INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team NeCS

Networked Control Systems

Grenoble - Rhône-Alpes

THEME NUM

Activity Report

2007

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1. Team

NeCS is a joint project-team with GIPSA-lab (CNRS, INPG and UJF).

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2. Overall Objectives

2.1. Introduction

The NeCS project-team goal is to develop a new control framework for assessing problems raised by the consideration of new technological low-cost and wireless components, the increase of systems complexity and the distributed and dynamic location of sensors (sensor networks) and actuators. In this framework, control design is performed under general resources constraints including communication, computation, and energy. In that, the team targets an innovative step forward in the feedback design for networked controlled distributed systems by the development of combined control, computing & communication co-design. The project-team is a bi-located at INRIA (Montbonnot) and at the GIPSA-LAB (at the Grenoble campus).

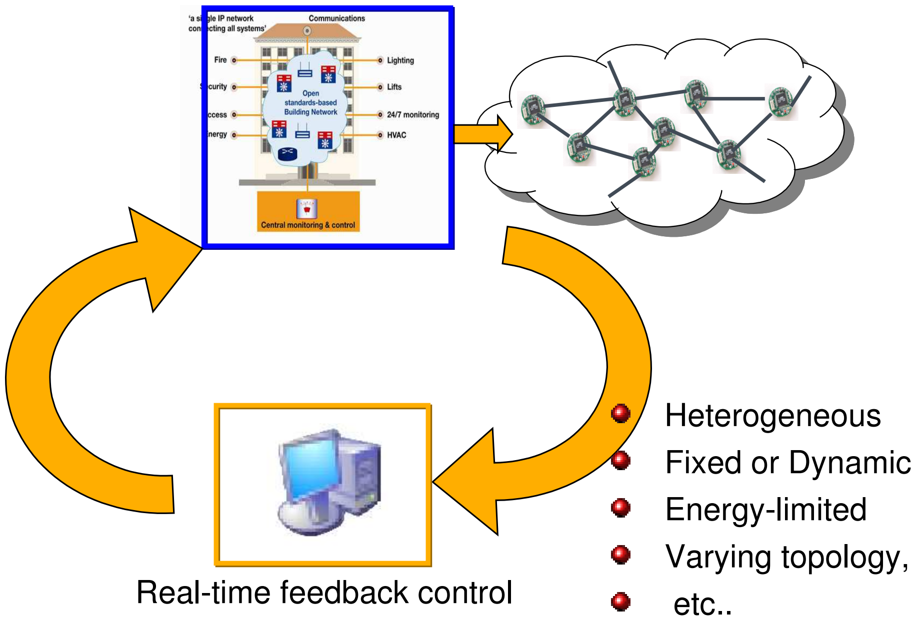

Figure 1. Overview of NeCS systems

The field of Networked Controlled Systems (NCS) refers to feedback systems controlled *over* networks, as shown in Fig 1. These systems result from the arrival of new control problems posed by the consideration of several factors, such as: new technological components (i.e. wireless sensors, RF communications, adhoc networks, etc.), increase of systems complexity (i.e. increase in vehicle components), the distributed location of sensor and actuator, and computations constraints imposed by their embedded nature (i.e. embedded systems, and systems on-chip). In this system class, the way that the information is transferred and processed (information constraints), and the manner in which the computation/energy resources are used (resources management), have a substantial impact in the resulting stability and performances properties of the feedback controlled systems. Inversely, the already designed feedback system, can be affected by the properties of the channel transmission (latency, delay jitter, lost of data, etc.), and the way that the computational and energy resources are used.

2.2. Highlights of the year

During the first year of existence of the NECS project-team (officially created on January 1, 2007) its members succesfully kept up the efforts towards external collaborations and funding which were initiated during the project creation phase, leading to two national and one european new contracts :

- CONNECT has been elected for funding by the ANR and started in May (8.1.2);
- ARAVIS started in October, in the framework of the Minalogic pole (7.1);
- Finally, last but not least, the FeedNetBack proposal as been elected for funding as a STREP project by the European Commission in December for an expected start by mid-2008 (8.2).

3. Scientific Foundations

3.1. Multi-disciplinary nature of the project

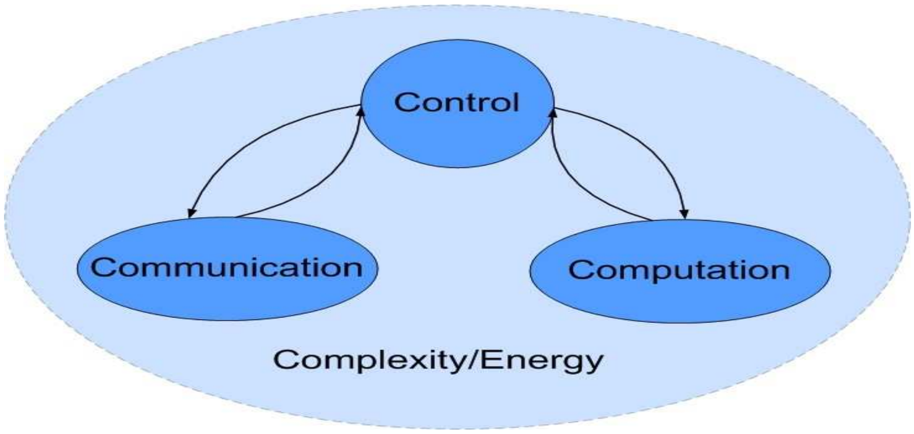

Figure 2. Relation of the NCS area with the fields of: Control, Communication, Computation.

The project propose to investigate problems in the area of NCS with the originality of integrated aspects on computation, communication and control. The combination of these three disciplines requires the interplay of the multi-disciplinary fields of: communication, real-time computation, and system theory (control). Figure 2, shows the natural interaction between disciplines that concern the NeCS project. The arrows describe the direction in which these areas interact, i.e.

(a) *Control in Communication*

(b) *Communication in Control*

(c) *Computation in Control*

(d) *Control in Computation*

Complexity and energy-management are additional features to be considered as well. Complexity here refers to the problems coming from: wireless networks with varying interconnection topologies, multi-agent systems coordination, scale of the number of sensors, etc. Energy management concerns aspect related to the efficient handling of energy in wireless sensors. That is the efficient may to send information, and perform computations.

3.1.1. (a) Control in Communication.

This area concerns more control applications where control methods are used to solve problems found in the communication field. Examples are: the Power control in cell telephones, and the optimal routing of messages in an Internet networks.

3.1.2. (b). Communication in Control.

This area concerns problems where communication and information theory interacts with system theory (control). A typical scheme of a networked controlled system (NECS) is shown in Fig. 3. As an example, of a classical paradigm we can mention the stabilisation problem under channel (communications) constraints. A Key result here [47] was to show that it was generically impossible to stabilise a linear system in any reasonable sense, if the feedback channel's *Shannon classical capacity* C was smaller than the sum of the logarithms, base 2, of the unstable eigenvalues. In other words, in order to be able the stabilisation problem under communication constraints, we need that

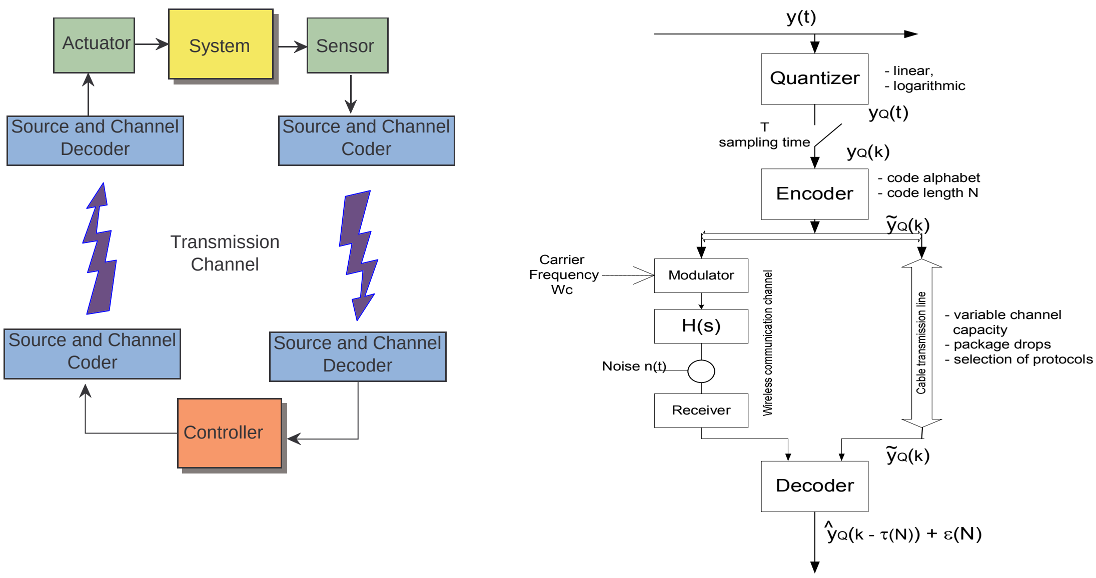

Figure 3. Block diagram of a networked controlled system. General closed-loop configuration (left), details of the transmission path (right)

$$C > \sum_i \log_2 \lambda_i$$

where the $\lambda_i's$ are unstable eigenvalue of the open loop system. Intuitively, this means that rate of information production (for discrete-time linear systems, the intrinsic rate bits/time equals $\sum_i \log_2 \lambda_i$) should be smaller than the rate of information that can be transmitted throughout the channel. In that way, a potentially growing signal can be cached out, if the information of the signal is send via a channel with fast enough transmission rate. In relation to this, a problem of interest is the coding and control co-design. This issue is motivated by applications calling for data-compression algorithms aiming at reducing the amount of information that may be transmitted throughout the communication channel, and therefore allowing for a better resource allocation and/or for an improvement of the permissible closed-loop system bandwidth (data-rate).

3.1.3. (c) Computation in Control.

This area concerns the problem of redesigning the control law such as to account for variations due to the resource allocation constraints. Computation tasks having different levels of priority may be handled by asynchronous time executions. Hence controller need to be re-designed as to account for non-uniform sampling times resulting in this framework. Question on how to redesign the control laws while preserving its stability properties are in order. These category of problems can arise in embedded systems with low computation capacity, or lows level resolution.

3.1.4. (d) Control in Computation.

The use of control methods to solve or to optimise the use of computational resources is the key problem in this area. This problem is also known as a scheduling control. The resource allocations are decided by the controller that try to regulate the total computation load to a prefixed value. Here, the "system" to be regulate is the process that generated and used the resources, and not any physical system. Hence, internal states are computational tasks, the control signal is the resource allocation, and the output is the period allowed to each task.

3.1.5. (c + d) Integrated control/scheduling co-design

Control and Computation co-design describes the possibility to study the interaction or coupling between the flows (c) and (d). It is possible, as shown in Figure 4, to re-frame both problems as a single one, or to interpret such an interconnection as the cascade connection between a computational system, and a physical system.

In our framework the feedback scheduling is designed w.r.t a QoC (Quality of Control) measure. The QoC criterion captures the control performance requirements, and the problem can be stated as QoC optimisation under constraint of available computing resources. However, preliminary studies suggest that a direct synthesis of the scheduling regulator as an optimal control problem leads, when it is tractable, to a solution too costly to be implemented in real-time [31]. Practical solutions will be found in the currently available control theory and tools or in enhancements and adaptation of current control theory. We propose in Figure 4 a hierarchical control structure : besides the usual process control loops we add an outer control loop which goal is to manage the execution of the real-time application through the control of the scheduling parameters of the inner loops. Together with the outer loop (working on a periodic sampled time scale) we also need a scheduling manager working on a discrete events time scale to process exception handling and admission control.

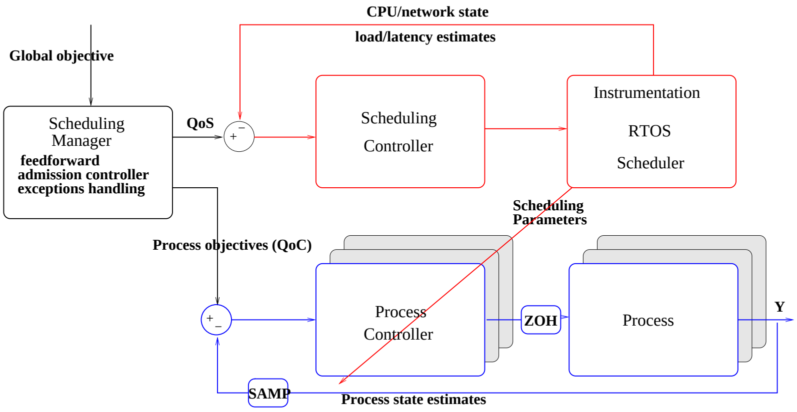

Figure 4. Hierarchical control structure.

The task periods directly affect the computing load, they have been chosen as actuators. They can be implemented through software variable clocks. As timing uncertainties cannot be avoided and are difficult to model or measure, we currently design robust control algorithms using the H_∞ control theory, which have been successfully simulated and experimentally validated [4].

This methodology is supported by ORCCAD where a run-time library for multi-rate multitasking has been developed and integrated. It will be further improved using a QoS-based management of the timing constraints to fully benefit from the intrinsic robustness of closed-loop controllers w.r.t. timing uncertainties.

3.2. Main Research Directions

The main objective of the project is to develop a unified control, communication, computing co-design methodology explicitly accounting for all the components involved in the system controlled over a network . This includes quantifier properties, scheduling parameters, encoder/decoder, alphabet length, bandwidth of the transmission media (wire or wireless), delays, resource allocation, jitter, etc...

These components, including the control laws, should be designed so as to optimise performance/stability trade-offs resulting from the ceiling of the computing resources, the channel capacity limitations and the quality of the send/received information protocols.

In short the project is centred along the following 3 main axis:

1. **Control under Communications Constraints.** One well established topic along this axis concerns the coding and control co-design. That is, the design of new code alphabets simultaneously than the design of the control law. Or equivalent, the ability of designing codex containing information pertained to the system model and the control law. The objective being the improvements of the overall closed-loop performances. Besides this matter, additional improvements pertain to the field of the information theory are also in order.
2. **Control under Computational resources constraints.** The main objective here is the design of control loops by explicitly accounting for the network and/or the computing resources. Dynamics allocation of such a resources depends on the desired controlled systems specifications. Keys aspects to be considered are: the design of controllers with variable sampling time, the robustness with respect time uncertainties such as the input/output latencies, the global control of resources and its impact over the performance and the robustness of the system to be controlled. We aim to provide an *integrated control and scheduling co-design* approach [5].
3. **Controlling Complexity** Design and control of partially cooperative networked (possible also multi-agent)systems subject to communication and computational constraints. Here, a large number of entities (agents), having each its own goal share limited common resources In this context, if there is no minimum coordination, dramatic consequences may follow, on the other hand, total coordination would be impossible because of the lack of exhaustive, reliable and synchronous information. Finally, a local "network of strategies" that are based on worst-case assumptions are clearly far from being realistic for a well designed system. The aim of this topic is to properly define key concepts and the relevant variables associated to the above problem (sub-system, partial objective, constraints on the exchanged data and computational resources, level of locally shared knowledge, key parameters for the central level, etc).

4. Application Domains

4.1. Industrial applications.

Keywords: *automotive*, *embedded systems*, *robotics*, *telecommunications*.

Closing feedback loops around Wireless sensor networks offers new challenges and new opportunities for the area of control. Several new application areas can be enabled, or enhanced if systematic methods are developed for the design of NCS. Examples include:

- Intelligent buildings, where sensor information on CO2 concentration, temperature, room occupancy, etc. can be used to control the heating, ventilation and air conditioning (HVAC) system under multi-objective considerations of comfort, air quality and energy consumption.
- Intelligent transportation systems, where traffic flow or density can be measured using novel wireless technologies and used to determine control inputs such as on-ramp metering schemes and variable message signs.
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- Disaster relief operations, where data collected by sensor networks can be used to guide the actions of rescue crews and operate automated rescue equipment.

- Surveillance using swarms of Uninhabited Aerial Vehicles (UAVs), where sensor information (from sensors on the ground and/or on-board the vehicles) can be used to guide the UAVs to accomplish their mission.
- Environmental monitoring and exploration using schools of Autonomous Underwater Vehicles (AUVs), where underwater sensors and communication are used to guide the AUVs.
- Infrastructure security and protection using smart camera networks, where the images collected are shared among the cameras and used to control the cameras themselves (pan-tilt-zoom) and ensure tracking of potential threat.

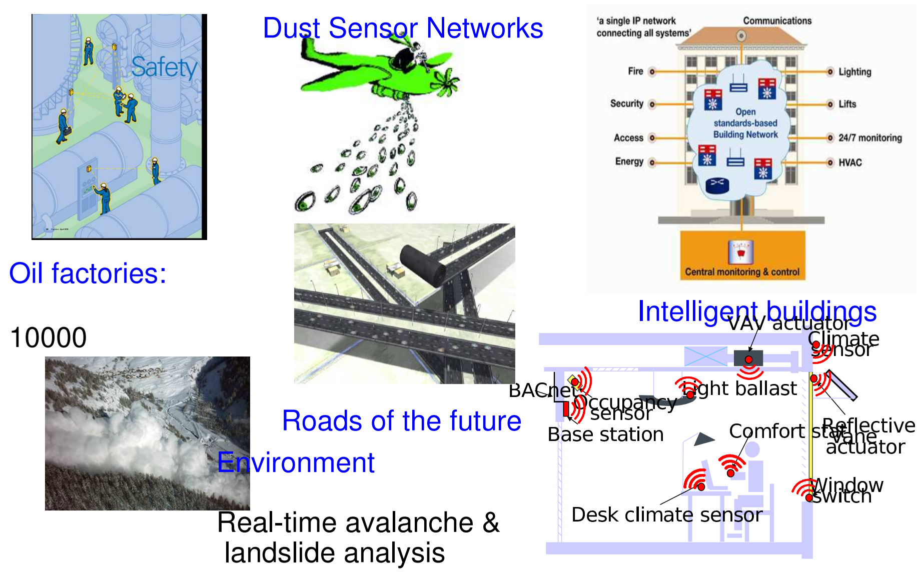

Figure 5. Potential applications of NeCS

In particular, the teal is already involved in the two areas described in detail below:

4.1.1. Underwater systems.

Underwater systems, as presently used or intended by the offshore industry and marine research, are subject to severe technological constraints. In autonomous vehicles (AUV) the on-board power is limited and calls for both control and computing optimisation. The links between the master and slave nodes use ultrasonic devices, which have a very low bandwidth and are subject to frequent transient loss, thus calling for sharing the decisional process among the nodes and for a robust implementation of the distributed control, taking into account the communication network features. These constraints together with the potential cost of failures make these systems good candidates for safe and flexible control, communication and computing co-design. The team already got a significant experience in this domain with a past collaboration with IFREMER and other EU projects. Currently, the project CONNECT deals with this type of problems. Details of this project are described in Section 8.1.2.

4.1.2. Car industry

Car industry has been already identified as a potential homeland application for networked controlled system [36], as the evolution of micro-electronics paved the way for introducing distributed control in vehicles. In addition, automotive control systems are becoming the more complex and iterative, as more on-board sensors and actuators are made available through technology innovations. The increasing number of subsystems, coupled with overwhelming information made available through on-board and off-board sensors and communication systems, rises new and interesting challenges to achieve optimal performance while maintaining the safety and the robustness of the total system. Causes of such an increase of complexity/difficulties are diverse: interaction between several control sub-systems (ABS, TCS, ESP, etc.), loose of synchrony between sub-systems, limitations in the computation capabilities of each dedicate processor, etc. The team had several past collaborations with the car industry (Renault since 1992, and Ford), and has recently initiate a new collaboration on observer design and fault diagnostics design for multi-sensor systems in Homogeneous Charge Diesel engines, in collaboration with the IFP.

5. Software

5.1. Orccad

Participants: S. Arias, R. Pissard-Gibollet, D. Simon [contact person].

ORCCAD [1] is a software environment that allows the design and implementation of the discrete and continuous components of complex control systems, e.g. robotics systems which provided it first ground ([28]). It also allows the specification and validation of missions to be realised by this system. It is mainly intended for critical real-time applications, in which automatic control aspects (*servo loops*) have to interact narrowly with the handling of discrete events (*exception handling*). ORCCAD offers a complete and coherent vertical solution, ranging from the high level specification to real-time code generation. ORCCAD is supported by the *Support Expérimentations & Développement (SED)* service of INRIA-Rhône-Alpes. ORCCAD is used by the experimental robotics platforms of INRIA-Rhône-Alpes and by the SAFE_NECS ANR project in a real-time simulator of a X4 drone. New functionalities and updates are developed jointly by the *SED* service and researchers of the NECS and POP ART teams.

Although it has been developed years ago, the basic concepts upon which the ORCCAD architecture relies still appear to be solid in the field of software development for robot control [44], and compares well with other tools dedicated for real-time control implementation [48]. However the ORCCAD V3 software was designed with proprietary tools that moreover are now becoming obsolete. ORCCAD V4 is currently deeply re-engineered to be compliant with open-source and free software tools (Java/Eclipse/XML). Current targets are Linux (Posix threads) and Xenomai, a real-time development framework cooperating with the Linux kernel (http://www.xenomai.org).

6. New Results

6.1. Stability and control design of asynchronous interconnected systems

Participants: C. Canudas-de-Wit [contact person], N. Marchand, J. Ramos-Cueli, M. Lopez.

Networked and embedded control systems usually operated under variable resources like communication rates and computational loads. This results in an asynchronous sub-systems interconnection, as the sampling time may be adapted *on the fly* as a function of the available resources at the moment. Examples of these systems can be found in many application fields such as remotely-operated systems, interconnected vehicle control loops, and more generally in component-based control design where synchronous exchange of information is not feasible.

[1] http://sed.inrialpes.fr/Orccad/

6.1.1. Passivity design for asynchronous feedback-interconnected systems

In this topic we have studied the passivity properties of asynchronously non-uniformly sampled systems. The idea of studying these systems comes from the necessity of developing theoretical tools for the analysis of systems that are asynchronously interconnected. Imposing certain passivity properties to each sub-system it is possible to design a local controller each sub-system disregarding the particular characteristic of the other system (modular design).

In particular we have studied the following items. First we introduce the notion of (MASP) *MAximum Sampling time preserving Passivity* for linear systems; given a continuous-time system with some dissipation properties specified, the notion of MASP give a maximum sampling time, T^* after which passivity is lost. A second aspect studied here concern the case of a system locally asynchronous but globally synchronous feedback interconnected systems. The notion of globally synchronous comes from the fact that we limit this study to samples T_i of each i-subsystem that are multiple integers among them, nevertheless we allows the sampling time of each individual sub-systems to be time-varying. Finally, we use these results as a design guidelines for the control design, and we propose a numerical algorithm to compute local feedback loops providing a MASP compatible with the maximum sampling-time upper-bound of each sub-system. Details are given in [32]

6.1.2. Event-based control design

Asynchronicity is becoming more and more meaningful in modern control architectures and some new control strategies are being developed by some research teams in the world. The principle of these control law is to compute the control law only when some event occurs, this event characterising a change in the system and therefore a need for a new control. These approaches are supposed to reduce the number of times the control is computed and to remove the real-time hard constraint on the computational system. However, all the proposed approach in the literature need the knowledge of the time which is sometimes far from being realistic and keep some sampling condition inherited from Shannon. To go further into fully asynchronously controlled systems, we developed a fully asynchronous control scheme for chain of integrators that insures the global stability of the system with only measures when the states cross a priori defined level. This work was submitted at the next IFAC world congress [39].

6.2. Communication and control co-design in feedback systems

Participants: C. Canudas-de-Wit [contact person], C. Siclet, J. Jaglin, M. Alamir, O. Sename.

Traditional control theory often disregards issues of connectivity, data transmission, coding and many other items of central importance in wireless sensor networks. In this topic we study new methodologies to design control for systems in which signals are exchanged through a communication network with limited capacity. Some of the general questions addressed here are:

- How the signal (source) coding algorithm can be designed jointly and simultaneously with the control law ?
- What are the mutual inter-dependencies between the control and communication design?
- How can one overcome the limitations of the wireless medium, and
- How energy of the sensors and the associated transmission media, can be optimised, by the appropriated energy-aware design of the coding and the control

More specifically, we have studied the following problems:

- Differential Coding for networked controlled systems [18], [19],
- Energy-aware and entropy coding in NCS [17], [16],
- Passivity design for asynchronous interconnected systems [32],
- Remote Stabilisation via Communication Networks [7], [12], [3].

6.2.1. Differential Coding for networked controlled systems

Delta modulation is a well-known differential coding technique used for reducing the data rate required for voice communication. The standard technique is based on synchronising a state predictor on emitter and receiver and just sending a one–bit error signal corresponding to the innovation of the sampled data with respect to the predictor. The prediction is then updated by adding a positive or negative quantity (determined by the bit that has been transmitted) of absolute value Δ, a known parameter shared between emitter and receiver.

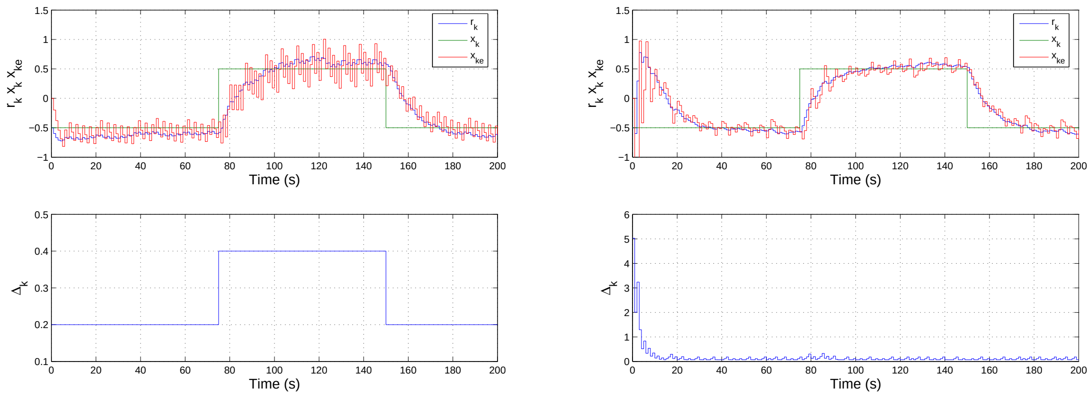

Figure 6. Simulation results for non–adaptive scheme, with Δ fixed along specific intervals (left). Simulation results for Δ_k adaptive scheme. (right)

In [18] we propose an *adaptive* extension a of *fixed-gain* differential coding scheme previously introduced by us (see [1]). For a constant Δ it was shown in [1] that only a limited domain of attraction can be obtained. In addition, the state was only guaranteed to converge asymptotically to a finite ball, begin its size related to the parameters of the openloop plant, and on the the userdefined parameter Δ. By making Δ an adaptive quantity, more effective schemes of Δ-modulation can be obtained. The idea is to design an update law for Δ, defined exclusively in terms of the information available both at the receiver and transmitter, aiming at improving the resolution of the differential coding by reducing the gain Δ for slowly varying signals, while enlarging Δ in case of rapid change of the input, and hence allowing for faster signal tracking and higher bandwidth of the transmitted signals. So far in the communication area, adaptation laws for Δ have been proposed under somewhat heuristic criteria, as little information is supposed to be available on the dynamics of the source signal. However, when dealing with feedback systems, the dynamical properties of the plant become very useful in designing the adaptive law. In fact, we show that the unstable eigenvalues of the open-loop plant are used to compute the Δ-update law resulting in global asymptotic stable scheme.

In [19], we propose a gain-scheduling multi-bit Delta-modulator. We first analyse modifications for the $\Delta - M$ algorithm proposed by [1] in order to stabilise discrete-time systems with eigenvalues $|a| > 2$. This is motivated by the previously mentioned cost issues associated with the simple $\Delta - M$ schemes. Secondly, we analyse the packet-loss issue, and determine a maximum allowable number of consecutive bits lost while keeping stability. This analysis is innovative since previous work on the subject have dealt with the limited-rate and the packet losses separately. Recent works considered packet losses but assumed unlimited channel rate, while research dealing with limited-rate channels have not included packet losses. Our results show that the maximum number of packets that can be lost sequentially depends on the region where a certain estimation error $\widetilde{x}_k = x(k) - \widehat{x}(k)$ lives. Using this fact, we redesign the $\Delta - M$ scheme used in [1] so the system can handle at least a minimum number of packet losses. This mechanism is based on the re-synchronisation between the encoder and decoder.

Further research on this issue will be carried out in this project, addressing quantisation of multiple samples and a comparative analysis with similar techniques. Additionally, the use of transform coding in the context of feedback systems is an interesting open lines of research to explore.

6.2.2. Energy-aware and entropy coding in NCS

In sensor network, each individual sensors will be packaged together with communication protocols, RF electronics, and energy management systems. Therefore, the development of such integrated sensors will be driven by constraints like: low cost, ease of replacement, low energy consumption, and efficient communication links. In particular, low cost technology will induce sensors with low resolution (binary sensors, at the extreme), low consumption (efficient sensor energy management, with; sleep and wake-up modes). As a consequence, communication protocols, modulation strategies, and control laws should be designed to account for substantial energy savings.

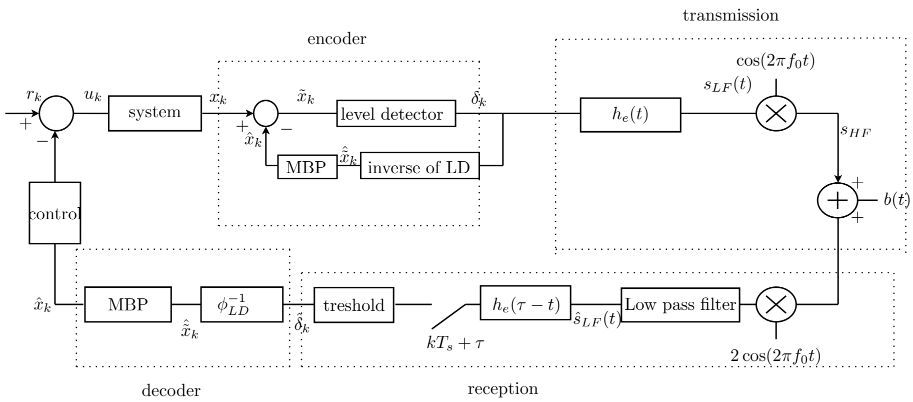

Figure 7. Block diagram of the complete estimation process including the coding and the modulation steps, for the energy-aware coding in NCS.

Event-driven communication protocols (and control), are usually adjusted for minimum transmission requirements (i.e. transmit and update control laws only when significant information for control is available), is a natural candidate to be used in this context. To this aim, we have propose to use a coding strategy with the ability to quantify and to differentiate stand-still signal events from changes in the source (level crossing detector) [17]. Coding is effectuated by defining a 3-valued alphabet. Then, the stand-still signal event is modulated with a low energy carrier, whereas the changes of levels will be modulated with enough energy. In [17]we study the closed-loop properties of such arrangement for one-dimensional system. In particular, we derive conditions required so that this coding algorithm preserves closed loop stability.

Other possible variant to improve data transmission efficiency by reducing the mean number of bits per unit of time needed for the transmission, and hence the mean energy, is to use entropy coding. Combination of entropy coding with non uniform (event-based) sampling has been demonstrated to result in efficient coding strategies [16]. Entropy coding is a source coding that assigns some probability distribution to the events. A pre-requisite for the entropy coding strategy is to design a mechanism with the ability to quantify and to differentiate stand-still signal events, to changes in the source (level crossing detector). For instance, this can be done by defining an alphabet where the source signal information is contained in the time interval between level crossing and in the direction of the level crossing. By assigning strings of the 2-tuple 00 to represent the time between signal level crossing, and 01 and 10 to denote the direction of level crossing, the output of the level crossing detector contains a high probability of the 0 symbol with makes it suitable for an entropy encoder to attain a “good” overall compression ratio. A fundamental difference with the differential coding algorithms mentioned in section 6.2.1 is that the error is coded on the basis of a 3-valued alphabet rather than a 2-valued one. The role of the entropy coding here is to render more efficient the transmission by improving in the mean number of bits per unit of time needed for the transmission.

6.2.3. Passivity design for asynchronous feedback-interconnected systems

In this topic we have studied the passivity properties of asynchronously non-uniformly sampled systems. The idea of studying these systems comes from the necessity of developing theoretical tools for the analysis of networked and embedded control systems, which usually operated under variable resources like communication rates and computational loads. This results in an asynchronous sub-systems interconnection, as the sampling time may be adapted *on the fly* as a function of the available resources at the moment. Examples of these systems can be found in many application fields such as remotely-operated systems, interconnected vehicle control loops, and more generally in component-based control design where synchronous exchange of information is not feasible.

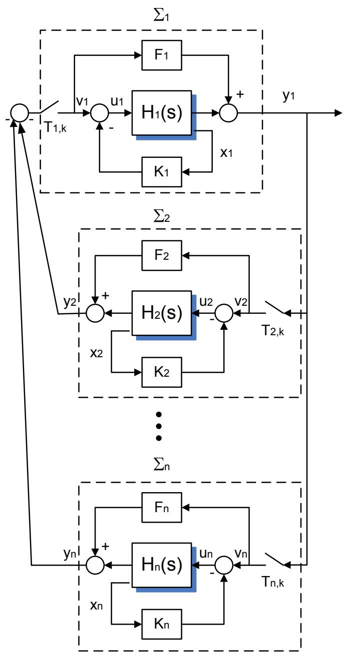

Figure 8.

We have studied the following issues. First we introduce the notion of (MASP) *MAximum Sampling time preserving Passivity* for linear systems; given a continuous-time system with some dissipation properties specified, the notion of MASP give a maximum sampling time, T^* after which passivity is lost. A second aspect studied here concern the case of a system locally asynchronous but globally synchronous feedback interconnected systems. The notion of globally synchronous comes from the fact that we limit this study to samples T_i of each i-subsystem that are multiple integers among them, nevertheless we allows the sampling time of each individual sub-systems to be time-varying. Finally, we use these results as a design guidelines for the control design, and we propose a numerical algorithm to compute local feedback loops providing a MASP compatible with the maximum sampling-time upper-bound of each sub-system. Details are given in [32]

6.2.4. Remote Stabilisation via Communication Networks and Tele-operation

The networked control systems constitute a new class of control systems including specific problems such as delays, loss of information and data process. The problem studied here concerns the remote stabilisation of unstable open-loop systems. The sensor, actuator and system are assumed to be remotely commissioned by a controller that interchanges measurements and control signals through a *lossless* communication network (all lost packets are re-emitted). We assume that this communication network has its own dynamics, and that a model for the average induced time-delay is available. As an example, such a model can be derived for local networks where the transfer protocol (TP) is set by the users and where a router (which can possibly inform the emitters of the instantaneous queue length) manages the packets. Another option is the estimation the average value of the delay with a simple algorithm based on the measurement of the round trip time

In [7], and in [12], we proposed to use a time-varying horizon predictor to design a stabilising control law that sets the poles of the closed-loop system. The computation of the horizon of the predictor is investigated and the proposed control law takes into account the average delay dynamics explicitly. The resulting closed loop system robustness with respect to some uncertainties on the delay model is also considered. Tele-operation subject to time-varying delays has been considered in [3].

An H_{infty} approach to robust control of bilateral teleoperation systems under communication time-delay is considered and applied on an experimental setup. Using a small gain approach an H_{infty} controller is first designed in the nominal case and a robust design is then proposed for any communication delay in the case of environment uncertainties. When delay independent stability cannot be achieved, a way to determine the maximal allowed time-delay is provided. Simulation and experimental results are provided on the teleoperation platform of the NECS project [11].

6.2.5. Multi-carrier modulation for underwater acoustic communication

CONNECT (CONtrol of NEtworked Cooperative sysTems) is a project granted by the ANR. In collaboration with IFREMER, GIPSA-lab, PROLEXIA and PGES, CONNECT aims at studying the problem of multi-agent control (AUVs) and coordination with heterogeneous networks, including underwater communication. In this context, we will interest to underwater acoustic communication.

Current underwater acoustic modems are based on very classical single-carrier modulation with a very low bit rate. In the same time, wireless radio-communications have been significantly improved during the latest ten years, in particular thanks to multicarrier modulations. These modulations are indeed now used in several high rate applications (ADSL, DVB-T [41], IEEE 802.11a/g, ...). These applications are all based on the same modulation, OFDM (Orthogonal Frequency Division Multiplex). Thanks to the use of a guard time [40] (or cyclic prefix), it is possible under certain conditions to simplify considerably the equalisation step, so that OFDM is particularly performing. That is why OFDM has also recently been considered for underwater communications : the underwater acoustic channel [38], [46] is indeed particularly frequency selective, so that OFDM is a potential interesting solution [37].

In spite of its advantages, OFDM also suffers from several drawbacks : the guard time induces a spectral efficiency loss, and, what is more, the pulse shape used for each carrier is rectangular, and therefore badly frequency localised. This spectral efficiency loss remains small if we use long duration symbols, but is may cause inter-carrier interferences if the transmission channel is not stationary during a symbol interval. Compensation techniques have then to be studied [34]. Lastly, the modulated signal has an amplitude which may by very high which is problematic for linear amplification.

Several alternatives have been proposed to solve these problems, among them oversampled OFDM/QAM modulations [43] and OFDM/OQAM modulations [35], [45], and their bi-orthogonal extensions (BFDM) [42]. For each of these types of modulation, it is possible to use non rectangular pulse shapes, optimised according to a given criterion (time-frequency localisation, frequency localisation...). They appear then to be promising and give more freedom degrees in their conception than classical OFDM. Nevertheless, the equalisation is more complex (in the OQAM case) and their implementation more expensive (in terms of computational complexity).

Our objective is to study multicarrier modulation systems (OFDM, oversampled OFDM/QAM, OFDM/OQAM as well as their bi-orthogonal extensions) and to determine the corresponding receptors, in the framework of underwater acoustic communications. We will then have develop a complete communication chain using and comparing these different modulations to classical underwater communication systems. We will thus interest to various problems : channel estimation, equalisation, synchronisation, non-linearity of digital to analog and analog to digital converters.

6.3. Modelling and control of web servers

Participants: N. Marchand [contact person], D. Simon, S. Durand, L. Malrait.

This work focuses on the design of a database server model by a fluid flow approach, taking into account elements of computing systems theory. This work is in collaboration with SARDES team of the INRIA.

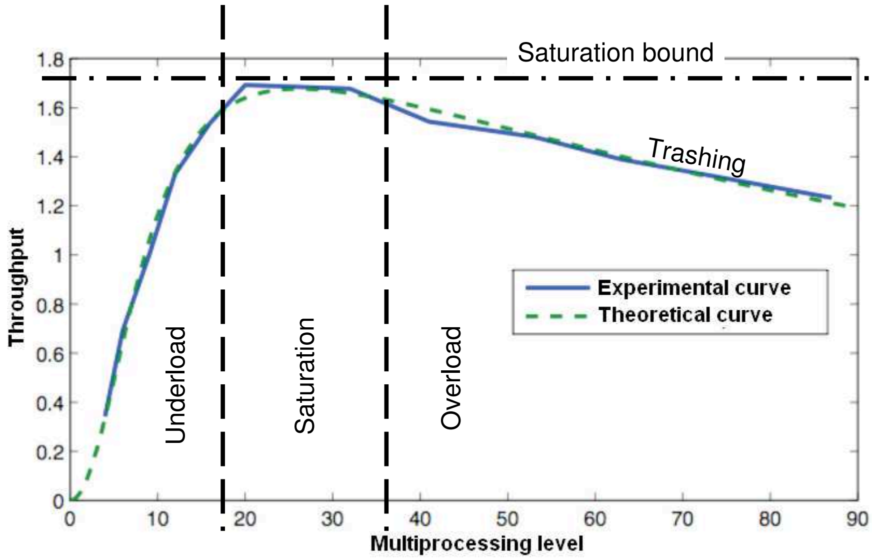

Figure 9. Real and modelled output of a PostgreSQL database server with emulated clients (TPC-C)

The aim is to provide a model which could describe the behaviour of a server whatever may be the load. A first model based on a two tank system was developed using the fluid conversation law and the Little law. This model is relatively simple and is a first order system with time constant and gain depending upon the input of the system - that is the load of server [25], [24]. We are now able to predict the output of the server through a model with self adaptive parameters. This model will then be used to build control laws to avoid the trashing phenomena that occurs in case of overload using admission control. The trashing phenomena is a nonlinear phenomena that increases the latency and decreases the performance of the server due to the increase of the multiprocessing level. We are now able to predict the output of the server through a model with self adaptive parameters.

6.4. Coordinated multi-agent systems

Participant: M. Alamir [contact person].

The goal of this research axis consists in deriving new models and control schemes for *partially cooperative* interconnected systems. The underlying idea is that the sub-systems have their own objectives, but are able to re-evaluate these objectives if the global system's integrity becomes an issue. This must be done using a decentralised decisional process, under constraints of limited communication capabilities and shared resources.

We first designed an abstract generic model for a connected entity; then we looked for a practical example found in shared computing resource problem.

6.4.1. An abstract generic model for a connected entity

We designed a generic modelling framework for dynamic entities networked with similar entities. The model handles the following tunable parameters :

1. an internal dynamics;
2. a sensitivity degree w.r.t. the lack of resources;
3. a scalar indicator measuring the distance to unstability.

The first enables to evaluate the internal complexity of each entity. The two others allows for some kind of *negotiation* between entities sharing limited resources, based on a limited amount of relevant information. Figure 10 shows a typical behaviour of an elementary model facing a drop of available resources.

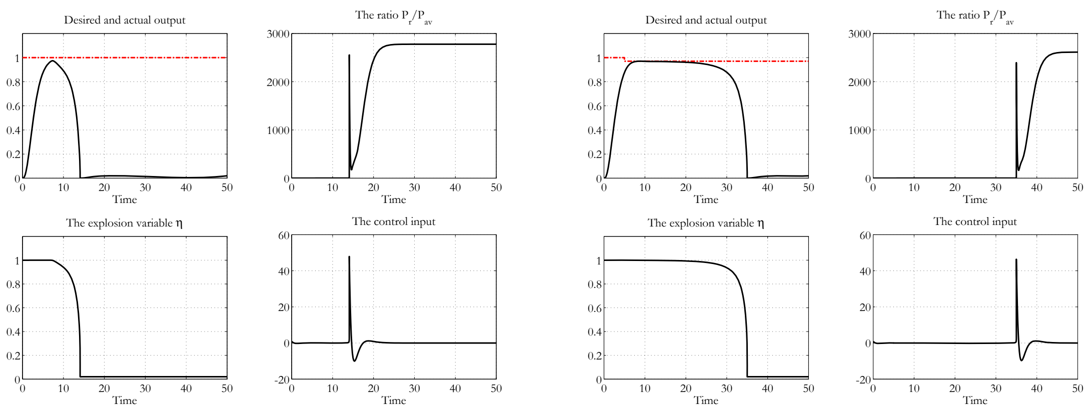

Figure 10. Behaviour of an interconnected entities under resources loss

It describes the behaviour of interconnected entities under resources loss when the desired performance is maintained despite a loss in resources (Figure 10left), that is represented by the ratio between the necessary resource P_r and the available resource P_{av}. In Figure 10right the resource loss is handled through a reduction of the desired performance. The system's collapse is characterised by the stalling of the *explosion* variable η.

This preliminary work will be continued following two directions :

1. Propose a benchmark for the control of open-loop unstable systems, interconnected under limited communications and resources. The generic framework defined above can be used for his purpose;
2. Looking for practical instances of such systems. It is for example the case for interconnected systems sharing computational resources, as described in the next section 6.4.2.

6.4.2. Systems sharing a limited computing resource

We have sought the problem of computational resources sharing following the ideas developed in section 6.4. It is shown in [14] that an argued choice of the sampling periods as a function of the resource usage can be defined w.r.t. the desired performance level. An instability scalar index has been defined to allow for a negotiation sparing the communication usage.

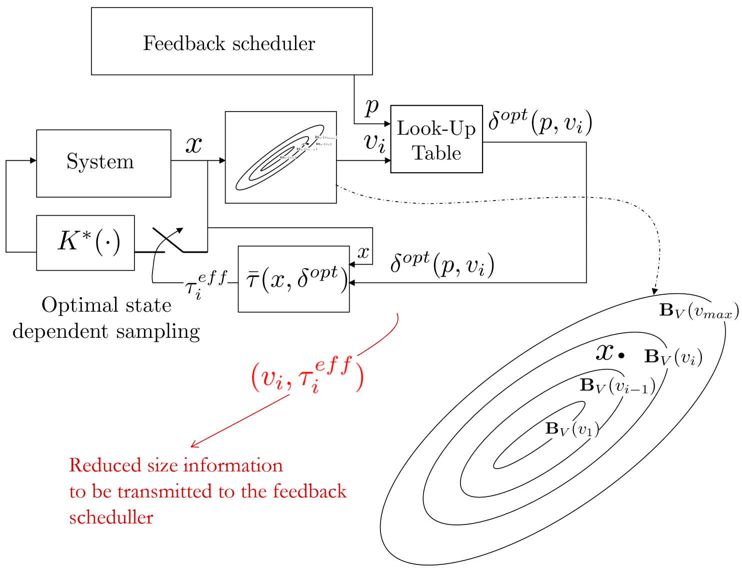

Figure 11. State dependent sampling rate : principle

Figure 11 shows how a state dependent sampling rate allows for a modulation of the resource usage w.r.t. the desired performance level. The actual sampling period τ_i^{eff} is computed based on the δ^{opt} parameter, which is itself a function of the distance to instability v_i and of the context vector p. This last item is made of the minimal allowed sampling period and of the desired performance.

Figure 12 depicts an example of the state dependant sampling scheme described above when applied to a non-linear inverted pendulum. The simulation is made of three phases corresponding to different levels of desired performance. The successive performance index values are 0.99, 0.7 and 0.85 (lower right picture). Note the corresponding change in the slope depicting the activation instants of the computer (lower left picture).

6.5. Observers design for multi-sensor systems: application to HDI engines

Participants: C. Canudas-de-Wit [contact person], R. Ceccarelli.

Collaboration with IFP (Institut Français du Petrole).

Research activity in vehicle industry targets pollutant emission reduction. Homogeneous charge compression engine ignition (HCCI) is an interesting alternative to this problem. New European community laws impose new stringer constraints to pollution, and as a consequence, forces the car industry to realise on board diagnosis system in order to detect engine failures that may result in an increase in the engine pollution. The control of pollutant emission, in diesel engine, is ensured by exhaust gas recirculation system (EGR). Its functioning

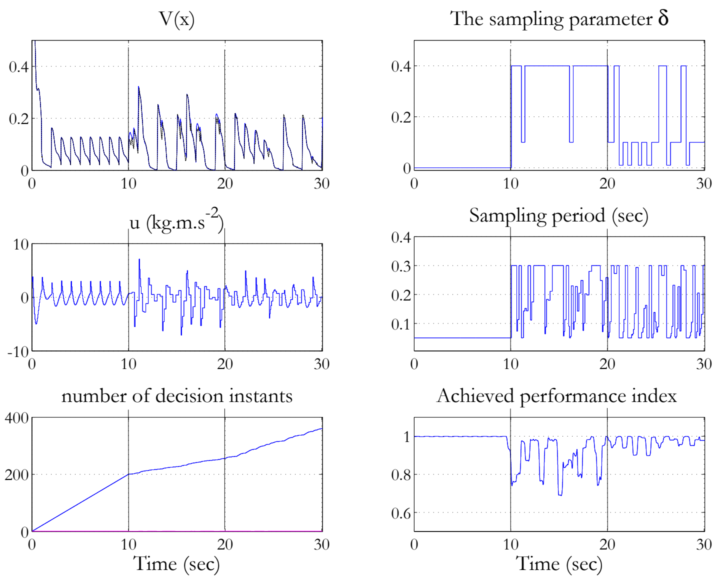

Figure 12. State dependent sampling rate applied to inverted pendulum

is very important and a fault detection and isolation system (FDI) is necessary in order to ensure good performances and poor emissions. Exhaust gas could be taken before or after compressor: respectively called high and low pressure EGR.

In this project carried out in collaboration with the IFP (Institut Français du Petrole), we aim at developing model-based observer allowing to identify several types of engine failures, like: gas leakage in the low and high pressure recirculation circuits, ill functioning of some of the sensors, and actuators (valves).

6.6. Energy-aware control for systems on-chip

Participants: C. Canudas-de-Wit [contact person], C. Albea-Sanchez, N. Marchand, D. Simon.

The NECS team is involved in the ARAVIS project (see 7.1) : the high level of integration in future chips will lead to heterogeneity in the performance of the various integrated components. It appears that introducing control loops at different levels of these chips will be necessary to be compliant with heterogeneous circuits.

6.6.1. Adaptive Control of the Boost DC-AC Converter

The control of boost DC-AC converters is usually accomplished tracking a reference (sinusoidal) signal. The use of this external signal makes the closed-loop control system to be non-autonomous and thus, making its analysis involved. Here we follow a different approach consisting in design a control law in order to stabilise a limit cycle corresponding to the desired oscillatory behaviour. In that way, no external signals are needed. In [15] we have proposed an adaptive control law for the nonlinear boost inverter in order to cope with unknown resistive load. This adaptive control is accomplished by using a state observer to one side of the inverter and by measuring the state variables. The stability properties are derived by resting to via singular perturbation analysis.

6.6.2. Energy aware computing power control

Achieving a good compromise between computing power and energy consumption is one of the challenge in embedded architecture of the future. This management is especially difficult for 45nm or 32nm known to be at the limit of the scalability. Automatic control loops have therefore to be designed in order to make the performance fit the requirement in order to minimise the energy loss in a context of highly unknown performance of the chip. The main objective is to control the computing power and the consumption using the voltage and frequency automatically according to the requirements of the OS. For this, appropriate sensors must be implemented on the chip and a high-performance repartition between hardware and software implementation must be made.

6.6.3. QoS control

An application software deployment based on a static and worst case point of view is no longer effective for such heterogeneous chips and more flexible designs must be used. It appears that closed-loop control can be integrated at several hardware and software levels of the chips to provide both adaptivity to the operation conditions and robustness w.r.t. variability.

On top of the nodes power control and computing speed control layers, the outer application layer will include a closed-loop controller of the application quality of service (QoS) under constraints of computing and energy resources availability. This loop uses the scheduling parameters provided by the operating system to regulate the application's QoS. In the context of ARAVIS the computing speed of each integrated node is assumed to be controllable and is also a possible control actuator used by the application level. A first step will be devising a formal definition of the required control performance and stating cost functions to formally associate the QoS with the usable scheduling parameters.

6.7. Control and scheduling co-design

Participants: D. Simon [contact person], O. Sename, M. Ben Gaid, A. Desvages, D. Robert.

We propose here a control/scheduling co-design approach. We aim to provide an *Integrated control and scheduling co-design* approach. Indeed closing the loop between the control performance and the computing activity seems to be promising for both adaptivity and robustness issues.

6.7.1. Synthesis of variable sampling control

As variable control periods are used as actuators in feedback schedulers it is necessary to ensure the stability of the control laws under variable sampling conditions. Indeed it is known that on-line switches between stable controlled systems sampled at different rates may lead to instability. The synthesis of control laws using variable sampling has been developed via new extensions of the gain scheduling and Linear Parameter Varying (LPV) design methods, considering here that the sampling period is the varying parameter [20].

The first point is the problem formulation such that it can be solved following the LPV design of [26]. We first propose a parametrised discretization of the continuous time plant and of the weighting functions, leading to the discrete-time LPV polytopic system (1) with h ranging in $[h_{min}; h_{max}]$. To get a polytopic model (and then apply an LPV design), we approximate the exponential by a Taylor series of order N with $H = [h \ h^2 \ \dots \ h^N]$, leading to:

$$\begin{aligned} A_d(h) &\approx I + \sum_{i=1}^{N} \frac{A^i}{i!} h^i := A_d(H) \\ B_d(h) &\approx \sum_{i=1}^{N} \frac{A^{i-1}B}{i!} h^i := B_d(H) \end{aligned} \tag{1}$$

As the gain-scheduled controller will be a convex combination of 2^N "vertex" controllers, the choice of the series order N gives a trade-off between the approximation accuracy and the controller complexity.

To decrease the volume and number of vertices of the matrices polytope we exploit the dependency between the successive powers of the parameter h. Recall that the vertices ω_i of $\mathcal{H}$ are defined by $h, h^2, \cdots, h^N$ with $h^i \in \{h^i_{min}, h^i_{max}\}$. Indeed the representative point of the parameters set is constrained to be on a one dimensional curve, so that the polytope of interest can be reduced to $N+1$ vertices

In the H_∞ framework, the general control configuration of figure 13 is considered, where W_i and W_o are weighting functions specifying closed-loop performances. The objective is here to find a controller K such internal stability is achieved and $\|\widetilde{z}\|_2 < \gamma \|\widetilde{w}\|_2$, where γ represents the H_∞ attenuation level.

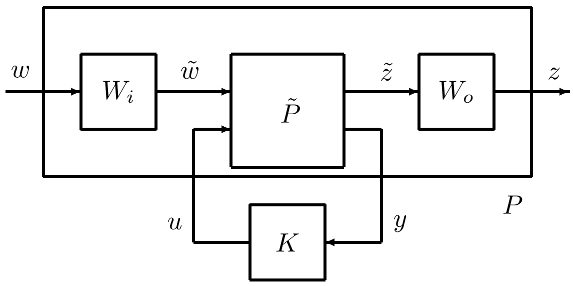

Figure 13. Focused interconnection

Classical control design assumes constant performance objectives and produces a controller with an unique sampling period. When the sampling period varies the usable controller bandwidth also varies and the closed-loop objectives should logically be adapted. Thus the performance templates W_i and W_o are made partly variable as a function of the sampling frequency.

The self-scheduled controller $K(\theta)$ is the convex combination of the elementary controllers synthesised at the vertex of the polytope (2); it only involves the on-line computation of the α_i coordinates which have simple explicit expressions for the case of the reduced polytope ([21], [22]).

$$\begin{aligned} K(\theta) : \begin{pmatrix} A_K(\theta) & B_K(\theta) \\ C_K(\theta) & D_K(\theta) \end{pmatrix} &= \sum_{i=1}^{r} \alpha_i \begin{pmatrix} A_{K_i} & B_{K_i} \\ C_{K_i} & D_{K_i} \end{pmatrix} \\ \text{with } \alpha_i \text{ such that } \theta &= \sum_{i=1}^{r} \alpha_i \omega_i \end{aligned} \tag{2}$$

Under mild conditions this controller ensures the quadratic stability of the closed-loop system and the limitation of the input/output transfer $\mathcal{L}_2$-induced norm whatever are the variations of the sampling period h in the specified range.

The feasibility of the method has been assessed through various simulations and experiments)[8], [20].

6.7.2. Process state based feedback scheduling

Variable sampling rate appears to be a decisive actuator in scheduling and CPU load control. Although it is quite conservative, the LPV based design developed in section 6.7.1 guarantees plant stability and performance level, whatever is the speed of variation of the control period inside its predefined range. Hence the control tasks periods of such controllers can be adapted on-line by an external loop (the feedback scheduler) on the basis of resource allocation and global quality of service (QoS), with no further care about the process control stability. Hence a quite simple scheduling control architecture, e.g. like a simple rescaling as proposed in [30], or an elastic scheduler as in [29].

Indeed, besides the flexibility and robustness provided by an adaptive scheduling, a full benefit would come by taking into account directly the controlled process state in the scheduling loop. It has been shown in [33] that even for simple case the full theoretic solution based on optimal control was too complex to be implemented in real-time. However it is possible to sketch effective solutions suited for some case studies as depicted in figure 14 taken from [8].

Conversely with previously studied CPU load regulators ([4]) the load allocation ratio between the control components is no longer constant and defined at design time. It is made dependent on the measure of the quality of control (QoC) to give advantage to the controller with higher control error. The approach relies on a modified elastic scheduler algorithm, where the "stiffness" of every control task depends on the control (through the M_i component in figure 14 which can be a simple gain). The approach is still simple to implement and, even if only tested in simulation up to now, has shown significant performance improvements compared with more simple (i.e. control quality unaware) resource allocation.

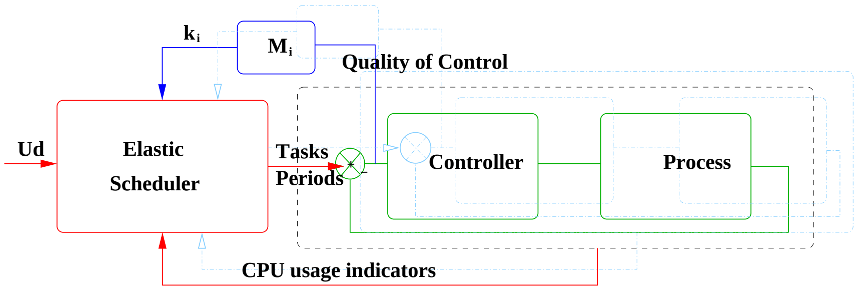

Figure 14. Integrated control/scheduling loops

However, the dynamic of the scheduling loop now includes the scheduling dependent dynamics of the process itself. Ensuring the stability of this integrated control/scheduling loop requires an adequate modelling of the relationships between the control quality and the scheduling parameters, which is still to be done in a general case.

6.7.3. Accelerable control tasks

A common assumption about the sampling rate of control tasks is that faster is the computation and better is the result, i.e. that control tasks are always accelerable. However recent investigations [27] revisited this assumption and indicated new directions.

An accelerable control task has the property that more executions are performed, better is the control performance. When used in conjunction with weakly-hard real-time scheduling design, an accelerable control task allows taking advantage of the extra computational resources that may be allocated to it, and to improve the control performance with respect to worst case design methods. In practice, however, control laws designed using standard control design methods (assuming a periodic sampling and actuation) are not necessarily accelerable. Case studies have shown that, when a control law is executed more often than allowed by the worst case execution pattern (with no gains adaption), the performance improvement may be state dependent, and that performance degradation can be observed.

Conditions for the design of accelerable tasks has been established, based on Bellman optimality principle, in the framework of a (m,k)-firm scheduling policy. Is is assumed that an optimal control law exists in the case of the worst case execution sequence, i.e. when only the *mandatory* instances of the control task are executed to completion. It is shown that, in the chosen framework, it is possible to systematically design accelerable control laws, which control performance increases when more instances of the control task can be executed during the free time slots of the system. The theory is quite general and does not require the process linearity.

6.7.4. Feedback-scheduling of a MPC controller for a thermal process

Model Predictive Control (MPC) is a very popular control method in industry for its ability to cope with complex non-linear systems. The basic idea consists in computing model based predictions of the future evolution of the system on a receding horizon. The main drawback of the method is its very high and variable computing cost, so that it is up to now only used for slow dynamic systems.

However, using a feedback scheduling approach allows for the on-line tuning of the timing parameters of a MPC controller, such as the sampling period and the size of the receding horizon. Such adaptation of the scheduling parameters to the operative conditions is expected to improve the method tractability w.r.t. the availability of computing resources.

The approach has been implemented on a thermal process available at Gipsa-lab. The on-line adaption of the sampling period requires the on-line discretization of the process continuous model, identified off-line as an ARMAX model. The method's overhead, due to the on-line discretization and to the elastic scheduler, are negligible compared to the constrained quadratic optimisation needed by the controller at each sample. The method has been successfully implemented using standard PCs and real-time Linux kernels, and show that it is able to easily adapt the controller's scheduling parameters w.r.t. the available computing resources ([23]).

7. Contracts and Grants with Industry

7.1. Pôle de compétitivité Minalogic/ARAVIS

ARAVIS (Architecture reconfigurable et asynchrone intégrée sur puce) is a project sponsored by the Minalogic Pole, started for 3 years in October 2007 (http://www.minalogic.com/posters2007/aravis.pdf). It will investigate innovative solutions needed by the integration of 32 nano-meter scale future chips. It is headed by STMicroelectronics, the other partners are Orange R&D, CEA-Leti, TIMA laboratory and the SARDES and NECS teams at INRIA.

7.2. IFP

Accompanying contract with IFP (Institut Français du Petrole), in the framework of the CIFRE PhD grant of Riccardo Ceccarelli (2007-2010). The goal sought with the Control Engine Dept. of IFP is the development of a model-based observer allowing to identify several types of engine failures.

8. Other Grants and Activities

8.1. National actions

8.1.1. ARA-SSIA Safe_NECS

SAFE_NECS is an « Action de Recherche Amont - Sécurité, Systèmes embarqués et Intelligence Ambiante » funded for three years by the ANR and started in January 2006 http://safe-necs.cran.uhp-nancy.fr/. The research topic is fault tolerant control of distributed process and the project focuses on both diagnosis and robust control under execution resources constraints. It gathers teams from CRAN and LORIA (Nancy), LAAS (Toulouse), and LAG and POP ART (Grenoble).

8.1.2. ANR PsiRob CONNECT

The CONNECT proposal (**CON**trol of **NE**tworked **C**ooperative sys**T**ems) deals with the problem of controlling multi-agent systems, i.e. systems composed of several sub-systems interconnected between them by an *heterogeneous* communication network. The control of a cluster of agents composed of autonomous underwater vehicles, marine surface vessels, and possibly aerial drones will be used as a support example all along the proposal. The partners are the NECS team, Ifremer robotics lab. and the PGES and Prolexia companies. It started for 3 years in May 2007 (http://www.lag.ensieg.inpg.fr/connect/).

8.1.3. Collaborations inside Inria

- Collaborations with the SARDES project-team have been initiated along two axis. The modelling and closed-loop control of web servers involves a shared PhD student. The QoS control of multimedia application based on the Think operating system is investigated in common to be the external layer of the ARAVIS project.
- The SED service at INRIA-Rhône-Alpes is maintaining ORCCAD and provides support for experiments within the SAFE_NECS project.
- C. Canudas-de-Wit and D. Simon participated at the Inria robotics meeting organised in september in Autrans.

8.1.4. Cooperations with other laboratories

- Carlos Canudas-de-Wit has a collaboration with University of Sevilla about NCS.
- C. Siclet has collaborations with L. Ros, C. Baras and J-M. Brossier at Gipsa-lab, and with P. Siohan at Orange Lab in Rennes.

8.2. European actions

The FEEDNETBACK proposal has been submitted as a STREP project at the FP7-ICT-2007-2 call in october 2007. It is coordinated by Carlos Canudas-de-Wit and gathers researchers from academia (INRIA-NeCS, ETH Zurich, Universidad de Sevilla, KTH Stockholm, Universita di Padova) and from industry (Ifremer, Vodera, Vitamib, Intellio and OMG). The objective of the FEEDNETBACK proposal is to generate a co-design framework, to integrate architectural constraints and performance trade-offs from control, communication, computation, complexity and energy management. This proposal has been elected for funding in December and is expected to start by mid-2008 (http://www.lag.ensieg.inpg.fr/canudas/feednetback.htm).

9. Dissemination

9.1. Scientific community

- Prof. K-J. Astrom from Lund Institute of Technology, Control Lab., has been invited in May by the NeCS team.
- Seminar "Control Vistas", INRIA-RA, May 22th, Montbonnot (K.J. Astrom, A. Benveniste, C. Canudas de Wit).
- Carlos Canudas-de-Wit organised an invited session at IEEE American Control Conference (Advances in networked controlled systems) and was chair of invited session IEEE Conference on Control Applications,Singapore (Coding with minimal information). Member of program committees in the 2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, and in 2008 IEEE Conference on Decision and Control, 10th International Workshop in Advanced Motion Control and IEEE Conference on Automation Science and Engineering. Guest editor of a special issue of the IEEE Robotics & Automation Society Magazine on walking and running robots. Guest editor a special issue of the International journal of Robust & Nonlinear Control on "Control with Limited Information". Member of the working group on Vehicle control, GdR MACS.
- M. Alamir is a member of the "Nonlinear Systems" IFAC technical committee and co-animator of the "Nonlinear Predictive Control" group of GDR-MACS. He is Associated Editor for the IFAC World Congress (South Korea, 2008) and editor of a Special issue of International Journal on Robust and Nonlinear Control. He was in the PhD jury of M. Porez (IRCCyN Nantes), A. Donze (VERIMAG, Grenoble) and G. Gallot (IRCCyN, Nantes).

- D. Simon is a member of the RTNS'07 and RTNS'08 (international conference on Real-Time and Network Systems), and ACD'07 (Advanced Control and Diagnosis) program committees.
- N. Marchand is a member of the ACD'07 (Advanced Control and Diagnosis) program committee.
- O. Sename is a member of the IAR/ACD 2007 organisation committee; member of the GDR-MACS SAR, MOSAR and Automatique-Automobile working groups.
- C. Siclet was in the PhD jury of A. Skrzypczak (Orange Lab Rennes).

9.2. Teaching

9.2.1. Courses

- Olivier Sename and Cyrille Siclet teach several courses in control and signal processing inside INPG schools; O. Sename teaches Robust Control (20h) in the M2R Automatique Master at INPG;
- Nicolas Marchand : *Nonlinear control systems*, 20h, ENSIEG Master, INPG; Summer school on Nonlinear Model Predictive Control (Santiago, Chile 2007).
- Mazen Alamir : Summer school on Nonlinear Model Predictive Control (Santiago, Chile 2007), Spring school on Nonlinear Model Predictive Control (Udine, Italy 2007), invited speaker at the Summer School on Nonlinear Moving Horizon Observers (Grenoble, France, 2007) and at the Journée Nationale de la Recherche en Robotique (NMPC for fast systems).

9.2.2. Advising

PhDs:

- David Robert, co-advised by D. Simon and O. Sename since 9/2003 until 01/007, INPG.
- Jonathan Jaglin, co-advised by C. Canudas and C. Siclet, INPG, 2006-09
- Sylvain Durand, co-advised by N. Marchand and D. Simon, INPG, 2007-2010.
- Luc Malrait, co-advised by N. Marchand and S. Bouchenak (SARDES), INPG, 2007-2010.
- Carolina Albea-Sanchez, co-advised by C. Canudas and F. Gordillo (Univ. Sevilla)
- Riccardo Ceccarelli, advised by C. Canudas and A Sciaretta (IFP)

Masters:

- Arnaud Desvages, co-advised by D. Simon, O. Sename and N. Marchand, M2R EEATS (GIPSA-LAB and ESISAR).
- Luc Malrait, co-advised by N. Marchand and D. Simon, M2R EEATS
- Sylvain Durand, co-advised by N. Marchand and D. Simon, ESISAR
- Emmanuel Broutier, co-advised by C. Canudas and O. Sename, M2R EEATS

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[4] D. SIMON, D. ROBERT, O. SENAME. *Robust control/scheduling co-design: application to robot control*, in "RTAS'05 IEEE Real-Time and Embedded Technology and Applications Symposium, San Francisco", march 2005.

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Doctoral dissertations and Habilitation theses

[8] D. ROBERT. *Contribution à l'interaction commande/ordonnancement*, Ph. D. Thesis, I.N.P. Grenoble, january 2007.

Articles in refereed journals and book chapters

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