARTIST2:
Embedded Systems Design

Activity Progress Report for Year 2

JPRA-Cluster Integration

Real-Time Techniques in Control System Implementation

Clusters:

Control for Embedded Systems

Activity Leader:

Professor Alfons Crespo (Universidad Politécncia 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 second year of the network.

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1. Overview of the Activity

1.1 ARTIST2 Participants: Expertise and Roles

Professor Pedro Albertos – UPVLC (Spain)
control systems.

Professor Alfons Crespo – UPVLC (Spain)
embedded computing.

Professor Karl-Erik Årzén – LUND (Sweden)
real-time control.

Ass. Prof. Anton Cervin – LUND (Sweden)
real-time techniques.

Ass. Prof. Patricia Balbastre – UPVLC (Spain)
scheduling and real-time techniques

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

Ass. Prof. Zdenek Hanzalek – CTU (Czech Republic)
co-design theory

1.2 Affiliated Participants: Expertise and Roles

Göran Arinder – ABB Automation Technology Products (Sweden)
feedback and input from the industrial automation sector.

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

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

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

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

Klas Engwall – Maquet Critical Care (Sweden)
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 the network, and most likely also continue after the termination of Artist2.

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 Year2

During the second year the main activity has been joint and individual research projects along the lines of the the roadmap and research agenda developed during the first year. The specific research problems investigated are discussed in more depth in Section 2.2.

1.6 Comments From Previous Review

1.6.1 Reviewers' Comments

The reviewers' comments regarding last years deliverables from the cluster were as follows: *Four deliverables were due from this cluster at the end of Y1:*

- *Deliv-JPIA-a-Control-Y1*
- *Deliv-JPRA-NoE Integration-c-Y1 (this cluster's contribution as planned in the DoW.)*
- *Deliv-JPRA - Cluster Integration – Control for Embedded - a -Y1*
- *Deliv-JPRA - Cluster Integration – Control for Embedded - b -Y1*

The deliverables were of uniformly excellent quality. The deliverable documents themselvesdescribed the problem to be addressed, the current state of the art, what was achieved using ARTIST2 funds in the past year, and natural integrative next steps for the coming 12/18 months. Where Roadmaps (or other collateral documents) were developed as part of a particular task, such documents were succinctly summarized in the deliverable, with pointers to the more complete document for the interested reader.

The specific comments related to this activity were as follows: "*This task is focused on advancing the state of the art in applying real-time system methodology for embedded control system implementation. The primary work items for Y1 were the creation of a research roadmap for this research area and development of course material for a graduate course in Embedded Control Systems. The key outcomes of the roadmap exercise and the graduate course are succinctly summarized in the deliverable document; the roadmap and a summary of the graduate course are provided as separate documents associated with this deliverable."*

1.6.2 How These Have Been Addressed

Since the reviewer's were very positive we have tried to continue along the same lines as previous year. 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. Hopefully this can be held during Year3.

2. Summary of Activity Progress

2.1 *Previous Work*

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 *Current Results*

2.2.1 *Technical Achievements / Outcomes / Difficulties encountered*

- **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.

Output from Achievement: Dissemination of Roadmap Material
The special session organised at *IEEE Computer-Aided Control Systems Design Symposium CACSD 2006*, with several papers *[1], [6],*

Difficulties with Achievement: Dissemination of Roadmap Material
No difficulties encountered.

- **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 analysys 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 partners 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.

Output from Achievement: Scheduling and control co-design techniques
Publications [1], [2], [3], [4], [11] and [12].

Difficulties with Achievement: Scheduling and control co-design techniques
A PhD student (Manuel Lluesma) from UPVLC who was working in these aspects left the University. A new student had to start with this topic..

- ## 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 can not 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.

Output from Achievement: Control kernel
Publications [5], [6], [7], [8], [9] and [10].

Difficulties with Achievement: Control kernel
None

- ## 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.

Output from Achievement: Operating system support for embedded systems
The publications [13] and [14].

Difficulties with Achievement: Operating system support for embedded systems
No difficulties encountered.

- ### 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 occured 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.

Output from Achievement: Developments in Sporadic Event-based control
The publication [17]

Difficulties with Achievement: Developments in Sporadic Event-based control
No difficulties encountered.

- ### 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.

Output from Achievement: Optimal on-line scheduling of multiple state feedback controllers
The publication [18]

Difficulties with Achievement: Optimal on-line scheduling of multiple state feedback controllers
No difficulties encountered.

- **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.

Output from Achievement: Scheduling of control calculations on FPGAs
The publication [19,20,21]

Difficulties with Achievement: Scheduling of control calculations on FPGAs
No difficulties encountered.

- **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.

Output from Achievement: Time-Delay Compensation
The publications [8,9]

Difficulties with Achievement: Time-Delay Compensation
No difficulties encountered.

2.2.2 Publications Resulting from these Achievements

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] Anton Cervin, Karl-Erik Årzén, Dan Henriksson, Manuel Lluesma Camps, Patricia Balbastre, Ismael Ripoll, Alfons Crespo. Control Loop Timing Analysis using TrueTime and Jitterbug. In *Proceedings of the 2006 IEEE Computer-Aided Control Systems Design Symposium,* October 2006. Accepted for publication.

[2] Manuel Lluesma Camps, Anton Cervin, Patricia Balbastre, Ismael Ripoll, Alfons Crespo. Jitter Evaluation of Real-Time Control Systems. In *Proc. 12th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications,*Sydney, Australia, August 2006.

[3] Anton Cervin, Johan Eker. The Control Server Model for Codesign of Real-Time Control Systems. In Hans Hansson (Eds.): *ARTES – A network for Real-Time research and graduate Education in Sweden 1997–2006,* Department of Information Technology, Uppsala University, Sweden, March 2006.

[4] Anton Cervin, Johan Eker. Control-Scheduling Codesign of Real-Time Systems: The Control Server Approach. *Journal of Embedded Computing,* **1:2**, pp. 209--224, 2005.

[5] P. Albertos, A. Crespo , Jose Simo. "Control Kernel: a Key Concept in Embedded Control Systems" 4th IFAC Symposium on Mechatronic Systems 2006.

[6] A. Crespo, P. Albertos, P. Balbastre, M. Vallés, M. Lluesma and J. Simó. Schedulability issues in complex embedded control systems IEEE International Conference on Control Applications October 4-6, 2006

[7] Garcia, P. and Castillo, P. and Lozano, R. and Albertos P. Robustness with respect to delay uncertainties of a predictor-observer based discrete-time controller. 45th IEEE Conference on Decision and Control Dec. 13-15, (San Diego, USA) 2006

[8] Garcia, P. and Albertos, P. and Hagglund. T. Control of unstable non-minimum-phase delayed systems. Journal of Process Control (in press).

[9] Garcia, P. and Albertos, P (2007) A simple dead-time compensator to control stable and integrating processes with dead-time. In submission

[10] Garcia P., Albertos P, Hägglund T. Control of unstable non-minimum phase delayed systems. Accepted for publication in Journal of Process Control.

[11] Patricia Balbastre, Ismael Ripoll and Alfons Crespo. Optimal Deadline Assignment for Periodic Real-Time Tasks in Dynamic Priority Systems. 18th Euromicro Conference on Real-Time Systems (ECRTS 06) Dresden, Germany July 5-7, 2006

[12] Patricia Balbastre, Ismael Ripoll, Alfons Crespo. Analysis of window-constrained execution time systems. Accepted for publication in Journal of Real-Time Systems

[13] A. Crespo, I. Ripoll, M. Masmano. Dynamic Memory Management for Embedded Real-Time Systems . IFIP Working Conference on Distributed and Parallel Embedded Systems. Braga, Portugal. October 11-13, 2006

[14] M. Masmano, I Ripoll, A. Crespo. A Comparison of Memory Allocators for RealTime Applications. The 4th International Workshop on Java Technologies for Real-time and Embedded Systems - JTRES 2006 11-13 October 2006. Paris, France

[15] A. Crespo. A. Alonso. Una Panorámica de los Sistemas de Tiempo Real. Revista Iberoamericana de Automática e Informática Industrial. Vol. 3, Núm. 2, Abril 2006

[16] P. Balbastre, M. Lluesma, I. Ripoll. Análisis y Compensación de los Retardos de Planificación en Sistemas de Control. Revista Iberoamericana de Automática e Informática Industrial. Vol. 3, Núm. 2, Abril 2006

[17] Toivo Henningsson, Anton Cervin. Event-Based Control over Networks: Some Research Questions and Preliminary Results. In *Proc. Reglermöte 2006,* Stockholm, Sweden, May 2006.

[18] Anton Cervin, Peter Alriksson. Optimal On-Line Scheduling of Multiple Control Tasks: A Case Study. In Proceedings of the 18th Euromicro Conference on Real-Time Systems, Dresden, Germany, July 2006.

[19] Premysl Sucha, Zdenek Hanzalek, Antonin Hermanek, Jan Schier. Scheduling of Iterative Algorithms with Matrix Operations for Efficient FPGA Design, Implementation of Finite Interval Constant Modulus Algorithm, The Journal of VLSI Signal Processing, Springer, accepted for publication

[20] Premysl Sucha, Zdenek Hanzalek. Scheduling of Tasks with Precedence Delays and Relative Deadlines, Framework for Time optimal Dynamic Reconfiguration of FPGAs. In IEEE International Parallel & Distributed Processing Symposium. New York: IEEE Press, 2006, s. 170. ISBN 1,4244,0054,6

[21] Zdenek Pohl, Premysl Sucha, Jiri Kadlec, Zdenek Hanzalek. Performance Tuning of Iterative Algorithms in Signal Processing. In International Conference on Field Programmable Logic and Applications (FPL). Toronto: IEEE, 2005, s. 404,412. ISBN 0,7803,9362,7.

3. Future Work and Evolution

3.1 Problem to be Tackled over the next 18 months (Sept 2006 – Feb 2008)

The nature of NoEs makes it difficult to give any hard guarantees with respect to which type of technical work that will be done during the next year. Some of the topics that we aim to pursue are studies of the fundamental trade-offs that exist between sampling rates, delays, and jitter in networked control, event-triggered feedback control, future development of the control kernel concept, server-based implementation methods for control systems, optimization-based scheduling, and the definition of a common framework for the interaction between controllers and the underlying OS-middleware-hardware layer.

An important issue that is common to all the cluster activities is the organization of a follow-up workshop to the Lund Workshop on Control for Embedded Systems. This is planned for the early spring 2007.

Another important item for this activity is the annual Graduate School on Embedded Control Systems. The coming year it will be hosted by LUND (May 2007). This time our aim is to have two parallel tracks during the first day of the course: one for students with a control background and one for students with a computer science background.

3.2 Current and Future Milestones

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:

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

3.3 Indicators for Integration

Joint research work indicated by joint high-quality publications, mobility of team members among the teams, and jointly organized workshops and sessions.

3.4 Main Funding

The main sources of funding for this work are:

- Nationally funded projects. For the Swedish partners these include FLEXCON, SAVE, SAVE++ and various projects funded by the Swedish Research Council. For UPVLC this includes the KESTREL project. For the partners from other countries the situation is similar.

- EU projects. The following are examples of currently running EU projects that to some extent cover these acivities: RUNES, SOCRADES, ATESST, DYSCAS, CEMACS, and FRESCOR.

3.5 Internal Reviewers for this Deliverable

Zdenek Hanzalek, CTU

Karl-Erik Årzén, LUND