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Antonio Pascoal
Vladimir Ufnarovsky (Eds.)

Networked embedded and control system technologies: European and Russian R&D cooperation

Proceedings of the 1st International Workshop on Networked embedded and control system technologies: European and Russian R&D cooperation - NESTER 2009

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In conjunction with ICINCO 2009
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Foreword

This book contains the papers from the NESTER Workshop, held on July 4-5, 2009 in Milan, Italy as a satellite event of the ICINCO conference. The key goal of the workshop was to strengthen R&D collaboration between the European Union and Russia in the field of Networked Embedded and Control System Technologies (NECS), a vibrant area of research with far reaching applications in a vast number of scientific and commercial sectors. To this end, representatives from both the research and industrial communities came together to share R&D experiences, present and discuss recent scientific and technological achievements, and identify areas of common interest and potential R&D collaboration in the field of NECS, namely in the scope of the upcoming calls for the EU 7th Framework Programme. The NESTER workshop was organised by the EC-funded NESTER project (Networked Embedded and Control System Technologies for Europe and Russia, www.nester-ru.eu). NECS is one of the key priority ICT areas defined in the 7th Framework Programme (ICT Work Programme). The NESTER project aims to identify opportunities for greater R&D cooperation between Europe and Russia in the field of NECS and to help R&D teams from European Union and Russia initiate joint NECS projects. The main objectives of the workshop were to:

- Meet with European and Russian leading players in the NESC field.

- Get insight into the latest technical developments presented by researchers with first hand experience in relevant practical issues.

- Take advantage of networking opportunities to establish new research-research and research-business contacts.

The workshop brought together a number of representatives with a wide range of qualifications (project managers, senior researchers, heads of laboratories, etc.) from European and Russian organisations (academia, research institutes & laboratories, multinational corporations, and SMEs) specializing in the areas that are at the core of the NESTER project. The focus areas of the Workshop included, but were not limited to the following:

- Real time software tools and their integration. Platform-based design.

- Design and engineering of monitoring and control for complex/

large scale systems, including wireless sensor networks.

- Homogeneous or heterogeneous multi-core and/or reconfigurable computer architectures, high-level programming languages, operating systems, compilers, and automatic parallelisation.

Of special interest were topics pertaining to the four industrial sectors designated by the NESTER project as high priority for EU-RU collaboration: transportation, telecommunications, energy, and public security infrastructure. The selection of papers reflects the broad spectrum of issues addressed within the area of NECS and affords the reader an overview of many of the multifaceted aspects of Networked Embedded and Control System Technologies as well as a vision of the future.

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PAPERS

Networked Embedded and Control Systems: Towards a Closer EU-Russian Collaboration

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Abstract. The paper presents the NESTER project "Networked Embedded and Control System Technologies (NECS) for Europe and Russia" funded by the European Commission under 7th Framework Programme, aimed to identify opportunities for deeper strategic cooperation between Europe and Russia in the field of NECS. Four sectors with highest potential for EU-Russian NECS R&D collaboration are analysed from the point of view of expected impacts and research challenges.

1 Introduction

Software and electronics are now embedded in various devices and objects. At the same time pervasive data changes how these intelligent objects dynamically pool information, cooperate under numerous constraints and reliably interact and control the physical world. The networked control system, i,e distributed hierarchical system of co-operating controllers and computing elements which are connected together, cope with failures and uncertainties with recovery through reconfiguration or self-restructuring. At the same time they use more and more new sensors and sensor networks, emerging from micro and nano-systems technologies, leading to further improvements in performance and efficiency. These complex engineering systems, situated on the edge between several domains with 3 key elements (3"C") – communication, computer and control, are known under the name of Networked Embedded and Control Systems (NECS).

One of the key elements of the research in the area of NECS is its multidisciplinarity. While individual contributions in the research and advances in the different application domains are at high level, there is very small interaction between the principal elements (3"C") and not enough of transversal research used in parallel in different domains. A better integration is required both at the technological level in order to avoid fragmentation and at the scientific level, where thorough and principled system-theoretic view is still missing. Even the meaning of the term "NECS" is ambiguous and still requires better definition, people coming from communication, computer and control communities have different understanding of NECS.

For example, despite the recent intersection between the application domains of network theory (communication) and control engineering (control), the necessary links for the transfer of ideas and tools between the two fields have yet to be established. This situation is largely due to fundamental differences between the methodologies and goals of the two communities. While control engineers build feedback systems to satisfy closed loop design specifications, network theorists seek models to explain the observed behaviour of existing networks. In fact, the starting points and objectives of a complex-network theoretician and a control engineer are reversed, even though they face the same problems in trying to understand their target systems. Despite the use of different analysis tools, network properties such as connectivity, efficiency, and robustness are critical to both control design and complex-network modeling.

Research on NECS have major strategic relevance for the European industry and society, since these systems form a key growth area in information and communication technologies with a broad range of applications that will affect the citizen in all aspects of their lives. Existing and emerging areas include, for example, automotive industry, energy management, biomedical and health care industries, environmental monitoring, factory automation, personal communication, process industry and transportation. But other information –based industries– such as telecommunications - are likely to benefit from advanced procedures for embedded decision making. Contrary to desktop computing where a few major players dominate the scene, NECS is still open field with enormous potential in the future markets of ambient intelligence.

In this situation, Europe should position itself as a major player, leading the development of intelligent and networked systems. Addressing these ambitious objectives requires merging of different system sciences and engineering as well as the mobilization of resources on a large scale. One of the urgent needs in the emerging area of embedded and networked control systems is to reinforce insufficient dialogues between the various NECS research groups. Indeed, one of the consequences of the present fragmentation of efforts undertaken in different countries positioning in the NECS technologies is the situation where the methodologies are rediscovered from one area to another with more or less difficulties and more or less knowledge of the available or promising fundamental tools that can be used.

Russia is the “old” scientific partner of the European Union. Traditionally very strong in the fundamental physic and mathematic research, the Russian researchers have outstanding competences in “hot” ICT topics such as software architecture, nanoelectronics components, robotics, infrastructures, embedded systems design. Even though the area of the NECS is quite new for Russian researchers, it is expected that NECS fields will be developed rapidly in the nearest future.

That is why the European Commission decided to support the NESTER project, aimed to propose the collaboration priorities between Russia and Europe in the field of NECS, to bring closer the European and Russian researchers in the field of NECS and to foster joint collaboration opportunities driven by industrial demands.

2 The NESTER Project

NESTER www.nester-ru.eu is an International cooperation support action on Networked Embedded and Control Systems, one of the key priority ICT areas defined in

Work Programme (FP7-ICT-2). The NESTER project is funded by the European Commission under the 7th Framework Programme.

The general objective of the NESTER project is to identify constituencies and opportunities for deeper strategic cooperation between Europe and Russia in the field of NECS. This might therefore have great impact on future policies, trends, practices and projects led by the European Commission.

The NESTER project is implemented by a consortium led by inno-TSD (France), the three other partners are EECI – European Embedded Systems Institute, RTTN – Russian Technology Transfer Network (Russian) and Lanit-Tercom (Russia). The consortium work closely with the NECS expert group composed of 5 European and 5 Russian NECS high-level specialists, each expert being closely linked to one of the four industrial sectors. The objective of the NECS expert group is to provide the NESTER consortium with a strategic vision on the European-Russian collaboration in the field of NECS and to help detecting collaboration opportunities between NECS players from Russia and Europe.

Throughout the 18-month project duration (April 2008 – September 2009), the NESTER project aims to:

– Identify opportunities for deeper strategic cooperation between Russia and the European Union in the field of NECS technologies
– Contribute to the definition of NECS EU-Russian cooperation strategy in at least four industrial sectors
– Promote common development of NECS technologies involving research and industry from EU and Russia.

The project bases its analysis on industrial sector needs in order to identify the four industrial sectors most propitious for cooperation. Developing common NECS classification, the NESTER project has screened Russian and European competences in the field of NECS technologies and mapped collaboration opportunities.

The building of the European and Russian NECS Network opened to researchers, industrials, and policy makers supports a constructive dialogue between Russia and the European Union. This creates new ideas, concepts and technologies that will catalyze knowledge transfer and allow to progress beyond the current NECS technological state-of-the-art. Thus, NESTER is a great opportunity to build industrial and research partnerships between Europe and Russia in the NECS field.

3 Identification of Four Industrial “Locomotive” Sectors with Highest Potential for European-Russian NECS Collaboration

The objective of the consortium was to analyze ten industrial sectors in order to select those with highest EU-Russian NECS collaboration potential.

The methodology of selection of 4 industrial “locomotive” sectors with highest potential to European-Russian NESC collaboration includes five main steps:

1. Constitution of the preliminary list of industrial sectors;
2. Organisation of 20 interviews with European and Russian specialists;
3. Analysis of over 20 relevant documents (reports, research agendas…);

4. Cross-mapping of the results obtained,
5. Selection of four “locomotive” sectors and their further analysis.

The following industrial sectors were analysed: (1) Telecommunication; (2) Smart manufacturing and logistics; (3) Bank and finance; (4) Transport (sea, land, public…); (5) Navigation; (6) Security; (7) Aerospace and avionics; (8) Energy production and distribution; (9) Health; (10) Multi-Media (game, photo, video), (11) Home centric design /smart home.

The analysis took into account the current status of the NECS technologies development and market trends in each of these sectors, as well as current scientific challenges, such as (1) Modeling, analysis and control design for multi-rate and multi-dimensional systems with structured interaction and large uncertainties; (2) Design of error correction codes for control purposes; (3) Event driven sensing and control for a more efficient energy management; (4) Concept of cooperative control in systems constituted by complex networks of autonomous agents; (5) Dynamic optimization of actuators and sensors positioning for performance optimization; (6) Multi – agent and dynamic aspects of the systems; (7) Generalization of problems arising in different application domains and their treatment on more fundamental level; (8) Big uncertainties in the systems description both for system identification and handling...

As a result of this work, the highest potential for EU-Russian NECS collaboration has been identified in the following four sectors: (1) Transport; (2) Energy; (3) Telecommunication; (4) Public infrastructure security (Fig. 1).

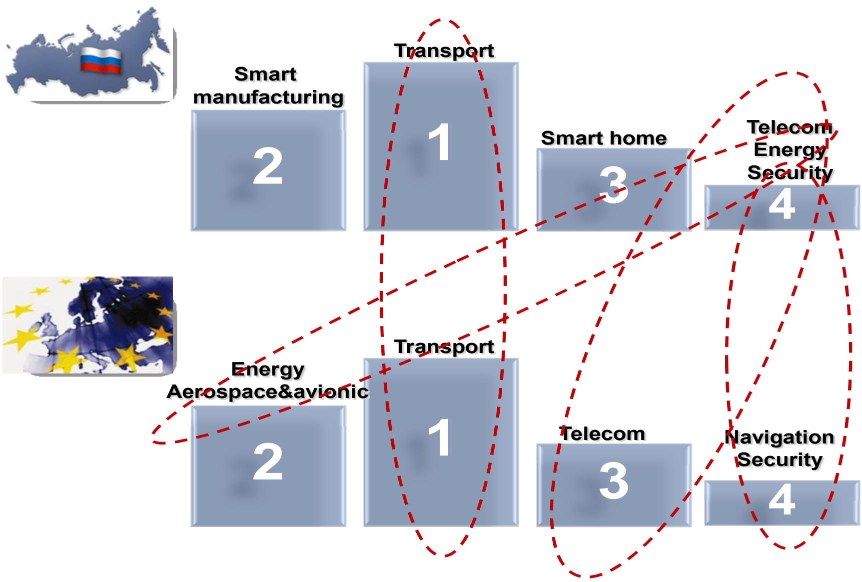

Fig. 1. Identification of four sectors with highest NECS EU-Russian collaboration potential: Russian and European visions.

4 Analysis of Four Industrial "Locomotive" Sectors with Highest Potential for European-Russian NECS Collaboration

Transport

The current state of practice exhibits the following weaknesses:

- Safety and Quality of service are considered separately;
- Model based design is performed but the information flow between abstraction levels is not standardized;
- Conflicting requirements are detected manually;
- Modular certification is not yet done;
- Product time-to-market pressure does formal methods not applicable in practice;
- Academia programs target low educational skills in formal methods (scientific vs. engineering approach).

Part of the gap existing between the current state-of-practice and state-of-the-art will be filled by the following achievements:

- New integrated platforms combining functional and non-functional properties
- New concepts of robustness and diagnosability
- Methodologies and tools coping with increasing system complexity
- Integration of formal methods and tools in development environments at different levels of detail according to domain/problem safety constraints.
- Modification of existing training practice

The European-Russian NECS cooperation should be structured in order to address these needs and shall provide techniques, methods and tool to improve safe mobility, to integrate diagnosability aspects in order to optimise life cycle costs and cover all transportation domains (eg. advanced driver assistance systems, advanced braking systems, flight management systems; power management systems, cost-efficient implementation…).

Main challenges include : (1) Improvement of cross fertilisation between transport domains to leverage globally the excellence of engineering of NECS for transportation; (2) Development time reduction despite increase of systems and software complexity; (3) Increasing quality and reliability of products and services with novel functionalities for end user.

Energy

Expected impact from EU-RU collaboration includes:

- Energy saving (low energy consumption)
- Distributed energy management & optimisation
- Energy efficiency
- Higher performances with reduced energy consumption (Energy/performance trade-off)

Main challenges include:

- Energy management especially for sensors, actuators and wearable or portable devices

- Design of energy autarkic mobile embedded devices
- Reduce emission and energy consumption through better situation awareness and improved vehicle global efficiency
- Reduce energy consumption of home, office and mobile equipment by reducing energy consumption
- Increased requirements for energy consumption for supporting security functions especially in battery-constrained embedded devices.
- Low energy/power electronics design with various requirements.

Telecommunication

The telecommunication sector is one of the most active in the Russian market. It is sufficiently financed and the use of NECS technologies and ICT in general, in this sector is really high and has excellent potential.

Expected impact from EU-RU collaboration includes:

- Development of new network interconnections which will allow better interoperability of services and forester the reduction of telecommunication costs and the introduction of new technologies.
- Creation of new software network applications which will enable interoperation across the EU-Russia ICT community
- Contributing to the promotion of common standards and certification methods
- Joint projects will help to increase efficiency and productivity of software development; therefore they will contribute to increasing the level of software technologies profitability
- Research and education networks: integrating russian researchers into European research community

The main challenge in the area of telecommunication is the provision of ubiquitous wireless connectivity under the constraints of minimum power consumption and limited bandwidth for real-time, secure and reliable communication. A particular focus appears in the development of systems with advanced properties:

- Development of both network architectures and protocols to enable connectivity and secure and dependable communications
- Tracking and wireless identification systems: These systems allow application and services based on the location of users and objects.
- Wireless Control Networks: These networks are constituted by sensors and actuators providing the infrastructure necessary for the realisation of ambient intelligence.
- Autonomous systems with context sensitive self properties that enable the efficient construction of self-organising embedded systems
- Interoperable service oriented architectures play an important role in order to get full interoperability among heterogeneous resulting in fully autonomous plug and play behavior
- Integration of heterogeneous communication technologies.

<u>Public Infrastructure Security</u>

Expected impact from EU-RU collaboration includes:

- Provide interconnected ES based solutions satisfying new needs (financial, medical, public safety, …)
- Create common standards for devices and protocols approaching the homeland security market
- Increase the market of Critical Infrastructure Protection
- Advanced security of the common transport system increasing business opportunities in all market domains
- Increase the market of methods ,tools and services to support cost effective processes for designing secure and dependable applications

Research challenges for joint European-Russian research in the domains include:

- Development of secure NECS at node level (secure software, scalability of the management of a large number of interacting devices, integrated security techniques that use modulation, encoding, encryption and interleaving technologies..)
- Secure real -time networking for NECS and critical infrastructures and secure, trusted, dependable and efficient data transfer (frequency agility and flexible transmission, flexible communication protocols providing trade off between performance (latency, jitter, throughput…), and security parameters (determinism, reliability, security….)
- Secure NECS services and applications (enhanced intrusion detection and prevention, large scale secure, dependable and resilient distributed NECS, continuous and upgradable security assessment of large scale distributed NECS, automatic security management in presence of limited resources of embedded nodes)
- Design tools and methodologies for large scale distributed NECS(support for security as built -in feature, develop generic modeling, simulation and analysis methodologies, develop tools to evaluate security, privacy and dependability/composability)
- Architectures, designs and processes (security/privacy specs: common framework, completeness evaluation, architectures: intrusion proof, upgradable, trusted, dependable, architectures for reliable fault tolerant and resilient ES

The following scientific topics are common for all of these sectors:

- Energy consumption management
- Development of dynamically reconfiguring architectures
- Languages and algorithms for the control of evolvable, distributed and adaptable systems
- System-level model-based tools and design processes
- Development of new test, validation and verification tools

All these R&D topics are transversal and are relevant for most of application sectors and therefore can be considered as priority R&D topics for European-Russian NECS collaboration.

5 Next Steps

The NESTER project will continue till Autumn 2009. The NESTER team will focus on condensing, evaluating and cross-comparing the information obtained from the previous phase, in order to:

- Develop a "competence map" of the most relevant technological areas for the European-Russian NECS R&D partnerships;
- Put in relation European and Russian research and industrials entities in order to encourage creation of partnership;
- Provide the recommendations to the European Commission on the strategic areas of cooperation between Europe and Russia in the NECS domain.

A workshop "Networked embedded and control systems technologies: European and Russian R&D cooperation" is taking place as a satellite event at ICINCO conference (Milan, July 2-5, 2009), where European and Russian researchers will have an opportunity to present their scientific results and discuss collaboration opportunities.

In summary, the NESTER project support and promote European competitiveness through strategic research partnerships with Russia in science and technology by engaging the best Russian scientists in the field of NECS to work with Europe.

Unıversal Wireless Sensor Networks Technology Platform and its Applications

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Abstract. Wireless sensor networks (WSN) are becoming more and more popular due to the growing area of their application. However, finding a single approach to different tasks is rather difficult, as each task has its own peculiarities. In this paper we propose a universal hardware platform as the first step to a quicker development of finished solutions based on WSN. We demonstrate the use of our platform in different types of applications.

1 Introduction

A wireless sensor network [8] is a distributed self-organizing network, consisting of miniature electronic devices, which exchange data through wireless channels. These devices (nodes) do not require special installation and do need to be serviced. The key feature of a sensor network is a possibility of retranslating messages from one node to another, which allows covering large territories without using high-power transmitters.

A common node of a WSN uses the ZigBee standard for wireless data transmission. The ZigBee is an international open standard, which was developed by the ZigBee Alliance. This standard allows using wireless connection with low-power consumption for different applications for monitoring and/or management. The Zigbee supports different network topologies, it has special network functions for self-organization as well as several methods to ensure secure transmission.

The most popular applications for WSN are different monitoring systems (e.g. security monitoring), different management and control systems (climate-control, home automation systems etc.), remote access control and positioning systems (tracking systems).

2 Universal Platform for WSN [1]

A proprietary universal wireless sensor network (WSN) platform was proposed, developed and released by the Wireless Sensor Networks Lab (VEK-21 Ltd.) of the Department of Computer Systems and Networks at Moscow State Institute of Electronics and Mathematics (MIEM) (Fig. 1) because now it’s necessary to use similar devices in different application areas. We also can save resources by using our platform because of the universality. It also allows us quickly change priorities of the system, which makes possible using our platform to achieve different goals by working with all popular COTS sensors.

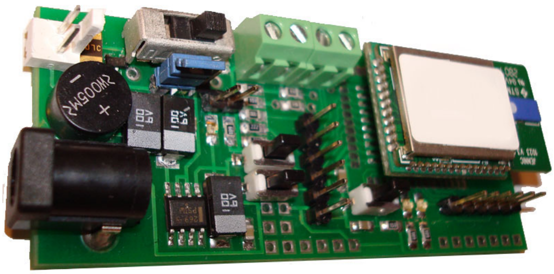


Fig. 1. Universal platform for WSN.

3 Energy Consumption and Lifetime

As sensor network applications depend so much on energy efficiency we want to analyze energy consumption and lifetime of our platform with microcontroller. Typical energy consumption for the sensor node: 37 mA – energy consumption for receiving, 37 mA – energy consumption for sending, 9mA – energy consumption for the CPU while transceiver is off, 0,002 mA – energy consumption in sleep mode. The time which is taken to wake from sleep mode is 15 ms and energy consumption 9mA (from the microcontroller data sheet):

$$9 \times 0{,}015 = 0{,}135 \text{ mAs (milli Ampere seconds).} \quad (1)$$

The microcontroller is running at a clock rate of 16MHz which means that a single cycle takes $1/10^6$ seconds. Let's assume that the average instruction takes 3 clock cycles and that we need 7,000 instruction for the measurement, for data processing and for preparing a packet for transmission over the network. This would result in

$$\frac{7000 \times 3}{16 \times 10^6} = \frac{21}{16 \times 10^3} = 1{,}312 \text{ ms.} \quad (2)$$

The amount of energy consumed at a current of 37mA would be:

$$37 \times \frac{21}{16 \times 10^3} = 0{,}0486 \text{ mAs .} \quad (3)$$

This means that the battery has to supply amount of energy which is equivalent to 1mA for 48.6ms.
And also the time to transfer data from I2C (for instance) is 5 ms with energy consumption – 9mA:

$$9 \times 0{,}005 = 0{,}045 \text{ mAs .} \quad (4)$$

Sending data takes place at a speed of 250,000 bits/s. We assume that our own measurements occupy 32 bytes of memory. A single bit takes 1/250000 seconds to be sent which sums up to:

$$32\ mA \times \frac{32 \times 8\ \ bits}{250000} s \approx 0{,}033\ \ mAs\,. \tag{5}$$

Time of calculating and sending took:

$$21/16 \text{ ms} + 1\text{ms}+15\text{ms}+5\text{ms} \approx 22{,}3\text{ms}. \tag{6}$$

This means that the node can sleep for about:

$$1\text{-}0{,}022 = 0{,}978 \text{ s}. \tag{7}$$

The node consumes:

$$0{,}978 \times 0{,}002 \approx 0{,}002 \text{ mAs}. \tag{8}$$

The total amount of energy is:

$$0{,}135+0{,}0486+0{,}045+0{,}033+0{,}002 \approx 0{,}262\text{mAs}. \tag{9}$$

We assume the AA battery delivers about 2300 mAh:

$$\frac{2300 mA \times 3600 s}{0{,}262} \approx 31{,}6 \times 10^6 s \text{ (365 days)}. \tag{10}$$

4 Our Projects based on WSN

We used our platform in implementation of some “standard” WSN applications as monitoring systems, SCADA and remote identification systems. Also some “unusual” applications to WSN technology were demonstrated built around proposed platform. These include autonomous system of secured wireless audio transmission and a wireless real-time 3D visualization system (WSN-based Motion Capture application for virtual environment simulation).

Security Monitoring System [3]. Security monitoring system based on WSN, which can work with different security sensors and integrated with GSM, can be used with existent security systems to increase reliability, it’s easier to install this system and it uses cheap data transmission channel than, for instance, Wi-Fi.

It consists of hardware (WSN devices) and special software (for devices and PC), which allows you to control object status through Internet.

Examples of using: private home security systems, offices security system.

Climate Control System (Home automation system) (temperature, illuminance, humidity) [4]. Climate control system based on WSN is a multifunctional system which gives us possibility to work with different electronic devices (air conditioners, light systems etc.) and might be integrated with other systems to increase efficiency of using electricity, water etc.

The main difference of this system from other monitoring applications is the use of special profiles that allow for using diverse devices with diverse algorithms. It also can use GSM channel.

Examples of using: climate control systems, home-automation systems etc.

Remote Identification System. Mobile objects wireless identification.

Fig. 2. Wearable sensor for wireless remote identification system.

We've developed a prototype of the system, which consists of different number of sensors. Each sensor measures power level of radio signal and sets up critical power level. If there is pair of sensors – one of them (base station) always measure power level, other – sends testing data packets. When someone is trying to walk between pair of sensors, one of them receives weak radio signal compare it with critical level, and if power level of the signal is less than critical level it sends interruption information to the central server and turns on alarm system. But if there is someone with special WSN device (Fig. 2) is trying to walk between pair of sensors, our system analyses situation and position of that person with WSN device and if that WSN device is registered at one of the sensors from that pair, system make a decision that there is no interrupt.

Base stations can be easily connected to GSM-channel or Internet.

Examples of using: security systems, special exhibition systems, home-automation systems.

Intellectual System of Wireless Audio Transmission [5]. This system is our first attempt of using WSN in "unusual" way – multimedia transmission. We have developed a prototype of a system, which will provide wireless access to different services using a WSN.

It consists of several base blocks (stations) and portable devices (handsets). A base block can be connected to a public telecoms network (throw special "bridge"), internet (VoIP service) or to a mobile phone. A portable device is a low-power handset using a 10 mW transmitter. Each element of this system is a node of a WSN. Therefore it contains an internal processor, which allows local data processing. For example, when a person talking on the phone listens to his (her) interlocutor, the data from his handset is not transferred thus minimizing the amount of traffic in the WSN.

General features:

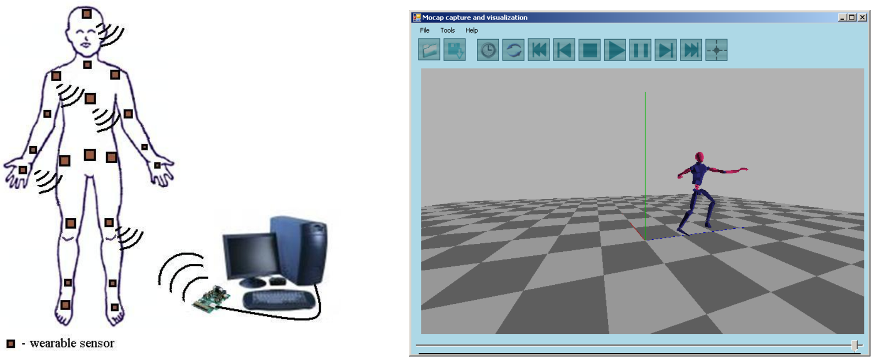
- base station translates incoming calls to portable devices;
- portable devices can accept incoming calls, close connection, call a Skype-

account;
- 400 meters distance between base station and portable devices;
- Internet-radio translation with reasonably good quality – up to 100 meters distance.

Bodynet System [7]. A wireless bodynet system consists of multiple wearable sensors and a central stationary module, each being a node of a sensor network. This system has two main applications – telemedicine and motion capture. The first one has focus on remote health monitoring of people with chronic diseases, patients in hospitals and elderly people. The task is solved with the use of sensors that measure blood pressure, pulse rate and other vital parameters.

A wireless tracking system [2] makes it possible to transform real movements of a person into a virtual 3D environment and visualize them in real-time. This is actually a first completely wireless system, which means that every sensor has a radio transmitter attached to it. In comparison, most existing solutions have a single communication module, which is usually placed in a rucksack, and all the sensors are connected to it with the help of wires. The system hardware consists of many end devices equipped with sensors for capturing acceleration and rotation of a certain part of a human body. A central unit collects all the data and transfers it to the computer, which performs all calculations and visualization. To measure all parameters we use MEMS-based accelerometers and gyroscopes, which are notable for their miniature size, low costs, low energy consumption and high performance. Apart from visualization, our software can also save all captured information for its future analysis in simulation programs, e.g. Autodesk 3ds Max, Maya, Blender.

The main applications for the motion capture system include:
- interface to 3D virtual reality;
- research in human-computer interaction;
- remote control of robots and manipulators with real movements;
- motion capture systems for character animation in films, games or television studios.



a) b)

Fig. 3. Wireless bodynet system.

A combination of different wearable sensors can be used for efficient control of police or fire squads during dangerous operations.

5 Future Work

We're planning to continue our work and we're going to develop:

- real time virtual reality system which will provide all possibilities of computer-human interface interaction;
- full home-automation system;
- sports-monitoring system;
- conveyor monitoring system (getting and analyzing all information about conveyor and environmental influence on it);
- home gaming systems, which will provide real interaction with the game;
- professional motion capture system for movie-making companies.

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Information and Telecommunication Intellectual Monitoring Technology and System for Complex Technical Objects under Dynamic Conditions in Real Time

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Abstract. The aim of the investigation is to develop methods, models and algorithms of synthesis and intellectualization of monitoring technology and system oriented to concurrent on-line user software assurance for all sorts of measuring information specifying states of complex technical objects under dynamic conditions in real time. This aim should be achieved by here suggested artificial intelligent information technology. The basis of this artificial intelligent information technology is flow computing models exploitable by state hipping (constraint programming) in real time and in territorially distributed computing network. At the same time each network node represents artificial intelligent agent. Furthermore, the problem of efficient information transmission between the complex technical objects and monitoring systems by means of contemporary wireless technologies is considered.*

1 Introduction

Many complex technical objects (CTO) are remotely controlled [1, 2, 3]. Operators (dispatchers) receive information about current CTO states in a form of telemetry. Complication of modern technical objects is resulted in expansion of their parameters to be measured and controlled. Today the number of such parameters can achieve several hundreds or thousands for various classes of technical systems [4, 5]. Usually CTO state monitoring is not automatized completely. Thus, operators receive semantic information about some elements of CTO rather than information characterizing integral CTO state. To estimate CTO state the operators should be able to analyze various context conditions of interaction between CTO elements and subsystems. There are no universal methods and technologies for solution of the above-mentioned problems [6, 7]. Existing program systems for gathering, processing, and analysis of CTO telemetry usually depend on characteristics of particular control objects and is

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not adaptable to undesired alteration of objects' structure. The methods and tools for construction of monitoring algorithms and systems are very specific and can be used in narrow domains. The problems of CTO monitoring were investigated rather thoroughly in USA and in Russia (former USSR), first of all for aerospace and electric power systems [7]. The most important results were received in this domain. However, semantic interpretation of integral CTO state remains the prerogative of operators.

Other feature of modern monitoring system for CTO (MS CTO) is the changeability of their parameters and structures as caused by objective and subjective reasons at different stages of the MS CTO life cycle. In other words we always come across the MS CTO structure dynamics in practice. Reconfiguration is a widely used variant of the MS CTO structure control. Reconfiguration is a process of the MS CTO structure alteration with a view to increase, to keep, or to restore the level of MS CTO operability, or with a view to compensate the loss of MS CTO efficiency as caused by the degradation of its functions. But, unfortunately, now MS CTO reconfiguration is not tied in with monitoring and control processes [2, 8 9].

So the following main problems complicate formalization of state-monitoring process and systems under dynamic conditions now: firstly, the rules of CTO interaction cannot be discovered and described in a simple way, secondly, there are no universal methods of interaction representation for a broad class of objects and finally, there are no universal methods and models of MS CTO optimal reconfiguration under dynamic condition [8,10]. We consider that description of monitoring procedures and system should be based on system methodology and modern conception of intelligent information technology in order to fit various classes of CTO. This description must be clear to different specialists implementing general rules of monitoring to particular objects. Our investigation contributes to a solution of the fundamental problem lying in synthesis and intellectualization of monitoring and control processes for complex technical objects under dynamic conditions via multiple-model complexes and multicriteria approaches.

So the first aim of our investigation is to develop methods, models and algorithms oriented to concurrent on-line user software assurance for all sorts of measuring information (information fusion) specifying states of complex technological process (situation assessment) at all phases of complex technological process life cycle and control function in real time. The second aim of our investigation is a development of models, methods and algorithms for real-time monitoring system reconfiguration under the presence of structure degradation.

Additionally, we develop simulation and analytical models as well as conduct testbed experiments for the analysis of the efficient monitoring information transmission between the MS and CTO. We believe that contemporary wireless communication technologies should be used for this purpose, especially for the cases when CTO are located distantly and in the regions difficult of access from the MS CTO. Due to the requirement of monitoring in real-time, communication technology should be chosen and configured appropriately in order to provide desired time-probabilistic characteristics of the transmission. This problem becomes challenging in wireless environment, where characteristics of the communication channel may significantly vary in time. Therefore, the third aim of our investigations is to conduct performance analysis and optimization of contemporary wireless protocols and standards.

2 Investigation Overview and Related Work

Analysis of a market dealing with modern software complexes oriented to monitoring automation for the states of complex technological processes shows that the existing software complexes have narrow application scopes strictly specified by controlled objects; they also have limited capacities for adaptation to environmental disturbances. This is why there exist many monitoring applicable software complexes having contiguous functionality and differing in organizational methods of computational processes, and in used operational environment. As an example, three directions in practical implementation of analyzed software complexes could be mentioned [4, 6, 11]:

1. Widely applied real time dynamic expert systems like G2 (software firm Gensym, USA), RT Works (software firm Talarian, USA), COMDALE/C (Comdale Techn., Canada), COGSYS (SC, USA), ILOG Rules (ILOG, France) are worth mentioning.

2. The results received through application of a so-called theory of unfinished computing based on constraint programming methods and the theory of multi-agent artificial intelligent systems. The following software packages demonstrate some advantages of this approach: integrated software product SPRUT (OCTORUS) and intelligent mathematical problems solver UniCalc.

3. The third direction incorporates so-called data fusion and control systems like SCADA-systems (Supervisor Control and Data Acquisition – data fusion and control system, operator's interface, etc.). Well known products: Genesis, IsaGRAF, Trace-Mode could be good examples of this development line.

A thorough study of theoretical results showed that there exists a great number of publications in the area of measuring information processing and analysis methods, on the other hand, research in the areas of design automation for monitoring software complexes, development of techniques allowing to arrange for parallel processing and analysis of measuring information in computing environment with changing structure are poorly reflected in literature [12, 13, 14]. The impact of types and structures of the processed information on the composition and structure of the considered software complexes is also not well investigated. The above-mentioned circumstances become important if to account for the fact that a certain successful experience in practical realization of software complexes for monitoring of states of complex technological process is based upon the better solutions of structural and functional as well as organizational problems dealing with the synthesis of software complexes. However, experimentally received positive results in software complexes for monitoring creation and implementation are of the heuristic nature and are based on intuition and experience of developers; their elaboration also requires time-consuming, labor-intensive experiments at the synthesis stage. Moreover, the existing methodology and software do not meet certain requirements for embedded special software of geographically distributed real-time complex technological systems with variable structures [14].

Development of flow-oriented knowledge-representation models, methods, and algorithms for monitoring and control of objects and for reconfiguration of monitoring system plays the important role in decision of the main problems of synthesis and intellectualization of monitoring technology and system for complex technical objects under dynamic conditions in real time. This task includes the following subtasks:

- development of methodological basics for accumulation and use of ill-formalized knowledge about states of complex technical objects under "rigid" constraints (for example, real-time operation mode and recurrence of computational processes) applied to both process of knowledge accumulation and process of state estimation; development of methodological basics for structure reconfiguration of objects and of monitoring system (first line of investigation);
- development of model-and-algorithmic basics for analysis and synthesis of reconfigurable monitoring system (second line of investigation);
- development of new information technology for creation and maintenance of monitoring software and software prototype; approbation of the technology in typical application domains (third line of investigation).

As a relatively separate subtask we emphasis the problem of performance evaluation of wireless communication protocols by means of analytical models, simulations and test-bed experiments. We consider the following contemporary wireless technologies IEEE 802.11 Wi-Fi, IEEE 802.16 WiMAX, IEEE 802.15.14 ZigBee etc. Our objective is to identify, design, test and evaluate wireless network technologies and architectures, which are able to interconnect CTO in an energy-efficient, secure, robust, and powerful way to MS CTO under dynamic conditions to guarantee real-time stable monitoring process. Mechanisms based on the conceptions of cognitive network for stable and energy-efficient operation of wireless mesh and sensor networks are required.

Cross-layer design conception is becoming increasingly important in wireless networks. They abuse the traditional layered approach by direct communication between nonadjacent layers or distribution of internal information among layers [21]. Cognitive radio is a paradigm in which either a network or a wireless node changes its transmission or reception parameters to communicate powerfully avoiding interference [22]. The cognitive radio concept is extended also to higher protocol layers, what results in the introduction cognitive networks [23]. A cognitive network can recognize current network conditions and adapt accordingly. The network can learn from these adaptations and use them to make decisions in the future.

Therefore, the forth line of investigations is the development of new protocols and architectures based on the above paradigms as well as performance evaluation of internationally standardized protocols.

3 The Results of Investigation

Within the first line of investigations the following scientific and practical results have been obtained by now.

It was established that the change from an automated processing of measuring information to a computer-aided analysis of received materials involves semantic aspects of data representation in place of syntactic ones. Thus, the information about control objects should rather be regarded as a set of interrelated parameters jointly characterizing objects' technical state than a simple collection of measurements. This provided for a conclusion that the metric-space concepts, typically used in simple monitoring problems, are weak and not suitable for our purposes, hence more general constructions should be used.

It was proved that the parameters of objects' technical states can be described via a system of open sets forming a base of topology. It was assumed that the set of parameters has a topological structure. Thus a system of neighborhoods (meeting the axioms of topological spaces) was established for each element. The notion of a technical state was worked out. By the technical state we meant an abstract collection of data including whole information both about object's current attributes and the state of computations within the monitoring process. This view lets optimize computations in order to receive monitoring results in real time. The following basic statements were proved: the whole set of technical-state parameters constructed trough the proposed model of knowledge representation is a lattice or a lattice ordered set; if the set of technical states have the greatest element and the least element (defining the initial data and the results correspondingly), then a complete lattice (an algebra over the set) can be formed via a construction of additive and multiplicative lattices; necessary and sufficient conditions for topology base existence were obtained for the set of technical parameters. The last result is very important, as the constructed topology is used for whole description of possible technical states and for planning of states analysis (for construction of computational scheme).

Moreover w*ithin the first line of investigations* we have been obtained the following the results [18, 19, 20]:

Formal description of all possible kinds of controlled states (assessed situation) accounting for their adequacy to actual actions and processes on controlled object caused by application of different mathematical apparatus for various functional objects. Multi-model formalization intends for describe actions and processes on the controlled object;

New integrated methods of program synthesis for automatic analysis (AA) of measuring information (MI) about CTO states were worked out. These methods, as distinct from known ones, give an opportunity of, firstly, interactive intellectual processing of data and knowledge about CTO states for different physical properties (for example, functional parameters, range parameters, signal and code parameters, and integrated parameters) and for different forms of states description without reference to their physical features and, secondly, automatic generation of alternative program schemes for MI analysis according to the objectives of CTO control under the presence of changing environment;

New algorithms of automatic synthesis of AA MI programs were proposed for poly-model description of monitoring processes via attribute grammars, discrete dynamic systems, and modified Petri nets. Applying of polytypic models resulted in adequate adaptation of the algorithms to different classes of CTO. Another distinguishing feature of the algorithms lied in application of underdetermined calculation and constraint-driven programming and provided that CTO states could be estimated rather adequately even if some parameters were omitted and the measuring information was incorrect and inaccurate;

A general procedure of automatic (computer-aided) synthesis of CTO monitoring programs was developed. This procedure includes the following steps.

The 1st step. Description of conditions and constraints for the problem of AA MI programs synthesis via a special network model connecting input data with goals. An operator (he need not be a programmer) uses a special problem-oriented language to execute this step.

The 2nd step. Automatic existence analysis for a solution of AA MI problem that is defined via a formal attribute grammar.

The 3rd step. If the solution exists then the alternative schemes for AA MI programs are generated and implemented in a special operational environment (problem solver of the CTO monitoring system).

The main advantage and substance of the proposed procedure is simple modeling of MI sources (models generation) that can be performed by a non-programming operator in the shortest time and the real-time implementation of the intellectual methods and algorithms of MI processing and analysis for arbitrary structure of the measuring information.

The proposed methods of monitoring automation and modeling let switch from heuristic description of the telemetry analysis to a sequence of well-grounded stages of monitoring program construction and adaptation, from unique skills to unified technologies of software design. These methods are based on a conclusion that a functional description of monitoring process is much less complicated than detailed examination of software realizations. Consecutive specification of software functions is the ground of technologies to be used for creation of monitoring systems. The suggested technology of continuous design process includes such well-known phases as new proposal phase based on special operational environment [18, 19, 20].

Within the second line of investigations the following scientific and practical results have been obtained by now [10].

System analysis of the ways and means to formalize and solve the problem of the control over structure dynamics of monitoring system (MS) servicing CTO under changing environment was fulfilled. It was shown that the problems of structure-functional synthesis of monitoring systems and intellectual information technologies as applied to complex technical objects and the problems of CTO structure reconfiguration are a special case of structure-dynamics control problem. Other variants of structure-dynamics control processes in MS are: changing of MS objectives and means of operation; reallocation of functions, tasks, and control algorithms between MS levels; control of MS reserves; transposition of MS elements and subsystems.

The basic concepts and definitions for MS structure-dynamics control were introduced. It was proposed to base formulating and solving of the structure-dynamic control problems on the methodologies of the generalized system analysis, the modern optimal control theory for the complex systems with reconfigurable structures and artificial intelligence. The stated methodologies find their concrete reflection in the appropriate principles. The main principles were marked out: the principle of goal programmed control, the principle of external complement, the principle of necessary variety, the principles of poly-model and multi-criteria approaches, the principle of new problems.

During our investigations the main phases and steps of a program-construction procedure for optimal structure-dynamics control in MS were proposed. At the first phase forming (generation) of allowable multi-structural macro-states is being performed. In other words a structure-functional synthesis of a new MS make-up should be fulfilled in accordance with an actual or forecasted situation. Here the first-phase problems come to MS structure-functional synthesis.

At the second phase a single multi-structural macro-state is being selected, and adaptive plans (programs) of MS transition to the selected macro-state are constructed. These plans should specify transition programs, as well as programs of stable MS operation in intermediate multi-structural macro-states. The second phase of program construction is aimed at a solution of multi-level multi-stage optimization problems.

One of the main opportunities of the proposed method of MS SDC program construction is that besides the vector of program control we receive a preferable multi-structural macro-state of MS at final time. This is the state of MS reliable operation in the current (forecasted) situation. The combined methods and algorithms of optimal program construction for structure-dynamics control in centralized and non-centralized modes of MS operation were developed too.

The main combined method was based on joint use of the successive approximations method and the "branch and bounds" method. A theorem characterizing properties of the relaxed problem of MS SDC optimal program construction was proved for a theoretical approval of the proposed method. An example was used to illustrate the main aspects of realization of the proposed combined method.

Algorithms of parametric and structural adaptation for MS SDC models were proposed. The algorithms were based on the methods of fuzzy clusterization, on the methods of hierarchy analysis, and on the methods of a joint use of analytical and simulation models

The SDC application software for structure-dynamics control in complex technical systems was developed too.

Within the third line of investigations the following scientific and practical results have been obtained by now: the pilot versions of computer-aided monitoring system (CMS) for CTO states supervision (in space systems and atomics) work in network of IBM/PC-compatible computers; it uses special operational environment [18, 19, 20], real-time database management system, multi-window interface, and programming language C/C++.

The prototypes of CMS belong under the class MMI/CACSD/SCADA/MAIS (man-machine interface/ computer-aided control system design/supervisory control and data acquisition/ multi-agent intellectual system).

Within the forth line of investigations the following scientific and practical results have been obtained by now: sufficient number of different analytical and simulation models for contemporary wireless networks, methods to compute time-probabilistic characteristics and to optimize the performance of these networks (e.g. [24], [25]).

4 Conclusions

Suggested intelligent information technology will allow reducing costs of complex technological process underlying the elaboration of a system for monitoring and control of states of complex technological process, and will facilitate significantly its further modification. At that systems for real time monitoring of states of complex technological process acquire principally new qualities. Particularly they allow monitoring in real time the states of complex technological process characterized by great number of measured parameters under structure reconfiguration of the controlled objects. The proposed information technology rises the automation level of complex technological processes control, increases possibilities of control of objects under degradation of their structures, improves reliability and efficiency of control processes, increases possibilities of early detection of various technical faults as well as timely prediction of catastrophes allowing to make right decision and to undertake appropriate prevention measures. The proposed approach to the problem of MS structure reconfiguration control in the terms of general context of MS structural dynamics control enables the following: common goals of MS functioning can be directly linked with those implemented (realized) in MS control process; a reasonable decision and selection (choice) of an adequate consequence of problems to be solved and operations to be fulfilled related to structural dynamics can be made (in other words, MS control method can be synthesized and developed); a compromise(trade-off) distribution of a restricted resources appropriated for a structural dynamics control can be found without additional expenses.

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Optimization of Digital Wireless Transceiver Embedded System Built on Xilinx FPGA

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Abstract. FPGA is becoming the most popular technology for developing new wireless systems. It makes design flow easier to realize even in a small company or academic institution with limited resources (human and/or budget). But when system is ready to enter production stage some drawbacks may stop its further progress. A short description of the wireless transceiver project for mobile vehicles is presented. Drawbacks are highlighted. The most critical of them, that reduces market attractiveness, is cost. To reduce cost a decision has been made to replace expensive Virtex4 by cheaper Spartan3 FPGA. This required making some changes in architecture. But the most part of previously created software and firmware were reused in new design.

1 Introduction

Today we can see a rapid growing market demand of high-rate wireless communication lines for mobile vehicles: cars, trains, ships, even more for unmanned vehicles. This communication line could be used to create ad-hoc type networks. Typical requirements for wireless transceivers of this communication line are following:

- Data rate up to 10 Mbits per second for uplink (to base station or control site);
- Data rate up to 100 kbits per second for downlink (control commands to mobile vehicle);
- Traffic types: high resolution color video, voice, control commands and telemetry;
- Vehicle speed from 0 up to 1000 km/h.

Existing and successfully selling technologies such as WiFi and WiMAX were tried to solve the problem but they do not fit requirement and are unusable. Fast movement of communicating objects causes OFDM signal structure totally degraded. Mobile WiMAX is not stable for today also. These technologies are too complex and have excessive functionality for asynchronous managed or ad-hoc networks. Furthermore implementations of WiFi and WiMAX modules presented at the market do not allow measuring power and other characteristics overload baseband and network layer logic required for cross layer optimization.

Worth mentioning that flexible and energy efficient ad-hoc networks needed cross layer interaction, another words, tight communication between baseband processing and software implementing network management should be enabled.

The challenge we have stated to ourselves is to create wireless digital communication line for mobile vehicles with parameters and characteristics described above.

2 Existing System

There is a short description of currently existing wireless transceiver that was designed at our labs. The transceiver uses super heterodyne architecture that implemented in two parts: analogue front-end and digital baseband processing coupled with control unit based on embedded system with embedded Linux OS running on PowerPC 405 CPU (Fig.1).

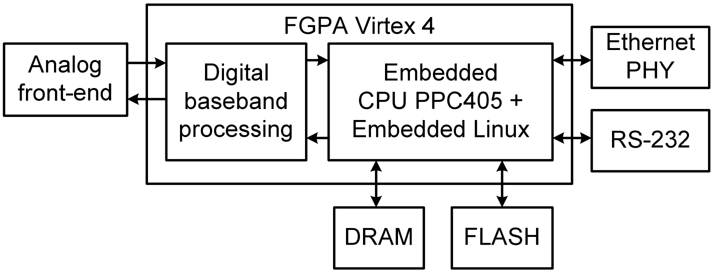

Fig. 1. Wireless transceiver embedded system.

Analog front-end made as digital-IF heterodyne architecture [1] and is presented on Fig.2. This architecture has some advantages and disadvantages:

Pluses.

- only single channel ADC and DAC are used,
- quadrature modulation/demodulation is in digital domain,
- absence of quadrature imbalance due to demodulation made in digital domain.

Minuses.

- high sample rates and dynamic range of AD/DA converters is required to digitize IF,
- extra band pass filtering stage (BPF2) for image rejection,
- reduced ability of miniaturization due to a big amount of external components.

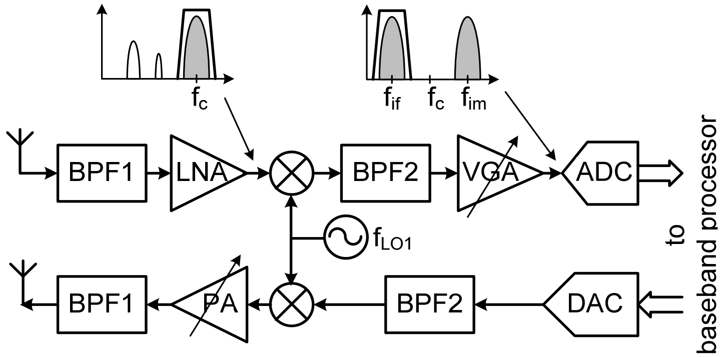

Fig. 2. Wireless transceiver analog front-end. f_c – carrier frequency; f_{if} – intermediate frequency; f_{im} – image center frequency; f_{LO1} – local oscillator frequency.

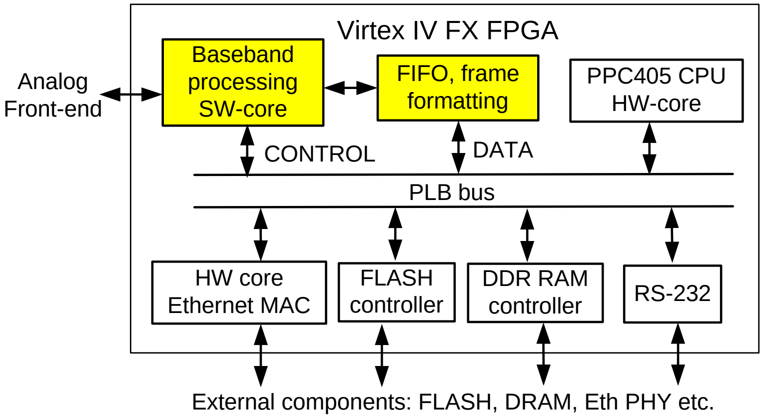

Fig. 3. Existing embedded system architecture for wireless transceiver based on Xilinx Virtex IV FPGA.

Main drawback of described transceiver is its cost. Main part of the transceiver is a Virtex 4 FPGA. This FPGA is very comfortable for engineer and is as flexible as it allows changing design and debugging in a very simple way. However, the price of Virtex 4 is few thousand dollars and it really disappoints potential customer.

Another one disadvantage is high sample rates of converters and additional bandpass filter stage for image rejection. The SAW filters are used in this architecture. They are expensive too and can not be used in reconfigurable SDR.

3 Modified Transceiver Architecture

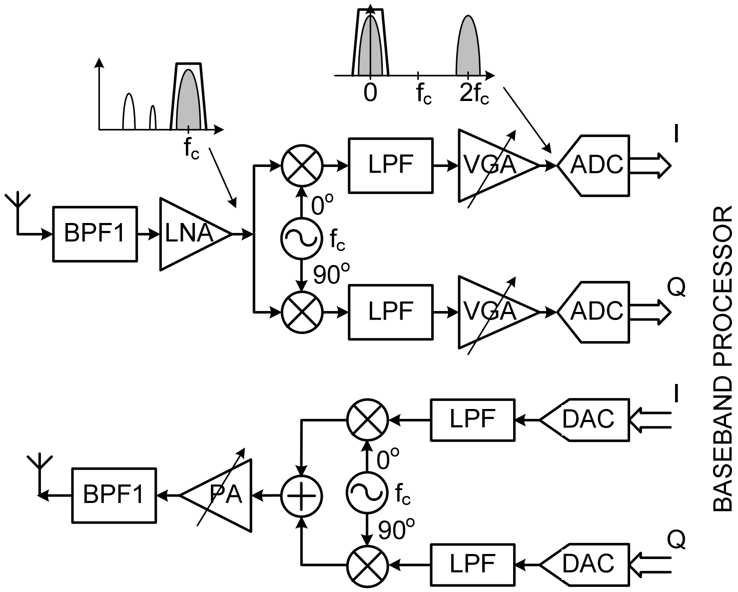

Fig. 4. Modified analog front-end architecture.

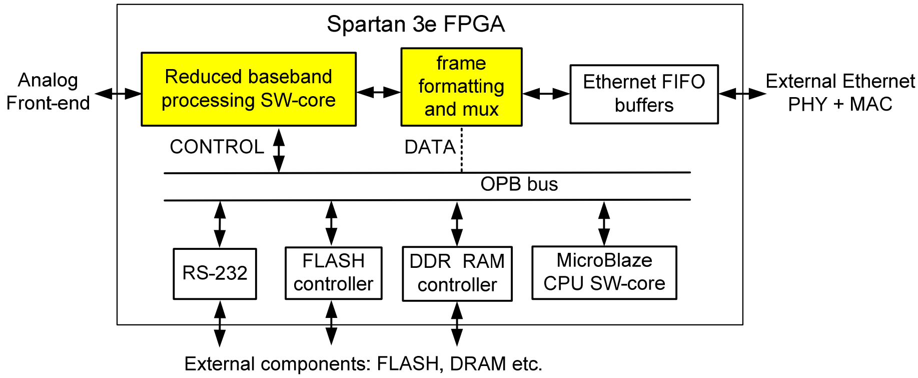

Fig. 5. Modified embedded system architecture for wireless transceiver.

As it can be seen after replacement of Virtex4 FPGA with Spartan3 embedded processor and peripheral bus are also changed from Power PC 405 hard-IP and PLB-bus to MicroBlaze soft-IP and OPB-bus. Fortunately there is Linux kernel and drivers for both architectures [2]. But we need to find proper Linux distribution for embedded Xilinx MicroBlaze CPU. A number of Linux embedded distributions are presented in Table 1.

Table 1. Embedded Linux Distributions supporting Xilnx FPGA embedded CPUs.

Name	URL	Supported CPUs	License	Real-time
ELDK	www.denx.de	PPC only	free	soft
Petalinux	www.petalogix.com	MB only	free	?
BlueCat	www.lynuxworks.com	both	commercial	soft/hard
MontaVista	www.montavistalinux.com	both	commercial	soft/hard
WindRiver	www.windriver.com	both	commercial	soft/hard

As we decided too reduce cost we refused commercial Linux distributions such as BlueCat, MontaVista and WindRiver. PetaLinux is the best choice for us. Unfortunately it does not have any real-time support. Possible solution is to use another SW platform, Quantum Leaps [3], for example. But major code revision will be required even more totally new code should be created.

Currently a novel ad-hoc network architecture is under development. One of the challenges we faced is to reduce real-time requirements of this network protocol. To determine what degree of real-time is requred the ad-hoc network immitation should be evaluated. This network can be created with cheap Spartan FPGA based development kits like “Spartan 3A Starter Kit” [4] with embedded PetaLinux onboard.

4 Conclusions

Two different wireless transceiver architectures are described. The first one has critical drawbacks that blocked successful entering to the market. The main core of the transceiver is an embedded system built on FPGA. The solution is to replace more powerful but expensive Virtex4 by Spartan3 FPGA. Such replacement requires to make some architecture improvements that were found and now are being implemened. Also a novel methods and algorithms of ad-hoc networks managing can be verified on this platform. We expect that this architecture with novel ad-hoc networking will help us to start commercial producing and distribution.

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4. Spartan-3A Starter Kit, http://www.xilinx.com/products/devkits/HW-SPAR3A-SK-UNI-G.htm

Modeling and Model-based Control of Homogeneous Charge Compression Ignition (HCCI) Engine Dynamics

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Abstract. The Homogeneous Charge Compression Ignition (HCCI) principle holds promise to increase efficiency and to reduce emissions from internal combustion engines. As HCCI combustion lacks direct ignition timing control and auto-ignition depends on the operating condition, control of auto-ignition is necessary. Since auto-ignition of a homogeneous mixture is very sensitive to operating conditions, a fast combustion phasing control is necessary for reliable operation. To this purpose, HCCI modeling and model-based control with experimental validation were studied. A six-cylinder heavy-duty HCCI engine was controlled on a cycle-to-cycle basis in real time using a variety of sensors, actuators and control structures for control of the HCCI combustion in comparison. The controllers were based on linearizations of a previously presented physical, nonlinear, model of HCCI including cylinder wall temperature dynamics. The control signals were the inlet air temperature and the inlet valve closing. A system for fast thermal management was installed and controlled using mid-ranging control. The resulting control performance was experimentally evaluated in terms of response time and steady-state output variance. For a given operating point, a comparable decrease in steady-state output variance was obtained either by introducing a disturbance model or by changing linearization point. The robustness towards disturbances was investigated as well as the effects of varying the prediction and control horizons. Increasing the horizons had a very limited effect on the closed-loop performance while increasing the computational demands substantially. As shown in the paper, modeling constitutes a necessary element for embedded networked control design applied to HCCI combustion engine design.

1 Introduction

The motivation for studying the homogeneous charge compression ignition (HCCI) engine principle is the promise of low levels of exhaust emissions with regards to NO_x, while still retaining an acceptable overall efficiency [15]. Pioneering efforts towards this new engine principle—also called controlled auto-ignition (CAI)—were reported in [42, 57, 21, 14, 30]. Depending on the purpose, modeling of HCCI engine dynamics may exhibit different complexity and format such as:

– Multi-zone models including chemical kinetics to simulate engine operation in a large operating range;

- Multidimensional CFD for optimization of fuel injection and combustion chamber design;
- Single-zone reduced-order dynamic models (for model-based control).

A significant challenge with HCCI is the control of the combustion phasing, this is essential in order to control the load, to obtain low fuel consumption and emissions. For closed-loop control of the combustion phasing, feedback signals are necessary and in-cylinder pressure feedback is, perhaps, the most straightforward approach. In practice, the crank angle α of 50% burnt fuel (CA50 or α_{50} or θ_{50}) has proved to be a reliable indicator of on-going combustion [41, 6]. In closed-loop control of an HCCI engine, several means to actuate the combustion phasing have been tested—*e.g.*, dual fuels [41, 6, 8], variable valve actuation (VVA) [1, 8], variable compression ratio [15, 27], and thermal management [38, 28].

For control design purposes and embedded control design exploiting information from networked sensors, appropriate models and system variables useful for feedback control are needed. Previously, it was shown that physical modeling and system identification can be used to obtain low-complexity models of the HCCI dynamics [58, 7, 51]. For closed-loop HCCI engine operation, it was reported that the combustion phasing can be stabilized by means of a PID controller [41]; LQG control [58]; and MPC control [8].

A fast and robust control of α_{50} appears to be necessary in order to stabilize HCCI engine control. It is also desirable that the load, peak cylinder pressure, peak rate of cylinder pressure and emissions are controlled simultaneously. This is a multi-input multi-output (MIMO) control problem where the controller has to be able to handle constraints on several variables. In a comparison among several control methods, it will be demonstrated that Model Predictive Control (MPC) control could be used with favorable properties [4, 35]. All of the actuators suggested have control constraints and MPC has the benefit of explicitly taking the constraints into account.

Whereas monitoring of α_{50} or other methods to sense on-going combustion for feedback control of an HCCI engine all rely on pressure sensors, these sensors may be expensive. One candidate to replace pressure sensors is the use of electronic conductive properties for the reaction zone [24]. This phenomenon is called ion current for which no expensive sensor is needed. Ion current has been successfully used in closed-loop control of SI engines [20]. The basic principle of ion current sensing is that a voltage is applied over an electrode gap inserted into the gas volume (combustion chamber) [24]. The common belief so far has been that ion current levels are not measurable for the highly diluted HCCI combustion. However, a recent study shows that it is not the dilution level in itself but the actual fuel/air equivalence ratio ϕ which is an important factor for the signal level [22, 58].

In this paper, we will report new modeling and experimental results on HCCI control, complementing our previously published results on control of a six-cylinder heavy-duty engine, evaluating a variety of control methods (MPC and PID) and actuators (VVA, dual fuel), and experimental results on HCCI control of a single-cylinder heavy-duty engine evaluating a variety of sensors (in-cylinder pressure, ion current) [8, 9, 7].

The purpose of this paper is to provide a survey of state-of-the-art HCCI engine modeling with particular attention to control-oriented modeling relevant for networked embedded system design. The structure of the paper is the following: An overview of HCCI modeling is given with particular emphasis on modeling suitable for model-based control, followed by a model-based control description, discussion and conclusions.

2 HCCI Modeling

There are two often used methods to obtain models of HCCI engine dynamics suitable for control; physical modeling [51] and modeling by means of system identification [7–9]. Physical modeling based on conservation laws and chemical kinetics has attractive intuitive component-based features but suffers from complexity issues with adverse effects in application. Whereas system identification has proved to be a very effective modeling tool for prototyping, it may provide results hard to interpret from a physical point of of view.

The purpose of modeling has an obvious influence on focus and the complexity of modeling [33, 19]. As modeling and simulation may easily become too detailed and computationally expensive to serve purposes of model-based control, low-complexity models and reduced-order models become relevant. A minimum requirement of physical modeling is explanation of the nature of the in-cylinder pressure traces where adiabatic compression combines with fuel-dependent auto-ignition [43], [10], [23]. In previous work, modeling choices involve aspects of chemical kinetics, cycle-to-cycle coupling, in-cylinder concentrations of reactants, wall temperature dynamics, pressure dynamics, and auto-ignition timing.

Modeling details fall into categories of single-zone models, multi-zone models, multidimensional computational fluid dynamics (CFD) models, sometimes combined with exosystem simulation on the form of stochastic disturbances, load modeling, sensor modeling. Both physical aspects and operational aspects require attention. Shaver *et al.* singled out six distinct stages in modeling of HCCI engine operation—*i.e.*, induction, compression, combustion, expansion, exhaust and residence in the exhaust manifold [52, 53, 45]. As for stable operation, combustion phasing control design requires appropriate models and system output variables usable for feedback control. Recently, mode-transition operation and control of Diesel-HCCI and SI-HCCI engines and other hybrid control aspects have received attention [54].

2.1 Fuel Modeling

The necessity of developing a practical iso-octane mechanism for HCCI engines was presented after various different experiments and currently available mechanisms for iso-octane oxidation being reviewed and the performance of these mechanisms applied to experiments relevant to HCCI engines being analyzed [48, 39]. A skeletal mechanism including 38 species and 69 reactions was developed, which could predict satisfactorily ignition timing, burn rate and the emissions of HC, CO and NO_x for HCCI multi-dimensional modeling [39]. Comparisons with various experiment data including shock tube, rapid compression machine, jet-stirred reactor and HCCI engine indicate good performance of this mechanism over wide ranges of temperature, pressure and equivalence ratio, especially at high pressure and lean equivalence ratio conditions. By applying the skeletal mechanism to a single-zone model of an HCCI engine, it was found that the results were substantially identical with those from the detailed mechanism developed by Curran et al. [18] but the computing time was reduced greatly [39].

A model for the auto-ignition of hydrocarbons applicable to 3D internal combustion engine calculations was proposed [16]. The limits of classical methods using an auto-ignition delay are investigated when cool flame phenomena are present. A method based on tabulated reaction rates was presented to capture the early heat release induced by low temperature combustion. Cool flame ignition delay when present and cool flame fuel consumption are also tabulated. The reaction rate, fuel consumption, and cool flame ignition delay tables were built a priori from complex chemistry calculations. The reaction rates, which directly depend on instantaneous changes of thermodynamic conditions, were then integrated during the 3D engine calculation. The model is first validated through comparisons with complex chemistry calculations in constant and variable volume configurations where good agreement was found. The model was applied both to a Diesel computation with spray injection and residual gases, and to a Diesel-HCCI configuration. Comparisons with experimental results showed that the auto-ignition essential features were well reproduced in these cases [16].

The combination of CFD computations with detailed chemistry leads to excessive computation times, and is not achievable with current computer capabilities. A reduced chemical model for $n-$heptane is described, in view of its implementation into a CFD simulation code [37]. Firstly, the reduction process to get to the 61-step mechanism is detailed and then the 26-step mechanism is described; this further reduction is carried out under various conditions that include a range of interest in engine applications. Validation work in reference to the original detailed mechanism and two reduced mechanisms was published in the literature, focusing on the prediction of ignition delay times under constant as well as variable volume conditions [37]. A good and accurate reproduction of both ignition delay times and heat release was reported to be reached with the 26-step model [37].

Despite the rapid combustion typically experienced in HCCI, components in fuel mixtures do not ignite in unison or burn equally. In experiments and modeling of blends of diethyl ether (DEE) and ethanol, the DEE led combustion and proceeded further toward completion, as indicated by ^{14}C-isotope tracing [36]. A numerical model of HCCI combustion of DEE and ethanol mixtures supports the isotopic findings. Although both approaches lacked information on incompletely combusted intermediates plentiful in HCCI emissions, the numerical model and ^{14}C-tracing data agreed within the limitations of the single-zone model. Despite the fact that DEE is more reactive than ethanol in HCCI engines, they were sufficiently similar and prevented incidence of a large elongation of energy release or significant reduction in inlet temperature required for light-off, both desired effects for the combustion event. This finding suggests that, in general, HCCI combustion of fuel blends may have preferential combustion of some of the blend components [36].

2.2 Auto-Ignition Modeling

Whereas HCCI engines have been shown to have higher thermal efficiencies and lower NO_x and soot emissions than spark ignition engines, the HCCI engines experience very large heat release rates which can cause too rapid an increase in pressure. One method of reducing the maximum heat-release rate is to introduce thermal inhomogeneities, thereby spreading the heat release over several crank angle degrees [55]. Direct numerical simulations (DNS) showed that both ignition fronts and deflagration-like fronts may be present in systems with such inhomogeneities [17]. Here, an enthalpy-based flamelet model was presented and applied to four cases of varying initial temperature variance. This model used a mean scalar dissipation rate to model mixing between regions of higher and lower enthalpies. The predicted heat-release rates agree well with the heat release rates of the four DNS cases. The model was shown to be capable of capturing the combustion characteristics for the case in which combustion occurs primarily in the form of spontaneous ignition fronts, for the case dominated by deflagration-type burning, and for the mixed mode cases. The enthalpy-based flamelet model shows considerably improved agreement with the DNS results over the popular multi-zone model, particularly, where both deflagrative and spontaneous ignition are occurring, that is, where diffusive transport is important [17]. Another fuel model is the Shell model used for auto-ignition below [26]. Further contributions on auto-ignition modeling can be found in [47].

2.3 Thermal Modeling and Auto-Ignition

HCCI combustion is often achieved without a completely homogeneous mixture. In order to derive a control-relevant model, however, we might firstly proceed by assuming that the mixture is homogeneous, thus allowing a single-zone cylinder model [5]. Such assumptions may be justified by laser-diagnostic measurements in our experimental set-up [46]. To reproduce the effects relevant for combustion phasing control it is required that the auto-ignition model captures the effects on ignition delay (induction time) of varying species concentrations, temperature trace, and fuel quality. Several alternative approaches are possible for modeling the instant of auto-ignition for fuels. High-complexity models—*e.g.*, (Primary Reference Fuels (PRF), 857 species, 3,606 reactions, CHEMKIN/LLNL) [56]—have been used to model complete combustion. In addition to ignition prediction, such models are also aimed at describing intermediate species and end product composition. Reduced chemical kinetics models, *e.g.*, (PRF fuels, 32 species, 55 reactions, CHEMKIN) [60], have also been proposed, where reactions with little influence on the combustion have been identified and removed. For simulation of multi-cycle scenarios it is necessary to keep the model complexity low in order to arrive at reasonable simulation times. An attractive and widespread alternative is to use the Shell model [26], which is a lumped chemical kinetics model using only five representative species in eight generic reactions. This model is aimed at prediction of auto-ignition rather than describing the complete combustion process. Compression ignition delay may also be described by empirical correlations, such as the *knock integral* condition

$$\int_{t=0}^{t_i} \frac{dt}{\tau} = 1 \tag{1}$$

where t_i is the instant of ignition and τ is the estimated ignition time (ignition delay) at the instantaneous pressure and temperature conditions at time t, often described by

Arrhenius type expressions [29, 49]. A drawback is that dependence on species concentrations is normally not regarded. An integral condition with concentration dependence was used in [50, 51] in a similar study for propane fuel, where also auto-ignition models based on very simple reaction mechanisms were evaluated. Alternatives to physical or physics-based models are to use system identification to obtain models or to use empirical look-up tables. The latter gives insufficient physical insight, and require substantial efforts to calibrate. In this work, the Shell model was chosen to describe the process of auto-ignition. A static model is then used to describe the major part of the actual combustion and corresponding heat release. The result from the Shell model was compared to results from an integrated Arrhenius rate threshold model and the Planet mechanism model [3, 2]. To the purpose of detailed treatise, modeling of the cylinder, auto-ignition, integrated Arrhenius threshold, combustion, and heat transfer are now provided:

Cylinder Gas Model—First Law of Thermodynamics. The cylinder gas dynamics are described by conservation laws such as the the first law of thermodynamics

$$\delta Q_{HR} = (1 + \frac{c_v}{R})p\mathrm{dV} + \frac{c_v}{R}V\mathrm{dp} + \delta Q_{HT} \tag{2}$$

where p is the cylinder pressure, V the volume, R_u the universal gas constant, $c_v = c_p - R_u$ the specific heat capacity, and n the molar substance amount contained in the cylinder. The time derivatives of Q_{HR} and Q_{HT} denote rates of heat released by the combustion process and heat flowing from the wall, respectively.

Gas Properties. The gas is described as a mixture of dry air and fuel, and the combustion products are nitrogen, carbondioxide and water. Specific heat for each species i is described by NASA polynomial approximations of JANAF data

$$c_{p,i}(T) = \frac{R_u}{M_i}\sum_{j=1}^{5} a_{i,j}T^{j-3} \tag{3}$$

where M_i is the molar mass of species i and T is the cylinder temperature [12, 25]. The mixture specific heat is then

$$c_p(T) = \frac{1}{n}\sum_{i} n_i M_i c_{p,i}(T) \tag{4}$$

where n_i is the mole of species i.

Shell Auto-ignition Model. The Shell auto-ignition model for hydrocarbon fuels [26], C_aH_b, is based on a general eight-step chain-branching reaction scheme with lumped species: The hydrocarbon fuel RH, radicals $\bar{R}$, intermediate species Q, and the chain branching agent B.

$$RH + O_2 \xrightarrow{k_q} 2\bar{R} \quad \text{(initiation)} \tag{5}$$

$$\bar{R} \xrightarrow{k_p} \bar{R} + \text{products and heat} \quad \text{(propagation cycle)} \tag{6}$$

$$\bar{R} \xrightarrow{f_1 k_p} \bar{R} + B \quad \text{(propagation forming } B\text{)} \tag{7}$$

$$\bar{R} + Q \xrightarrow{f_2 k_p} \bar{R} + B \quad \text{(propagation forming } B\text{)} \tag{8}$$

$$\bar{R} \xrightarrow{f_3 k_p} \text{out} \quad \text{(linear termination)} \tag{9}$$

$$\bar{R} \xrightarrow{f_4 k_p} \bar{R} + Q \quad \text{(propagation forming } Q\text{)} \tag{10}$$

$$2\bar{R} \xrightarrow{k_t} \text{out} \quad \text{(quadratic termination)} \tag{11}$$

$$B \xrightarrow{k_b} 2\bar{R} \quad \text{(degenerate branching)} \tag{12}$$

Auto-ignition is described by integrating the time variations of species concentrations from the beginning of the compression stroke.

$$\begin{aligned} \frac{d[\bar{R}]}{dt} &= 2\left\{k_q[RH][O_2] + k_b[B] - k_t[\bar{R}]^2\right\} \\ &\quad - f_3 k_p[\bar{R}] \end{aligned} \tag{13}$$

$$\frac{d[B]}{dt} = f_1 k_p[\bar{R}] + f_2 k_p[Q][\bar{R}] - k_b[B] \tag{14}$$

$$\frac{d[Q]}{dt} = f_4 k_p[\bar{R}] - f_2 k_p[Q][\bar{R}] \tag{15}$$

$$\frac{d[O_2]}{dt} = -g k_p[\bar{R}] \tag{16}$$

The species $\bar{R}$, Q, and B are not considered in thermodynamic computations for the gas mixture. The stoichiometry is approximated by assuming a constant CO/CO_2 ratio, ν, for the complete combustion process, with oxygen consumption $g = 2[a(1-\nu)+b/4]/b$ mole per cycle. The heat release from combustion is given by

$$\frac{dQ_{HR}}{dt} = k_p q V[\bar{R}] \tag{17}$$

where q is the exothermicity per cycle for the regarded fuel. The propagation rate coefficient is described as

$$k_p = \left(\frac{1}{k_{p,1}[O_2]} + \frac{1}{k_{p,2}} + \frac{1}{k_{p,1}[RH]}\right)^{-1} \tag{18}$$

To capture dependence of induction periods on fuel and air concentrations the terms f_1, f_3, and f_4 are expressed as

$$f_i = f_i^\circ [O_2]^{x_i}[RH]^{y_i} \tag{19}$$

Rate coefficients and rate parameters k_i and f_i° are then described by Arrhenius rate coefficients

$$k_i = A_i \exp\left[\frac{-E_i}{R_u T}\right], \quad f_i^\circ = A_i \exp\left[\frac{-E_i}{R_u T}\right] \tag{20}$$

We use the acronym FuelMEP to denote the mean effective pressure calculated from the quantity of fuel injected. Calibrated parameters for a number of fuels, including a set of Primary Reference Fuels (PRF), are found in the literature [26]. PRFx is a mixture of n-heptane and iso-octane, where the octane number x is defined as the volume percentage of iso-octane. Parameters for PRF90 were used in the simulations. Auto-ignition was defined as the crank angle where the explosive phase of combustion starts.

Integrated Arrhenius Rate Threshold. The Arrhenius form can be used to determine the rate coefficient describing a single-step reaction between two molecules [62]. The single-step rate integral condition is based on the knock integral with

$$K_{th} = \int_{\theta_{\mathrm{IVC}}}^{\theta} 1/\tau \; d\theta/w \tag{21}$$

$$1/\tau = A\exp(-E_a/(R_u T))[\mathrm{Fuel}]^a[O_2]^b \tag{22}$$

where θ is the crank angle and θ_{IVC} is the crank angle of the inlet valve closure. The integral condition describes a generalized reaction of fuel and oxygen and this is an extreme simplification of the large number of reactions that take place during combustion. The empirical parameters A, E_a, a, b and K_{th} are determined from experiments. Values for n-heptane and iso-octane from [62] were used in the comparison below with $A = 4.65 \cdot 10^{11}$, $E_a = 15.1$, $a = 0.25$, $b = 1.5$, $K = 1.6 \cdot 10^5$. Auto-ignition was defined as the crank angle where the integral condition has reached the threshold K_{th}. Sensitivity analysis of integrated Arrhenius rate thresholding was made by Chiang and Stefanoupolou [32].

Combustion. When auto-ignition is detected by the Shell model or the Integrated Arrhenius Rate Threshold, the completion of combustion is described by a Wiebe function [65].

$$x_b(\theta) = 1 - \exp\left[-a(\frac{\theta - \theta_0}{\Delta\theta})^{m+1}\right] \tag{23}$$

where x_b denotes the mass fraction burnt, θ is the crank angle, θ_0 start of combustion, $\Delta\theta$ is the total duration, and a and m adjustable parameters that fix the shape of the curve. The heat release is computed from the rate of x_b and the higher heating value of the fuel.

Heat Transfer. Heat is transfered by convection and radiation between in-cylinder gases and cylinder head, valves, cylinder walls, and piston during the engine cycle. In this case the radiation is neglected. This problem is very complex, but a standard solution is to use the Newton law for external heat transfer

$$\frac{dQ_W}{dt} = h_c A_W (T - T_W) \tag{24}$$

where Q_W is the heat transfer by conduction, A_W the wall area, T_W the wall temperature, and the heat-transfer coefficient h_c given by the Nusselt-Reynolds relation by Woschni [66]

$$h_c = 3.26 B^{-0.2} p^{0.8} T^{-0.55} (2.28 S_p)^{0.8} \tag{25}$$

where S_p is the mean piston speed and B is the bore.

3 Experiments

Detailed reviews of experimental set-up and conditions are given in [8, 9, 11].

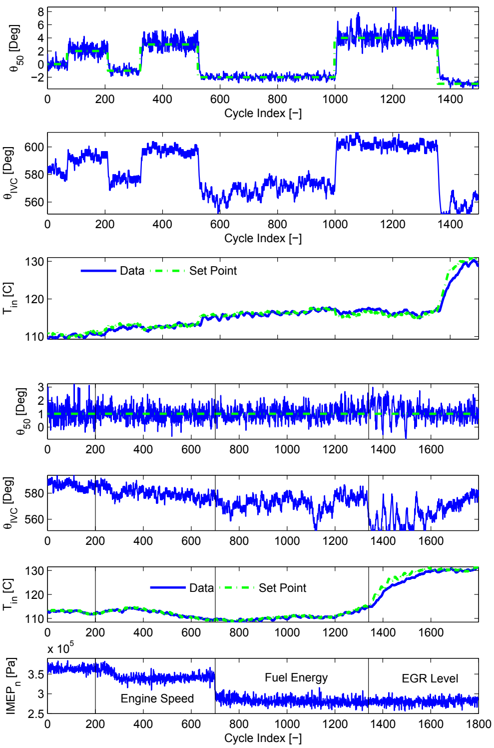

Fig. 1. Results of consecutive set-point changes (*upper*) and response to disturbances (*lower*) [63].

A cycle-resolved model of HCCI presented in [64] was used to design model predictive controllers. The controlled output was the crank angle of 50 % burnt fuel (here denoted θ_{50}). The control signals were the inlet air temperature and the crank angle of inlet valve closing. A fast thermal management system was used to obtain fast intake temperature actuation.

As witnessed by Fig 1, successful model-based control was accomplished both for setpoint tracking and disturbance rejection.

4 Conclusions

In addition to aspects of modeling related to thermodynamics, chemical combustion kinetics, and engine operation, careful attention is required for control-oriented combustion modeling and the interactions among dynamics, control, thermodynamics and chemical combustion properties. Modeling of engine-load transients as well as thermal transients also belong to this important domain of modeling (Fig. 1). Progress in this area is important and necessary for successful and robust control such as model-predictive control.

Within the project a cycle-resolved, physics-based, model of HCCI has been developed. The model includes a low-complexity model of the cylinder wall temperature dynamics in order to capture the relevant time-scales of transient HCCI when only small amounts of hot residuals are trapped in the cylinder. The temperature evolution of the gas charge is modeled as isentropic compression and expansion with three heat transfer events during each cycle.

Recently, research focused on design and evaluation of model predictive controllers based on linearizations of the model. The considered control signals were the inlet valve closing and the intake temperature. Simulations were used for the initial control design and the resulting controller was tested experimentally. The control performance was evaluated in terms of response time to set-point changes and the resulting output variance.

It was found that a comparable decrease in the output variance in some operating points could be achieved either by introducing a disturbance model or by changing linearization. All tested set-point changes were accomplished within 20 engine cycles or less. Only minor changes to the intake temperature were required for moderate changes. The closed-loop system showed good robustness towards disturbances in engine speed, injected fuel energy, and the amount of recycled exhaust gases.

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Output Feedback Control for a Class of Nonlinear Delayed Systems

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Abstract. In this work, delays affecting either the output measurements or the input for a class of nonlinear systems are coped with. This problem is particulary challenging since time delays arise in variety of applications, such as systems communicating through (wireless) networks. Indeed when the controller is a remote one, delays must be taken into account, affecting both the input and the output of the system. We first present a set of cascade high gain observers for triangular nonlinear systems with delayed output measurement. A sufficient condition ensuring the exponential convergence of the observation error towards zero is given. This approach is then applied to design an output feedback control in the presence of input delay. These results are illustrated through numerical simulations.

1 Introduction

Systems communicating through wireless network are now quite common. Data transmissions such as output measurements or control laws are necessarily subject to delays inherent to the communication process. The aim of this paper is twofold. Delays affecting either the output measurements or the input for a class of nonlinear systems are coped with. This problem is particulary challenging since time delays affecting input or output measurements arise in a variety of applications. One can cite for example systems which are controlled by a remote controller. In these systems, the input or the output data are transmitted between the controller and the system throughout a communication system, which can be a wireless network. This network introduces a time-delay between the process and the controller. The design of controllers for such systems can be viewed as an output feedback design based on state prediction system. In the linear case, this problem has been solved by the well-known *Smith predictor* [1] and several predictive control algorithms [2], [3]. Recently, for the nonlinear case, a new kind of chained observers which reconstruct the state at different delayed time instants for *drift observable* systems has been presented in [4]. The authors showed, by using *Gronwall* lemma, that under some conditions on the delay, exponential convergence of the chained observers is ensured. These conditions have been relaxed in [5] by using an approach based on a first-order singular partial differential equation. On the other hand, in [6] a novel predictor for linear and nonlinear systems with time delay measurement has been designed. This predictor is a set of cascade observers. Sufficient conditions based on *linear matrix inequalities* are derived to guarantee the asymptotic convergence of this predictor. Concerning delays affecting the input of the system, very little attention has been paid to this subject. For relevant work, the reader is referred to [7] and the references therein.

In the present work, the design of nonlinear observers in the presence of delayed output measurement is first dealt with. To this purpose, we design a set of cascade high gain observers for nonlinear triangular systems by considering a time delay in the output measurement. We will show that the general high gain observer design framework developed in [8], [9], [10], to mention a few, for delay-free output measurements can be extended to systems with delayed output. More precisely, we propose to use a suitable *Lyapunov-Krasovskii functional* and a sufficient number of high gain observers, in order to guarantee the exponential convergence of the estimated state at time t towards the true state at time t, even if the output is affected by any constant and known delay. We will also give an explicit relation between the number of observers and the delay. Then in a second part, this observer is used to design a feedback controller based on a dual approach of high gain techniques [11].

The present paper is organized as follows : In section 2, we present the class of considered systems and the different assumptions. In the third one, we present the proposed observers and prove their convergence. Section 4 is devoted to the design of a feedback control law based on the previous observers. In the last section, we illustrate our results throughout simulations on academic examples.

2 Preliminaries and Notations

First some mathematical notations which will be used throughout the paper are introduced.
The euclidian norm on $\mathbb{R}^n$ will be denoted by $||.||$. The matrix X^T represents the transposed matrix of X. $e_s(i) = \underbrace{(0,\ldots,0,\overbrace{1}^{i^{th}},0,\ldots,0)}_{\text{s components}} \in \mathbb{R}^s, s \geq 1$ is the i^{th} vector of canonical basis of $\mathbb{R}^s$. The convex hull of $\{x, y\}$ is denoted as $\mathrm{Co}(x, y) = \{\lambda x + (1-\lambda)y, 0 \leq \lambda \leq 1\}$. $\lambda_{min}(S)$ and $\lambda_{max}(S)$ are the minimum and maximum eigenvalues of the square matrix S.

In the first part of this paper, we consider the following class of nonlinear systems:

$$\begin{aligned} \dot{x} &= Ax + \phi(x,u) \\ y &= Cx(t-\tau) \end{aligned} \tag{1}$$

where

$$A = \begin{pmatrix} 0 & 1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & 0 & \vdots \\ \vdots & 0 & \ldots & 1 & 0 \\ \vdots & \vdots & \ldots & \ldots & 1 \\ 0 & \ldots & \ldots & \ldots & 0 \end{pmatrix} \tag{2}$$

$$C = \begin{pmatrix} 1 & 0 & \ldots & 0 \end{pmatrix} \tag{3}$$

$$\phi(x,u) = \begin{pmatrix} \phi_1(x,u) \\ \vdots \\ \phi_n(x,u) \end{pmatrix} \tag{4}$$

The term τ represents the measurement time delay, $x(t) \in \mathbb{R}^n$ is the vector state which is supposed unavailable. The output $y(t) \in \mathbb{R}$ is a linear function of the state x at time $t - \tau$. The input $u \in U$ where U is a compact set in $\mathbb{R}$. The functions $\phi_i, \quad i = 1, \ldots, n$ are supposed smooth. This class represents the class of uniformly observable systems. It has been shown [8], [9] that these models concern a wide variety of systems, such as bioreactors...

Throughout the paper, we assume that the following hypotheses are satisfied.

$\mathcal{H}1$. The functions $\phi_i(x,u)$ are triangular in x, i.e $\frac{\partial \phi_i(x,u)}{\partial x_{k+1}} = 0$, for $k = i, \ldots, n-1$

$\mathcal{H}2$. The functions $\phi_i(x,u)$ are globally Lipschitz, uniformly in u

$\mathcal{H}3$. The time delay τ is supposed constant and known.

3 Observer Design

In this section, we consider an arbitrary long time delay τ affecting the output measurement of system (1). The proposed nonlinear observer for system (1) is a set of m cascade high gain observers. Each one of them estimates a delayed state vector with sufficiently small delay $\frac{\tau}{m}$.

In order to present the proposed observer, we use the following convenient notations adopted from [4]:

$$x_j(t) = x(t - \tau + j\frac{\tau}{m})$$

where $j = 1, \ldots, m$

Then the proposed observer can be written in the following form, for $j = 1, \ldots, m$:

$$\begin{aligned} \dot{\hat{x}}_1 &= A\hat{x}_1 + \phi(\hat{x}_1) - \theta\Delta^{-1}S^{-1}C^{'}C(\hat{x}_1(t - \frac{\tau}{m}) - x(t-\tau)) \\ \hat{y}_1 &= C\hat{x}_1(t - \frac{\tau}{m}) \\ \vdots &= \vdots \\ \dot{\hat{x}}_j &= A\hat{x}_j + \phi(\hat{x}_j) - \theta\Delta^{-1}S^{-1}C^{'}C(\hat{x}_j(t - \frac{\tau}{m}) - \hat{x}_{j-1}(t)) \\ \hat{y}_j &= C\hat{x}_j(t - \frac{\tau}{m}) = C\hat{x}_{j-1}(t) \end{aligned} \tag{5}$$

where θ is a positive constant satisfying $\theta > 1$.

S is a symmetric positive definite matrix, solution of the following algebraic Lyapunov equation:

$$SA + A^T S - C^T C = -S \tag{6}$$

and Δ is a diagonal matrix which has the following form :

$$\Delta = Diag\left(1, \ldots, \frac{1}{\theta^{i-1}}, \ldots, \frac{1}{\theta^{n-1}}\right). \tag{7}$$

We will show that the vector $\hat{x}_j(t)$ estimates the delayed state $x_j(t)$, $j = 1, \ldots, m-1$ and $\hat{x}_m(t)$ estimates $x(t)$.

Before proving the exponential convergence of the proposed chained observers, we consider the case when the delay τ is sufficiently small. Then only one high gain observer is required to estimate the state of system (1).

Lemma 1. *Consider the following observer:*

$$\begin{aligned}\dot{\hat{x}} &= A\hat{x} + \phi(\hat{x}, u) - \theta\Delta^{-1}S^{-1}C^T C(\hat{x}(t-\tau) - x(t-\tau))\\ \hat{y} &= C\hat{x}(t-\tau)\end{aligned} \tag{8}$$

Then for sufficiently large positive θ, there exists a sufficiently small positive constant τ_1 such that $\forall \tau \leq \tau_1$, observer (8) *converges exponentially towards system* (1)*.*

Proof
First let us denote the observation error as $\tilde{x} = \hat{x} - x$.
Then we will have:

$$\dot{\tilde{x}} = A\tilde{x} + \phi(\hat{x}, u) - \phi(x, u) - \theta\Delta^{-1}S^{-1}C^T C\tilde{x}(t-\tau) \tag{9}$$

If we apply the relation

$$\tilde{x}(t) = \tilde{x}(t-\tau) + \int_{t-\tau}^{t} \dot{\tilde{x}}(s)ds \tag{10}$$

and the change of coordinates $\bar{x} = \Delta\tilde{x}$, system (9) can be rewritten in the following manner:

$$\dot{\bar{x}} = \theta(A - S^{-1}C^T C)\bar{x} + \Delta(\phi(\hat{x}, u) - \phi(x, u)) + \theta S^{-1}C^{'}C\int_{t-\tau}^{t} \dot{\bar{x}}(s)ds. \tag{11}$$

In order to derive an upper bound τ_1 for the delay τ, to ensure the exponential convergence to zero of the error $\bar{x}$, we use the following *Lyapunov-Krasovskii functional* [12]:

$$W = \bar{x}^T S\bar{x} + \int_{t-\tau_1}^{t}\int_{s}^{t} ||\dot{\bar{x}}(\xi)||^2 d\xi ds. \tag{12}$$

This functional can be written after an integration by parts as follows (see [12] for more details):

$$W = \bar{x}^T S\bar{x} + \int_{t-\tau_1}^{t} (s - t + \tau_1)||\dot{\bar{x}}(s)||^2 ds \tag{13}$$

If we compute its time derivative, we obtain

$$\begin{aligned}\dot{W} \leq\; &\theta\bar{x}^T(A^T S + SA - 2C^T C)\bar{x} + 2\bar{x}^T S\Delta(\phi(\hat{x}) - \phi(x))\\ &+2\theta\bar{x}^T C^T C\int_{t-\tau}^{t} \dot{\bar{x}}(s)ds + \tau_1||\dot{\bar{x}}(t)||^2 - \int_{t-\tau_1}^{t} ||\dot{\bar{x}}(s)||^2 ds\end{aligned} \tag{14}$$

Using (6), we have

$$\dot{W} \leq -\theta\bar{x}^T S\bar{x} + 2\bar{x}^T S\Delta(\phi(\hat{x}) - \phi(x)) + -\theta\bar{x}^T C^T C\bar{x} + 2\theta\bar{x}^T C^T C\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds$$
$$+ \tau_1||\dot{\bar{x}}(t)||^2 - \int_{t-\tau_1}^{t}||\dot{\bar{x}}(s)||^2 ds. \qquad (15)$$

Note that by using the mean value theorem [13], we can write

$$\Delta\left(\phi(\hat{x}) - \phi(x)\right) = \Delta\left(\sum_{i,j=1}^{n,n} e_n(i)^T e_n(j)\frac{\partial\phi_i}{\partial x_j}(\xi)\right)\Delta^{-1}\bar{x} \qquad (16)$$

where $\xi \in \mathrm{Cov}(x, \hat{x})$.

Then we will have

$$2\bar{x}^T S\Delta(\phi(\hat{x}) - \phi(x)) = 2\bar{x}^T S\Delta(\sum_{i,j=1}^{n,n} e_n(i)^T e_n(j)\frac{\partial\phi_i}{\partial x_j})\Delta^{-1}\bar{x} \qquad (17)$$

Using the triangular structure and the Lipschitz properties of the functions ϕ_i, and the fact that $\theta > 1$, we deduce that

$$||2\bar{x}^T S\Delta(\phi(\hat{x}) - \phi(x))|| \leq k_1 V \qquad (18)$$

where $V = \bar{x}^T S\bar{x}$ and k_1 is a positive constant which does not depend on θ.
Using the following property :

$$2\theta\bar{x}^T C^T C\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds - \theta\bar{x}^T C^T C\bar{x}$$
$$= -\theta(Cx + C\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds)^T(Cx + C\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds)$$
$$+ \theta(\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds)^T C^T C(\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds). \qquad (19)$$

This means that

$$2\theta\bar{x}^T C^T C\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds - \theta\bar{x}^T C^T C\bar{x} \leq \theta(\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds)^T C^T C(\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds) \qquad (20)$$

From this, we will have

$$\dot{W} \leq -\theta V + k_1 V + \theta(\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds)^T C^T C(\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds)$$
$$+\tau_1||\dot{\bar{x}}(t)||^2 - \int_{t-\tau_1}^{t}||\dot{\bar{x}}(s)||^2 ds \qquad (21)$$

Now, let us remark that if we use equation (11), it comes:

$$||\dot{\bar{x}}(t)||^2 \leq \theta^2 k_2[V + ||\int_{t-\tau}^{t}\dot{\bar{x}}(s)ds||^2] \qquad (22)$$

where k_2 is also a positive constant which does not depend on θ.
Using this and equation (21), we will have:

$$\dot{W} \leq -\theta V + k_1 V + \theta I^T C^T C I + \tau_1 \theta^2 k_2 [V + ||I||^2] - \int_{t-\tau_1}^{t} ||\dot{x}(s)||^2 ds. \quad (23)$$

where $I = \int_{t-\tau}^{t} \dot{x}(s) ds$.
To prove the above lemma (1), it is sufficient to find conditions which guarantee the inequality $\dot{W} + \frac{1}{\sqrt{\theta}} W < 0$.
From (23), we can write

$$\dot{W} + \frac{1}{\sqrt{\theta}} W \leq -\theta V + k_1 V + \frac{V}{\sqrt{\theta}} + \theta I^T C^T C I + \tau_1 \theta^2 k_2 [V + ||I||^2] + \frac{\tau_1}{\sqrt{\theta}} \int_{t-\tau_1}^{t} ||\dot{x}(s)||^2 ds - \int_{t-\tau_1}^{t} ||\dot{x}(s)||^2 ds. \quad (24)$$

If we use the following *Jensen's* inequality :

$$\int_{t-\tau_1}^{t} ||\dot{x}(s)||^2 ds \geq \frac{1}{\tau_1} ||I||^2 \quad (25)$$

and if $\tau_1 \leq \sqrt{\theta}$, we have

$$\dot{W} + \frac{1}{\sqrt{\theta}} W \leq -(\theta - k_1 - \tau_1 \theta^2 k_2 - \frac{1}{\sqrt{\theta}}) V - (\frac{1}{\tau_1} - \theta - \tau_1 \theta^2 k_2 - \frac{1}{\sqrt{\theta}}) ||I||^2 \quad (26)$$

Then, we can say that lemma 1 is verified for

$$\begin{cases} \theta \geq \max\{2, (k_1 + k_2 + \frac{1}{\sqrt{2}})\} \\ \tau_1 = \frac{1}{\theta^2}. \end{cases} \quad (27)$$

To summarize Lemma 1, it gives the maximum delay supported by observer (8) which enables $\hat{x}(t) \rightarrow x(t)$, once θ has been fixed according to conditions (27). To cope with a larger measurement delay, we propose in next paragraph a procedure to estimate $x(t)$, based on a chain of high-gain observers: each observer will estimate the state at a given fraction of the output delay.

Cascade High Gain Observers. After proving that the convergence of the observer (8) requires a small delay, we will see that when the delay is arbitrary long, a set containing a sufficient number of cascade high gain observers (5) can reconstruct the states of system (1).

Theorem 1. *Let us consider system (1), then for any constant and known delay τ, there exist a sufficiently large positive constant θ and an integer m such that the observer (5) converges exponentially towards the system (1).*

Proof
The convergence of the cascade observer will be proved step by step :

Step 1: We consider the first observer in the chain:

$$\dot{\hat{x}}_1 = A\hat{x}_1 + \phi(\hat{x}_1) - \theta\Delta^{-1}S^{-1}C^TC(\hat{x}_1(t-\frac{\tau}{m}) - x(t-\tau))$$
$$\hat{y}_1 = C\hat{x}_1(t-\frac{\tau}{m}) \tag{28}$$

We remark that $x(t-\tau) = x_1(t-\frac{\tau}{m})$ and consequently, if we choose θ sufficiently large, and by choosing the integer m such that $m \geq \theta^2\tau$, then $\hat{x}_1(t)$ converges towards $x_1(t) = x(t-\tau+\frac{\tau}{m}) = x(t-(m-1)\frac{\tau}{m})$.
Indeed, we are brought back to conditions of Lemma 1, since the delay to handle with is now $\frac{\tau}{m}$, which is assumed smaller than $\frac{1}{\theta^2}$.

Step j: at each step $(j = 2, \ldots, m)$, we estimate the delayed state $x(t-\tau+j\frac{\tau}{m})$ by using the following observer:

$$\dot{\hat{x}}_j = A\hat{x}_j + \phi(\hat{x}_j) - \theta\Delta^{-1}S^{-1}C^TC(\hat{x}_j(t-\frac{\tau}{m}) - \hat{x}_{j-1}(t))$$
$$\hat{y}_j = C\hat{x}_j(t-\frac{\tau}{m}) = C\hat{x}_{j-1}(t) \tag{29}$$

It is not difficult to see that by considering the observation error vector $\tilde{x}_j = x_j - \hat{x}_j$, if we add and subtract the term $\theta\Delta^{-1}S^{-1}C^TCx_{j-1}(t)$ in the previous equation, we obtain

$$\dot{\tilde{x}}_j = A\tilde{x}_j + \phi(\hat{x}_j) - \phi(x_j) - \theta\Delta^{-1}S^{-1}C^TC(\tilde{x}_j(t-\frac{\tau}{m}) - \tilde{x}_{j-1}(t)) \tag{30}$$

If we consider the following change of coordinates $\bar{x}_j = \Delta\tilde{x}_j$, we will have

$$\dot{\bar{x}}_j = \theta(A - S^{-1}C^TC)\bar{x}_j + \Delta(\phi(\hat{x}_j) - \phi(x_j))$$
$$+ \theta S^{-1}C^TC\int_{t-\frac{\tau}{m}}^{t} \dot{\bar{x}}_j(s)ds - \theta S^{-1}C^TC\bar{x}_{j-1}. \tag{31}$$

In order to prove by recurrence the convergence of the error $\bar{x}_j$, we suppose that the observation error $\bar{x}_{j-1}(t)$ converges exponentially towards zero.
Then we consider the following *Lyapunov-Krasovskii functional*

$$W_j = \bar{x}_j^TS\bar{x}_j + \int_{t-\frac{\tau}{m}}^{t}(s-t+\frac{\tau}{m})||\dot{\bar{x}}_j(s)||^2ds \tag{32}$$

Then its time derivative satisfies the following inequality:

$$\dot{W}_j \leq -\theta\bar{x}_j^TS\bar{x}_j + 2\bar{x}_j^TS\Delta(\phi(\hat{x}_j) - \phi(x_j)) + -\theta\bar{x}_j^TC^TC\bar{x}_j - 2\theta\bar{x}_j^TC^TC\bar{x}_{j-1}$$
$$+2\theta\bar{x}_j^TC^TC\int_{t-\tau}^{t}\dot{\bar{x}}_j(s)ds + \tau_1||\dot{\bar{x}}_j||^2 - \int_{t-\tau_1}^{t}||\dot{\bar{x}}_j(s)||^2ds. \tag{33}$$

As in the proof of the lemma 1, we will also have:

$$\dot{W}_j \leq -(\theta - k_1')V_j + \theta I_j^TC^TCI_j - 2\theta\bar{x}_j^TC^TC\bar{x}_{j-1} + \tau_1||\dot{\bar{x}}_j||^2 - \int_{t-\tau_1}^{t}||\dot{\bar{x}}_j(s)||^2ds \tag{34}$$

where $V_j = \bar{x}_j^T S\bar{x}_j$, $I_j = \int_{t-\tau}^{t} \dot{\bar{x}}_j(s)ds$ and k_1' is a positive constant which does not depend on θ and $k_1' \geq k_1$.
Now, by using Young's inequality, we derive the following inequalities

$$||\dot{\bar{x}}_j||^2 \leq \tau_1 k_2' \theta^2 (V_j + ||I_j||^2 + ||\bar{x}_{j-1}||^2) \tag{35}$$

$$-2\theta\bar{x}_j^T C^T C\bar{x}_{j-1} \leq \frac{1}{\sqrt{\theta}} V_j + \frac{\theta^2\sqrt{\theta}}{\lambda_{min}(S)} ||\bar{x}_{j-1}||^2. \tag{36}$$

where k_2' is a positive constant which does not depend on θ and $k_2' \geq k_2$.
Choosing $\tau_1 = \frac{1}{\theta^2}$, and using (34), (35) and (36), we derive

$$\begin{aligned}\dot{W}_j + \frac{1}{\sqrt{\theta}} W_j \leq -(\theta - k_1' - \tau_1\theta^2 k_2' - \frac{2}{\sqrt{\theta}})V_j - (\frac{1}{\tau_1} - \theta - \tau_1\theta^2 k_2' - \frac{2}{\sqrt{\theta}})||I_j||^2 \\ +(\frac{\theta^2\sqrt{\theta}}{\lambda_{min}(S)} + k_2')||\bar{x}_{j-1}||^2\end{aligned} \tag{37}$$

Then, we can say that if

$$\left\{ \theta \geq 2 + k_1' + k_2', \quad \tau_1 = \frac{1}{\theta^2} \right. \tag{38}$$

we will have

$$\dot{W}_j \leq -\frac{1}{\sqrt{\theta}} W_j + (\frac{\theta^2\sqrt{\theta}}{\lambda_{min}(S)} + k_2')||\bar{x}_{j-1}||^2 \tag{39}$$

Using the comparison lemma [14], we conclude that if $\bar{x}_{j-1}$ converges exponentially towards zero, then $\bar{x}_j$ converges also exponentially towards zero. Note that conditions (38), also ensure the convergence of the first observer $(j = 1)$, then we deduce, recursively, that all observation errors converge exponentially towards zero.

4 Output Feedback Controller Design

In previous section, we addressed an observer synthesis issue, when the output measurement is affected by any delay. Now we consider what can be thought of as a dual problem. The aim is to design a stabilizing feedback control law when the controller is a remote one, which inevitably leads to delays on the system input. To this end we consider the following class of nonlinear systems:

$$\begin{cases} \dot{x}(t) = Ax(t) + \phi(x(t)) + bu(t-\tau) \\ y(t) = Cx(t) \end{cases} \tag{40}$$

and we assume that hypotheses $\mathcal{H}_1$ to $\mathcal{H}_3$ are fulfilled.
We detail now a solution to the above problem that makes use of the previous results. In order to cope with the input delay, we use the above cascaded observer (5) to derive a prediction of state $x(t)$ used in the feedback control $u(t-\tau)$. For sake of simplicity, we suppose that we need only one observer to face this delay. The same reasoning as in previous section can be extended to deal with a larger delay, with cascaded observers.

Using the work developed in [11], the feedback control which stabilizes (40) can be expressed as:

$$u(t) = -\lambda^n b^T \bar{S} \Delta_\lambda \hat{x}(t+\tau) \tag{41}$$

where $\lambda > 0$ is a suitable tuning parameter like the parameter θ in the observer design and the matrix Δ_λ is defined as in (7) where θ is replaced by λ.

Using the results detailed in previous section, $\hat{x}(t+\tau)$ can be computed, see (5). Then this predicted state is used to compute eq. (41). As a consequence, this prediction cancels the effects of the delay affecting the transmission of the control law.

We give now a sketch of how to proceed. • Make the following variable change to obtain an estimation of the predicted state: $z(t) = \hat{x}(t+\tau)$. This is equivalent to $\hat{x}(t) = z(t-\tau)$.
Then the observer can be expressed as:

$$\dot{z}(t) = Az(t) + \phi(z(t)) + bu(t) - \theta\Delta_\theta^{-1} S^{-1} C^T \left(y(t) - z(t-\tau)\right) \tag{42}$$

where $u(t) = -\lambda^n b^T \bar{S} \Delta_\lambda z(t)$.
We are now brought back to the former problem of section 3. • The key point is to use the delayed control law $u(t-\tau)$ in the system dynamics, which corresponds to the real applied control, whereas we use $u(t)$ in the observer's dynamics.
•The reader is referred to [11] for a detailed proof of the stabilization of the system (40) and the convergence of the observer (42).

5 Example

To illustrate the obtained results, consider the following nonlinear system, affected first only by delayed measurements:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = -2x_1(t) + 0.5\tanh(x_1(t) + x_2(t)) + x_1(t)u(t) \\ y(t) = x_1(t-\tau) \end{cases} \tag{43}$$

The input is $u(t) = 0.1\sin(0.1t)$. System (43) belongs to the considered class of triangular systems with Lipschitz nonlinearities (1).
The initial conditions for the system and for the observer have been chosen as $x(t) = \begin{pmatrix} 1 & -1 \end{pmatrix}^T, \quad \hat{x}(t) = \begin{pmatrix} 0 & 0 \end{pmatrix}^T, \quad \forall t \in [-\tau, 0]$.
Simulations have been performed using Matlab-Simulink, and a fourth order Runge-Kutta integration routine. The high gain parameter is set to $\theta = 2$, the control parameter is set to $\lambda = 2$. We show the efficiency of the stabilizing control law given in eq. (40) and (41), based on observer (42), on the example below:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = -2x_1(t) + 0.5\tanh(x_1(t) + x_2(t)) + u(t-\tau) \\ y(t) = x_1(t) \end{cases} \tag{44}$$

The stabilization of the controlled state to zero is shown in figure 1.

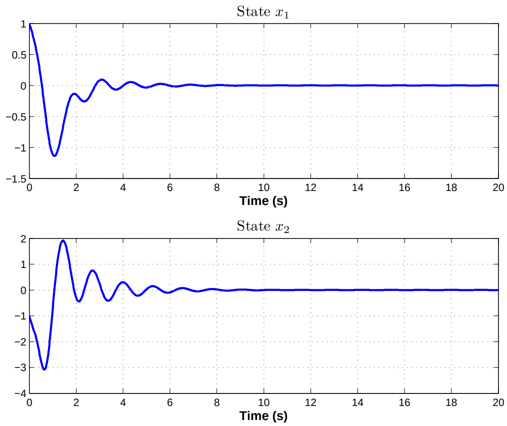

Fig. 1. Evolution of the controlled states.

6 Conclusions

In this paper, a novel predictor based on high gain observer has been presented. This observer can be applied to the class of nonlinear uniformly observable systems, subject to input or output delays arising from communication networks for example. The case of a variable delay can be considered on the basis of the presented work. The design of adaptive observers for nonlinear systems with delayed output and uncertain or unknown parameters is under investigation.

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Hierarchical Control System for Complex Dynamical Plants

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Abstract. The paper is devoted to a concept of hierarchical control for complex dynamical plants and suggests architecture of control system consisting of robust, adaptive, and intelligent levels. Intelligent features of the proposed system are mostly concentrated at the third level incorporated into self-organizing algorithm and decision making approach realized by developers and process engineers. Some results are presented from present groundwork of research performed and future work is outlined. Case study has been chosen from the area of plasma magnetic and kinetic control in tokamak-reactor.

1 Introduction

Recent advances in control strategies, communications, hard and soft-computing technologies have favored an increasing trend towards the new generation of networked control systems for complex plants. The proposal described herein will address the development of scalable control methods and systems in accordance with the Information and Communication Technologies (ICT) Work Programme of the European Commission (EC), the objective ICT-2009 3.5a: Engineering of Networked Monitoring and Control systems with target outcome of Foundations of Complex Systems Engineering [1].

The engineering of networked monitoring and embedded systems is a challenge common to a wide scope of strategic application domains for complex processes. The project is focused on complex automation problems aiming at development of control theory and a framework for future technological and scientific breakthroughs in the conjunction with state-of-the-art of control theory, distributed and embedded computations, communications and intelligent systems. Proposal multidisciplinary fields include *control theory* (multi-sensor systems approach, linear and nonlinear stability, robust and adaptive control, and so forth), *computer science* (reconfigurable architectures, high-performance computations, signal processing, combinatorial optimization, and so forth), networking and monitoring *application-specific issues* (data fusion, fault tolerant and so forth), *network theory* (dynamic QoS management), and *artificial intelligence-based techniques* (fuzzy, neural and neuro-fuzzy systems).

Interdisciplinary and multidisciplinary essence of this proposal relies on all hierarchical levels of control, from local controllers linked to physical objects (processes) up to networked monitoring and complete managing of complex processes. On the one hand, a key issue is to make control systems easily implemented, self-configuring, and self-optimizing. Proposal goes beyond the current state-of-the-art improving the computational efficiency and the ways in which embedded systems interact with the physical world. On the other hand, the system has to guarantee fault-tolerance and efficiency of networking and monitoring.

To meet the goal stated by the EC a three level hierarchical control system was suggested in Bauman Moscow State Technical University to be applied to solve control problems of complex dynamic plants in science, engineering, and industry.

2 Philosophy of Hierarchical Control

The project is focused on design and development of scalar (Single-Input/Single-Output: SISO) and multivariable (Multi-Input/Multi-Output: MIMO) control systems based on scalable control algorithms for uncertain time-varying nonlinear complex dynamic plants. The major innovation of the proposal implies the elaboration of a new methodology for designing hierarchical adaptive self-organizing control systems to be applied to complex production processes, such as: plasma energy release, chemical and biological processes, casting in metallurgy, oil refinery, and so forth.

2.1 Features of Hierarchical and Heterarchical Control

Today's technologies are enabling complex processes to become more and more autonomous. Industry and academia have investigated a wide range of decentralized control architectures ranging from hierarchical decomposition to a completely decentralized (heterarchical) approach where individual controllers are assigned to subsystems and may work independently or may share data and information.

The main disadvantage of heterarchical approaches is that global optima cannot be guaranteed and predictions of the system's behaviour can only be made at the aggregate level. Hierarchical and heterarchical architectures lie at opposite ends of the distributed control architectures spectrum. The hierarchical approach is rigid and suffers from many of the shortcomings of the centralized approach, whereas it provides clear advantages in terms of overall system coordination alternatively. Despite the large amount of results related with hierarchical control methods, much work has still to be done to extend many theoretical results (stability, performance, robustness) nowadays available from advanced control implementations (H_∞, MPC) and non-traditional control strategies (e.g., neurofuzzy control systems) to the hierarchical structure [2]. In order to synthesize hierarchical control laws, the knowledge of suitable simulation functions is useful. However, an effective characterization of the simulation functions and of the associated interfaces for complex plants is not straightforward [3].

Hierarchical control can be used to integrate extra information (in addition to that concerning the usual control-loop variables such as output, error, etc.) into the control decision-making process. In many situations a hierarchical approach is an advantageous option for process optimization, instead of sophisticated design and implementation of high-performance low-level controllers.

Thanks to its own structural essence, the hierarchical control scheme ensures flexibility and compatibility with other controllers that have already been installed. It has other strong points as well, such as the relatively low cost of investments in improving automation scheme performance, the possibility of exploiting already-installed low-level regulation systems, and the relatively low cost of measurement systems which makes hierarchical control a wise choice from economic and practical viewpoints.

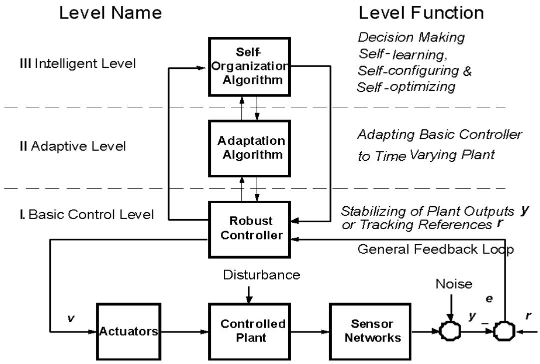


Fig. 1. General configuration of three levels hierarchical control system

2.2 Idea of Three Levels Hierarchical Control System

Whenever hierarchical levels are to be applied, goals and tasks must be broken down into levels of resolution. The architecture of the suggested hierarchical control system is composed of three levels (Fig. 1).

Basic Control Level (I) contains a controlled process under Disturbance, Actuators, Sensor Networks, and a multivariable Robust Controller capable of operation under process uncertainties. Here $\boldsymbol{r}$ is reference action, $\boldsymbol{y}$ is plant output containing Sensor Networks outputs with Noise and measurement inaccuracy, $\boldsymbol{e}$ is an error between reference $\boldsymbol{r}$ and plant output $\boldsymbol{y}$ which is related to the controller input, $\boldsymbol{v}$ is Actuators' input. This level is designed to monitor the process itself and its environment in order to undertake corresponding actions to reject internal and external disturbances and noise in output signals being measured. General Feedback Loop of Basic Control Level is to solve one of two control problems: *Stabilizing of Plant Output* $\boldsymbol{y}$ or *Tracking of Reference* $\boldsymbol{r}$. In the case of unstable process General Feedback Loop is to stabilize plant dynamics. Sensor Networks monitor processing conditions, and if plant input actions are required, changes are made by the Actuators. Robust Controller provides General Feedback Loop capability to work in the presence of plant uncertainties and is to secure acceptable trade-off between robust stability and robust performance.

Adaptive Level (II) contains scalable Adaptation Algorithm which provides *Adapting Basic Controller to Time-Varying Plant* Parameters and Disturbance to achieve the goal of adaptation at this level. Adaptive Level helps Basic Control Level to accomplish closed-loop system trade-off at each discrete moment and to provide the best possible dynamical features of General Feedback Loop.

Intelligent Level (III) with *Self-Organizing, Self-Learning, Self-Configuring*, *Self-Optimizing, and Decision-Making* algorithms has more complex functions. This level is organized by rule base (knowledge base), working memory (facts), and inference engine (rule engine). The rule base contains declarative rules defined by user; the facts are instances of templates to be stored in working memory. The inference engine matches the facts against rules, fires rules, and executes associated actions. The actions are taken by the Robust Controller and carried out by Actuators at Basic Control Level. Adaptation to changing conditions or optimization of control processes is achieved at Self-Organizing Level by changing the structure of Robust Controller, switching separate subsystems on or off, qualitatively changing algorithms of Adaptive Level, changing connections between subsystems and their subordination schemes, and so on.

2.3 Levels Cooperation and Decision Making

The basic difference between Adaptive and Self-Organizing Levels means that Adaptive Level (II) provides tuning of the Basic Control Level (I) mostly through quantitative changes, whereas Self-Organizing Level (III) adjusts lower levels (II) and (I) through qualitative changes. In other words, Self-Organization Algorithm dynamically reconfigures system architectures. At this level self-learning models may be used to get on-line plant parameter and structure changes in order to predict optimal control at each discrete moment.

It is extremely complicated and unreliable to delegate decision making functions at level (III) to artificial intelligent agent. At this level the decision making procedures are assumed to be done by systems developers and process engineers in accordance with the best choice of control algorithms which are the most effective in the case studies and industry applications to complex plants under control (plasma in thermonuclear reactors, oil refinery plants and the like) taking into account expert system database and data knowledge.

3 Statements of Control Problems and Implementation

A number of new important complex control problems have to be studied, discussed and formulated to achieve control goals of acceptable trade-off between robust stability and performance of feedback systems. The problem statements concern the stabilization and tracking process output signals, optimal distribution of process parameters in space in the presence of non-modeled process dynamics, unobserved disturbances, nonlinearities, in particular saturations, wideband insufficiently known noise in output signals, non-minimum-phase dynamics, and time-varying parameters.

To solve these control problems a set of approaches from linear and nonlinear control theory will be explored and developed to achieve scalable H_∞ robust, decoupling, model predictive, adaptive, hierarchy, cascade, soft-computing based control (e.g., neuro-fuzzy control systems), and facilitate decision-making in new appropriate combinations within continuous and discrete time of the three-level hierarchic control system (Fig. 1). Scalable control algorithms mean that the algorithms may be generalized to any numbers of controlled plant inputs, outputs, and space states.

The main scientific and technical contributions of the project imply the integration and synergy achieved as a result of the implementation of advanced control methods, relevant computational strategies and state-of-the-art technologies for embedded and networked systems. In the process of hierarchical structure control systems design the synthesis, analysis, and numerical modeling approaches are proposed to be performed in MATLAB/SIMULINK environment. The controllers to be designed are planned to be implemented in a test bed with primary objective to evaluate functionality of control systems in real time. The test bed should consist at least of two basic electronic blocks: dynamic process model under control and feedback hierarchical controller which interconnection should demonstrate advantages of scalable control algorithms to be elaborated and modern high-performance computations in real time.

4 Case Study of Plasma Energy Release

In order to advance the suggested control approaches plasma energy release case study is planned to be investigated on plasma in tokamaks. Nuclear fusion should be a new source of practically inexhaustible energy and tokamaks are the leaders in thermonuclear energy release area. The plasma control systems under investigation are supposed to be applied to ITER (International Thermonuclear Experimental Reactor).

It is an intense and challenging time for ITER to design the whole set of coupled plasma magnetic and kinetic control systems. Magnetic control systems have to provide accurate control of plasma magnetic configuration [4] and stabilize plasma against the main MHD modes [5]. Kinetic control systems are to control power fusion and power flow to the diverter [6, 7] as well as profiles of plasma kinetic parameters: plasma current, temperature, and density [8].

Reliable control of plasma shape and current in ITER is still a challenging problem because of necessity of controller change during transition from limiter to divertor phases, existence of separate loop to suppress plasma vertical speed of unstable vertical position, currents saturations in poloidal field (PF) coils, and so forth. Plasma tokamak configuration with a free boundary defined by currents in PF active coils and passive contours is described by vector Kirchhoff equation [9] and Grad-Shafranov nonlinear partial differential equation [9, 10]. These equations together with equation of magnetic field diffusion into plasma are realized numerically by DINA plasma-physics code [9].

Plasma magnetic control in ITER is planned to be realized by two-loops control system presented in Fig. 2: fast scalar loop stabilizes plasma vertical speed around zero and slower multivariable loop tracks (on ramp-up and ramp-down phases) and stabilizes (on quasi-stationary phase) plasma shape and current [11].

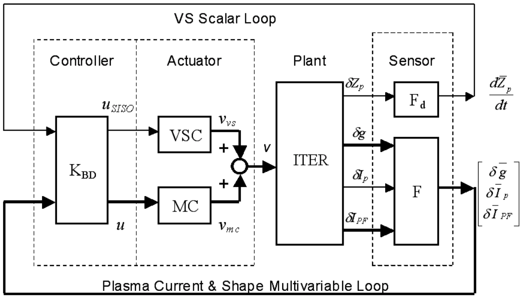
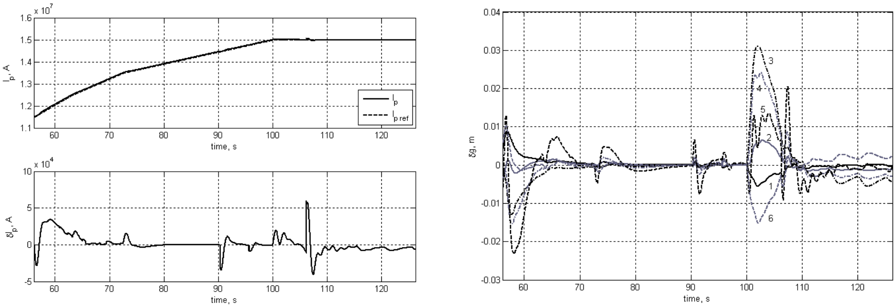


Fig. 2. Two-loops control system: K_{BD} is block-diagonal controller, MC is multivariable main converter, VSC is vertical stabilization converter, F_d is derivative filter, F is filter for plasma shape, current and control currents, g is a vector of gaps between separatrix and the first wall, I_p is plasma current.

Plasma in ITER is a MIMO plant that has 11 inputs (voltages on 11 superconductive magnetic coils) and 19 outputs (6 gaps, plasma current, currents in 11 PF coils, plasma vertical speed). At the moment we have simulation results on DINA code of application of three control methodologies for plasma magnetic control specifically cascade decoupling with PI controllers, H_∞, and Model Predictive Control (MPC). Decoupling approach gave a chance to track plasma current (Fig. 3a) and gaps (Fig. 3b) on the plasma current ramp up phase [11]. In particular H_∞ and MPC control systems were applied at plasma current flat-top phase (Fig. 4a) where MPC showed better performance at minor disruptions but H_∞ system had larger robust stability margin [12].

The fragments of plasma magnetic control were applied for ITER reference scenario 2 with plasma current on flat-top of 15 MA. Multivariable robust controller design (Fig. 1) on level (I) *with adaptation* on level (II) is proposed to be done for the *whole plasma discharge* of plasma current ramp-up, ramp-down, and at quasi stationary stages. It is planned to be applied for ITER reference scenario 2 and for reversed share scenario 4 of plasma current of 9 MA.

The project control methodologies are planned to be advanced to solve *plasma kinetic control problem* as well. Plasma kinetic control means creation and maintenance of *optimal* plasma current, temperature, and density profiles by means of additional heating sources. Such regimes are necessary for stationary operation of tokamak-reactors. As the first step in this direction the kinetic plasma model was created on the base of diffusion equation which dynamically connects 5 inputs from power of heating sources for current drive and 5 outputs that are densities J_p of plasma current at 5 predetermined points of tokamak major radius [13]. For this kinetic model the identification problem was solved at zero frequency and then 5×5 -multivariable controller was designed with the usage of decoupling principle and PI diagonal entries. Controller was simulated on the original kinetic model and showed capability of work in the range of plasma temperature on magnetic axis from 100 eV to 5 keV. Transient process from initial plasma current profile to designated positions at the given points as well as relaxation process after disconnection of the feedback are presented in Fig. 4b [13].



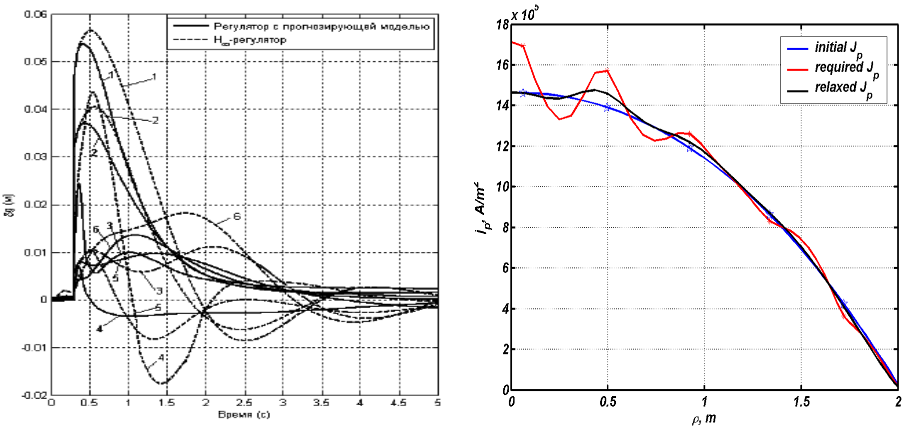
a) **b)**

Fig. 3. Tracking of plasma current and gaps: I_p is plasma current, δI_p is its tracking error (a); δg is a vector of gaps tracking errors (b).

Development of more full kinetic plasma models of plasma current, temperature, and density profiles and their identification taking into account dynamics of the plant are supposed to be done. Then design and modeling of plasma profiles control system in the temperature range at magnetic axis from 100 eV to 18 keV are assumed to be performed. Increasing of temperature range on plasma magnetic axis may arise of application of adaptation at the level (II) of hierarchical control system in Fig. 1.

The final issue of plasma control activity is assumed to be integration of plasma magnetic and kinetic control systems into joint system containing balanced subsystems with the usage of integrated plasma magnetic and kinetic models.

The ITER functionality is planned to be performed by means of CODAC software specifically Control, Data Access, and Communications (www.iter.org) via which one can install hierarchical control scheme proposed.



a) **b)**

Fig. 4. Six gaps stabilization by means of H_∞ and MPC controllers at plasma current flat-top phase when minor disruption occurs (a). Transient process from initial plasma current profile to predetermined profile and relaxation process result after feedback disconnection (b).

One of the main obstacles of plasma control systems design is to solve linearization and identification problems aiming at controller synthesis. In order to improve results on this way one can try to apply modern techniques with the help of neural networks and fuzzy logic. These approaches alone or combined (neurofuzzy) are able to model complex plants without knowledge of plant First Principle Equations using black-box or grey-box modeling approaches. In some cases these models are obtained from experimental input/output data or using simulation data from very complicated original plant models.

5 Intelligent Identification and Control Algorithms

Classic and non-traditional control strategies will be combined in order to incorporate self-* capabilities. Internal-model control (IMC) is a well-established approach to design controllers in which the process model is explicitly used in the control-system design procedure [14]. The use of the IMC paradigm theoretically guarantees control system robustness and stability in the presence of external disturbances. The actual roots of MPC are indeed in the IMC paradigm.

A block diagram of an internal model control based on Artificial Neural Networks (ANN) and Fuzzy Logic (FLC) is depicted in Fig. 5. All disturbances are considered to take place in the process output. In the figure G_M denotes a model of the process (direct model), G_M' is an approximate inverse of G_M, G_F is a low-pass filter, L denotes dead-time process plus network-induced delay, G_p denotes the process. The main assumptions are that an approximate reference model G_r is required and a maximum allowable delay (bounded delays) is known to deal with uncertainties and nonlinearities of the controlled process and delays in the corresponding network-based application.

Construction of the IMC system consists of two stages: (**i**) selection of a controller (usually the inverse model) to achieve perfect control and (**ii**) the introduction of a filter.

First an ANN is trained to learn the dynamics of the process and is therefore given known input- and output-data sets. So, one of the neural-network models developed is selected as a basis for IMC control. The inverse model is obtained on the basis of generalized training. Therefore, the network is trained off-line to minimize quadratic criteria $J(\theta)=\sum_{t=1}^{M}\left(v(t)-\hat{v}(t)\right)^2$.

Another ANN is trained to learn the inverse dynamics of the process and to work as a nonlinear controller. The back-propagation of error is applied for tuning $\theta=\left[K_F, K_{CF}\right]$ corresponding to the input scaling factors of the fuzzy block that can replace the inverse model (Fig. 5). The goal is the optimal setting of input scaling factors $\left[K_F, K_{CF}\right]$ to ensure that the overall system follows the reference signal $y'_r(t)$ closely. If inverse model actually describes the inverse dynamic of the plant, there will be a perfect cancellation and we should attempt to find $\theta=\left[K_F, K_{CF}\right]$ such that $v_{\mathrm{NN}}(t) \cong v_{\mathrm{FLC}}(t)$. Using the forward model one can estimate the Jacobians: $\partial y(t)/[\partial v(t-1)] \cong \partial\hat{y}(t)/[\partial v(t-1)]$.

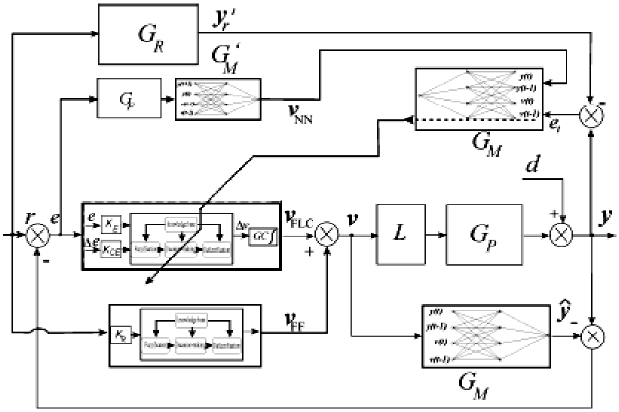


Fig. 5. A tailored scheme based on internal model control with self-learning, feedforward compensation and self-optimization based on ITAE criterion via error back-propagation

An important issue is the stopping condition to avoid overestimating $\theta = [K_F, K_{CF}]$. The best course is to use the integral of time multiplied by the absolute value of error (ITAE) criterion to optimize the transient response and to penalize lengthy transients $J_2 = \int_0^T t \cdot e(t)\, dt$. The ITAE criterion of J_2 is selected to obtain smaller overshoots and oscillations, which are quite harmful for the cutting tools used in machining.

It is important to remark that hybridization of FLC with ANN can also be applied in the IMC-based approach using other neuro-fuzzy inference systems [15].

6 Conclusions

The concept of three levels hierarchical control system was presented and discussed namely: philosophy of hierarchical control, statement of control problems, implementation, case study of plasma energy release, and intelligent identification and control algorithms.

The project will result in the creation of new process models, procedures of their identification and reduction, efficient, robust, predictable, and safe ICT control methodologies, scalable control algorithms, and high-performance controllers for the problem oriented hierarchical systems under consideration. Scientific, engineering, and industrial results will be accumulated in the data and knowledge bases with accurate classification, qualitative and quantitative assessment, and generalization.

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Minimum Tracking with SPSA and Applications to Image Registration

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Abstract. An application of simultaneous perturbation stochastic approximation (SPSA) algorithm with two measurements per iteration to the problem of object tracking on video is discussed. The upper bound of mean square estimation error is determined in case of once differentiable functional and almost arbitrary noises. Weak restrictions on uncertainty allow to use random sampling instead of full pixelwise difference calculation. The experiments show significant increase in performance of object tracking comparing to the classical Lucas-Kanade algorithm. The results can be generalized to improve more recent kernel-based tracking methods.

1 Introduction

Object tracking on video is an important problem for security surveillance systems. One of possible approaches to this problem is to look for a disparity vector h between object's locations in consequent frames I_n and I_{n+1} of the video stream. Disparity vector h can include object size and other properties as well. Well known algorithm of B. Lucas and T. Kanade [1] uses the functional of pixelwise differences in consequent frames. $F_{n+1}(x) = \sum_{p \in O_n} \frac{1}{w(p)}((I_{n+1}(x+p) - I_n(x_n+p))^2$, where O_n is a set of object's pixels p in the n-th frame, $\sum_{p \in O_n} w(p) = 1$, x_n is a center of previous object's location, p represents the relative position of a pixel woth respect to the object's center. The functional needs to be minimized to find real disparity $x^*_{n+1} = argminF_{n+1}(x)$. If the object's locations on consequent frames have significant intersection, then the algorithm of minimum tracking based on convex optimization can be applied to this problem. Stochastic optimization allows to use not all the pixels of the object's image O_n, but some random sample $R_n \subset O_n$ to compute the functional each iteration, because the convergence of the algorithm can be proved in this case. This property allows to descrease the amount of pixelwise difference measurements per algorithm iteration. The experiments' results in the end of the paper show significant increase in the performance of the method. The same approach of randomization of the pixel sample combined with srtochastic optimization can be used in more recent kernel-based object tracking algorithms, described in [2].

More specifically, in this article the convergence of the SPSA (simultaneous perturbation stochastic optimization) algorithm of stochastic optimization class will be proved in case of minimum tracking. The functional measurement $y_n = F(x_n, w_n)$ depends on two arguments, one of which is the actual point of measurement (in case described above, $x_n = h_n$) and the second one is the uncertainty presented by random variable w, $\int P(dw) = 1$. The minimization is understood in average risk setting, such that $f_n(x) = E_w F(x, w, n) \to \min$.

In case of object tracking on video, we consider $F(x, w, n+1) = \sum_{p \in R_n} (I_{n+1}(x+p) - I_n(x_n + p))^2$, $f(x, n) = \sum_{p \in O_n} \frac{1}{w(p)} F(x, w, n)$. The average risk setting is perfectly suitable here, since we would like to evaluate a pixelwise difference on a randomly chosen subset of pixels. We demonstrate this approach in the example provided below, where the pixelwise difference is computed only 2 times per iteration.

Problem of functional optimization arises in many practical cases. While in some cases extreme points could be found analytically, many engineering applications deal with unknown functional, which can only be measured in selected points with possible noise. In some cases functional itself could vary over time and its extreme points could drift. In this case problem setting could be different, depending on goals of optimization and possible measurements. In general, there are two different variants of a function behavior over time - it has a limit function, to which it tends when time goes to infinity, or there is no such function [3]. In this paper we consider the second variant.

Non-stationary optimization problems can be described in discrete or continuous time. In our paper we consider only discrete time model. Let $f(x, n)$ be a functional we are optimizing at the moment of time n ($n \in \mathbf{N}$). In book [4] Newton method and gradient method are applied to problems like that, but they are applicable only in case of two times differentiable functional and $l < \nabla^2 f_k(x) < L$. Both methods require possibility of direct measurement of gradient in arbitrary point.

In real world measurement always contains noise. Sometimes the algorithms that perfectly solve the problem on paper do not provide good estimates in practical cases. Robustness is important in engineering applications. For problems with noise the Robbins-Monro and Kiefer-Wolfowitz stochastic approximation algorithms were developed in 1950s. The history of development of such algorithms is described in [5, 8]. Common approach used in these algorithms can be formalized in a following way:

$$\hat{\theta}_{n+1} = \hat{\theta}_n - \alpha_n \hat{g}_n(\hat{\theta}_n), \tag{1}$$

where $\{\hat{\theta}_n\}$ —is the sequence of extreme points estimates generated by algorithm, g_n — pseudo-gradient (replacing the gradient from Newton method). Pseudo-gradient has to approximate the true gradient. The important properties of algorithms described in this form are simplicity and recurrence. Because of these properties they are often applied in different areas.

Kiefer-Wolfowitz algorithm with randomized differences is also known as SPSA (Simultaneous perturbation stochastic approximation). Algorithms of this type with one or two measurements on each iteration appeared in papers of different researchers in the end of the 1980s [9–12]. Later in the text we will refer to this class of algorithms as SPSA for simplicity. These algorithms are known for their applicability to problems with almost arbitrary noise [8]. The measurement noise should be bounded and only slightly correlated with perturbation on each iteration. Moreover, the number of measurements made on each iteration is only one or two and is independent from the number of dimensions of the state space d. This property sufficiently increases the rate of convergence of the algorithm in multidimensional case ($d >> 1$), comparing to algorithms, that use direct estimation of gradient, that requires $2d$ measurements of function in case if direct measurement of function gradient is impossible. Detailed review of development of such methods is provided in [8, 13].

Stochastic approximation algorithms were initially proven in case of the stationary functional. The gradient algorithm for the case of minimum tracking is provided in [4], however the stochastic setting is not discussed there. Further development of these ideas could be found in paper [3], where conditions of drift pace were relaxed. The book [5] uses the ordinary differential equations (ODE) approach to describe stochastic approximation. It addresses the issue of applications of stochastic approximation to tracking and time-varying systems in a following way: it is proven there that when the step size goes to zero in the same time as the number of the algorithm's iterates over a finite time interval tends to infinity, then the minimum estimates tend to true minimum values. This is not the case here, since we consider the number of iterates per unit of time to be fixed. In this paper we consider application of simultaneous perturbation stochastic approximation algorithm to the problem of tracking of the functional minimum. SPSA algorithm does not rely on direct gradient measurement and is more robust to non-random noise than gradient-based methods mentioned earlier. The most closely case was studied in [6], but we do not use the ODE approach and we establish more wide conditions for the estimates stabilization. In the following section we will give the problem statement that is more general than in [3, 4], in the third section we provide the algorithm and prove its estimates mean squared stabilization. In the last section we illustrate the algorithm, applying it to minimum tracking in a particular system.

2 Problem Statement

Consider the problem of minimum tracking for average risk functional:

$$f(x, n) = E_w\{F(x, w, n)\} \to \min_x, \tag{2}$$

where $x \in \mathbf{R}^d$, $w \in \mathbf{R}^p$, $n \in \mathbf{N}$, $E_w\{\cdot\}$ — mean value conditioned on the minimal σ-algebra in which w is measurable.

The goal is to estimate θ_n — minimum point of functional $f(x, n)$, changing over time:

$$\theta_n = argmin_x f(x, n).$$

Let us assume that on the iteration we can do a following measurement:

$$y_n = F(x_n, w_n, n) + v_n, \tag{3}$$

where x_n — arbitrary measurement point chosen by algorithm, w_n — random values, that are non-controlled uncertainty and v_n — observation noise.

Time in our model is discrete and implemented in number of iteration n.

To define the quality of estimates we will use the following definition:

Definition 1. *[7] A random matrix (or vector) sequence* $\{A_k, k \geq 0\}$ *defined on the basic probability space* $\{\Omega, \mathcal{F}, P\}$ *is called* L_P*-stable (*$p > 0$*) if*

$$\sup_{k \geq 0} E\|A_k\|^p < \infty.$$

We will use the definition 1 in case of $p = 2$.

Further we will consider generation of sequence of estimate $\{\hat{\theta}_n\}$ for problem (2), satisfying the definition 1 for p=2, in following conditions.

We will assume that drift of the minimum point is limited in following sense:

$$(\mathbf{A}) \quad \|\theta_n - \theta_{n-1}\| \leq A.$$

Function $f(\cdot, n)$ is a strictly convex function for each n:

$$(\mathbf{B}) \quad \langle \nabla f(x, n), x - \theta_n \rangle \geq \mu \|x - \theta_n\|^2.$$

Gradient $\nabla F(\cdot, w, n)$ is Lipschitz with constant B, $\forall n, \forall w$:

$$(\mathbf{C}) \quad \|\nabla F(x, w, n) - \nabla F(y, w, n)\| \leq B\|x - y\|.$$

Average difference of function $F(x, \cdot, n)$ in any point x for moments n and $n + 1$ is limited in a following way:

$$(\mathbf{D}) \quad E_{w_1,w_2}|F(x, w_1, n + 1) - F(x, w_2, n)| \leq C\|x - \theta_n\| + D.$$

$(\mathbf{E})$ Local Lebesgue property for the function $\nabla F(w, x)$: $\forall x \in \mathbb{R}^d \, \exists$ neigbourhood U_x such that $\forall x' \in U_x$ $\|\nabla F(w, x)\| < \Phi_x(w)$ where $\Phi_x(w) : \mathbb{R}^p \to \mathbb{R}$ is integrable by w: $\int_{\mathbb{R}^q} \Phi_x(w)dw < \infty$

The last condition is necessary for the commutation of differentiation and integration operations, that is used to change order of expectation and gradient in the proof of the theorem. For more discussions about such properties see [18].

$(\mathbf{F})$ For the observation noise v_n the following conditions are satisfied:

$$|v_{2n} - v_{2n-1}| \leq \sigma_v,$$

or if it has statistical nature then:

$$E\{|v_{2n} - v_{2n-1}|^2\} \leq \sigma_v^2.$$

Here we should make several notes:

1). Sequence $\{v_n\}$ could be of non-statistical but unknown deterministic nature. 2). Constraint (**A**) allows both random and deterministic drift. In certain cases Brownian motion could be described without tracking. Tracking is needed when there is both determined and non-determined aspects of drift. Similar condition is introduced in [4], it is slightly relaxed in [3]. For example it could be relaxed in a following way:

$$(\mathbf{A}') \quad \theta_n \leq A_1\theta_{n-1} + A_2 + \xi_n,$$

where ξ_n is random value.

In this paper we will only consider drift constraints in form **(A)**. Mean square stabilization of estimation under condition **(A)** implies its applicability to wide variety of problems.

3 Algorithm and Stabilization of Estimates

In this section we are introducing a modification of SPSA algorithm provided by Chen et al [16], which takes one perturbed and one non-perturbed measurement on each step.

Let perturbation sequence $\{\Delta_n\}$ be an independent sequence of Bernoulli random vectors, with component values $\pm 1/\sqrt{d}$ with probability $\frac{1}{2}$. Let vector $\hat{\theta}_0 \in \mathbb{R}^d$ be the initial estimation. We will estimate a sequence of minimum points $\{\theta_n\}$ with sequence $\{\hat{\theta}_n\}$ which is generated by the algorithm with fixed stepsize:

$$\begin{cases} x_{2n} = \hat{\theta}_{2n-2} + \beta\Delta_n,\ x_{2n-1} = \hat{\theta}_{2n-2}, \\ y_n = F(x_n, w_n, n) + v_n, \\ \hat{\theta}_{2n} = \hat{\theta}_{2n-2} - \frac{\alpha}{\beta}\Delta_n(y_{2n} - y_{2n-1}), \\ \hat{\theta}_{2n-1} = \hat{\theta}_{2n-2}. \end{cases} \tag{4}$$

(**G**) We will further assume that random values Δ_n generated by algorithm are not dependent on $\hat{\theta}_k$, w_k , $\hat{\theta}_0$ and on v_k (if they are assumed to have random nature) for $k = 1, 2, \ldots, 2n$.

Let us define $H = (\alpha^2 B + \frac{\alpha^2}{\beta^2}D + \frac{\alpha^2}{\beta^2}\sigma_v)(\beta B + C) + \alpha AB + \alpha\beta B + A$. Let K and $\delta > 0$ be constants satisfying following condition:

$$K = 1 - 2\alpha\mu + \frac{\alpha^2}{\beta}B + \frac{\alpha^2}{\beta^2}C + \delta < 1.$$

Denote $L = \frac{H^2}{\delta} + A^2 + 2\alpha\beta AB + \frac{\alpha^2}{\beta^2}((\beta^2 B + D)^2 + \sigma_v^2 + 2(\beta^2 B + D)\sigma_v)$.

Theorem 1. *[15, 19] . Assume that conditions* **(A)–(G)** *on functions f, F and ∇F and values θ_n, $\hat{\theta}_n$, v_n, w_n, y_n and Δ_n are satisfied. Let us further assume that constants $\alpha, \beta > 0$ satisfy the inequality:*

$$0 < \delta < 2\alpha\mu - \frac{\alpha^2}{\beta}B - \frac{\alpha^2}{\beta^2}C. \tag{5}$$

Then estimates provided by the algorithm (4) stabilize in mean squares and following inequality holds:

$$E\{\|\theta_n - \hat{\theta}_n\|^2\} \leq K^n\|\theta_0 - \hat{\theta}_0\|^2 + \frac{L(1-K^n)}{1-K}. \tag{6}$$

Note that Theorem 1 provides asymptotically effective value for the estimates:$\bar{L} = L/(1-K)$.

Conditions **(A)–(C)**,**(E)–(G)** are standard for SPSA algorithms [8]. Earlier the proof of the similar theorem was given in [15] with more strict conditions. See the proof of Theorem 1 in appendix.

The condition (5) on α can be satisfied only when inequality $0 < \alpha < 2\mu\frac{\beta^2}{B\beta+C}$ is true. It follows from the result of the Theorem 1 that $E\{\|\theta_n - \hat{\theta}_n\|^2\} \le O(\frac{A^2}{\alpha})$ $(\alpha \to 0)$ which leads to a simple decision rule: to presume the upper bound α should tend to zero with the same pace as A^2. α can be arbitrarily close to 0, which diminishes the effects of the gradient approximation bias and the noise.

To build the upper bound of the algorithm's estimates error using Theorem 1, it is needed to find α and β satisfying the condition (5), then to find δ which gives minimum value of the fraction $\frac{L}{1-K}$. Using the resulting bound obtained, it is possible to reduce it by applying the ideas concerning the relation of α and dreif parameters such as A and the function parameters such as B or μ. The resulting estimates behavior will be the trade-off between the tracking ability and noise sensitivity. The similar problem of algorithm parameters choosing was studied in [17] for the same algorithm but in the linear case.

4 Application to Object Tracking

Here we would like to present the derivation of the basic convergence conditions (A)-(F), which is done considering the application of the theorem to the object tracking problem. The problem itselkf was descibed in the beginning of the article. The conditions should be true in some neighbourhood of the object.

$$(\mathbf{A}) \quad \|x_n - x_{n-1}\| \le A.$$

That is a constraint on the speed of object's movement.

Function $f(\cdot, n)$ is a strictly convex function for each n:

$$(\mathbf{B}) \quad \langle \sum_{p \in O_n} \frac{1}{w(p)} 2(I_n(x+p) - I_{n-1}(x_{n-1}+p)), x - x_n^* \rangle \ge \mu \|x - x_n^*\|^2.$$

This condition is about the difference between the object and the background.

Gradient $\nabla F(\cdot, w, n)$ is Lipschitz with constant B, $\forall n, \forall w$:

$$(\mathbf{C}) \quad \|2I_n(x+p) - 2I_n(y+p)\| \le B\|x - y\|.$$

This describes the local proximity of pixels in the picture.

Average difference of function $F(x, \cdot, n)$ in any point x for moments n and $n+1$ is limited in a following way:

$$(\mathbf{D}) \quad \sum \frac{1}{w(p_1)w(p_2)} |(I_n(x+p_1) - I_{n-1}(x+p_2) + I_{n-1}(x+p_1) - I_{n-2}(x+p_2))$$
$$(I_n(x+p_1) - I_{n-1}(x+p_2) - I_{n-1}(x+p_1) + I_{n-2}(x+p_2))| \le C\|x - x_n^*\| + D.$$

This condition means that the object's pixels are similar to each other, and in the same time different from the background.

$(\mathbf{E})$ Local Lebesgue property for the function $\nabla F(w, x)$: $\forall x \in \mathbb{R}^d \, \exists$ neigbourhood U_x such that $\forall x' \in U_x$ $\|\nabla F(w, x)\| < \Phi_x(w)$ where $\Phi_x(w) : \mathbb{R}^p \to \mathbb{R}$ is integrable by w: $\int_{\mathbb{R}^q} \Phi_x(w)dw < \infty$

The last condition is necessary for the commutation of differentiation and integration operations, that is used to change order of expectation and gradient in the proof of the theorem. For more discussions about such properties see [18].

$(\mathbf{F})$ For the observation noise v_n the following conditions are satisfied:

$$|v_{2n} - v_{2n-1}| \leq \sigma_v,$$

or if it has statistical nature then:

$$E\{|v_{2n} - v_{2n-1}|^2\} \leq \sigma_v^2.$$

The noise boundary depends on the light conditions and camera properties.

5 Object Tracking Example

The application of the algorithm to the problem of object tracking on video is demonstrated by the following example. We took an image presented at the Fig. 5 as a second image, I_{n+1}. The object is a rectangle with a picture of butterfly, of size 208x120=24960 pixels. The image I_n contains the object in tyhe lower-right corner. Vector h is 2-dimensional.

Fig. 1. Experiment with tracking of an object on video.

The results are presented at the Table 1. We see significant increase in performance gained from the application of more advanced optimization technique.

6 Conclusions

In our work we apply the SPSA-type algorithm to the problem of object tracking on video. The novelty of the approach comes from the use of stochastic optimization instead of standard pseudogradient technique to find a location of an object. SPSA does

Table 1. The results of the experiment: amount of pixelwise difference calculation for Lucas-Kanade and SPSA-based algorithms.

Characteristic	Lucas-Kanade	SPSA-based
Number of measurements per iteration	24960	2
Number of iterations	3	1201
Number of measurements	74880	2402

not require possibility of direct gradient measurement, needs only 2 function measurement on each iteration and once differentiable function. Drift is only assumed to be limited, which includes random and directed drift. It was proven that the estimation error of this algorithm is limited with constant value. The modeling was performed on a multidimensional case.

The results show the potential performance gains of using the SPSA-type algorithms for tracking of objects on video. Probably, more sofisticated algorithms based on optimization such as kernel-based methods of tracking [2] can also be improved by the same technique. Authors want to try such application in future.

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Prospects of “One-level” Architecture of Control Systems on the basis of Ethernet Network - DCS "Tornado-N" with “One-level” Architecture on the basis of Ethernet

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Abstract. Modern DCS of technological processes have “multi-level” architecture. The “low” level of DCS is represented by controllers. They provide three main functions: data acquisition, processing and control of object. Input-output devices are connected directly to controller for information interchange with object and processing unit (CPU). The upper level connects controllers together and provides their interaction with "the top" level of a system. In systems with such architecture, controller which needs to obtain variables connected to an other controller, it requires to have a special complex service for interconnection with the other controller: for performance of base “low” level function of input-output, upper level is involved. Many suppliers of control systems do not have a solution for it, i.e. the data exchange function of controller in vast majority of systems is absent. Level of today's network technologies allows to construct homogeneous “one-level” control system on the basis of a high-efficiency local network, for example Fast Ethernet. In such systems network is used not only for interaction of workstations, servers, but for direct interaction with input-output devices, connected directly to Fast Ethernet network. Thus the concept of classical controllers disappears and control algorithms may be carried out in any point of the system.

1 Introduction

The idea of common bus interface now exists for more than 30 years. This principle is being used to construct separate subsystems (e.g. computers, controllers) and integration of such subsystems. There exists a majority of bus interfaces for these purposes.

Bus (e.g. PCI) merges all the primary devices in computers and servers, bus interface in controllers merges all processor and I/O modules. Thus, different subsystems use different inner bus interfaces. Modern distributed control systems (DCS) of technological processes have “multi-level” architecture. The “low” level of controllers providing information interchange and commands with object through the devices of input-output, connected directly to the controller (Figure 1).

The next upper level connects controllers together and provides their interaction with "the top" level of a control system. In systems with such architecture, controller which needs to obtain variables connected to an other controller requires to have the special complex service for interconnection with the other controller, i.e. for performance of base “low” level function of input-output, upper level will be involved.

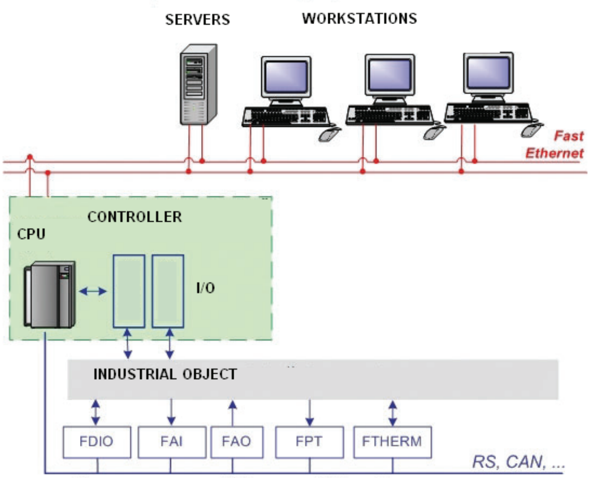

Fig. 1. Traditional heterogeneous architecture.

This problem not so is simple, as may seem and many suppliers of control systems do not have a solution for it, i.e. the data exchange function of the controller’s in vast majority of systems is absent. The level of today's network technologies allows to construct homogeneous “one-level” control system on the basis of a high-efficiency local bus interface (Fig. 2). In such systems the network is used not only for interaction of workstations, servers, but for direct interaction with input-output devices, connected directly to network. It is quite possible to suggest the possibility of building the whole system based on one common bus interface (a homogeneous system). Nowadays Ethernet technology gives the developers of Industrial Control Systems all the sufficient facilities.

2 Fast Ethernet Bus

Analyzing the history of computer systems progress one can note such tendency that with development of new technologies the system constructor gets an opportunity to deal with more and more higher-level interfaces of informational exchange. Nowadays Ethernet is a Bus Interface of high-level for building DCS. If I/O modules are connected directly to the common-system bus interface, we have different architecture of DCS with a list of new advantages; controllers are assumed as something different from familiar sight.

Thus the concept of classical controllers disappears. Control algorithms can be carried out in any point of the system, but for reasons of reliability it is more preferable and better to allocate special computing devices of "an automation server".

It is possible to consider such architecture almost "ideal", possessing nearby considerable advantages. It is possible to expect that the future development of control systems will go this way.

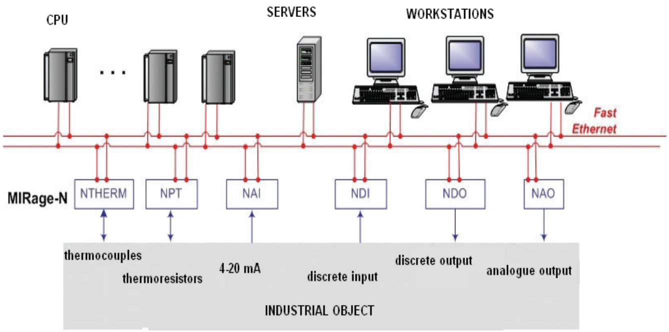

Fig. 2. Homogeneous architecture.

The main goal of "Modular Systems Tornado" company's (www.tornado.nsk.ru, Nosovibirsk, Russia) developers was to create the automation facilities for maximum broad spectrum of process tasking, to have an opportunity to use these facilities on really large major industrial objects. MIRage-N I/O modules with duplex Ethernet bus may be successfully implemented not only in systems of general-automation use but the module line is sufficient for objects with enhanced reliability, fail-safety and high-availability requirements. Distributed I/O modules of this product line can be implemented both as parts of DCS and for local means of visualization and maintenance.

Unlike the other products of distributed I/O, MIRage-N line provides the data of industrial workflow directly to the common Fast Ethernet industrial bus aggregating all elements of the automation system: CPU modules, servers and workstations.

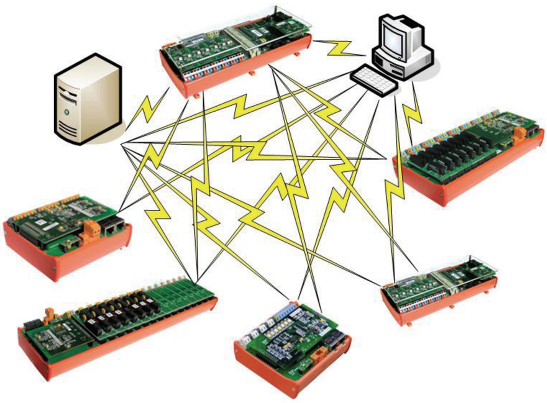

Fig. 3. MIRage-N: equal right DCS member.

Architecture with absence of controllers (in usual assumption) gives a new degree of freedom to developer. There is no need in affixment of I/O modules to the specified definite CPU (like in all common systems). This factor substantially simplifies the process of DCS cabinet's construction: MIRage-N modules transfer data to any active CPU of the system attaining the state of distribution of data collecting and data processing.

2.1 MIRage-N Advantages

Thereby systems with distributed I/O based on MIRage-N modules have such advantages:

- It's standard and innovative, specified by use of progressive Ethernet technologies and organization of data transfer services by copper cables, optical cables and radio communication;
- Fail-safety provided by duplex Ethernet bus. Communication channel restoration is an expensive long-run and complicated procedure. Duplication of the industrial bus gives an opportunity to detect and restore the failure troubles. Such system is operable and runs even with failure of one communication subsystem. Also according to requirements it is possible to duplicate the functional parts and assemblies of the system;
- Reduction of charges: as an industrial bus interface, Fast Ethernet (10/100 Mbit/sec) gives a wide variety of computing sources from industrial CPU to PC-compatible devices that dramatically reduces the upper-level cost of industrial control system. Distributed structure of the system allows to make changes "on-site" enhancing operational and metrological characteristics of the system and substantially reducing expenditures for cable materials;
- High Availability: the system architecture allows to make hot-swap of any system element, replacement of defective modules without an impact on the rest of the system with minimum time;
- hot-swap of any system element, replacement of defective modules without an impact on the rest of the system with minimum time;
- Convenience in exploitation. The module construction allows the mounter to make the replacement of defective elements without demounting of field cables. Signals from sensors are plugged directly in MIRage-N modules in WAGO spring clips that do not require periodic maintenance;
- Scalability, extensibility. The functioning system may be populated with additional modules. The scaling procedure does not require any modification of functioning part of the system. Industrial interface bus of large and major industrial objects may contain several segments that use different communication mediums, e.g. copper wire, optical cable and radio connection;
- Developed software for integration of MIRage-N modules with ISaGRAF programming environment. Developed applications include .dll libraries implementing Modbus interfaces; OPC DA server supplying compatibility with SCADA systems for Windows OS supplying duplex Ethernet bus interface; components for usage of modules in LabView environment;
- Fixed time cycle of data acquisition for all devices equal to time of answering interval for one device (1 msec). The possibility of same time device scan rids from necessity of passive reply wait.

Open standards and technologies used in bus interface modules MIRage-N give the possibility to develop and maintain any systems of automation with different configuration of Ethernet, any processing devices, any programming environments and SCADA-systems, servers, e.t.c. The configuring of MIRage-N modules and visualization of data is maintained with "Configurator" software.

Unified module body of MIRage-N allows the installation of the module on DIN-rail (35 mm), it provides electrical insulation, galvanic isolation, fail-safe connection of the sensor cables. Field cable cross section square is 0,08 to 2,5 mm2.

2.2 Module Construction

Every MIRage-N module is a two-part construction – motherboard and plug-in boards - mezzanines. Mezzanines contain all the active elements. Figure 4 features MIRage-N parts:

1. Motherboard with no active elements;
2. Field Terminal blocks;
3. Mezzanine connectors;
4. Protective device;
5. Power supply connection;
6. Fast Ethernet connection inputs.

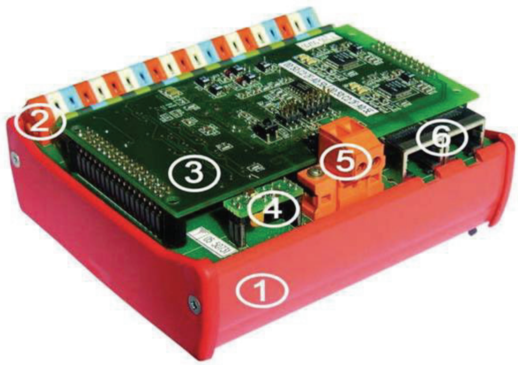

Fig. 4. MIRage-N module construction (with cover removed).

2.3 MIRage-N Line

The MIRage-N line includes all types I/O modules to fulfil the requirements of Industrial Control Systems:

- MIRage-NAI – 16 differential channels or 32 single channels, analogue signal input -20 + 20- mA, -10 +10 V, 16-bit delta-sigma ADC, 3-pole digital filter, individual DC-DC converter to power supply of sensor.
- MIRage-NDIO – 24 discrete channels. 12 input channels, 12 output channels. 24 V, 220 V.
- MIRage-NDI – 24 input channels. 24 V or 220 V, 4mA input current.

- MIRage-NDO – 24 output channels. 24 V or 220 V AC/DC: 3 A – AC, 0,5 A – DC.
- MIRage-NAO – 4 analogue output channels, 8 programmable discrete channels.
- NIRage-NTHERM – 8 analogue channels, thermocouples.
- MIRage-NPT – 8 analogue channels, thermoresistors.

The company "Modular Systems Tornado" has finished system engineering of DCS "Tornado-N" with “one-level” architecture on the basis of Ethernet. Today DCS “Tornado-N” is used to build industrial control systems of large power units for power stations.

3 Conclusions

In architecture where all system elements are connected directly to integrated Ethernet bus interface the developer gets one of the most promising solutions applicable in DCS development. DCS “Tornado-N” architecture with common Ethernet bus based on MIRage-N distributed I/O line gives substantial economic benefits; in comparison with other world well-known industrial automation companies DCS “Tornado-N” decreases expenses up to 30 % in major automation systems of heat and power engineering plants with hundreds and thousands of signals and furthermore gives developer new levels of freedom in system construction allowing to use different connection schemes and benefit from open standards and technologies underlying in described approach philosophy.

Described above architecture approach is currently being implemented in automation systems of power stations, thermal power plants and other major industrial objects in Russia and CIS and demonstrated it’s positive qualities.

It is very likely that soon this approach will become the most widespread architecture in modern DCS.

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Semiglobal Asymptotic Stabilization of a Class of Nonlinear Sampled-data Systems using Emulated Controllers

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Abstract. Considering nonlinear sampled-data systems, it has been shown in [14] - that emulating a continuous-time controller that ensures some global asymptotic stability properties in continuous-time. In this study, we provide a similar result, for a general class of systems, using a hybrid formulation that allows deriving explicit bounds on the maximum allowable sampling period.

1 Introduction

A number of researches focused on the stabilization problem of nonlinear sampled-data systems during the last decades (see the overview [13] and [14] and the references cited therein). A common approach consists in emulating a known continuous-time controller using a sample-and-hold device. Based on discrete-time model approximations and using results of [17], it has been shown in [14] that, by choosing a sufficiently small sampling period, asymptotic stability properties are recovered in an appropriate practical sense, under mild conditions. Practical state convergence might be an issue in practice, especially when the sampling period cannot be taken small enough. It is also important for engineers to know an explicit bound on the sampling period that can be taken so that designed controllers ensure the desired asymptotic state convergence. Thus, a number of papers propose solutions for the asymptotic stabilization of nonlinear sampled-data systems and the knowledge of an explicit bound on $\mathrm{T}_{\mathrm{MASP}}$. In most of these works, global asymptotic stability properties are studied. Two exceptions are however available in the literature. First in [9] where a hybrid stabilization method is proposed for some classes of systems: it consists in decomposing the state space in a number of regions for which a controller is designed in order to reach the next region that is closer to the origin. A semiglobal asymptotic stability property is shown to hold for system in output feedback form in [21] but no explicit bound on $\mathrm{T}_{\mathrm{MASP}}$ is given. Concerning results on global asymptotic stability properties for nonlinear systems, some papers are available in the literature. In [4], global Lipschitz conditions on system and static state-feedback nonlinearities are supposed to apply, thus the global exponential stability of the system origin is recovered under sampling. In [1], considering the Euler approximation of a dynamic feedback controller, Lyapunov stability results for impulsive systems are applied, under similar conditions than in [4]. A small gain theorem for a class of hybrid systems that does not satisfy the classical semi-group property is developed in [7] that allows to design discrete-time controllers for classes of nonlinear systems. The same authors in [9] derive an analytic bound on $\mathrm{T}_{\mathrm{MASP}}$ when using emulated controllers, by modeling sampled-data systems as time-delay systems. Recently, techniques firstly developed for networked systems have been applied to the stabilization problem of nonlinear sampled-data systems [16]. Writing nonlinear sampled-data systems with emulated controllers as hybrid systems in the modeling framework of [3, 2], sufficient Lyapunov-type conditions are proposed and an explicit bound on the T_{MASP} is given.

In this study, considering a known controller that is supposed to ensure the input-to-state stability w.r.t. measurement errors of the closed-loop system in continuous-time, it is shown that the emulated controller will ensure the asymptotic stability of system origin if the sampling period satisfy an explicit boundedness condition. Similarly to [16], the system is written as the interconnection of the continuous-time closed-loop system and the 'error' system due to the sampling. The stability analysis relies on trajectory based arguments and the Lyapunov-like analysis to ensure bounds on the state and sampling error.

2 Notations

The Euclidean norm of a vector is denoted by $|\cdot|$, for a function $f : \mathbb{R} \to \mathbb{R}^n$ and $t_1 \leq t_2 \in \mathbb{R}$, $\|f\|_{[t_1,t_2)}$ stands for $\sup_{\tau\in[t_1,t_2)} |f(\tau)|$. Let $C(\mathbb{R}^p, \mathbb{R}^q)$, p, $q \in \mathbb{N}$, denote the space of all continuous mapping $\mathbb{R}^p \to \mathbb{R}^q$. $B_d \subset of R^n$ denotes the open ball centered at 0 and of radius d. For initial conditions we use notations $t_\circ \geq 0$, $x_\circ = x(t_\circ)$, $e_\circ = e(t_\circ)$, finally, to simplify the notations we sometimes omit the arguments and when it is clear from the context, we write $V(x(t))$, or even $V(t)$ in place of of $V(x(t, t_\circ, x_\circ))$.

3 Problem Statement

Consider a system:

$$\dot{x}_p = f_p(x_p, u), \tag{1}$$
$$y = h_p(x_p), \tag{2}$$

where $x_p \in \mathbb{R}^{n_{x_p}}$ denotes the state vector of the plant, $u \in \mathbb{R}^{n_u}$ the input vector, $y \in \mathbb{R}^{n_y}$ the output vector, $n_{x_p}, n_u, n_y \in \mathbb{N}$, $f_p \in \mathbb{R}^{n_{x_p}} \times \mathbb{R}^{n_u} \to \mathbb{R}^{n_{x_p}}$ is locally Lipschitz with $f_p(0,0) = 0$, and $h_p \in \mathbb{R}^{n_{x_p}} \to \mathbb{R}^{n_y}$ is differentiable, its partial derivatives are locally Lipschitz and $h_p(0) = 0$.

The following dynamic output-feedback controller is considered for the system (1)-(2):

$$\dot{x}_c = f_c(x_c, y), \tag{3}$$
$$u = h_c(x_c, y), \tag{4}$$

where $x_c \in \mathbb{R}^{n_{x_c}}$ denotes the state vector of the controller, $n_{x_c} \in \mathbb{N}$, $f_c \in \mathbb{R}^{n_{x_c}} \times \mathbb{R}^{n_y} \to \mathbb{R}^{n_{x_c}}$ is locally Lipschitz with $f_c(0,0) = 0$ and $h_c \in \mathbb{R}^{n_{x_c}} \to \mathbb{R}^{n_u}$ is differentiable with locally Lipschitz partial derivatives and $h_c(0) = 0$. For the sake of generality, all the results are stated for the system (1)-(4), but they apply also for the case of output or state static feedbacks. Denoting $x = [x_p^\top, x_c^\top]^\top \in \mathbb{R}^{n_x}$, $n_x = n_{x_p} + n_{x_c}$, the following assumption is supposed to apply throughout the paper.

Assumption A 1. *The origin $x = 0$ is globally asymptotically stable for the closed-loop system (1)-(4).*

Attention is focused on the case where the input u and the measure vector y are sampled at the same instants $\{t_k\}_{k\in\mathbb{N}}$ using a sample-and-hold device. In the sequel we will use the following assumption on the sampling instants.

Assumption A 2. *Sequence of sampling instants $\{t_k\}$, $k \in \mathbb{N}$ satisfies the following:*
(i) There exist positive constants $\upsilon, T_{max} \in \mathbb{R}_{>0}$ such that $\upsilon \leq t_{k+1} - t_k \leq T_{max}$ for all $k \geq 0$.
(ii) The sequence $\{t_k\}_{k\in\mathbb{N}_0}$ is unbounded.

Remark. Assumption A2 allows the sampling sequence to be non-uniform. The lower boundedness condition on the sampling periods is not restrictive since υ can be taken arbitrarily small.

Considered sampled-data system can be rewritten in the following way, for $k \in \mathbb{N}$ and $t \in (t_k, t_{k+1}]$,

$$\dot{x} = f(x, e), \tag{5}$$
$$\dot{e} = g(e, x), \tag{6}$$

for $t = t_k$,

$$x(t_k^+) = x(t_k), \tag{7}$$
$$e(t_k^+) = 0, \tag{8}$$

where $e = x - x(t_k)$, $f = [f_p(x_p, h_{ce})^\top, f_c(x_c, h_{pe})^\top]^\top$, $h_{pe}(x, e) = h_p(x(t_k)) = h_p(x_p - e_p)$, $h_{ce}(x, e) = h_c(x_c(t_k), y_k) = h_c(x_c - e_c, h_{pe})$ and $g(e, x) = f(x, e)$. Due to the properties of the functions f_p, f_c, h_p, h_c thus introduced functions f and g are locally Lipschitz. Since by assumption A2 the sampling sequence is not generated independently, the system (5)-(8) satisfies the classical semigroup property (see Example 2.12 in [7]).

The proposed presentation of the sampled data system is similar to this of [16] with the difference in the definition of the variable e.

Our objective is to establish certain stability properties of the system (5-8) in case where Assumptions A1-2 are satisfied. Namely we are interested in semi-global stability property defined next.

Definition 1. *System (5-8) is said to be **Semi-Globally Asymptotically Stable** (SGAS) with respect to T if for all $\Delta \in \mathbb{R}_{>0}$, there exist $T_{\max\in\mathbb{R}_{>0}}$, $\beta \in \mathcal{KL}$ such that for all $T \in [\upsilon, T)_{\max}$, $x(t_\circ) \in B_\Delta$ and for all $t \in [t_\circ, \infty)$ the following inequality holds:*

$$|[x(t)^\top, e(t)^\top]| \leq \beta(|[x(t_\circ)^\top, e(t_\circ)^\top]|, t - t_\circ). \tag{9}$$

*If (9) holds for $\Delta = \infty$, then system (5-8) is said to be **Globally Asymptotically Stable** (GAS).*

The approach we use is quite similar to the one proposed in [8] for design of hybrid observers for sampled-data systems. Indeed, similar to [8] an ISS-like property with respect to the measurement errors is exploited for the stability analysis. Actually, we base our analysys on the following theorem which is similar to the result given in Theorem 2 of [20] but in our case the bound on the possible input does not depend on the system initial condition but rather on the radius of the ball of initial conditions for the state Δ and a chosen overshoot.

Theorem 1. *Consider the system*

$$\dot{x} = f(x, u), \tag{10}$$

where $x \in R^n$ and function $f : R^n \times R^m \to R^n$ is continuous and locally Lipschitz. Let $\Delta \in \mathbb{R}_{>0}$ be arbitrary and $x_\circ \in B_\Delta$. If the system (10) is GAS with the input $u \equiv 0$, then there exist function $\beta \in \mathcal{KL}$, a continuous positive definite function $\delta : R_{\geq 0} \to R_{\geq 0}$ and for each $\Delta > 0$ there exists function $\gamma_\Delta \in \mathcal{K}$ such that for any $t_\circ$, $t \geq 0$, $t \geq t_\circ$ and each measurable, essentially bounded input $u(\cdot)$ for which

$$\|u\|_{[t_\circ,\, t)} < \delta(\Delta), \tag{11}$$

the solution of (10) exists at least for $\tau \in [t_\circ, t)$ and satisfies on this interval the following bound

$$|x(\tau) \leq \beta(|x|_\circ, \tau - t_\circ) + \gamma_\Delta(\|u\|_{[t_\circ,\, t)}). \tag{12}$$

Proof. Since the origin $x = 0$ is GAS for the system $\dot{x} = f(x, 0)$, then it follows from Proposition 13 in [18] (see also [22]) that there exist functions $\alpha_1, \alpha_2 \in \mathcal{K}_\infty$ and $\alpha_3 \in \mathcal{K}$ and a Lyapunov function $V \in C^1(\mathbb{R}^n, \mathbb{R})$ such that for all $x \in \mathbb{R}^n$ we have

$$\alpha_1(|x|) \leq V(x) \leq \alpha_2(|x|), \quad \frac{\partial V}{\partial x} f(x, 0) \leq -V(x), \quad |\frac{\partial V}{\partial x}(x)| \leq \alpha_3(|x|).$$

Then, for the system (10) we have

$$\frac{\partial V}{\partial x} f(x, u) \leq -V(x) + \frac{\partial V}{\partial x}\,[f(x, u) - f(x, 0)] \leq -V(x) + \alpha_3(|x|)|f(x, u) - f(x, 0)|$$

Since the function f is continuous, it follows from the Lemma 2 that there exist a strictly increasing function $c \in C(\mathbb{R}, [1, \infty))$ and a function $d \in \mathcal{K}$ such that $|f(x, u) - f(x, 0)| \leq c(|x|)d(|u|)$ and therefore we have

$$\frac{\partial V}{\partial x} f(x, u) \leq -V(x) + c_1(|x|)d(|u|),$$

where $c_1(s) = \alpha_3(s)(s)$. Notice that the function $c_1 \in \mathcal{K}$
Let Δ, $\epsilon > 0$ and $x_\circ \in B_\Delta$ be fixed and arbitrary otherwise, define functions δ_1 and $\psi \in \mathcal{K}_\infty$ as follows

$$\psi(s) = (1 + \epsilon)\alpha_1^{-1} \circ \alpha_2(s), \quad \delta(s) = \frac{\alpha_1 \circ \psi(s) - \alpha_2(s)}{c\,(\psi(s))}.$$

Functions $\alpha_1, \alpha_2 \in \mathcal{K}_\infty$ and $\alpha_2(s) \geq \alpha_1(s)$ hence we have that function $\psi \in \mathcal{K}_\infty$ and $\psi(s) > \alpha_1^{-1} \circ \alpha_2(s) > s$ for all $s > 0$, therefore $\alpha_1 \circ \psi(s) - \alpha_2(s) > 0$ for all $s > 0$.

Since $c(s) \geq 1$ for all $s \geq 0$, function δ defined above is a continuous, positive definite function.

Claim 1. If the input satisfies the bound (11) for $\tau \in [t_\circ,\, t)$, then it holds that

$$\|x\|_{[t_\circ,\, t)} \leq \psi(\Delta). \tag{13}$$

Proof of the Claim 1. We proceed by contradiction. Assume that there exists $t^* \in [t_\circ,\, t)$ such that $|x(t^*)| = \psi(\Delta)$ and let $t_1 = \inf\{\tau \in [t_\circ,\, t) \,:\, |x(\tau)| = \psi(\Delta)\}$.

Then for all $\tau \in [t_\circ, t_1]$ we have that

$$\dot{V}_(10) = \frac{\partial V}{\partial x} f(x,e) \leq -V(x) + c(\psi(\Delta))d(|e|),$$

using the comparison principle [10] we obtain that for all $\tau \in [t_\circ, t_1]$ we have

$$\begin{aligned} V(x(\tau)) &\leq V(x_\circ)e^{-(\tau - t_\circ)} + \int_{t_\circ}^{\tau} c(\psi(\Delta))d(||e||_{[t_\circ,\tau)}) \exp(-\tau)d\tau \\ &\leq V(x_\circ)e^{-(\tau - t_\circ)} + c(\psi(\Delta))d(||e||_{[t_\circ,\tau)}). \end{aligned} \tag{14}$$

Combining the last inequality with (13) we obtain that for all $\tau \in [t_0, t_1]$

$$V(x(\tau)) \leq V(x_\circ) + \alpha_1(\psi(\Delta)) - \alpha_2(\Delta) < \alpha_1(\psi(\Delta)).$$

Thus, $V(x(t_1)) < \alpha_1(\psi(\Delta))$ which implies that $|x(t_1)| < \psi(\Delta)$ and we came to the contradiction with the initial assumption that $|x(t_1)| = \psi(\Delta)$ and hence Claim 1 is proved.

Next, since for any $\tau \in [t_\circ, t)$ we have that $|x(\tau)| \leq \psi(\Delta)$ then it follows from (14) and properties of the function $V(x)$ that on the same interval

$$\begin{aligned} \alpha_1(\|x(\tau)\|) \leq V(x(\tau)) &\leq V(x_\circ)e^{-(t-t_\circ)} + c(\psi(\Delta))d(||e||_{[t_\circ,\tau)}) \\ &\leq \alpha_2(\|x_\circ\|)e^{-(t-t_\circ)} + c(\psi(\Delta))d(||e||_{[t_\circ,\tau)}) \end{aligned}$$

and therefore

$$\begin{aligned} \|x(\tau)\| &\leq \alpha_1^{-1}\left(\alpha_2(\|x_\circ\|)e^{-(t-t_\circ)} + c(\psi(\Delta))d(||e||_{[t_\circ,\tau)})\right) \\ &\leq \alpha_1^{-1}\left(2\alpha_2(\|x_\circ\|)e^{-(t-t_\circ)}\right) + \alpha_1^{-1}\left(2c_\Delta d(||e||_{[t_\circ,\tau)})\right), \end{aligned}$$

where $c_\Delta = c(\psi(\Delta))$.

Since $\alpha_1,\, \alpha_2 \in \mathcal{K}_\infty$ and $d \in \mathcal{K}$, it is clear from the last inequality that there exists function $\beta \in \mathcal{KL}$ and for each $\Delta > 0$ there exists function $\gamma_\Delta \in \mathcal{K}$ such that for all $t \in [t_\circ,\, t)$ the bound (12) is satisfied.

□

4 Main Results

As mentioned in the Introduction, it is well known that the sampling of the system output and the control input is usually source of instability and that the only possibility to overcome this issue consists in restricting the upper bound on the sampling period.

The effect of the sampling is mostly due to the dynamics of the variable e. Thus, it is interesting to estimate an upper bound of this variable taking into account the fact that $e(t_k^+) = 0$, $k \geq 1$, i.e. we start every sampling period with zero initial condition for this variable

Lemma 1. *Consider the system (10) and assume that the function f is continuous, locally Lipschitz and $f(0,0) = 0$. Then, for any $\mu \in \mathbb{R}_{>0}$ there exist a C^1 function $W : \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ with bounded $\partial W(x)/\partial x$ and a C^1 function $\gamma \in \mathcal{K}$ such that for all $(x,e) \in R^n \times R^m$*

$$\frac{\partial W}{\partial x}(x), f(x,u) \leq \mu W(x) + \gamma(|u|). \tag{15}$$

The proof of the lemma 1 is presented in the appendix. It shows that the function ρ is not necessarily unbounded. Thus, according to Lemma 1, for any $\mu \in \mathbb{R}_{>0}$, there exist $\bar{\alpha} \in \mathbb{R}_{>0} \cup \{\infty\}$ such that $\rho : \mathbb{R}_{\geq 0} \to [0, \bar{\alpha})$ of class $\mathcal{K}$ ($\mathcal{K}_\infty$ if $\bar{\alpha} = \infty$).

Remark. Lemma 1 is similar to Lemma 11 in [18], but here, instead of finding an exponentially decreasing positive definite function of the state, an exponentially increasing one is obtained.

In the remaining part of the paper we assume that for the system (6) a function W is constructed according to Lemma 1 with a constant $\mu \in \mathbb{R}_{>0}$ given. Note that, since W is locally Lipschitz, using the arguments given in the footnote 8 in [15], this holds for almost all $(x,e) \in \mathbb{R}^{n_x+n_e}$, along solutions to (6):

$$\dot{W}(e) \leq \mu W(e) + \gamma(|x|). \tag{16}$$

The following proposition considers the case when subsystem (5) is ISS and gives the conditions under which there exists $T_{\max}$ such that the system (5)-(8) is GAS if the maximal sampling period is less than $T_{\max}$.

We start with introduction of the following assumption which will be used to ensure that the solutions of the sampled data system do not explose during the first sampling period.

Assumption A 3. *The system*

$$\dot{x} = f(x, x + c_e) \tag{17}$$

is forward complete for any parameter $c_e \in R^n$.

Remark 1. From the Theorem 2, [23] it follows that assumption A3 is equivalent to assuming existence of a proper and smooth function function $\Psi(x) : R^n \to R_{\geq 0}$ such that along solutions of (17) we have

$$\dot{\Psi} \leq a\Psi \tag{18}$$

for any $c_e \in R^n$.

Remark 2. Assumption A3 can actually be replaced by the equivalent assumption on forward completeness for the system $\dot{e} = g(e, e + c_x)$. Choice of the assumption depends rather on the simplicity to verify the assumptions for these two systems.

Theorem 2. *Consider the system (5)-(8) and let assumptions* **A1- A3** *hold. Suppose that for the system (5)-(6) there exist positive definite functions* $V, W : R^n \to R_{\geq 0}$*, functions* $\alpha_{iv},\, g_v,\, g_w \in \mathcal{K}_\infty$*,* $\alpha_{iw} \in \mathcal{K}$*,* $i = 1, 2$ *and positive constants* μ *and* σ *such that along solutions of the system (5)-(6) we have*

$$\alpha_{1v}(|x|) \leq V(x) \leq \alpha_{2v}(|x|) \tag{19}$$
$$\alpha_{1w}(|e|) \leq W(e) \leq \alpha_{2w}(|e|) \tag{20}$$
$$\dot{V} \leq -\sigma V + g_v(|e|) \tag{21}$$
$$\dot{W} \leq \mu W + g_w(|x|), \tag{22}$$

and functions $g,\, \alpha$ *satisfy the following* linear gain *conditions*

$$g_v \circ \alpha_{1w}^{-1}(s) \;\leq k_1 s \tag{23}$$
$$g_w \circ \alpha_{1v}^{-1}(s) \;\leq k_2 s, \tag{24}$$

where $k_1,\, k_2$ *are positive constants. Then if* $T_{\max}$ *from the assumption* **A2** *satisfies the inequality* $T_{\max} < T_*$*, where* $T_* = \frac{1}{\mu+\sigma} \ln \left(1 + \frac{\sigma(\sigma+\mu)}{k_1 k_2}\right)$*, then the system (5)-(8) is GAS.*

Proof. We start the proof with the remark that there is important difference between the first sampling interval and the rest of the sequence since it is only at the beginning of the 1st sampling interval we can have that $e(t_\circ) \neq 0$ while for all other intervals ($k \geq 1$) we have $e(t_k^+) = 0$, see (8). Therefore, we will teat here these two cases separately and later combine the results together. We start with the case of the first sampling interval.
<u>*Case I.*</u> $\mathbf{k} = \mathbf{0}$. On the interval $[t_\circ, t_1)$ we can rewrite the system (5)-(6) as follows:

$$\dot{x} = f(x, x + e_\circ)$$
$$\dot{e} = g(e, e + x_\circ).$$

Due to assumption A3 there exists a function $\Psi : R^n \to R_{\geq 0}$ such that (18) is satisfied, hence for any initial conditions $(x_\circ, e_\circ)$ we have that $\dot{\Psi} \leq \Psi$ and therefore, during the interval $[t_\circ, t_1) \subset [t_\circ, t_\circ + T_*)$ we have that $\Psi(x(t, x_\circ, e_\circ), e_\circ) \leq \Psi(x_\circ, , e_\circ)e_*^T$. Since function Ψ is proper and positive definite, there exist functions $\alpha_{i\psi} \in \mathcal{K}_\infty$, $i = 1, 2$ such that $\alpha_{1\psi}(|x|) \leq V(|x|) \leq \alpha_{2\psi}(|x|)$, thus for all $t \in [t_\circ, t_1]$

$$|x(t), e(t)| \leq \alpha_{1\psi}^{-1} \left(\alpha_{2\psi}(|x_\circ,\, e_\circ|)e^{T_*}\right). \tag{25}$$

<u>*Case II.*</u> $\mathbf{k} \geq \mathbf{1}$. This part of the proof is based on the following two observations:
– starting with $k = 1$ we have that at the beginning of each sampling period $e(t_k^+) = 0$ and therefore we can use (22) to estimate the error $e(t)$ during the sampling period.
– to ensure asymptotic stability it is enough to show that there exists a Lyapunov function $V(x)$ such that for any $k \geq 1$ and any $t \in (t_k, t_{k+1}]$ we have

$$V(x(t)) \leq V(x(t_k)) \tag{26}$$

and moreover, there exists $\varepsilon > 0$ such that

$$V(x_{k+1}) \leq \varepsilon V(x(t_k)). \tag{27}$$

Notice that condition (26) insures Lyapunov stability of solutions, while (27) ensures decreas of the Lyapunov function during each sampling period and thus it's convergence to zero. From convergence to zero of the sequence $V(x_k)$ follows convergence to zero of the $x(t_k)$, hence of $x(t)$ and therefore of the differences $e(t) = x(t) - x(t_k)$.

Thus we only need to ensure that conditions of the theorem guarantee that during any sampling period of the lenght less than T_* inequalities (26), (27) are satisfied. In order to prove (26) we proceed by contradiction. We assume that there exists $k \geq 1$ such that (26) is not true and $t_* \in (t_k, t_{k+1})$ is the first moment such that $V(x(t_*)) = V(x(t_k))$.

Let $t \in (t_k, t_*]$. Since $e(t_k^+) = 0$, then from (22) it follows that

$$\begin{aligned} W(e(t)) &\leq e^{\mu(t-t_k^+)} \int_{t_k}^{t} e^{-\mu\tau} g_w(|x(\tau)|)d\tau \\ &\leq e^{\mu(t-t_k^+)} \int_{t_k}^{t} e^{-\mu\tau} g_w \circ \alpha_{1v}^{-1}(V(x(\tau)))d\tau \leq k_2 e^{\mu(t-t_k^+)} \int_{t_k}^{t} e^{-\mu\tau} g_w V(x(\tau))d\tau \end{aligned}$$

By assumption, for $\tau \in (t_k, t_*]$ we have that $V(x(\tau)) \leq V(x(t_k))$ and therefore we conclude that

$$W(t) \leq \frac{k_2}{\mu} V(x(t_k)) \left(e^{\mu(t-t_k)} - 1\right). \tag{28}$$

In a similar way, from (21) we obtain that

$$\begin{aligned} V(t) &\leq V(t_k)e^{-\sigma(t-t_k)} + e^{-\sigma(t-t_k)} \int_{t_k^+}^{t} e^{\sigma\tau} g_v(|e(\tau)|)d\tau \\ &\leq V(t_k)e^{-\sigma(t-t_k)} + k_1 e^{-\sigma(t-t_k)} \int_{t_k^+}^{t} e^{\sigma\tau} W(e(\tau))d\tau \\ &\leq V(t_k)e^{-\sigma(t-t_k)} + \frac{k_1 k_2}{\mu} V(t_k)e^{-\sigma(t-t_k)} \int_{t_k^+}^{t} e^{\sigma\tau} \left(e^{\mu(\tau-t_k)} - 1\right) d\tau, \end{aligned}$$

where we used (28) in the last inequality.
After simple but tedious calculations we obtain that

$$V(t) \leq V(t_k) f(t), \tag{29}$$

where

$$f(t) = \frac{k_1 k_2}{\mu(\mu+\sigma)} e^{\mu(t-t_k)} + \left(1 + \frac{k_1 k_2}{\mu(\mu+\sigma)}\right) e^{-\sigma(t-t_k)} - \frac{k_1 k_2}{\mu\sigma}. \tag{30}$$

Notice that $f(t_k^+) = 1$, while during the interval $[t_k^+, t_k^+ + T_*)$ derivative of $f(t)$ satisfies the following bound

$$\begin{aligned} f'(t) &\leq e^{-\sigma(t-t_k^+)} \left(-(\sigma + \frac{k_1 k_2}{\mu+\sigma}) + \frac{k_1 k_2}{\mu+\sigma} e^{(\mu+\sigma)T_{\max}} \right) \\ &< e^{-\sigma(t-t_k^+)} \left(-(\sigma + \frac{k_1 k_2}{\mu+\sigma}) + \frac{k_1 k_2 + \sigma(\mu+\sigma)}{\mu+\sigma} \right) = 0 \end{aligned}$$

and therefore for all $t \in (t_k, t_k + T_*)$ we have that $f(t) < 1$[1]. Now, since $t^* \in (t_k, t_{k+1})$, we have that $t^* \le t_k + T_{\max} < t_k + T_*$ and therefore from (29) it follows that

$$V(t^*) \le V(t_k^+) f(t^*) < V(t_k^+) = V(t_k)$$

and we came to the contradiction. Hence the estimate (26) is satisfied during any sampling interval $(t_k, t_{k+1}]$. Next, let $\varepsilon = f(T_{\max})$. Since $T_{\max} < T_*$, we have that $\varepsilon < 1$ and then from (29) we obtain that on any sampling interval

$$V(t_{k+1}) \le V(t_k) f(t_{k+1}) \le V(t_k) f(T_{\max}) \le \varepsilon V(t_k)$$

and so the bound (27) is satisfied for any sampling period $(t_k, t_{k+1}]$. □

5 Conclusions

In this paper, for a general class of nonlinear systems we presented a result on asymptotic stability of a continuous time system in a closed loop with an emulated controller. We use a hybrid formulation that allows to give explicit bounds on the maximum allowable sampling period.

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[1] Notice that actually we need a T_* which corresponds to the positive solution of the equation $f(t) = 1$. Expression for T_* used in the theorem corresponds to the interval where $f'(t)$ is negative. This is done to give a simple expression for T_*. However we can use (30) to get numerically a better estimate for T_*

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Appendix

Proof of Lemma 1. Let $\mu > 0$ be arbitrary and define an auxiliary function $\Phi(x) = \|x\|$. Similar to Lemma 11 in [18] this function will serve the basis to construct function W which satisfies inequality (15). Taking derivative of Φ along the solutions of (10) we obtain

$$\frac{\partial \Phi}{\partial x}(x)\, f(x,u) \leq \|f(x,u)\|\,. \tag{31}$$

Notice that function f satisfies the assumptions of Lemma 2 and therefore there exist C^1 functions λ_i, C^1 functions $\varkappa \in \mathcal{K}$ and *positive* constants $c_i > 0$, $i = 1,2$ such that

$$\lambda_i(s) = (\varkappa_i(s) + c_i)\, s, \tag{32}$$

and

$$\|f(x,u)\| \leq \lambda_1(\|x\|) + \lambda_2(\|u\|). \tag{33}$$

It follows then that

$$\frac{\partial \Phi}{\partial x}(x)\, f(x,u) \le \lambda_1(|x|) + \lambda_2(|u|) = \lambda_1(\Phi(x)) + \lambda_2(\|u\|).$$

Next we define the function ρ as

$$\begin{cases} \rho(\tau) = \exp\left(\int_1^\tau \frac{a}{\lambda_1(s)} ds\right) & \text{for all} \quad \tau \in \mathbb{R}_{>0} \\ \rho(0) = 0 \end{cases} \tag{34}$$

where $a = \max\{\mu, 2(c_1 + \varkappa_1(1)\}$.

Claim 1. Thus defined function ρ is a continuous, locally Lipschitz function and there exists a constant $c > 0$ such that $\rho'(s) \le c$ for all $s > 0$.
We will prove this Claim a little bit later while for now we assume that it is true and define function W as $W = \rho \circ \Phi$. Function W is locally Lipschitz (as a composition of 2 locally Lipschitz functions) and we have

$$\begin{aligned} \frac{\partial W}{\partial x}(x) f(x,u) &= \frac{a}{\lambda_1(\Phi(x))} W(x) \frac{\partial \Phi}{\partial x}(x) f(x,u) \\ &\le \frac{a}{\lambda_1(\Phi(x))} W(x) \left(\lambda_1(\Phi(x)) + \lambda_2(|u|)\right) \\ &\le \mu W(x) + \frac{\mu W(x)}{\lambda_1(\Phi(x))} \lambda_2(|u|) \\ &= \mu W(x) + \mu \rho'(\Phi(x)) \lambda_2(|u|) \le \mu W(x) + c\mu \lambda_2(|u|). \end{aligned} \tag{35}$$

This would end the proof of the lemma.
Proof of the Claim. Function ρ defined in (34) is continuous on $\mathbb{R}_{>0}$ and strictly increasing. From (32) we have that for all $s \in [0,1]$

$$c_i s \le \lambda_1(s) \le (c_1 + \varkappa_1(1))\, s \tag{36}$$

and therefore $\int_1^\tau \frac{a}{\lambda_1(s)} ds \le \int_1^\tau \frac{a}{c_1 + \varkappa_1(1)} \frac{ds}{s}$. Since the last integral diverges to $-\infty$ as τ goes to zero we have that function ρ is continuous on $R_{\ge 0}$ and therefore $\rho \in \mathcal{K}$.

In contrast with [18] we can not guarantee that thus constructed function ρ belongs to $\mathcal{K}_\infty$. Actually, this function will belong to $\mathcal{K}_\infty$ only under certain conditions.

Next we will prove that the function ρ is locally Lipschitz. Since it is a C^2 function on $\mathbb{R}_{>0}$, it is enough for us to show that $\lim_{\tau \to 0^+} \rho'(\tau)$ exists and is bounded.[2]
For $\tau \ne 0$ we have

$$\rho'(\tau) = \frac{a}{\lambda_1(\tau)} \rho(\tau), \qquad \rho''(\tau) = \left(\frac{a^2}{\lambda_1^2(\tau)} - \frac{a\lambda_1'(\tau)}{\lambda_1^2(\tau)}\right) \rho(\tau). \tag{37}$$

From (32) it follows that $\lambda_1'(0) = c_1$ and $\lambda'(\tau) > 0$ for all $\tau \ge 0$. Thus there exists a constant $\delta > 0$ such that for $0 < \tau < \delta$ we have $\lambda_1'(\tau) \le 2c_1$ and we have that on the

[2] In doing this we mostly retrace the steps of proof of Lemma 11, [18]

interval $(0, \delta)$ the function ρ' is positive and strictly increasing and hence $\lim_{\tau\to 0^+} \rho'(\tau)$ exists.

Next we show that this limit is bounded. From the first inequality in (37) we have that on the interval $(0, 1)$

$$\begin{aligned}\rho'(\tau) &= \frac{a}{\lambda_1(\tau)} \exp\left(-\int_\tau^1 \frac{a}{\lambda_1(s)} ds\right) \\ &\leq \frac{a}{c_1\tau} \exp\left(-\int_\tau^1 \frac{a}{c_1 + \varkappa_1(1)} \frac{ds}{s}\right) = \frac{a}{c_1\tau} \exp\left(\frac{a}{c_1 + \varkappa_1(1)} \ln\tau\right) \\ &= \frac{a\tau^{\frac{a}{c_1+\varkappa_1(1)}}}{c_1\tau} \leq \frac{a}{c_1}\tau, \end{aligned} \tag{38}$$

where we used definition of the constant a in the last inequality. From (38) it follows trivially that $\lim_{\tau\to 0^+} \rho'(\tau) = 0$ and therefore we proved that the function ρ is locally Lipschitz. [3]

To prove boundedness of ρ' on $\mathbb{R}_{\geq 0}$ we are left only with the case $\tau \geq 1$. From (32) it follows that there exists $\tau_\star > 0$ such that $\varkappa(\tau_\star) + c_1 = a$. Without loss of generality we can assume that $\tau_\star > 1$. Using lower estimate $\lambda_1(\tau) \geq c_1\tau$ and (37) we obtain that for all $\tau \in [1, \tau_\star]$ the following holds

$$\rho'(\tau) \leq \frac{a}{c_1\tau} \exp\left(\int_1^\tau \frac{a}{c_1 s}\, \mathrm{d}s\right) = \frac{a}{c_1\tau} \exp\left(\ln\tau^{\frac{a}{c_1}}\right) = \frac{a}{c_1}\tau^{\left(\frac{a}{c_1}-1\right)} \leq \varDelta,$$

where $\varDelta = \frac{a}{c_1}\tau_\star^{\left(\frac{a}{c_1}-1\right)}$ Finally for all $\tau \geq \tau_\star$ the following holds

$$\begin{aligned}\rho'(\tau) &\leq \frac{a}{c_1\tau} \exp\left(\int_1^{\tau_\star} \frac{a}{c_1 s}\, \mathrm{d}s + \int_{\tau_\star}^\tau \frac{a}{as}\, \mathrm{d}s\right) = \frac{a\varDelta}{c_1\tau} \exp\left(\int_{\tau_\star}^\tau \frac{ds}{s}\right) \\ &\leq \frac{a\varDelta}{c_1\tau} \exp\left(\ln\frac{\tau}{\tau_\star}\right) \leq \frac{a}{c_1}\tau_\star^{\left(\frac{a}{c_1}-2\right)}, \end{aligned}$$

and therefore the function ρ' is bounded on $R_{>0}$. □

Lemma 2. *Let $n, m, l \in \mathbb{N} -\ 0$ and $F : \mathbb{R}^{n+m} \to \mathbb{R}^l)$ be continuous function then the following statements are correct for all $(x, y) \in \mathbb{R}^{n+m}$*

A1. *There exists a function $\alpha \in \mathcal{K}$ and a continuouslu differentiable, strictly increasing function $c : R_{\geq 0} \to [1, +\infty)$ such that the following inequality holds*

$$|F(x, y) - F(x, 0)| \leq c(|x|)d(|y|). \tag{39}$$

A2. *If in addition, function F is locally Lipschitz and $F(0, 0) = 0$, then there exist continuously differentiable functions $\gamma_i \in \mathcal{K}$ and nonnegative constants $c_i \geq 0$ $(i = 1, 2)$ such that*

$$|F(x, y)| \leq \lambda_1(|x|) + \lambda_2(|y|), \tag{40}$$

where $\lambda_i(s) = [c_i + \gamma_i(s)]\, s$, $i = 1,\ 2$.

[3] Actually, following reasoning of Lemma 11 of [18] and slightly increasing the constant a we can ensure that ρ is a C^1 function. However, since function $\varPhi$ is only locally Lipschitz, in general we can not expect to find a C^1 function W.

Proof.

A1. From Lemma A.1, [12] we have that there exist functions $\gamma_0,\ \gamma_1 \in \mathcal{K}_\infty$, $\gamma_1 \in C^1$ such that, for all $(x, y) \in \mathbb{R}^{n+m}$,

$$|F(x, y) - F(x, 0)| \leq \gamma_0(2|y|) \left(1 + \gamma_1(|x|^2 + |y|^2)\right).$$

Using properties of class $\mathcal{K}_\infty$ functions and denoting $c(s) = \left(1 + \gamma_1(2s^2)\right)$, $d(s) = \gamma_0(s) \left(1 + \gamma_1(2s^2)\right)$ we obtain

$$\begin{aligned} |F(x, y) - F(x, 0)| &\leq \gamma_0(|y|) \left(1 + \gamma_1(2|x|^2) + \gamma_1(2|y|^2)\right) \leq \\ &\leq \gamma_0(|y|) \left(1 + \gamma_1(2|x|^2)\right) + \gamma_0(|y|)\gamma_1(2|y|^2) \\ &\leq \left(\gamma_0(|y|) + \gamma_0(|y|)\gamma_1(2|y|^2)\right) \left(1 + \gamma_1(2|x|^2)\right) = c(\|x\|)d(\|y\|). \end{aligned}$$

Continuous differentiability of the function c and other properties follow straightforward from the definitions of the functions c and d and the fact that $\gamma_1 \in C^1$.

A2. Define $z \in \mathbb{R}^{n+m}$ as $z = (x^\top, y^\top)^\top$ and let $\tilde{F}(z) = F(x, y)$. Since function $\tilde{F}$ is locally Lipschitz in z, hence there exists a continuous function $L : R^{n+m} \to R_{\geq 0}$ such that $\left\|\tilde{F}(z)\right\| \leq L(z) \|z\|$. Based on $L(x)$ we define function $l_0 : R_+ \to R_+$ as follows $l(s) = \sup_{\{z:\|z\|\leq s\}} L(z)$ and $l_0(0) = L(0)$. Since $L(z)$ is continuous, the function $l_0(s)$ is well defined, continuous at $s = 0$ and nondecreasing. It is easy to show that we can always upperbound function l_0 by a strictly increasing continuously differentiable function, i.e there always exists a C^1 function $l_1 \in \mathcal{K}$ and a constant $c_1 \geq 0$ such that $l_0(s) \leq l_1(s) + c_1$ for all $s \geq 0$.
Notice that $\|z\| \leq \|x\| + \|y\|$ and $l_l(s_1)s_2 \leq l_1(s_1)s_1 + l_1(s_2)s_2$ for any $s_1, s_2 \geq 0$; the last one is due to the fact that $l_1 \in \mathcal{K}$. Using this inequalities we obtain that for all $s \geq 0$

$$\begin{aligned} \|F(x, y)\| = \left\|\tilde{F}(z)\right\| &\leq (l_1(\|z\|) + c_1) \|z\| \leq (l_1(\|x\| + \|y\|) + c_1) (\|x\| + \|y\|) \leq \\ &\leq (l_1(2\|x\|) + l_1(2\|y\|) + c_1) (\|x\| + \|y\|) \\ &\leq (3l_1(2\|x\|) + c_1) \|x\| + (3l_1(2\|y\|) + c_1) \|y\| \end{aligned}$$

□

New Paradigm of Context based Programming-Learning of Intelligent Agent

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Abstract. In this paper we propose new paradigm combining concepts "programming", "learning" and "context" for usage in development of control system of mobile robots and other intelligent agents in smart environment. And we suggest architecture of robot's control system based on context and learning with natural language dialog. The core of this architecture is associative memory for cross-modal learning. Main features and requirements for associative memory and dialog subsystem are formulated.

1 Introduction

One of challenges in development of intelligent robots and other intelligent agents is human-robot interface. Two kinds of such known interfaces are oriented on programming and learning respectively. Programming is used usually for industrial robots and other technological equipment. Learning is more oriented for service and toy robotics.

There are many different programming languages for different kinds of intelligent equipment, for industrial robots-manipulators, mobile robots, technological equipment [1], [2]. The re-programming of robotic systems is still a difficult, costly, and time consuming operation. In order to increase flexibility, a common approach is to consider the work-cell programming at a high level of abstraction, which enables a description of the sequence of actions at a task-level. A task-level programming environment provides mechanisms to automatically convert high-level task specification into low level code. Task-level programming languages may be procedure oriented [3] and declarative oriented [4], [5], [6], [7], [8] and now we have a tendency to focus on second kind of languages. But in current time basically all programming languages for manufacturing are deterministic and not oriented on usage of learning and fuzzy concepts like in service or military robotics. But it is possible to expect in future reduction of this gap between manufacturing and service robotics.

On the other hand in service and especially domestic robotics most users are naive about computer language and thus cannot personalize robots using standard programming methods. So at last time robot-human interface tends to usage of natural language [9], [10] and, in particular, spoken language [11], [12]. The mobile robot for example must understand such phrases as "Bring me cup a of tea", "Close the door", "Switch on the light", "Where is my favorite book? Give it to me", "When must I take my medication?”.

Using natural language dialog with mobile robot we have to link words and phrases with process and results of perception of robot by neural networks. In [13] to solve this problem the extension of robot programming language by introducing of corresponding operators was proposed. But it seams that such approach is not enough perspective.

In this paper we suggest novel bio- and psychology-inspired approach combining programming and learning with perception of robot based on usage of neural networks and context as result of recognition and concepts obtained by learning during dialog in natural language. In this approach we do not distinguish learning and programming and combine: a declarative (description of context) and procedural knowledge (routines for processing of context implementing elementary behavior) on the one hand, learning in neural networks and ordering of behavior by dialog in natural language on the other hand.

2 Proposed Paradigm and Architecture of Intelligent Agent

Our paradigm is based on relationships with other known paradigms and is shown in Fig.1.

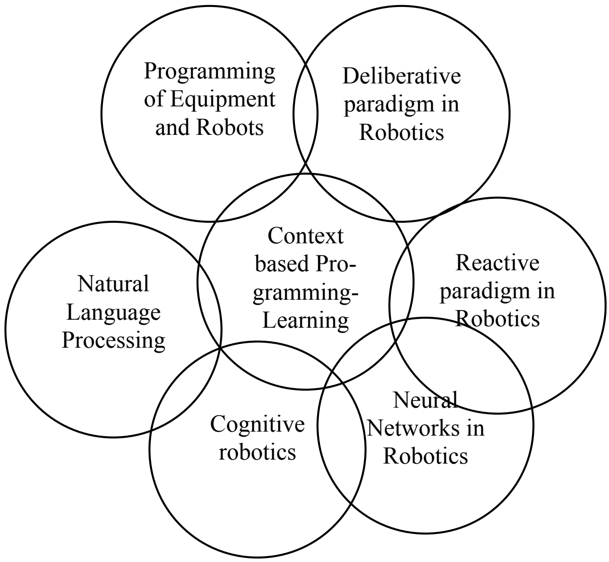

Fig. 1. Relationships between paradigm “Context based Programming-Learning” and other paradigms.

Concepts are associations between images (visual and others) and phrases (words) of natural language. In simple case we will name as concept just name of them (phrases). These phrases are using for determination of context in which robot is perceiving environment (in particular, natural language during dialog) and planning actions. We will name them as *context variables*.

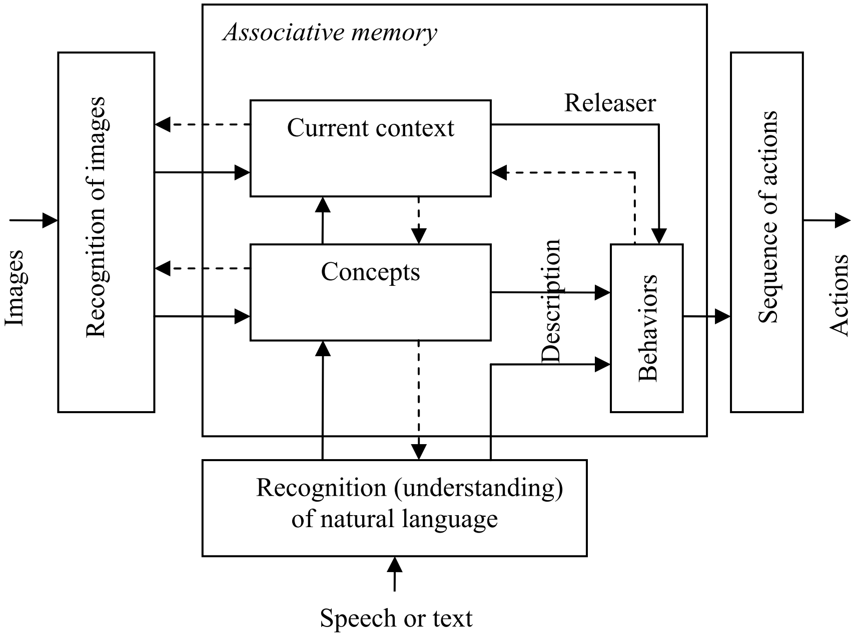

Fig. 2. Intelligent agent functional structure oriented on context based programming-learning.

Context is a tree of concepts (context variables) and is recognizing by sensor information and determining by dialog with user. Feedbacks between concepts/context and recognition of images/phrases mean that recognition is controlled by already recognized things.

Dialog with user aims to describe elementary behaviors and conditions for its starting. To start any behavior the system recognizes corresponding concept-releaser as in reactive paradigm of control system of robot.

Behavior is not influence on just actions but also on context. Moreover, behavior may be not connecting directly with actions in environment. In this case we have only thinking under context variables. And even when behavior is oriented on execution of actions it is possible to block this connection and in this case we have any simulation in mind sequence of actions (e.g., it may be mean as planning).

The associative memory must satisfy to follow requirements:

1) to allow usage of both analog and binary inputs/outputs,
2) to provide incremental learning,
3) to provide storing of chain of concepts (as behavior or scenarios).

The elementary behavior is similar to subroutine and contains sequence of actions adaptable to context variables which may be viewed as parameters of subroutine. Of cause, we need to use some primitives directly connecting with elementary actions and describing parameters of these actions or basic context variables. Connections between these primitives and words of natural language must be a prior knowledge of robot obtaining at development of robot or during a preliminary teaching by specialist. It may be simple language similar to CBLR, proposed by author for context based programming of industrial robots in [9], [14]. Feature of this language is absence of different motion primitives. There we have just one motion primitive. All other primitives aims to represent of context variables needed for execution of this motion primitive. To distinguish these primitives and usually using motion or geometric primitives we will call its below as *output primitives*.

3 Cross-Modal Incremental Learning and Associative Memory

Associative memory satisfied to above requirements may be based on hybrid approach and similar to Long-Short Term Memory (LSTM) [15] or table based memory proposed by author in [16].

Concept in Fig. 2 is more common thing as *context*. Concepts are introducing by dialog subsystem for determination of objects, events, properties and abstraction. But *context* consists of several concepts separated by three rules: 1) preliminary defined concepts (names) are using as names of “parameters” to utilize in elementary behavior (see 4); 2) some concepts are using as values of these “parameters”; 3) some concepts (releasers) are using as names of any events causing any behavior.

Dialog subsystem must provide robustness to faults in sentences. For it implementation may be used approach proposed by author in [17] and based on semantic networks combining with neural networks algorithms. This approach is oriented on fuzzy recognition of semantics. Dialog subsystem must provide attend the visual recognition subsystem to link word (phrase) with recognizing image. In this case the recognition subsystem create new cluster with center as current feature vector. And couple of this feature vector and word (phrase) is storing in associative memory for concepts. It may be as result of processing of follow sentence “This is table”. In contrast to that case when system processes sentence “Table is place for dinner” the new cluster is not created and associative memory is used for storing of association between words (phrases).

Thus associative memory must be able to store associations between both couple of symbolic information and couple of word (phrase) and feature vector. Besides concept storing in associative memory must have some tags: basic concept (preliminary defined) or no, name or value, current context or no. And every concept in associative memory must be able to link in chain with other ones. The order of concepts in chain may be defined by dialog subsystem.

4 Output Primitives for Mobile Robot

Set of output primitives may be selected by different way. One approach to that is determination of enough complex behaviors, such as “Find determined object”, “Go to determined place” and so on. These actions may be named as *motion primitives*. Determined *object* and *place* must be obtained from context as value of corresponding context variable. And these variables may be viewed as another kind of output primitives: *context primitives*. In this case such actions must include inside any strong intelligence and ones limit capabilities to learn mobile robot. Another approach may be based on very simple *motion primitives* such as “act”, which may be just one. If we want to make capability to say anything by robot not only during dialog inside dialog subsystem we need introduce also at least one motion primitive "say". All another *output primitives* are *context primitives* and ones define features of execution of primitive "act". In other words ones are parameters of subroutine "act". Examples of robot's context variables are shown in Table 1

Table 1. Examples of context primitives.

Name of context primitive	Possible value	How this parameter influence on execution of motion primitive
Object	Name of object	May be used in action "say"
Internal state	Good, Bad, Normal	May cause motion to or from *Object*
Direction	Left, Right, Forward, Back	May cause corresponding turn depending on *Internal state*
Person	Name of person	May be used in action "say"
Obstacle distance	Far, Middle, Close	May be used in "act"
Obstacle type	Static, Dynamic	May be used in "act"
Speed	Low, Normal, High	May be used in "act"

5 Conclusions

In this paper we have suggested new paradigm combining programming and learning of mobile robot based on usage of context and dialog in natural language. Architecture of programming/learning of mobile robot was proposed. Some features of associative memory and dialog subsystem were formulated. Now this architecture is developing for simulated mobile robot and then to be implemented in real robot. This approach may be used for programming/learning of smart object in ambient intelligence [18].

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Problems of Abstract Representation of Embedded Systems at High-level Stages Design

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Abstract. Conditions and nature of embedded systems design demand today serious revision of techniques and technologies of their creation. To a considerable degree artificial dividing the computer system into hardware (HW) and software (SW) components and, moreover, allocation of the SW industry in a separate sphere only aggravates the situation. One of the ways of this problem decision can be usage of architectural abstractions system directed on the creation of an integrated design space of the computational process organization in which for the computer system a representation of traditional HW and SW implementations becomes unified, there are obviously functional and nonfunctional aspects of designing and the tool component is integrated.

1 Introduction

Impetuous growing requirements for embedded systems (ES) forces developers to improve actively design methods and tools. The ES share with a complex internal organization actively grows that becomes apparent in the multiprocessor heterogeneous architecture, the distributed character of calculations, a wide range of computational resources potentially accessible to the developer. The significant part of the most complex ES has the distributed organization and refers to a category of network embedded control systems (NECS).

It is necessary to consider as the key feature of the ES creation the necessity of the complex approach to the designing, covering practically all levels of the computer system (CS) organization. The developer really faces with the necessity to analyze the large number of various potentially-possible variants of the architectural organization both a target system created, and a project infrastructure as a whole (it is a matter, first of all, of design technologies and tools). An experience of development of microprocessor systems convinces of the necessity of joint (parallel) designing HW and SW parts of the system that in practice within the limits of traditional technologies is realized extremely seldom.

From a space of the limited set of canonical structures and circuit decisions designers can today already move in a space of practically free architectural design.

Change of the situation on a background of growing needs in ES and requirements to them demands overcoming crisis of designing, which becomes apparent in insufficient speed of creation and bad quality of a product. The disturbing state in the field of ES design is marked by all leading experts of this sector of informatics and computer engineering [6, 13, 12].

Top priority importance in overcoming the crisis has the further development of methods and means of high-level (architectural) ES design. Still there are opened questions of creation effective CAD of complex (through all stages) design of ES.

2 Problems of Embedded Systems Design

Custom Microprocessor Systems Design. The hands-on experience of ES design bases on the fine-tuned technological methods and tools and consists in a choice of one of canonical computational platforms on the basis of which due to a program superstructure the applied task is solved. Other variant is also applied: computer platform is being chosen and along with upwards completion updating downwards modification is carried out. Such way is used less often because of high labour-intensiveness.

The first problem, which ES developers face with, consists in the following:

– existing programming languages assume the description of a task for idealized virtual (language) machine;
– the compiler maps this language machine on the real machine, bringing the certain restrictions and leaving out many important technical features of the executive machine realization;
– there is no uniform system of the language machine description, the compiler and the executive machine.

The second problem - the large number of tasks, especially in the field of control systems of physical objects, which badly keep within the scheme of implementation on the basis of canonical computer platform with a program realized superstructure. Such tasks demand specialized computer platform, for example, with a high degree of parallelism and specialization of operational blocks, and in this case efficiency of the traditional scheme of designing can appear to be inadmissibly low.

The third problem is connected with constantly growing volume of necessary ES designing. Particularly the disunity of descriptions noted above, prevents from a reuse of the developed components (hardware blocks, programs, realizations of algorithms).

State and Perspectives of High-level ES Design. The basic directions of researches for overcoming the listed problems lay in the field of perspective techniques of high-level (system) ES design (HLD). For these directions the following design levels are determined by specialists:

– *mission (or operational, or specification) level* - development of the system behavior script in the form of «the executed system specification/model»; modeling of an external system environment.

architecture (or macroarchitecture, or performance) level - formation of system architecture, irrespectively to a way of realization: the analysis of architecture for conformity with functional and nonfunctional requirements/restrictions.

- microarchitecture (or functional) level or (especially with reference to development digital VLSI and SoC) - electronic system level (ESL) - a choice of a way of realization of architectural model components is carried out, algorithms, interfaces are being developed, specifications and the environment of verification are prepared for the implementation stage of the system.

General problems of accessible methodologies, tools and environments of designing (frameworks), inducing to the certain choice of directions and development of research works in the field of system designing for ES are fixed below:

- particular (especially nonfunctional) aspects of designing are considered separately within specialized entire system models: power consumption, reliability, information protection, etc. It is necessary to develop such structure and the form of architectural components description, which obviously will offer aspect estimations (weights) that are reflected in the concept of the architectural aggregate (AA), which is explained further in this article.
- explicit priority of the functional aspect at an architectural level is held true. The nonfunctional aspects either play a role of auxiliary (secondary) criteria of the project, or many of them are not taken into consideration at all. But in general case for ES functionality not always appears the most higher-priority requirement. These issues should be taken into consideration in the tool development process of the system architectural description.
- a set of variants of the microarchitecture realization is limited by HW/SW of the runtime phase. Search of project decisions at a variation of Design/Run Time ratio, consideration of various levels of architecture virtualization, integration of a tool component in most cases within the limits of the system designing is not carried out.

The decision of the specified problems is probable through integral perception of target system space project, and project infrastructure. This assumes integrated space creation of ES design in terms of computational abstractions (computational mechanisms, functional converters, virtual machines, architectural aggregates), and, accordingly, a new model of the design process. The necessary conditions of the creation of such space are:

- unification of hardware/software treatments;
- *ES representation within the limits of possibly a lot of design steps (from the beginning) without dividing on HW/SW realization;*
- using «aspect technologies», which allows to track explicitly transformations of key ES components in the design process (functionality, tool, reliability aspect, and others), and to consider during designing factors, which explicitly are not present in specification requirement, but seriously influence on results (tool aspect, the possibilities of the team, accessible technologies, taking into account a groundwork and team interests, and others).

3 Integrated Design Space of Embedded Systems

Computational Process Organization. The concept of computational process in ES occupies the central position. We consider, that *process of the computer system design* as the object solving a specific target of the user, it is reasonable to consider as *the organization of a computational process in space and time in the restrictions specified by the technical requirements*.

Tools of the realization of computational process are:

– design concepts (platform-oriented, model-oriented, actor-oriented, and others);
– computational models (models of computation - MoC);
– virtual machines;
– platforms (computational, tool, protocols of interaction, and so on);
– mechanisms (as technical decisions from various areas-aspects in an abstract representation);
– element base (as a set of mechanisms realizations).

The carrier of a run-time component of computational process is ES architecture - ES representation with a minimum refinement level, showing all its unique technical decisions in relation to the computational process organization. Depending on the one to whom given ES architectural representation is addressed, the set of "known" elements can essentially differs.

Embedded Systems Programmability. Modern ES is accepted to name SW-dominated systems, which are created on the basis of «highly programmable platforms» [1, 13] that is caused by inseparable connection of a computational platform and an applied level.

The most part of modern element base is programmed or configured. In whole it expands the developer potentialities, simultaneously significantly increasing risk of an error and a labor intensiveness of low-level design. The range of system organization levels, which the developer is forced to cover for the qualitative hardware control, is extremely wide. Attempts to minimize the low-level design volume in the ES field didn't have any success, as imposing on the developer in this case the limited number of configuration patterns significantly worsens design quality.

Models of Computations. There are various MoC definitions, which can be divided into two directions. One of them [5, 7] is based on the desire to be limited by use of simple (by «a principle of action») models of one (abstract) level (model of data-flows, FSM models, models of synchronous processes, and others). Another direction assumes a formalization of computer devices representation as virtual machines irrespective of their complexity and a belonging to the computational hierarchy level.

In a context of integrated design space MoC is interpreted as *mathematical model showing to the user computational possibilities and rules of the computer device use.*

Virtual Machines. *The virtual machine is understood as the computer device, for which rules of behavior are certain* (for example, command system, conditions of command and data input, reception of the result, a rule of process synchronization), *allowing unambiguously to describe algorithm of the task decision*. The virtual machine description shows only external properties of the computer device and the rule of its use, not concerning of its organization. A principle of extraction of virtual machines is powerful technological instrument, allowing to structure the design process, to provide portability and a reuse of groundwork, to get scale project decisions.

Computational Platforms, Mechanisms, Element Base. A *computational platform* formalism takes the important place in computer engineering. In the context of the integrated design space the *platform can be considered as unity of "external" and "internal" representation [any] of a functional-completed and a functional-significant object in ES structure.*

The computational mechanism as an abstraction solving a particular task plays a role of the «building block» in the computational process organization. The range of functional complexity of computational mechanisms is limited only by developer imagination that creates serious problems for formalization of their representation and operations on them [8, 10].

The element base is considered as a set of mechanisms realizations. It is necessary to expand this concept by inclusion in it a set of objects (physical, informational, technological, and others), which belong to all aspects of the design space.

Design/Run Time Space is effective means of ES analysis. In many respects a template type of nowadays ES designing uses in the majority of cases empirical decisions. Chains of computational process realization include such elements, as compilers, interpreters, virtual machines, hardware programmed processors, special functional hardware blocks, and many other things. The developer, often not consciously, distributes elements of the computational process inside of tool (design-time) and performing (run-time) phases of the project. The analysis and the realized choice of decisions in both phases of ES existence allow to increase significantly quality of designing.

4 Aspect Technology Bases of Embedded Systems Design

Today Aspect-Oriented Software Development was formed as an independent direction in programming [14]. Abstractions of aspect representations have actively started to be used in ES design [2], however, this direction is in a formation stage.
The authors demonstrate below the use of the aspect ideology in a combination with the system of architectural abstractions in ES design.

On the top level of aspect technology the developer deals *with project architecture* and *product architecture* (ES designed), which contain all components respectively of design process and product created. We shall name such components as *aspects of designing* (or simply aspects).

Let's define *ES architecture* as a *set of ES conceptual aspects of some refinement level, completely representing designed system for the given level of consideration*. In the list of conceptual ES aspects, besides traditional structural and functional elements reliable, constructive-technological, power assumption, conditions of maintenance, tools, reuse, organizational-economical, documental, and others elements are included.

Certain elements of architectural representation we shall name *aggregates*. Thus, *the architectural aggregate* (AA) represents a base element of the system design process.

AA, describing not all aspects, is named an *abstract.* Complete AA (describing all project aspects), which cannot be realized now by a concrete team in an element base accessible to it, we name *virtual*. It mast be said, that AA virtuality can be determined not only by objective limitation of the element base, but also by subjective restrictions, such as requirements specification, predilections, and interests of the team. Accordingly, complete AA for which there are all necessary conditions of realization, we shall consider realizable.

The system model expressed in AA terms, we shall name *architectural model* or *A-model* of the system. A-model can be abstract, virtual and realizable.

Abstract A-model contains at least one abstract AA. The model essentially unrealizable and demands further completion. But such models have their way of application, namely, such models should be considered as *platforms*. Abstract A-models, passed in the category of the standard platforms is possible to consider standard interfaces, protocols, computational cores, operational systems, and many others. Some abstract A-models are convenient as a reusable platform within the team bounds which can fix the certain successful decision, designate a direction of development, to provide continuity, having determined abstract A-model of the system and developing it in variety of concrete applications.

Virtual A-model. In such model abstract AA's are not present, but there is at least one virtual AA. Such model cannot be realized because of the virtual AA's, but it is already completely determined and, in principle, can be realized if to expand accessible element base. For successful realization of the model it is necessary to get rid of virtual AA's. It is achieved in two ways: by changing the model or changing external factors. In the first case developers change model (carry out design process) until virtual AA's don't remain in its structure. In the second case the model remains constant, and external factors vary (requirements specification accurate definition along the lines of restrictions changes; team education; transition to other computational cores; use of new technologies for team).

Realizable A-model consists only of realizable AA. Such model can be realized by the team in an element base and a technology accessible to it.

During designing of target system at the initial stages there is a concrete definition and verification of A-model. The result of that becomes "golden" model. *The "golden" model is the verified and fixed architectural model of the system, which is not limiting ways of the implementation.* An important task of the "golden" model becomes a creation of initial specifications for developers who are engaged in final realization of components and units of the system. Being A-model the "golden" model specifies the whole set of aspects of ES being realized.

An architectural platform acts as the reuse tool of the conceptual decisions within the bounds of aspect ideology. *The* architectural platform should be considered as association of following elements of design:

– aspect space of design process (the list of design aspects);
– model (models) of computation (MoC, behavioral aspect);

- external factors setting admissible different aspects ratio (design criterions);
- list of the fixed patterns of reuse;
- element base.

Architectural platform reconfigurability is defined as an ability to change MoC "embodied" at realization. The superstructure on the architectural platform, created with the purpose to change MoC, is named *as an operational environment*.

Tool aspect of ES designing on importance ranks with functionality [11] that assumes its taking into consideration not only "outside" on a course of the project, but also its inclusion at an early stage in the initial specification of the project/system.

5 Conclusions

Formalization and automatization of design processes always demands enormous efforts. Field of custom ES design - an example, where such efforts are necessary to make. A serious obstacle on the way of design technologies implementation on the basis of computational architecture abstractions is the problem of specialists education in the field of computer engineering and informatics possessing HLD-ideology is represented.

It is necessary to recognize, that a large number of ES developers teams nowadays insufficiently high estimate a role and labor-intensiveness of high-level design stages. They do not have adequate technical language for communication at this level, mutual understanding and a correctness of differentiation of developers' responsibility zones suffers, and there is no due integration.

The understanding of responsibility zones by HLD-specialists in a context of offered integrated ES design space determines of the design efficiency. The scope of ES architectural abstraction should extend by means of system engineering from the bottom border of computer system organization up to the top border of the project, which the requirements specification containing computational functionality of the project in aggregate with nonfunctional components is. As the bottom border the computational mechanisms distinctly showing the organization of computational process in analyzed structure (today it is RTL level) acts.

The system of architectural abstraction allows creating effective communication language in the field of ES design, qualitatively to advance technologies and tools, dramatically to improve the engineering documentation. For this purpose the coordinated efforts of operating developers of computer engineering and specialists of universities are necessary.

In St. Petersburg State University ITMO [15] within the framework of direction ES/NECS works on development aspect technology of design are carried out. Objective-event models of computations OEMoC, DOMoC [9, 11] have been offered and developed, researches in the field of virtual machines with a dynamic set of instructions [4] are carried out, models of actualization of ES computational process [3] are developed and investigated.

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Early Creation of Cross Toolkits for Embedded Systems

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Abstract. Cross toolkits (assembler, linker, debugger, simulator, profiler) play a key role in the development cycle of embedded systems. Early creation of cross toolkits and possibility to quickly adapt them allows using them as early as at the hardware/software codesign stage, which becomes an important success factor for the entire project. Challenging issues for cross toolkits development is efficiency of simulation and CPU instruction set alterations at the design phase. Developing cross toolkits in C/C++ produces highly efficient tools but requires extensive rework to keep up with instruction set changes. Approaches based on automatic toolkit generation from some top level specifications in Architecture Description Languages (ADLs) are less sensitive to this problem but they produce inefficient tools, especially simulators. This paper introduces a new approach to cross toolkits development that combines the flexibility of ADL and efficiency of C/C++ based approaches. This approach was implemented in the MetaDSP framework, which was successfully applied in several industrial projects.

1 Introduction

Nowadays we witness emerging of various embedded systems with rather tough constraints (chip size, power consumption, performance) not only for aerospace and military applications but also for industry and even consumer electronics. The constant trend of cost and schedule reduction in microelectronics hardware design and development makes it reasonable to develop customized computing systems for particular applications and gives new momentum to the market of embedded systems. Such systems consist of a dedicated hardware platform developed for a particular application and a problem-specific software optimized for that hardware.

The process of simultaneous design and development of hardware and software components of an embedded system is usually referred to as *hardware/software codesign and codevelopment*. This broad term covers a number of subprocess or activities related to embedded system creation:

1. design phase, including functional design, when requirements are studied and transformed into functional architechture, and hardware/software partitioning, when functions are divided between hardware and software components;
2. development phase or software/hardware codevelopment when both hardware and software teams develop their components; both development activities may influence each other;
3. verification; it spans from unit and module tests to early integration testing in simulator/emulator.

Hardware/software codesign and codevelopment are crutial factors for success of embedded systems. They reduce time-to-market by better parallelization of the development wrokflows, and improve the quality by enabling early identification of design flaws and optimization the performance of the product.

Cross toolkits play an important role in hardware/software codesign and codevelopment. Primary components of such cross toolkits are assembler, linker, simulator, debugger, and profiler. Unlike chip production, development of cross toolkits does not require precise hardware design description; it is sufficient to have just a high-level definition of the target hardware platform: the memory/register architecture and the instruction set with timing specification. This allows developing cross tools as soon as the early design stages even if the detailed VHDL/Verilog specification is not ready yet. Cross tools could be used in the following scenarios:

- Hardware prototyping and design space exploration (e.g. [4] and [15]) – early development, execution and profiling of sample programs allows study and estimation of the overall design adequacy as well as efficiency of particular design ideas such as adding/removing instructions, functional blocks, registers or whole co-processors.
- Early software development including development, debugging and optimizing the software *before* the target hardware production.
- Hardware design validation. The developed cross-simulator could be used to run test programs against VHDL/Verilog-based simulators. This capability could not be overestimated for the quality assurance before the actual silicon production.

1.1 Paper Overview

In this paper, we present a new approach to cross toolkit development to be used in hardware/software co-development environments. The method enables software developers to create the cross tools as early as the system design phase, to follow rapidly hardware design changes, most notably instruction set modifications, thus reducing the overall time frame of the design phase.

The article is organized as follows. Section 2 discusses generic requirements to cross toolkit develpment that hardware/software codevelopment imposes. Section 3 presents the new ADL language for defining instruction set called *ISE*. Section 4 introduces MetaDSP framework for cross toolkit development that uses hybrid hardware description with both high-level ADL part and efficient C/C++ part. Section 5 briefly overviews several industrial applications of ISE and MetaDSP framework. Conclusion summarizes the lessons learned and gives some perspectives for future development.

2 Hardware/Software Codesign and Codevelopment Requirements to Cross Toolkit Development

Let's consider a typical co-development process depicted at the fig. 1. The development process involves at least two teams - one is working on the hardware part of the system while another one focuses on software development.

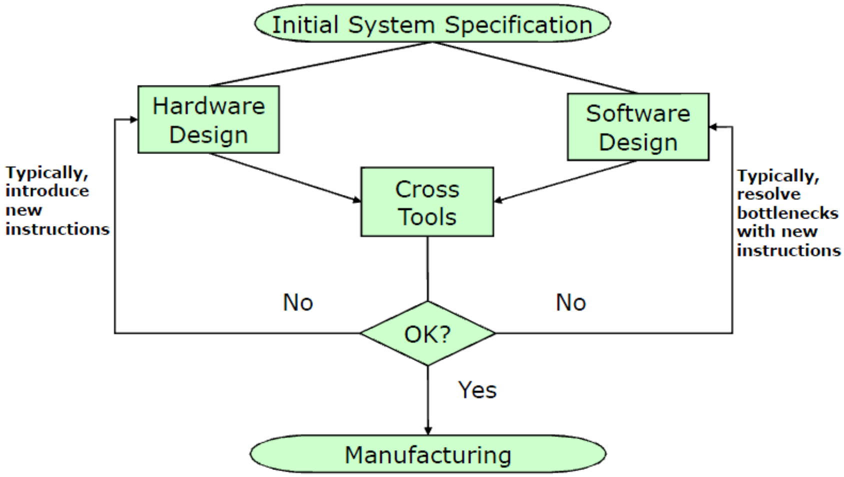

Fig. 1. Co-development process.

Cross tools make it possible to run software on simulators or emulators of the target hardware early in the development process. Bottlenecks and performance problems identified during running the software might require modification of the design, most notably changes in instruction set or register file of the target embedded CPU.

Alterations in hardware design are characterisic features of co-development processes in the industry. In section 5 we provide basic statistics on several industrial project. The number of major changes in hardware specification vary from 25 to 39 with average 31 change per project.

In order to make the process seamless and continious cross toolkit developers must rapidly react to such changes and produce new versions of the toolkit in short terms. Changes in instruction set require updates in every tool of the cross toolkit. Cross tookit developers must be very careful not to introduce errors during the modification process.

Another critical issue for cross-toolkits application in the co-development process is performance of the tools. Special attention should be paid to the performance efficiency of the simulator. High-performance simulators are required to perform validation and profiling of the target software on real-life data within reasonable time. For instance, processing a 10-seconds long speech sample on a DSP board takes about $7 \cdot 10^{11}$ CPU cycles. Running this sample on a simulator slower that 10 MCPS (10 millions of cycles per second) result in more that two hours long test execution which could hardly be considered feasible.

Simulator must be cycle-precise to guarantee correctness of profiling data. Usual practice is not to require simulation of the funcional decomposition of the hardware. The externally observable behavior of the simulator must be equivalent to that of the actual hardware while the internal design need not follow the design of the target hardware (pipline structure, ALU and FPU, internal buses etc.)

2.1 Related Work

Efficient cross toolkit development process requires automation to minimize time and effort necessary to update the toolkit to match new requirements. Such automation is built around a machine-readable definition of the target hardware platform. There are three groups of languages suitable for this task:

- Hardware Definition Languages (HDL, [10]) used for detailed definition of the hardware;
- Architecture Description Languages (ADL, [9] and [13]) used for high-level description of the hardware;
- and general purpose programming languages (such as C/C++).

HDL specifications define CPU operations with very high level of detail. All three major modern HDL – VHDL [5], Verilog [6], and SystemC [7] – have execution environments that can serve as a simulator to run any assembly language programs for the target CPU: Synopsys VCS, Mentor Graphics ModelSim, Cadence NC-Sim and other. Still, low performance of HDL-based simulators is one of the major obstacles for HDL application in cross toolkit development. Another issue is the late moment of HDL description availability: it appears after completing the instruction set design and functional decomposition. Furthermore, HDL does not contain an explicit instruction set definition that makes automated assembler/disassembler development impossible. These issues prevent from using HDL to automate cross toolkit development.

Architecture Description Languages (such as nML[1], ISDL[2], EXPRESSION[3]) are under active development during the recent decade. There are tools created for rapid hardware prototyping at the high level including cross toolkit generation. Corresponding approaches are really good for early design phase since they help to explore key design decisions. Unfortunately, at the later design stages details in an ADL description become smaller, the size of the description grows and sooner or later it comes across the limitations of the language. As a result, is breaks the efficiency of the simulator generated from the ADL description and makes the profiler to give only rough performance estimates without clear picture of bottlenecks. Cross toolkits completely generated from an ADL description are not applicable for industrial-grade software development yet.

Manual coding with C or C++ language gives full control over all possible details and allows creation of cross toolkits of industrial quality and efficiency. Many companies offer services on cross toolkit development in C/C++ (e.g. TASKING, Raisonance, Signum Systems, ICE Technology, etc.). Still it requires significant efforts and (what is more important) time to develop the toolkit from scratch and maintain it aligned with the requirements. Long development cycle makes it almost impossible to use cross toolkits developed in C/C++ for hardware prototyping and design space exploration.

3 ISE Language

We developed ISE (*I*nstruction *S*et *E*xtension) language to specify hardware design elements that are subject to most frequent changes: memory architecture and CPI instruction set. ISE description is used to generate assembler and disassembler tools completely and to generate components of the linker, debugger and simulator tool.

The following considerations guided the language design:

- the structure of an ISE description should follow the typical structure of an instruction set reference manual (like [14] or [12]) that usually serve as the input for the ISE description development;
- support for irregular encoding of instructions typical for embedded DSP applications including support for large number of various formats, distributed encoding of operands in the word, etc.;
- operational definition of data types, logic and arithmetic instructions, other executable entities should be specified in a C-like programming language.

ISE module consists of 7 sections:

1. **.architecture** defines global CPU architecture properties such as pipeline stages, CPU resources (buses, ALUs, etc.), initial CPU state;
2. **.storage** defines memory structure including memory ranges, I/O ports, access time;
3. **.ttypes** and **.otypes** define data type to represent registers and instruction operands;
4. **.instructions** defines CPU instruction set (see 3.1);
5. **.aspects** defines various aspects of binary encoding of CPU instructions or specifies additional resources or operational semantics of instructions;
6. **.conflicts** specifies constraints on sequential execution of instructions such as potential write after read register or bus conflict; assembler uses conflict constraints to automatically insert NOP instructions to prevent conflicts during software execution.

3.1 Instruction Definition

.instruction section is the primary section an ISE module. It defines the instruction set of the target CPU. For each instruction cross toolkit developers can specify:

- mnemonics and binary encoding;
- reference manual entry;
- instruction properties and resources used;
- instruction constraints and inter-instruction dependencies;
- definition of execution pipeline stage.

Mnemonics part of an instruction definition is a template string that specifies fixed part of mnemonics (e.g. `ADD`, `MOV`), optional suffixes (e.g. `ADDC` or `ADDS`) and operands. A singe instruction might have several definitions depending on the operand types. For example, `MOV` instruction could have different definitions for register-register operation, register-memory and memory-memory operations.

Binary encoding is a template that specifies how to encode/decode instructions depending on the instruction name, suffixes and operands.

Reference manual entry is a human-readable specification of the instruction.

Properties and resources specify external aspects of the instruction execution such as registers that it reads and writes, buses that the instruction accesses, flags set etc. This information is used to detect and resolve conflicts by the assembler tool. Besides this the instruction definition might specify explicit dependencies on preceding or succeeding instructions in the constraints and dependencies section.

ISE language contains an extension of C programming language called ISE-C. This extension is used to specify execution of the operation on each pipeline stage. ISE-C has extra types for integer and fixed point arithmetic of various bit length, new built-in bit operators (e.g. shift with rotation), built-in primitives for bit handling. ISE-C has some grammar extension for handling operands and optional suffixes in mnemonics. Furthermore ISE-C expression can use a large number of functions implemented in ISE core library.

An example of instruction specification is presented at figure 2.

Please note that unlike classic ADL languages ISE specification does not provide the complete CPU model. The purpose of ISE is to simplify definition of the elements that are subject to the most frequent changes. All the rest of the model is specified using C/C++ code. This separation allows for flexible and maintainable hardware definition along with high performance and cycle-precise simulation.

4 Application to the Codevelopment Process

The proposed hybrid ADL/C++ hardware definition is supported by the *MetaDSP* framework for cross-toolkit development. The framework is intended for use by software developers. Typical use case is as following:

1. hardware developers provide the software team with hardware definition in the form of ISE specification;
2. software developers generate cross tools from the specification;
3. software team develops the software in Embedded-C[8] and build using the generated cross-assembler and cross-compiler;
4. the machine code is executed and profiled in simulator.

To support this use case the framework includes:

- ISE translator that generates components of cross tools from the ISE specification;
- pre-defined components for ISE development (e.g. ISE-C core functions library);
- an IDE for hardware definition development (in ISE and C++), target software development (in Embedded C and assembly languages), controlled execution within simulator; the Embedded C compiler supports a number of optimizations specific for DSP applications[11].

The figure 3 presents the structure of the MetaDSP framework.

MetaDSP toolkit uses ISE specification to generate cross tools and components. For example, the MetaDSP tools generate assembler and disassembler tools completely from the ISE specification. For linker MetaDSP generates information about instruction binary encodings, instruction operands and relocatable instructions. Debugger and profiler use memory structures and operand types from the ISE specification.

The cycle-precise simulator is an important part of the toolkit. Figure 4 presents its architecture. MetaDSP tools generate several components from the ISE specification: memory implementation (from `.storage` section), resources (from `.architectu-`

```
/*
 * This is a C-style block comment.
 */
// This is a C++-style one-line comment.
// <ALU001> - the identifier of the definition.
// ADD[S:A][C:B]  - instruction mnemonics with
// optional parts. Actually defines 4 instruc-
// tions: ADD, ADDS, ADDC, ADDSC.
//  GRs, GRt - identifiers of a general-purpose
//  register. Rules for binary encoding of GRs
//  and GRt are defined in .otypes section.
<ALU001>  ADD[S:A][C:B] {GRs}, {GRt}
 // Binary encoding rule.
 // For example, "ADDC R0, R1" is encoded as
 // 0111-0001-1000-1001
 0111-0A0B-1SSS-1TTT
 // The reference manual string.
 "ADD[S][C] GRs, GRt"
 // instruction properties:
 //  reads the registers GRs and GRt,
 //  writes the register GRs.
 properties [ wgrn:GRs, rgrn:GRs, rgrn:GRt ]
 // Operation of the EXE pipeline stage
 // specifies using ISE-C language.
 action {
  alu_temp = GRs + GRt;
  // If the suffix 'C' is set in mnemonics
  // use 'getFlag' function from the core
  // library.
  if (#B) alu_temp += getFlag(ACO);
  // If the suffix 'S' is set in mnemonics
  // use 'SAT16' function from the core
  // library.
  if (#A) alu_temp = SAT16(alu_temp);
  GRs = alu_temp;
 }
```

Fig. 2. An example of instruction specification.

`re` section), instruction implementations and decoding tables (from `.instruction` section), as well as conflicts detector and instruction metadata.

Within the presented approach certain components are specified in C++:

- control logic, including pipeline control (if any), address generation, instruction decoder;
- memory control;
- model of the peripheral devices including I/O ports.

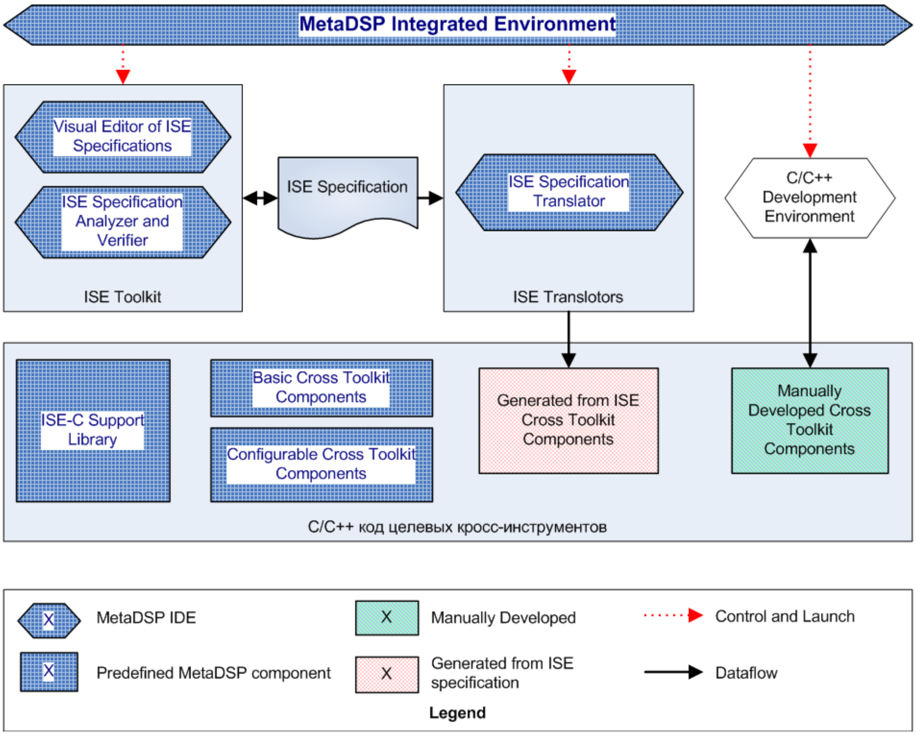

Fig. 3. MetaDSP framework structure.

For most of the manual components MetaDSP tools generate stubs or some basic implementation in C++. Developers may use the generated code to implement peculiarities of the target CPU, such as jumps prediction, instruction reordering, etc.

Using C/C++ to implement CPU control logic and memory model facilitates high performance of the simulator. Another benefit of using C/C++ compared to true ADL languages is an early development of the cross toolkit: it might start before completing the function decomposition of the target CPU; thus the simulator could be used to experiment with design variations.

The framework includes OSCAR Studio, the IDE for target software development within the MetaDSP framework. The IDE closely follows the look-and-feel style of Microsoft Visual Studio and provides the following capabilities to developers of embedded systems:

1. Project Navigator. It displays the tree of the source files and data files.
2. Source Code Editor. The editor supports syntax highlight and instruction autocompletion (from the ISE specification). The editor window is integrated with the debugger - it marks break points, frame count points and trace points.
3. Stack Memory window that displays the contents of the stack.
4. Call Stack window that displays the enclosing frames (both assembly subroutines and C functions).

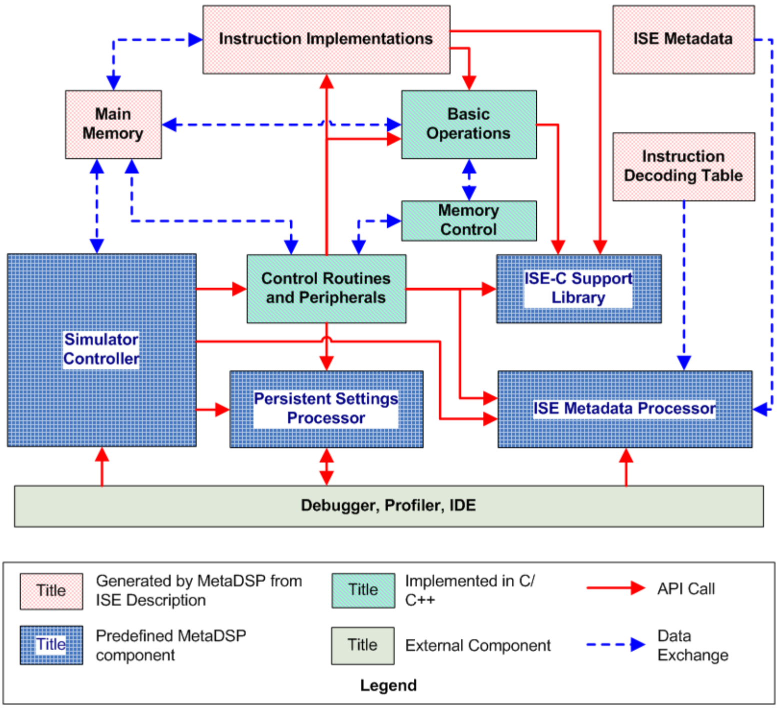

Fig. 4. MetaDSP simulator architecture.

5. Register window that displays the contents of the CPU registers.
6. Memory dump window that displays contents of various memory regions.
7. Watch window that displays the current value of arbitrary C expressions.
8. Code Memory that window to track instructions being executed in the debugger. It supports both binary and disassembly forms as well as displaying the current pipeline stage (fetch, decode, execute, etc.).
9. OS debugger that enables steb-by-step debugging at C and assembler level with various breakpoints and tracing the state of the execution environment (OS): list of the current tasks, semaphores, mutexes, etc.
10. Profiler collecting various profiling data. The profiler is integrated with the editor as well – the editor can show profiling information associated with code elements.

5 Industrial Applications

The approach presented in this paper and MetaDSP framework were applied to five industrial projects. Please note that the each "major releases of the cross toolkit" mentioned in the project list below is caused by a major change in CPU design such as modification of the instruction set or memory model alteration.

– 16-bit RISC DSP CPU with fixed point arithmetic. Produced 25 major releases of the cross-toolkit.

- 16-bit RISC DSP CPU with support for Adaptive Multi-Rate (AMR) sound compression algorithm. Produced 25 major releases of the cross-toolkit.
- 32-bit RISC DSP CPU with support for Fourier transform and other DSP extensions. Produced 39 major releases of the cross-toolkit.
- 16/32-bit RISC CPU clone of ARM9 architecture.
- 16/32-bit VLIW DSP CPU with support for Fourier transform, DMA, etc. Produced 33 major releases of the cross-toolkit.

The following list summarizes lessons learned from the practical applications of the approach. We compared time and effort needed in a pure C++ development cycle of cross toolkits with the ISE-enabled process:

- size of assembler, disassembler and simulator sources (excluding generated code), in lines of code: reduced by 12 times;
- cross-toolkit development team (excluding C compiler development): reducing from 10 to 3 engineers;
- number of errors detected in the presentation of hardware specifications in cross tools: reduction by the factor of more than 10;
- average duration of the toolkit update: reduced from several days to hours (even minutes in many cases).

5.1 Performance Study

This section presents a performance study of a production implementation of the AMR sound compression algorithm. The study was performed on Intel Core 2 Duo 2.4 GHz.

The size of the implementation was 119 C source files and 142 C header files, and 25 files in the assembly language; total size of sources was 20.2 thousand LOC without comments and empty lines. The duration of the audio sample (10 seconds voice speech) lasted 670 million of cycles on the target hardware.

Table 1 presents elapsed time measurements of the generated cross tools for the AMR case study. Table 2 presents measurements of the generated simulator in MCPS (millions of cycles per second).

Table 1. AMR sample – cross toolkit performance.

Operation	Duration, sec.
Translation (.c → .asm)	22
Assembly (.asm → .obj)	14
Link (.obj → .exe)	1
Build, total	**37**
Execution on the audio sample (fast mode)	53
Execution on the audio sample (debug mode with profiling)	93

Table 2. AMR sample – simulator performance.

Execution mode	MCPS
Fast mode	12.6
Debug mode with profiling	7.2
Peak performance on a synthetic sample	25.0

6 Conclusions

The paper presents an approach to automation of cross toolkit development for special-purpose embedded systems such as DSP and microcontrollers. The approach aims at creation the cross tools, namely assembler/disassembler, linker, simulator, debugger, and profiler, at early stages of system design. Early creation of the cross tools gives opportunity to prototype and estimate efficiency of design variations, co-development of the hardware and software components of the target embedded system, and verification and QA of the hardware specifications before silicon production.

The presented approach relies on a two-level description of the target hardware: description of the most flexible part – the instruction set and memory model – using the new ADL language called *ISE* and description of complex fine grained functional aspects of CPU operations using a general purpose programming language (C/C++). Having ADL descriptions along with a framework to generate components of the target cross toolkits and common libraries brings high level of responsiveness to frequent changes in the initial design that are a common issue for modern industrial projects. Using C/C++ gives cycle-accurate simulation and overall efficiency of the cross toolkits that meets the needs of industrial developers. The approach is supported by a family of tools comprising MetaDSP framework.

The approach is applicable to various embedded systems with RISC core architectures. It supports simple pipelines with fixed number of stages, multiple memory banks, instructions with fixed and variable cycle count. These facilities cover most of modern special purpose CPUs (esp. DSP) and embedded systems. Still some features of modern general purpose high performance processors lay beyond the capabilities of the presented approach: superscalar architectures, microcode, instruction multi-issue, out-of-order execution. Besides this, the basic memory model implemented in MetaDSP does not support caches, speculative access, etc.

Despite the limitations of the approach mentioned above it was successfully applied in a number of industrial projects including 16 and 32-bit RISC DSPs and 16/32 ARM CPUs. Number of major design changes (with corresponding releases of cross toolkits) ranged in those projects from 25 to 40. The industrial applications of the presented approach proved the concept of using the hybrid ADL/C++ description for automated development of cross toolkits in a volatile design process.

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An Algorithm for the Accessibility Assessment of Object Manipulation for a Disabled Person with or without Wheelchair

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Abstract. This paper presents an algorithm for the accessibility assessment of object manipulation for a disabled person with or without wheelchair. It addresses the problem of accessibility to the object manipulation by a person with reduced mobility in an indoor environment. The main originality is based on a combination of the animation of an articulated structure in virtual reality by using the techniques of inverse kinematics. We propose a numerical approach based on an incremental iterative algorithm to determine the joint variables of the kinematic chain which minimize the distance between the end effector (the hand) and target point we want to reach.

1 Introduction

The control of a robot manipulator is a research topic that is discussed for a long time. Today the animation of avatars in virtual scenes and humanoid robotics see solutions to the inverse kinematics for systems with a number of important degrees of freedom in real time. In this paper we address the problem of evaluating the accessibility of a handicapped person in its environment. Depending on the degree of disability a person may or may not have access to all points of space. In case of non-accessibility we have to adapt and modify the environment. We offer a contribution to this evaluation by determining for each space area if there is a possibility of access or inability. The method we use is to check if the inverse kinematics of a humanoid, constraint in its movement provides a way to reach all points of space.

2 Related Work

As part of the animation of virtual humans two approaches have been developed in recent years. The first aims to improve the techniques of inverse kinematics, the second focuses on the automatic generation of movements from the simulation of the forces animating a human body. While giving it visually acceptable results quickly reached its limits. The control of various parts of a skeleton is, from a mathematical point of view, to calculate the inverse of the direct model. A first methodological approach is to linearize the system of nonlinear equations that form the direct model.

A common approach is to calculate the generalized inverse and especially of pseudo inverses. Using an algorithm of singular value decomposition in this method has the advantage of providing a minimum standard solution when it exists and if not an optimal solution in the sense of least squares. The introduction of the pseudo inverse enables process a subtask without impeding the achievement of the primary task is the calculation of inverse kinematics. The secondary task is an optimization which depends on the application. We can calculate the different joints to reach the position of the terminal while trying to minimize the violation of the constraints as well made. This method is cumbersome in computation time and can be unstable in some singularities [1].

Therefore, other methods exist to solve the problem of inverse kinematics such as the Cyclic Coordinate Descent (CCD) method [20]. At each iteration we try to minimize the position error of end effector, adjusting each articulation sequentially. This method is fast and can deal with constraints such as limited angle by preventing the angle of joints exceed certain limit values during the iterations. It has the advantage of easy implementation, speed of execution in most cases and its stability for the configurations of singular contrast to the method based on the pseudo inverse. It has some disadvantages as does promote final joint because of evaluating the treatment from the end effector to the root. Indeed, the joint angles terminals are the first to be modified and therefore are more likely to undergo the largest rotation. This method also has drawback of not always produce natural movements. We can reduce this adverse effect by limiting the angular changes at each iteration. Recently two similar approaches have been developed based on a triangulation method [2] [19] attempting to resolve the problem but, as the CCD, it has the disadvantage of requiring an angle of rotation in some relatively large situations and avoid situations considering the constraints. An improved version of this method [17] is to provide solutions to the problem of inverse kinematics avoiding large angles of rotation. All these methods use iterative numerical approaches. They always converge but the results are not reproducible. Frequently, analytical and numerical methods are combined. The first one is used whenever possible [9] and in other cases they are combined by generating a posture analytical and adaptation by iterative method [18]. Controlling humanoid synthetic interaction with the environment requires the application of methods for solving the inverse kinematics in real time. In general, control of virtual structures articulated need to accelerate the resolution of the algorithm while ensuring the realism of motion generated [3], [4], [6], [7]. Analytical approaches have been suggested introducing constraints on the geometric structure articulated to reduce the number of degrees of freedom. These methods allow finding all solutions to the inversion problem. This is the case of kinematic inversion methods that apply to HAL (Human-Like-Arm) chains. A synthetic review of these methods applied to kinematic chain constraints is presented by Tolani et al. [7].

A number of approaches known as linear programming proposing to transform the problem of inverse kinematics problem of a non-linear programming [8], [9], [10], [12]. The authors associate with the target potential function expressing the distance between the position of the end effector and the goal. This type of method can effectively solve the problem of inverse kinematics, without explicitly calculating the inverse of the Jacobian matrix. In another way, the optimization by gradient descent leads to local minima. The approach does not guarantee the realism of performed motion. As used, the methods of inverse kinematics have no neurophysiological relevance. In addition, they cannot manage changes in the environment or to address the anatomical variability between individuals.

Other approaches to solving the inverse kinematics problem have been proposed by use of biological models that are consistent with the neuro-physiological assumptions. Soechting [13] proposes a review of empirical studies used to control the movement of human arm. It proposes an algorithm for the kinematic inversion, reviewed by Koga et al. for the planning of movement [14]. Another approach also leads to a sensorimotor transformation to produce the arms motion within a number of invariant laws of human movement [9], [10], [11]. This approach is based on a method of gradient descent associated with the integration in the loop sensorimotor control functions biologically plausible. Another solution to the problem of inverse kinematics using a method based on a principle of optimization by using genetic algorithms. Indeed, this family of optimization methods that was used by J. Parker [15] to solve an inverse kinematics system has the advantage of being simple to implement, to be effective and be applicable to many types of problems. This iterative algorithm based on the metaphor of natural selection which assumes that the best individual is more likely to survive and reproduce.

Other less conventional algorithms exist to solve the problem of inverse kinematics, such as algorithms based on the transposed Jacobian [16] or those based on neural networks. We present in this article an algorithm based on gradient descent methods that provide some answers to the various constraints of the articulated complex structures while avoiding the disadvantages described above. The computation time reduces the number of iterations low and taking into account the joint limits have an opportunity to make application to the animation of a virtual human handicapped for the evaluation of the access to a built environment.

3 Problem Statement and Context

This paper aims to detail our approach to the problem of accessibility to the manipulation of objects in an environment of everyday life. The basic approach is to label it, so fast, all points of an environment that is accessible or not in terms of evaluation of a minimum distance between the tip of the hand and all items in the room. The work requires consideration of several parameters:

- The ability of residual mobility of the person according to which we carry out the assessment. From a biomechanical model of the human body, each person has specific characteristics, however activation joints in terms of constraints on the amplitude of mobility. The evaluation of accessibility will be individualized in relation to the person living in this room.
- The required accuracy of computing is not very important because we can consider that the compliance of the human body can compensate for errors in details.
- We believe that the person or persons living in the area to be assessed moves either by wheelchair or with a trolley. Both types of mobility do not have the same swept volume and bulk which respectively leads to different algorithm treatments.
- The proposed algorithm have necessary to be fast, in a reasonable way, in order to access to all points of the environment.

4 General Principle

The work proposed in this paper is divided into three different aspects:

- The environment;
- The person living in the environment;
- The relation between the person and his environment.

4.1 The Environment

To check the accessibility it is necessary to have a representation of each point that must be assessed. For this we propose to build a 3D environment to quickly obtain the coordinates of each point. This aspect of our work is not detailed here. Several studies including the Jongbae Kim [21] proposes a methodology for rapid modelling of the built environment. We have an environment modelled as representative 3DStudioMax kitchen (Figure 1). Furniture that make up the room are not represented because we consider only the stationary parts. The other can be moved if necessary to solve the accessibility problem.

Fig. 1. The environment application.

4.2 The Person

Algorithm is performed by the joint constraints and the choice of positioning parameters of each joint. The model we use is that proposed by [22] from which we extracted a model at 21 degrees of freedom (figure 2) from the torso at the end of the right hand. Other models, such as the Michigan model cited in [25] with 15 degrees of freedom could be used, but we are opted for a more precise one so that the movement is more realistic

4.3 The Interaction with the Environment

The basic principle of the proposed approach is to calculate the existence of a solution to the inverse kinematics of the articulated structure to achieve a target of a modelled

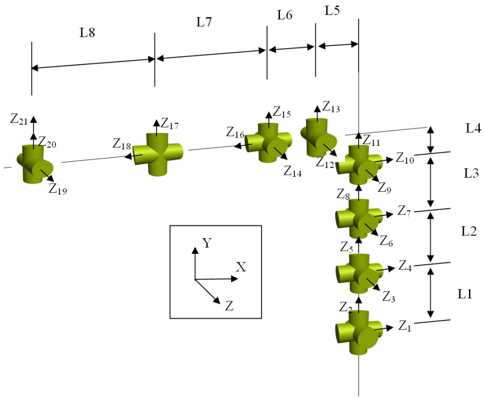

Fig. 2. The kinematic chain of joints used 21 DDL.

space. A point is considered to be achievable if the distance between the tip of the articulated structure and the target point is below a predefined value. We believe that the basis of the joint structure is moving in a plane parallel to the ground and the volume depends on the sweeping nature of the mobility model. If the person uses a trolley then the position of the structure base reference frame is articulated at the position of the waist of a standing person and the swept volume is a circle of a given radius. If the person is in an electric or a manual wheelchair then the position of the structure base reference frame is located at the waist of the position of a seated person and the swept volume is a rectangle. We do not take into account in this work, the constraints du to the non-holonomic wheelchair structure. A point is considered to be achievable if there is a solution to the inverse kinematics without considering the path to reach this position (figure 3).

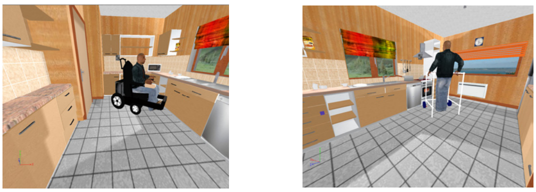

Fig. 3. Interaction with the environment.

5 Inverse Kinematics

5.1 Introduction

The major problem of our approach is to define a method for solving the inverse kinematics of fast considering the constraints on the joints and the person swept volume. The proposed method is similar to the algorithm Cyclic Coordinate Descent (CCD) [23] in that it is iterative, it presents the characteristic of being fast enough without local minimum and it can take into account the joint angle limits.

5.2 Principle of the Proposed Algorithm

We define **f([Θ])=[X]**avec [Θ]= (Θ_1, Θ_2, Θ_i,… Θ_n) and **[X]** an objective vector we want to achieve. We have a nonlinear equations system and the objective consist in evaluating the values of the variables Θ_i. The idea is to compute each variable value Θ_i from the base to the end effector in order to minimize the distance ε such as:

$$f([\Theta])-[X]=\varepsilon \quad (1)$$

We get the following algorithm:

- 1. Initialise randomly the joint variables Θ_i
- 2. Define the increment Inc (i)
- 3. **Do**
  - 3.1 for each variable Θ_i
    - 3.3.1. $\Theta_i=\Theta_i$ + Inc (i)
      - Compute the distance between current

      Solution and goal such $\varepsilon=f([\Theta])-[X]$
      - **if** (Δε Variation) <0) then keep Θ_i
      - **Else** $\Theta_i=\Theta_i - 2*$ Inc (i)
        - $\varepsilon = f([\Theta])-[X]$
        - **if** (Δε <0) then keep Θ_i
        - **Else** $\Theta_i=\Theta_i$ + Inc (i) (keep the original value)
- 4. **While** Stop Conditions not verified

The Θ value is kept only if it is within given limits. This algorithm is very simple to apply to any joint structure. It is important to carefully choose a few settings to speed up the computing. We propose three types of stop conditions:

- A minimum distance error ε;
- A minimum value of the distance variation Δε
- A maximum number of iterations (an iteration is defined when applying the increment to all the joint variables of line 3.1. of the algorithm). In general, this parameter is used only when a bad choice of other parameters is done.

5.3 Improving the Algorithm

This algorithm is fast and has no local minimum. It presents an algorithm structure equivalent to the CCD in the way to move each joint sequentially. The difference point lies in how to compute the increment.

5.3.1 Choice of the Inc(i) Values

The increment Inc is calculated for each joint i as

Inc(i) = (Max(i)-Min(i)) * IncrementRate

with Max(i) and Min(i) respectively the minimum and the maximum values of the joint i. IncrementRate allows to adjust the speed of convergence of the algorithm. The parameters Inc(i) is very important in both sign and amplitude that contribute to the speed of convergence. In the gradient descent methods like Newton-Raphson, gradient matrices and the inverse of the Hessian fulfil these roles. The optimization of these values helps to speed up convergence. In our case we modify the basic algorithm by storing the sign of the Inc for each variable i and use the same sign at the next iteration. The algorithm converges without local minimum. Convergence is rapid initially and then the variation becomes weaker in the vicinity of the solution. We propose a modification of the algorithm by adjusting the value of the increment Inc(i) depending on the magnitude of the change in distance in a non-linear way as in equation (2). Other adaptation functions of could be applied.

$$\begin{gathered}\text{if (Distance Variation == 0)}\\ \text{IncrementRate} = \text{IncrementRate} / \gamma\end{gathered} \tag{2}$$

The value γ have to be defined. In our work we take $\gamma = 2$. A linear adjustment does not improve the speed of convergence. If the increment Inc(i) is sufficiently large, the change in distance is rapidly becoming zero around the solution (Figures 4). We use a given minimum value $\Delta\varepsilon$ (may be zero) to decrease the value of the increment Inc(i). The sign remains in memory.

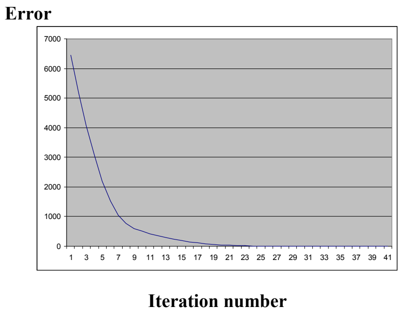

Fig. 4a. The distance (error) evolution versus the number of iterations. Parameter IncrementRate is fixed with the value 0,015. Iterations stop when the error is less than 0.5 units.

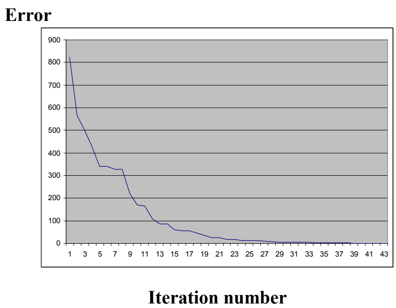

Fig. 4b. Application of the algorithm with non-linear adjustment of the increment. With IncerementRate = 0.2 initially and divided by two at each cancellation of the $\Delta\varepsilon$. Iterations stop when the error is less than 0.5 units.

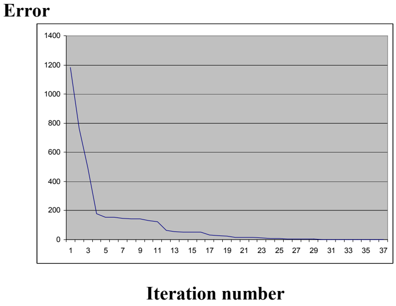

Fig. 4c. Another example with non-linear adjustment of the increment with IncerementRate = 0.5 initially and divided by 3 at each cancellation of Δ**ε**. Iterations stop when the error is less than 0.5 units.

5.3.2 Calculation of the Direct Model

In literature the algorithm acceleration of gradient descent, BFGS of CCD is often based on minimizing the number of iterations, which we have proposed in the previous paragraph. The sequential nature of the algorithm allows accelerate the speed by another way which is the computing of the direct model. In carrying out the modification of one single variable system matrix corresponding to this variable is affected. The model is based on the multiplication of Denavit-Hartenberg matrices [24] whose prototype is given below:

$$DH_{i,i-1} = \begin{bmatrix} \cos\Theta_i & -\cos\alpha_i \sin\Theta_i & \sin\alpha_i \sin\Theta_i & a_i \cos\Theta_i \\ \sin\Theta_i & \cos\alpha_i \cos\Theta_i & -\sin\alpha_i \cos\Theta_i & a_i \sin\Theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

And for n joints :

$$DH_{0,n} = DH_{0,1} \ldots DH_{i,i+1} \ldots DH_{n-1,n} \quad (4)$$

For any vector V given in an homogeneous coordinates in the reference frames n, we compute in the R_0 word frame :

$$V_{R_0} = DH_{0,n} V_{R_n} \quad (5)$$

We can write $DH_{0,\,n}$ as composed of two matrices

$$DH_{0,n} = DH_{0,i} * DH_{i+1,n} \quad (6)$$

If we want to change the matrix corresponding to the joint variable i we can write that

$$DH_{0,n}^{q+1} = DH_{0,i-1}^{q} * DH_i^{q+1} * (DH_i^{q})^{-1} * DH_{i+1,n}^{q} \quad (7)$$

With q the iteration number. This method requires only three multiplications instead of n. The inverse matrix DH^{-1} is given directly by the following expression :

$$DH_i^{-1} = \begin{bmatrix} \cos\Theta_i & \sin\Theta_i & 0 & -a_i \\ -\cos\alpha_i \sin\Theta_i & \cos\alpha_i \cos\Theta_i & \sin\alpha_i & -d_i \sin\alpha_i \\ \sin\alpha_i \sin\Theta_i & -\sin\alpha_i \cos\Theta_i & \cos\alpha_i & -d_i \cos\alpha_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

The computing time for the direct model is independent of the number of degrees of freedom of the structure and the algorithm will perform 3n matrix multiplications per iteration.

5.3.3 Results

We conducted an implementation of the algorithm in Visual C + + on a PC Pentium 4 running at 3.4 GHz under Windows. Table 1 outlines the average scores in 10,000 calculations for the 21 dof articulated structure defined above. The parameters are defined as follows: 0,015 = Increment Rate constant for versions A, B, C and D. For version E Increment Rate is set at 0.5 initially and when the change in distance is less than 0.1 Increment Rate is divided by 3. These parameters are defined experimentally and can be adapted to each case of articular structures.

5.3.4 Considering the Constraint Limits

Our algorithm, as the CCD algorithm, does not achieve several tasks simultaneously. Execution time is very fast, however we can work on several solutions and choose the one that meets the criteria we wish to optimize. The solution is not unique, it depends on the initialization of variables before the application of the algorithm. The best solution in terms of constraints is determined by calculating several solutions and applying one or more selection criteria. In applying to the human like structure our constraint is the posture comfort. We believe that a posture is comfortable if it does not move away too much of a neutral configuration Θ_i^N.

We keep the solution that minimizes the following criterion: $C = \sum_n w_i \left|\Theta_i^N - \Theta_i\right|$

Each candidate solution is calculated from a set of variables different origins. For a set of 6 solutions (this number can be changed according to the results that we want to get) we obtain an acceptable solution to the meaning of the result we wish to obtain according to the constraints. Execution time will be dependent on the number of solutions before applying the criterion.

Table 1. Different improvements of the algorithm.

	A	B	C	D	F
	Modelling direct multiplication of all matrices	With the memory of the sign	Modelling incremental adaptation of a matrix DH when editing a variable	Modelling with incremental storage of the sign	Incremental modelling with sign storage and non-linear variation of the increment
Mean execution times	42 ms	34 ms	7.2 ms	6.1 ms	8 ms
Mean error	0.51	0.51	0.51	0.51	0.43
Average number of iterations	23.2	23.2	24.2	23.2	25.5

5.3.5 Taking into Account the Person Mobility Type

We assume that the model can move in a space defined by $\phi(x,y,z)$. The objective is to determine whether there is a solution to the problem of accessibility by considering the model and the area in which it is moving. The basic problem remain the same which is to find a solution to $f(\Theta)=[X]$ model but the objective is no more a position but an area. The new algorithm can find a solution to this problem

$$f([\Theta])=[X]-\phi(x,y,z) \tag{9}$$

$$f([\Theta])=\Gamma([X],x,y,z) \tag{10}$$

The problem is to determine whether there is a set of variables Θ_ι In our case, $f([\Theta])$ have to reach the space area ϕ. The mobility area is a polygon formed

by considering the structure motion area which is a polygon parallel to the ground. Instead of considering the mobility of the articulated structure that we postpone the mobility on the objective point and we get the system (9) or (10) that we must solve. The point to achieve turns to a polygon as shown on Figure 5. As the space of solutions is larger, the computing time is reduced. On the same computer as before we obtain an average execution time of 1.2 ms with an average error is 0.1 units and a average number of iterations of 1.4.

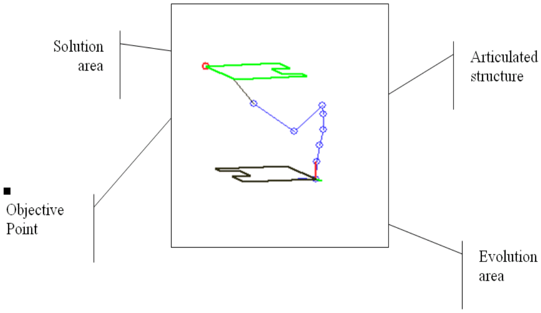

Fig. 5. Result obtained.

5.3.6 Taking Into Account the Evolution of the Shape of the Base and the Base Rotation Θ_0

To ensure full mobility of the person we add to the model a degree of freedom Θ_0 to the root. In order to not transform the initial model we have applied the additional degree freedom in order to remain compatible with the constraints of the Denavit-Hartenberg model. Now we change the world frame for the new configuration of Figure 6.

The computing procedure we have detailed above does not take into account the geometry and volume of the articulated structure. We consider that it is materialized as a point. In the real case we need to consider the bulk. We consider several types of mobility, the person is either with a trolley or seated in an electric or manual wheelchair. The first type of mobility is determined by the algorithm that considers the person is a circular area with the plane defined by the ground and the orientation of the structure does not affect the structure control. The second type of mobility constitutes a problem because the structure surface depends on the orientation of the wheelchair. We propose to calculate the configuration of the wheelchair according to the instantaneous orientation Θ_0. Thus the previous algorithm is used whereas to reach

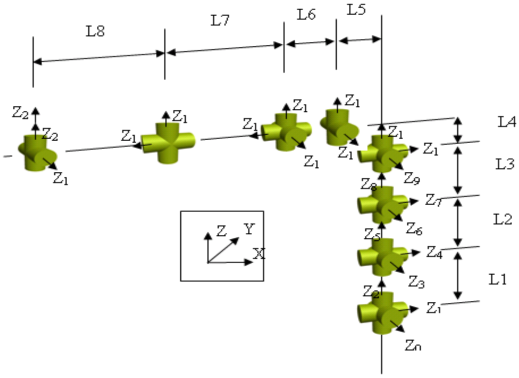

Fig. 6. New configuration frame.

the polygon is changed according to the orientation of dof 0 added. For a given orientation angle we compute the allowable polygon as given on the following figure 7. The polygon computing is not the subject of this paper.

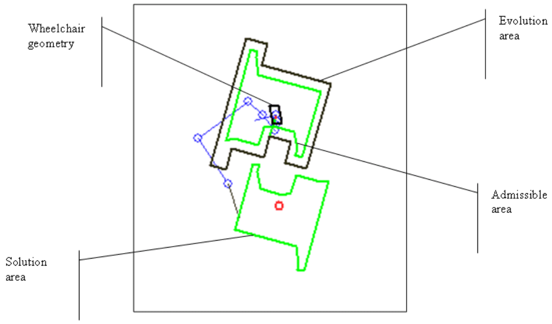

Fig. 7. The evolution areas and admissible area for a rectangular wheelchair.

Table 2. Comparative table for the same examples, the same variable initializations and the same objective points. The results in this table are average values over 10,000 tests on a PC Pentium 4 running at 3, 4 GHz.

	21 Dof with a point base	22 Dof with a circular base	22 Dof with a rectangular base
Mean Execution Times	1,25 ms	1,34 ms	2,9 ms
Mean Errors	0,10	0,09	0,12
Average number of iterations	1,47	1,02	1,49

6 Discussions

The proposed algorithm belongs to the class of gradient descent algorithms. The main difference is in the sequential change of each variable and not in the calculation of all variables like the algorithms of Newton-Raphson or BFGS. This approach would aim at a longer calculation but it is possible, with the sequential approach, to calculate the position of the structure effector (the orientation could be calculated the same way) incrementally by the multiplication of three matrices Denavit-Hartenberg (DH) instead of n that constitute the structure. For this reason in the worst case 6n matrix calculations are required. Three for the matrices DH computing doubled in case of bad choices of increment (line 3.3.1. of the algorithm). When storing the increment sign, the DH matrices computing approximates 3n per iteration.

7 Conclusions

The proposed algorithm has the advantage of being fast and offer a solution within the joints imposed limits. Currently it is possible to find an acceptable solution in terms of application to the human anatomical structure within a short time which allows the use of selection criteria based on constraints. He was shown a possibility of using a criterion of comfort, other criteria may be used in the same manner in the application. This work as we announced in the text is applied to assess the accessibility of a handicapped person to grip an object in a place of life. It is necessary so that the work is complete to check the path made by the structure in order to avoid collision with objects. This is object of the perspective of this work.

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Appendix

Hereby is given the Denavit-Hartengerg parameter table for the used articulated structure defined in the text above.

Table 3. Table of Denavit-Hartenberg considered kinematic chain.

	Θ	D	α	a
1	PI/2	0	PI/2	0
2	PI/2	0	PI/2	0
3	PI/2	L1	PI/2	0
4	PI/2	0	PI/2	0
5	PI/2	0	PI/2	0
6	PI/2	L2	PI/2	0
7	PI/2	0	PI/2	0
8	PI/2	0	PI/2	0
9	PI/2	L3	PI/2	0
10	PI/2	0	PI/2	0
11	PI/2	0	PI/2	0
12	-PI/2	L4	PI/2	L5
13	0	0	PI/2	0
14	0	0	-PI/2	L6
15	0	0	PI/2	0
16	PI/2	0	PI/2	0
17	0	L7	-PI/2	0
18	0	0	PI/2	0
19	PI/2	L8	PI/2	0
20	PI/2	0	PI/2	0
21	0	0	0	0

L1=10; L2=10; L3=10; L4=5; L5=10; L6=10; L7=30; L8=30; length of Hand = 20 (to calculate the position of the terminal).

A Globally Exponentially Convergent Immersion and Invariance Speed Observer for n Degrees of Freedom Mechanical Systems with constraints

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Abstract. The problem of velocity estimation for mechanical systems is of great practical interest. Although many partial solutions have been reported in the literature the basic question of whether it is possible to design a globally convergent speed observer for general n degrees of freedom mechanical systems remains open. In this paper an affirmative answer to the question is given by proving the existence of a $3n+1$–dimensional globally *exponentially* convergent speed observer. Instrumental for the construction of the speed observer is the use of the Immersion and Invariance technique, in which the observer design problem is recast as a problem of rendering attractive and invariant a manifold defined in the extended state–space of the plant and the observer.

Notation. For general mappings $S:\mathbb{R}^n\times\mathbb{R}^p\to\mathbb{R}^q$, $(x,\zeta)\mapsto S$ we define $\nabla_x S(x,\zeta) := \frac{\partial S(x,\zeta)}{\partial x}$ and $\nabla_\zeta S(x,\zeta) := \frac{\partial S(x,\zeta)}{\partial \zeta}$. For brevity, when clear from the context, the subindex of ∇ and, in general, the arguments of all the functions are omitted.

1 Problem Formulation

We consider general n degree of freedom mechanical systems with nonholonomic constraints described in Lagrangian form by [11], [13],

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + \nabla U(q) = G(q)u + A(q)\lambda, \tag{1}$$

$$A^\top(q)\dot{q} = 0, \tag{2}$$

where $q(t), \dot{q}(t) \in \mathbb{R}^{\mathrm{n}}$ are the generalized positions and velocities, respectively, $u(t)\in\mathbb{R}^m$ is the control input, $A(q)\lambda$ are the constraint forces with $A:\mathbb{R}^n\to\mathbb{R}^{n\times k}$, $\lambda\in\mathbb{R}^k$, $G:\mathbb{R}^n\to\mathbb{R}^{n\times m}$ is the input matrix, $M:\mathbb{R}^n\to\mathbb{R}^{n\times n}$ is the mass matrix with

$M = M^\top > 0$ and $U : \mathbb{R}^n \to \mathbb{R}$ is the potential energy function. $C(q,\dot q)\dot q$ is the vector of Coriolis and centrifugal forces, with the (ik)–th element of the matrix $C : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^{n\times n}$ defined by

$$C_{ik}(q,\dot q) = \sum_{j=1}^{n} C_{ijk}(q)\dot q_j,$$

where $C_{ijk} : \mathbb{R}^n \to \mathbb{R}$ are the Christoffel symbols of the first kind defined as

$$C_{ijk}(q) := \frac{1}{2}\left\{ \frac{\partial M_{\mathrm{ik}}}{\partial q_{\mathrm{j}}} + \frac{\partial M_{\mathrm{jk}}}{\partial q_{\mathrm{i}}} - \frac{\partial M_{\mathrm{ij}}}{\partial q_{\mathrm{k}}} \right\}. \tag{3}$$

We consider $q(t)$ to be measurable and assume that the input $u(t)$ is such that $q(t), \dot q(t)$ exist for all time, that is, the system is forward complete. Our objective is to design a globally asymptotically convergent observer for $\dot q(t)$.

Speed observation is a longstanding problem whose complete theoretical solution has proven highly elusive. The first results were reported in 1990 in the fundamental paper [14], and many interesting partial solutions have been reported afterwards. Particular attention has been given to the case in which the system (1) can be rendered linear in the unmeasurable velocities via partial changes of coordinates, see, *e.g.*, [6, 16]. An intrinsic local observer, exploiting the Riemannian structure of the system, has been recently proposed in [1] (see also [2] for a Lyapunov analysis and [7] for a generalization). A solution for a class of two degrees of freedom systems has been recently reported in [8]. The reader is referred to the recent books [5, **?**,**?**] for an exhaustive list of references.

A complete solution to the problem is given by the proposition below. As will become clear in the proof, the construction of the observer relies on the use of the Immersion and Invariance (I&I) technique—first reported in [4] and further developed in [3, 10]. In I&I the observer design is recast as a problem of rendering attractive a suitably selected invariant manifold defined in the extended state–space of the plant and the observer. It should be mentioned that the observers in [8, 16] are also based on the I&I approach.

2 Main Result

Proposition 1. *Consider the system (1), and assume* u *is such that trajectories exist for all* $t \geq 0$. *There exist smooth mappings* $A : \mathbb{R}^{3n-2k+1} \times \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^{3n-2k+1}$ *and* $B : \mathbb{R}^n \to \mathbb{R}^{(n-k)\times(3n-2k+1)}$ *such that the dynamical system*

$$\dot\chi = A(\chi, q, u) \tag{4}$$

with state $\chi(t) \in \mathbb{R}^{3n-2k+1}$, *inputs* $q(t)$ *and* $u(t)$, *and output*

$$\eta = B(q)\chi, \tag{5}$$

has the following property.

All trajectories of the interconnected system (1), (2), (4) are such that

$$\lim_{t\to\infty} e^{\alpha t}[\mathcal{N}(q)\dot{q}(t) - \eta(t)] = 0, \tag{6}$$

for some $\alpha > 0$ *and for all initial conditions* $(q(0), \dot{q}(0), \chi(0)) \in \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^{3n-2k+1}$*, where* $\mathcal{N}(q) : \mathbb{R}^n \to \mathbb{R}^{n-k} \times \mathbb{R}^n$ *is a left invertible matrix. That is, (4), (5) is a globally exponentially convergent speed observer for the mechanical system (1)-(2).*

Remark 1. For the special case of a mechanical system with no nonholonomic constraints, it is clear that $k = 0$ and subsequently the matrix $\mathcal{N}(q)$ becomes an invertible square matrix.

3 A Preliminary Lemma

Before giving the proof of the main result, we recall that the system (1)-(2) can be written in the port-Hamiltonian form [13] as

$$\begin{bmatrix} \dot{q} \\ \dot{p} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{pmatrix} \nabla_q H(q,p) \\ \nabla_p H(q,p) \end{pmatrix} + \begin{bmatrix} 0 \\ G(q) \end{bmatrix} u + \begin{bmatrix} 0 \\ A(q) \end{bmatrix} \lambda, \tag{7}$$

$$A^\top(q)\lambda = 0, \tag{8}$$

where $p = M(q)\dot{q}$ are the generalized momenta and

$$H(q,p) = \frac{1}{2} p^\top M^{-1}(q) p + U(q)$$

represents the total energy stored in the system. Further, as per [13], the system (7)-(8) when restricted to the constrained space

$$\mathcal{X}_c = \{(q, \dot{q}) | A^\top(q)\dot{q} = 0\},$$

takes the form

$$\begin{bmatrix} \dot{q} \\ \dot{\tilde{p}} \end{bmatrix} = \begin{bmatrix} 0 & \tilde{S}(q) \\ -\tilde{S}^\top(q) & J(q,\tilde{p}) \end{bmatrix} \begin{pmatrix} \nabla_q H(q,\tilde{p}) \\ \nabla_{\tilde{p}} H(q,\tilde{p}) \end{pmatrix} + \begin{bmatrix} 0 \\ B_c(q) \end{bmatrix} u + \begin{bmatrix} 0 \\ A(q) \end{bmatrix} \lambda, \tag{9}$$

$$H(q,\tilde{p}) = V(q) + \frac{1}{2} \tilde{p}^\top \tilde{M}^{-1}(\tilde{q}) \tilde{p}, \tag{10}$$

with $\tilde{p} \in \mathbb{R}^{n-k}$ being given as $\tilde{p} = \tilde{S}^\top(q)p$ where $\tilde{S}(q) \in \mathbb{R}^{n \times n-k}$ is the full rank annihilator of the matrix $A(q)$ satisfying the condition $A^\top(q)\tilde{S}(q) = 0$. The matrix $J(q,\tilde{p})$ is skew-symmetric and is given by

$$J_{ij}(q,\tilde{p}) = -p^\top [\tilde{S}_i, \tilde{S}_j], \tag{11}$$

where $[\tilde{S}_i, \tilde{S}_j]$ denotes the standard Lie bracket of the column vectors S_i, S_j and the matrix $\tilde{M}(q) \in \mathbb{R}^{n-k \times n-k}$ is symmetric positive-definite.

In order to streamline the presentation in this section, we introduce a factorization of the mass matrix

$$\tilde{M}^{-1}(q) = T^\top(q)T(q), \tag{12}$$

where $T : \mathbb{R}^n \to \mathbb{R}^{n-k\times n-k}$ is a full rank matrix[4] and define the mappings $L : \mathbb{R}^n \to \mathbb{R}^{n\times n-k}$ and $F : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^{n-k}$ as

$$L(q) = \tilde{S}(q)T^\top(q), \tag{13}$$

$$F(q,u) = L^\top(q)[B_c(q)u - \nabla U(q)]. \tag{14}$$

Notice that, since q and u are measurable, these mappings are known. We next state the following proposition.

Lemma 1. *The system dynamics (9)-(10) when expressed in the new coordinates* $(y,x) = (q, T(q)\tilde{p})$, *admits a state space representation of the form*

$$\dot{y} = L(y)x, \tag{15}$$

$$\dot{x} = S(y,x)x + F(y,u), \tag{16}$$

where

$$S = TJT^\top + \sum_{i=1}^{n}(\{\frac{\partial T}{\partial y_i}T^{-1}x\}\{L^\top e_i\}^\top - \{L^\top e_i\}\{\frac{\partial T}{\partial y_i}T^{-1}x\}^\top), \tag{17}$$

and e_i *is the* i^{th} *basis vector of* $\mathbb{R}^{n-k}$.

Proof. We directly obtain (15) by differentiating y and by using (9), (10), (13). We next compute the following,

$$\dot{x} = \dot{T}\tilde{p} + T\dot{\tilde{p}}, \tag{18}$$

$$= \dot{T}\tilde{p} - T\tilde{S}^\top\frac{\partial}{\partial y}(\frac{1}{2}\tilde{p}^\top\tilde{M}^{-1}(\tilde{q})\tilde{p}) - T\tilde{S}^\top\nabla U + T\tilde{S}^\top B_c u + TJT^\top x, \tag{19}$$

$$= \dot{T}\tilde{p} - L^\top\frac{\partial}{\partial y}(\frac{1}{2}\tilde{p}^\top\tilde{M}^{-1}(\tilde{q})\tilde{p}) + F + TJT^\top x, \tag{20}$$

where we have made use of (10), (13) and (14). We now compute that,

$$\dot{T}\tilde{p} = \sum_{\mathrm{i}=1}^{\mathrm{n}}(\frac{\partial T}{\partial y_{\mathrm{i}}}\tilde{p})(e_{\mathrm{i}}^\top\tilde{S}\tilde{M}^{-1}\tilde{p}),$$

$$= \sum_{\mathrm{i}=1}^{\mathrm{n}}(\frac{\partial T}{\partial y_{\mathrm{i}}}\tilde{p})(e_{\mathrm{i}}^\top L)x, \tag{21}$$

and further obtain

$$\frac{\partial}{\partial y}\{\frac{1}{2}\tilde{p}^\top\tilde{M}^{-1}\tilde{p}\} = \frac{\partial}{\partial y}\{\frac{1}{2}\tilde{p}^\top T^\top Tp\}$$

$$= \sum_{\mathrm{i}=1}^{\mathrm{n}} e_i\{\frac{\partial T}{\partial y_{\mathrm{i}}}\tilde{p}\}^\top x. \tag{22}$$

[4] Since M is positive definite this factorization always exists. It may be taken to be the (univocally defined) Cholesky factorization, as proposed in [9].

Substituting (21) and (22) in (20) we obtain the dynamics of x as,

$$\dot{x} = \sum_{i=1}^{n}(\{\frac{\partial T}{\partial y_i}T^{-1}x\}\{L^\top e_i\}^\top - \{L^\top e_i\}\{\frac{\partial T}{\partial y_i}T^{-1}x\}^\top)x + TJT^\top x + F,$$
$$= Sx + F, \tag{23}$$

where we have used (17) to obtain the equation (23). This concludes the proof.

Remark 2. It can be verified easily that matrix $S(y,x)$ defined in (17) satisfies the following properties:

(i) S is skew–symmetric, that is,
$$S + S^\top = 0.$$

(ii) S is linear in the second argument, that is,
$$S(y, a_1x + a_2\bar{x}) = a_1S(y,x) + a_2S(y,\bar{x}),$$
for all $y, x, \bar{x} \in \mathbb{R}^n$, and $a_1, a_2 \in \mathbb{R}$.

(iii) There exists a mapping $\bar{S} : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^{n\times n}$ such that
$$S(y,x)\bar{x} = \bar{S}(y,\bar{x})x,$$
for all $y, x, \bar{x} \in \mathbb{R}^n$.

Remark 3. Lemma 1 implies that the speed observer problem for system (1)-(2) can be recast as an observer problem for system (15)-(16) with output y.

Remark 4. For the special case of no nonholonomic constraints, we have $k = 0$ and

$$J(q,\tilde{p}) = 0, \tilde{S}(q) = I, \tilde{M}(q) = M(q), L(q) = T^\top(q).$$

This subsequently simplifies the expression for $S(y,x)$ as

$$S(y,x) = \sum_{i=1}^{n}(\{\frac{\partial T}{\partial y_i}T^{-1}x\}\{Te_i\}^\top - \{Te_i\}\{\frac{\partial T}{\partial y_i}T^{-1}x\}^\top). \tag{24}$$

It can be shown (refer to [16]) that the (jk)–th element of S is $S_{jk} = -\{T^{-1}x\}^\top[\mathcal{T}_\mathrm{j}, \mathcal{T}_\mathrm{k}]$.

4 Proof of the Main Result

The observer is constructed in four steps.

(S1) Following the I&I procedure [3], we define a manifold (in the extended state-space of the plant and the observer) that should be rendered attractive and invariant[5]. As is well–known, to achieve the latter objective a partial differential equation (PDE) should, in principle, be solved.

[5] The manifold should be such that the unmeasurable part of the state can be reconstructed from the function that defines the manifold.

(S2) To avoid the need to solve the PDE the “approximation” technique proposed in [10] is adopted. Using this approximation induces some errors in the observer error dynamics.
(S3) Always borrowing from [10], we introduce a dynamic scaling that dominates—in a Lyapunov–like analysis—the effect of the aforementioned disturbance terms, proving that the scaled observer error converges to zero.
(S4) To prove that the dynamic scaling factor is bounded and, consequently, that the actual observer error converges, exponentially, to zero, high gain terms are introduced in the observer dynamics to, again, dominate sign–indefinite terms in a Lyapunov–like analysis.

Step 1. (Definition of the manifold) For the system (15)-(16), we propose the manifold

$$\mathcal{M} := \{(y, x, \xi, \hat{y}, \hat{x}) : \xi - x + \beta(y, \hat{y}, \hat{x}) = 0\} \subset \mathbb{R}^{5n-3k}, \tag{25}$$

where $\xi \in \mathbb{R}^{n-k}, \hat{y} \in \mathbb{R}^{n-k}, \hat{x} \in \mathbb{R}^{n}$ are (part of) the observer state, the dynamics of which are defined below, and the mapping $\beta : \mathbb{R}^{3n-2k} \to \mathbb{R}^{n-k}$ is also to be defined.

To prove that the manifold $\mathcal{M}$ is attractive and invariant it is shown that the off–the–manifold coordinate

$$z = \xi - x + \beta(y, \hat{y}, \hat{x}), \tag{26}$$

the norm of which determines the distance of the state to the manifold $\mathcal{M}$, is such that:

(C1) $z(0) = 0 \Rightarrow z(t) = 0$, for all $t \geq 0$ (invariance);
(C2) $z(t)$ asymptotically (*exponentially*) converges to zero (attractivity).

Notice that, if $z(t) \to 0$, an asymptotic estimate of x is given by $\xi + \beta$.

To obtain the dynamics of z differentiate (26), yielding

$$\begin{aligned} \dot{z} &= \dot{\xi} - \dot{x} + \dot{\beta} \\ &= \dot{\xi} - S(y, x)x - F + \nabla_y \beta \dot{y} + \nabla_{\hat{y}} \beta \dot{\hat{y}} + \nabla_{\hat{x}} \beta \dot{\hat{x}}. \end{aligned}$$

Let

$$\dot{\xi} = F - \nabla_{\hat{y}} \beta \dot{\hat{y}} - \nabla_{\hat{x}} \beta \dot{\hat{x}} + S(y, \xi + \beta)(\xi + \beta) - \nabla_y \beta L(y)(\xi + \beta), \tag{27}$$

where $\dot{\hat{y}}$ and $\dot{\hat{x}}$ are to be defined. Replacing (27) in the equation of $\dot{z}$ above, and invoking properties (ii) and (iii) of Lemma 1, yields

$$\begin{aligned} \dot{z} &= -S(y, \xi + \beta - z)(\xi + \beta - z) + \\ &\quad + S(y, \xi + \beta)(\xi + \beta) - \nabla_y \beta L(y) z \\ &= S(y, x)z + S(y, z)(\xi + \beta) - \nabla_y \beta L(y) z \\ &= S(y, x)z + \bar{S}(y, \xi + \beta)z - \nabla_y \beta L(y) z. \end{aligned} \tag{28}$$

From (28) it is clear that condition (C1) above is satisfied. On the other hand, condition (C2) would be satisfied if we could find a function β that solves the PDE

$$\nabla_y \beta = [k_1 I + \bar{S}(y, \xi + \beta)] L^{-1}(y), \tag{29}$$

with $k_1 > 0$, where $L^{-1}(y) : \mathbb{R}^n \to \mathbb{R}^{n-k\times n}$ is the full rank left inverse of the matrix $L(y)$. Indeed, in this case, the z–dynamics reduce to $\dot{z} = (S - k_1)z$, achieving the desired exponential convergence property. Unfortunately, solving the PDE (29) is a daunting task, and we don't even know if a solution exists. Therefore, in the next step of the design we proceed to "approximate" its *solution*.

Step 2. ("Approximate solution" of the PDE) Define the "ideal $\nabla_y\beta$" as

$$H(y, \xi + \beta) := [k_1 I + \bar{S}(y, \xi + \beta)]L^{-1}(y), \tag{30}$$

and denote the columns of this $n - k \times n$ matrix by $H_i : \mathbb{R}^n \times \mathbb{R}^{n-k} \to \mathbb{R}^{n-k}$ for $i = 1, \ldots, n$, that is,

$$H(y, \xi + \beta) = \left[\, H_1(y, \xi + \beta) \mid \cdots \mid H_n(y, \xi + \beta) \,\right].$$

Now, mimicking [10], define[6]

$$\begin{aligned} \beta(y, \hat{y}, \hat{x}) := \int_0^{y_1} H_1([s, \hat{y}_2, \ldots, \hat{y}_n], \hat{x})ds + \cdots + \\ + \int_0^{y_n} H_n([\hat{y}_1, \ldots, \hat{y}_{n-1}, s], \hat{x})ds. \end{aligned} \tag{31}$$

From the definition of the mapping β, and adding and substracting $H(y, \xi + \beta)$, we have that $\nabla_y\beta$ can be written as

$$\begin{aligned} \nabla_y\beta(y, \hat{y}, \hat{x}) = H(y, \xi + \beta) - \Big\{ H(y, \xi + \beta) - \\ \left[\, H_1(y_1, \hat{y}_2, \ldots, \hat{y}_n, \hat{x}) \; \ldots \; H_n(\hat{y}_1, \ldots, \hat{y}_{n-1}, y_n, \hat{x}) \,\right] \Big\}. \end{aligned}$$

Since the term in brackets is equal to zero if $\hat{y} = y$ and $\hat{x} = \xi + \beta$, and all functions are smooth, there exist mappings $\Delta_y : \mathbb{R}^n \times \mathbb{R}^{n-k} \times \mathbb{R}^n \to \mathbb{R}^{n-k\times n}$, $\Delta_x : \mathbb{R}^n \times \mathbb{R}^{n-k} \times \mathbb{R}^{n-k} \to \mathbb{R}^{n-k\times n}$ such that

$$\nabla_y\beta(y, \hat{y}, \hat{x}) = H(y, \xi + \beta) - \Delta_y(y, \hat{x}, e_y) - \Delta_x(y, \hat{x}, e_x), \tag{32}$$

with

$$e_y := \hat{y} - y, \quad e_x := \hat{x} - (\xi + \beta), \tag{33}$$

and such that

$$\Delta_y(y, \hat{x}, 0) = 0, \quad \Delta_x(y, \hat{x}, 0) = 0, \tag{34}$$

for all $y, \hat{y}, \in \mathbb{R}^n$ and $x, \hat{x} \in \mathbb{R}^{n-k}$.

Replacing (30) and (32) in (28) yields

$$\dot{z} = (S - k_1)z + (\Delta_y + \Delta_x)L(y)z. \tag{35}$$

[6] We attract the readers attention to the particular selection of the arguments used in the integrands. Namely that, with some abuse of notation, the vector $\hat{y}$ has been spelled out into its components.

Recalling that S is skew–symmetric and $k_1 > 0$, it is clear that the mappings Δ_y and Δ_x play the role of disturbances that we will try to dominate with a dynamic scaling in the next step of the design.

Step 3. (Dynamic scaling) Define the scaled off–the–manifold coordinate

$$\eta = \frac{1}{r} z, \tag{36}$$

with r a scaling dynamic factor to be defined below. Differentiating (36), and using (35), yields

$$\begin{aligned}\dot\eta &= \frac{1}{r}\dot z - \frac{\dot r}{r}\eta \\ &= (S - k_1)\eta + (\Delta_y + \Delta_x)L(y)\eta - \frac{\dot r}{r}\eta.\end{aligned}$$

Consider the function

$$V_1(\eta) = \frac{1}{2}|\eta|^2,$$

and note that its time derivative is such that

$$\begin{aligned}\dot V_1 &= -(k_1 + \frac{\dot r}{r})|\eta|^2 - \eta^\top(\Delta_y + \Delta_x)L(y)\eta \\ &\le -\left(\frac{k_1}{2} + \frac{\dot r}{r} - \frac{1}{2k_1}\|[\Delta_y + \Delta_x]L\|^2\right)|\eta|^2 \\ &\le -\left(\frac{k_1}{2} + \frac{\dot r}{r} - \frac{1}{k_1}\left(\|\Delta_y L\|^2 + \|\Delta_x L\|^2\right)\right)|\eta|^2,\end{aligned} \tag{37}$$

where $\|\cdot\|$ is the matrix induced 2—norm and we have applied Young's inequality (with the factor k_1) to get the second bound. Let

$$\dot r = -\frac{k_1}{4}(r-1) + \frac{r}{k_1}\left(\|\Delta_y L\|^2 + \|\Delta_x L\|^2\right), \quad r(0) \ge 1. \tag{38}$$

Notice that the set $\{r \in \mathbb{R} \mid r \ge 1\}$ is invariant for the dynamics (38). Replacing (38) in (37) yields the bounds

$$\begin{aligned}\dot V_1 &\le -\left(\frac{k_1}{2} - \frac{k_1}{4}\frac{r-1}{r}\right)|\eta|^2 \\ &\le -\frac{k_1}{4}|\eta|^2,\end{aligned} \tag{39}$$

where the property $\frac{r-1}{r} \le 1$ has been used to get the second bound. From (39) we conclude that $\eta(t)$ converges to zero exponentially.

Step 4. (High–gain injection) From (36) and the previous analysis it is clear that $z(t) \to$

0 if we can prove that $r \in \mathcal{L}_\infty$, which is the property established in this step. To enhance readability the procedure is divided into two parts. First, we make the function

$$V_2(\eta, e_y, e_x) = V_1(\eta) + \frac{1}{2}(|e_y|^2 + |e_x|^2),$$

a strict Lyapunov function. Then, the derivative of the function

$$V_3(\eta, e_y, e_x, r) = V_2(\eta, e_y, e_x) + \frac{1}{2}r^2, \tag{40}$$

is shown to be non–positive—establishing the desired boundedness of r. In both steps the objectives are achieved adding, via a suitable selection of the observer dynamics, negative quadratic terms in η, e_y, e_x in the Lyapunov function derivative. We recall that e_y and e_x are measurable quantities, defined in (33).

Towards this end, define

$$\dot{\hat{y}} = L(y)(\xi + \beta) - \psi_1(y, r)e_y, \tag{41}$$

with $\psi_1 : \mathbb{R}^n \times \mathbb{R}_+ \to \mathbb{R}_+$ a gain function to be defined. The error dynamics, obtained combining (15) and (41), are

$$\dot{e}_y = Lz - \psi_1 e_y. \tag{42}$$

Now, select

$$\dot{\hat{x}} = F + S(y, \xi + \beta)(\xi + \beta) - \psi_2(y, r)e_x, \tag{43}$$

with $\psi_2 : \mathbb{R}^n \times \mathbb{R}_+ \to \mathbb{R}_+$ a gain function to be defined. Recalling (27) the error dynamics for e_x become

$$\dot{e}_x = \nabla_y \beta L z - \psi_2 e_x. \tag{44}$$

Using (39), (42) and (44) and doing some basic bounding, yields

$$\begin{aligned} \dot{V}_2 \leq & -\frac{k_1}{4}|\eta|^2 + r e_y^\top L\eta - \psi_1 |e_y|^2 + \\ & + r e_x^\top \nabla_y \beta L \eta - \psi_2 |e_x|^2 \qquad (45) \\ \leq & -(\frac{k_1}{4} - 1)|\eta|^2 - \left(\psi_1 - \frac{r^2}{2}\|L\|^2\right)|e_y|^2 - \\ & - \left(\psi_2 - \frac{r^2}{2}\|\nabla_y \beta\|^2 \|L\|^2\right)|e_x|^2. \qquad (46) \end{aligned}$$

Selecting

$$\begin{aligned} \psi_1 &= k_2 + \psi_3 + \frac{r^2}{2}\|L\|^2, \\ \psi_2 &= k_3 + \psi_4 + \frac{r^2}{2}\|\nabla_y \beta\|^2 \|L\|^2, \end{aligned} \tag{47}$$

with $k_2, k_3 > 0$ and $\psi_3, \psi_4 : \mathbb{R}^n \times \mathbb{R}_+ \to \mathbb{R}_+$ to be defined, we conclude that

$$\dot{V}_2 \leq -\frac{1}{2}(k_1 - 2)|\eta|^2 - k_2|e_y|^2 - k_3|e_x|^2,$$

which, selecting $k_1 > 4$, establishes that $\eta, e_y, e_x \in \mathcal{L}_2 \cap \mathcal{L}_\infty$ and the origin of the (non-autonomous) subsystem with state η, e_y, e_x is uniformly globally exponentially stable.

We are now ready for the *coup de grâce*, namely the selection of ψ_3 and ψ_4 to guarantee that $r \in \mathcal{L}_\infty$. For, recall (34), which ensures the existence of mappings $\bar{\Delta}_y : \mathbb{R}^n \times \mathbb{R}^{n-k} \times \mathbb{R}^n \to \mathbb{R}^{n-k \times n}$, $\bar{\Delta}_x : \mathbb{R}^n \times \mathbb{R}^{n-k} \times \mathbb{R}^{n-k} \to \mathbb{R}^{n-k \times n}$ such that

$$\begin{aligned} \|\Delta_y(y, \hat{x}, e_y)\| &\leq \|\bar{\Delta}_y(y, \hat{x}, e_y)\| \; |e_y| \\ \|\Delta_x(y, \hat{x}, e_x)\| &\leq \|\bar{\Delta}_x(y, \hat{x}, e_x)\| \; |e_x|. \end{aligned} \tag{48}$$

Now, evaluate the time derivative of V_3, defined in (40), replace (47) in (46), and use the bounds (48) to get

$$\begin{aligned} \dot{V}_3 \leq -(\frac{k_1}{4} - 1)|\eta|^2 - \left(\psi_3 - \frac{r^2}{k_1}\|\bar{\Delta}_y\|^2\|L\|^2\right)|e_y|^2 - \\ - \left(\psi_4 - \frac{r^2}{k_1}\|\bar{\Delta}_x\|^2\|L\|^2\right)|e_x|^2. \end{aligned}$$

Fixing

$$\begin{aligned} \psi_3 &= \frac{r^2}{k_1}\|\bar{\Delta}_y\|^2\|L\|^2 \\ \psi_4 &= \frac{r^2}{k_1}\|\bar{\Delta}_x\|^2\|L\|^2 \end{aligned}$$

ensures $\dot{V}_3 \leq 0$, which ensures $r \in \mathcal{L}_\infty$.

To prove condition (6) note that equation (39) implies

$$|\eta(t)| \leq |\eta(0)|e^{-\frac{k_1}{8}t},$$

hence

$$|z(t)| \leq \frac{r(t)}{r(0)}|z(0)|e^{-\frac{k_1}{8}t} \leq \sup_{t\geq 0}\{r(t)\}|z(0)|e^{-\frac{k_1}{8}t},$$

which yields the claim, by boundedness of $r(t)$.

The proof is completed defining the state vector of the observer as $\chi = (\hat{x}, \hat{y}, \xi, r)$, obtaining $A(\chi, q, u)$ from (43), (41), (27), and (38), and defining

$$B(y) := \left[T^{-1}(y) \; 0 \; 0 \; 0\right].$$

Remark 5. The four components $\hat{x}$, $\hat{y}$, ξ and r of the state vector of the observer can be given the following interpretation. The component $\hat{x}$ is the estimate of x and a filtered version of $\xi + \beta$. The component $\hat{y}$ is a filtered version of the measured variable y. The ξ-dynamics render the set $z = 0$ invariant, regardeless of the selection of the other dynamics, and ξ can be regarded as the *state* of a reduced order observer [7]. Finally, the r-dynamics are used to trade stability of the nominal design for robustness against the *disturbances* Δ_y and Δ_x.

[7] To clarify this point note that, *ideally*, the PDE (29)should have a solution β which is a function of y alone. In this case the variable ξ would play the role of the state of the (reduced) order observer(see the examples in [8]).

Remark 6. Although the analysis of the performance of the proposed observer in the presence of noise is not within the scope of the paper, it is worth noting the following. The Lyapunov argument establishing uniform asymptotic stability of the zero equilibrium of the (η, e_y, e_x)-subsystem yields robustness againsts small additive perturbations on the measured variables u and y. In the presence of such perturbations the variables e_y and e_x do not converge to zero. Nevertheless, as long as they are sufficiently small, equation (38) can be regarded as describing a linear (non-autonomous) scalar differential equation in which, by equations (34), the coefficient of the linear term is uniformly negative. This ensures boundedness of $r(t)$ for all t.

5 Conclusions

A definite affirmative answer has been given to the question of existence of a globally convergent speed observer for general mechanical systems of the form (1). No assumption is made on the existence of an upperbound for the inertia matrix, hence the result is applicable for robots with prismatic joints. Also, no conditions are imposed on the potential energy function. The only requirement is that the system is forward complete, *i.e.*, that trajectories of the system exist for all times $t \geq 0$—which is a rather weak condition.

In some sense, our contribution should be interpreted more as an existence result than an actual, practically implementable, algorithm. Leaving aside the high complexity of the observer dynamics, that can be easily retraced from the proof of Section 4, the difficulty stems from the fact that the key function β is defined via the integrals (31), whose explicit analytic solution cannot be guaranteed *a priori*. Of course, the (scalar) integrations can always be numerically performed leading to a numerical implementation of the observer. Given the recent spectacular advances in computational technology this does not seem to constitute an unsurmountable difficulty.

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Networked Control of Multiple Marine Vehicles: Theoretical and Practical Challenges in the Scope of the EU GREX Project

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Abstract. This paper overviews some of the theoretical and practical issues that arise in the process of developing advanced motion control systems for cooperative multiple autonomous marine vehicles (AMVs). Many of the problems addressed were formulated in the scope of the EU GREX project, entitled Coordination and Control of Cooperating Heterogeneous Unmanned Systems in Uncertain Environments. The paper offers a concise introduction to the general problem of cooperative motion control that is well rooted in illustrative mission scenarios developed collectively by the GREX partners. This is followed by the description of a general architecture for cooperative autonomous marine vehicle control in the presence of time-varying communication topologies and stringent communication constraints. The results of simulations with the NetMarSyS (Networked Marine Systems Simulator) of ISR/IST are presented and show the efficacy of the algorithms developed for cooperative motion control. The last part of the paper focuses on practical issues and describes the results of a series of tests at sea in the Azores, in the Summer of 2008. The paper concludes with a discussion of theoretical and practical implementation issues that warrant further research and development effort.

1 Introduction

Worldwide, there has been increasing interest in the use of autonomous marine vehicles (AMVs) to execute missions of increasing complexity without direct supervision of human operators. A key enabling element for the execution of such missions is the availability of advance systems for motion control of AMVs. The past few decades have witnessed considerable interest in this area. The problems of motion control can be roughly classified into three groups: *i)* point stabilization, where the goal is to stabilize a vehicle at a given target point with a desired orientation; *ii)* trajectory tracking, where the vehicle is required to track a time parameterized reference, and *iii)* path following, where the vehicle is required to converge to and follow a desired geometric path, without a timing law assigned to it.

Current research goes well beyond single vehicle control. In fact, recently there has been widespread interest in the problem of cooperative motion control of fleets of AMVs. A particular important scenario that motivates the cooperation of multiple autonomous vehicles and poses great challenges to systems engineers, both from a theoretical and practical standpoint, is automatic ocean exploration/monitoring for scientific and commercial purposes. In this scenario, one can immediately identify two main disadvantages of using a single, heavily equipped vehicle: lack of robustness to system failures and inefficiency due to the fact that the vehicle may need to wander significantly to collect data over a large spatial domain. A cooperative group of vehicles connected via a mobile communications network has the potential to overcome these limitations. It can also reconfigure the network in response to environmental parameters in order to increase mission performance and optimize the strategies for detection and measurement of vector/scalar fields and features of particular interest. Furthermore, in a cooperative mission scenario each vehicle may only be required to carry a single sensor (per environmental variable of interest) making each of the vehicles in the formation less complex, thus increasing its reliability.

As an example, Fig. 1.a captures a conceptually simple mission scenario where an autonomous surface craft (ASC) and an autonomous underwater vehicle (AUV) maneuver in synchronism along two spatial paths, while aligning themselves along the same vertical line, so as to fully exploit the good properties of the acoustic communications channel under these conditions. This is in striking contrast to what happens when communications take place at slant range, for this reduces drastically the bandwidth of the channel, especially due to multipath effects in shallow water operations.

Cooperative Autonomous Marine Vehicle Motion Control is one of the core ideas exploited in the scope of the EU GREX project, entitled Coordination and Control of Cooperating Heterogeneous Unmanned Systems in Uncertain Environments, see [1]. Both theoretical and practical issues are addressed in the scope of the project. It is worth to stress that from a theoretical standpoint, the coordination of autonomous robotic vehicles involves the design of distributed control laws in the face of disrupted inter-vehicle communications, uncertainty, and imperfect or partial measurements. This is particular significant in the case of underwater vehicles. It was only recently that these subjects have started to be tackled formally, and considerable research remains to be done to derive multiple vehicle control laws that can yield good performance in the presence of severe communication constraints. For previous work along these lines, the reader is referred to [3], [4], [14], [17], [18], [19], [22], [30], [31], [32], [34].

The structure of the paper is as follows. In section 2 we give the practical motivation for the problem of cooperative multiple vehicle control with the help of a representative scientific mission scenario that emerged naturally in the scope of the EU Project GREX. Section 3 describes a general architecture for cooperative autonomous marine vehicle control in the presence of time-varying communication topologies and communication losses. Section 4 contains the results of computer simulations aimed at assessing the efficacy of the algorithms developed for cooperative motion control. Section 5 contains experimental results. Finally, Section 6 summarizes the main re

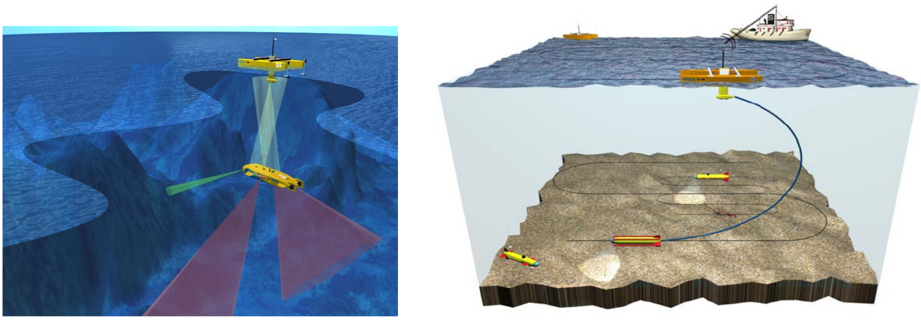

Fig. 1. a) Cooperative control of two (surface and underwater) autonomous marine vehicles for data gathering at sea; b) Marine habitat mapping scenario.

sults obtained and discusses briefly issues that warrant further research and development work.

2 Practical Motivation and Scientific Mission Scenarios

In what follows we describe one of a large number of mission scenarios that have been discussed and defined in detail by the GREX partner group. The mission scenarios envisioned are rooted in challenging problems in the field of marine science. They also bring out the ever increasing important role that marine technology is having in terms of affording marine scientists the tools that are needed to explore and exploit the ocean. We place the focus on missions for which two basic ingredients are required: i) the missions require the use of several intelligent autonomous vehicles equipped with appropriate instrumentation, and ii) inter-vehicle coordination and mission control is dynamic and highly dependent on the type of information obtained as the missions unfold.

Mission Scenario: Marine Habitat Mapping

Habitat maps of the marine environment, that is, maps containing data on the bathymetry and nature of the seabed as well as on the type and localization of biological species, are the key to an in-depth understanding of the distribution and extent of marine habitats. Knowledge of the distribution of marine habitats serves to establish sensible approaches to the conservation needs of each habitat and to facilitate a better management of the marine environment through an understanding of how particular human activities are undertaken in relation to marine habitats. This will in turn allow for the establishment of policies capable of ensuring sustainable development. This subject is receiving widespread attention worldwide because of its far reaching implications and has led to the definition of a number of guidelines and directives for the study and preservation of marine habitats. At an European level, for example, Annex I of the celebrated EU Habitats Directive establishes that marine habitats classified as Special Areas of Conservation (Natura 2000) need special assessment in order to verify their accordance with the European Union requirements. The mission scenario for marine habitat mapping proposed here was greatly influenced by and aims to automate and improve classical procedures that are normally used by marine scientists. The key ideas can be explained by referring to Fig. 1.b). For simplicity of exposition, we start by focusing on the ASV/ROV ensemble in the figure, where the ROV is connected to the ASV through a thin umbilical for fast data transmission.

In this scenario, the ASV executes a lawn mowing manoeuvre above the seabed automatically, while the ROV executes a similar manoeuvre in cooperation with the ASV. Using this set-up, the ROV transmits pictures of the seabed back to the support ship (and thus to the scientist in charge) via a radio link installed on-board the ASV. A number of AUVs stay dormant either on the seabed or at the sea surface. Upon detection of interesting patterns on the seabed by the scientist in charge, a signal is sent to a selected member of the AUV fleet (via an acoustic communication link installed on-board the ASV), to dispatch it to the spot detected so as to map the surrounding region in great detail. Meanwhile, the ASV/ROV ensemble continues to execute the lawn mowing manoeuvre in search of other sites of interest. With the methodology proposed, sites that are interesting from an ecological viewpoint are easily detected along the transects.

To execute the abovementioned challenging missions, a number of autonomous vehicles must work in cooperation, under high level human supervision. This entails the development of advanced systems for cooperative motion control and navigation in the presence of severe underwater communication constraints, together with the respective software and hardware architectures.

3 A General Architecture for Multiple Vehicle Cooperation

This section describes a very general architecture for multiple vehicle cooperative motion control that has emerged naturally out of a research effort in which the authors have been participating. The section further describes key single and multiple vehicle motion control primitives that were judged appropriate for practical implementation of the architecture developed on a set of multiple heterogeneous vehicles, in the scope of the GREX project.

3.1 Multiple Vehicle Cooperative Motion Control

The systems that are at the root of the architecture adopted for multiple vehicle cooperation are depicted in Fig. 2. See [3] for a fast paced introduction to the subject. The scheme depicted is quite general and captures basic trends in current research.

Each vehicle is equipped with a *navigation* and *control* system that uses local information as well as information provided by a subset of the other vehicles over the communication network, so as to make the vehicle manoeuver in cooperation with the whole formation. *Navigation* is in charge of computing the vehicle's state (e.g. position and velocity). Control accepts references for selected variables, together with the corresponding navigation data, and computes actuator commands so as to drive tracking errors to zero. The cooperation strategy block is responsible for implementing *cooperative navigation and control.* Its role is twofold: *i)* for *control* purposes, it issues high level synchronization commands to the local vehicle based on information available over the network (e.g. speed commands to achieve synchronization of a number of vehicles executing path following maneuvers); *ii)* For *navigation* purposes, it merges local navigation data acquired with the vehicle itself as well as by a subset of the other vehicles. This is especially relevant in situations where only some of the vehicle can carry accurate navigation suites, whereas the others must rely on less precise sensor suites, complemented with information that is exchanged over the network. Finally, the system named *logic-based communications* is responsible for supervising the flow of information (to and from a subset of the other vehicles), which we assume is asynchronous, occurs on a discrete-time basis, has latency, and is subject to transmission failures.

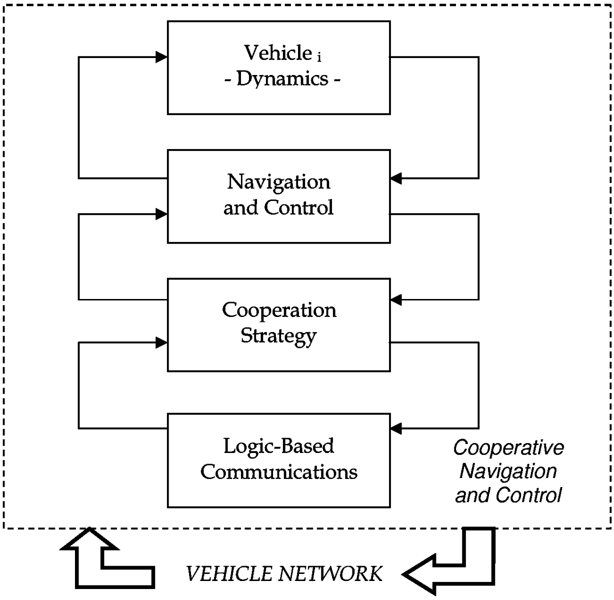

Fig. 2. A general architecture for multiple vehicle cooperation.

Central to the above scheme is the fact that each vehicle can only exchange information with a subset of the remaining group of vehicles. Furthermore, and because of the intrinsic nature of the underwater communications channel, communications should be parsimonious and take place at a very low data rate. This calls for the implementation of systems to decide when and what minimum information should be transmitted from each of the vehicles to its neighbours. Interestingly enough, analogous constraints appear in the vibrant area of networked control systems, from which interesting and fruitful techniques can be borrowed.

Close inspection of the general architecture for multiple vehicle cooperation described above reveals the plethora of problems to be solved:

- Cooperative Control (CC) (e.g. cooperative path following and cooperative trajectory tracking),
- Cooperative Navigation (CN),
- CC and CN under strict communication constraints over a faulty, possibly

switched network.

In the scope of the GREX project, considerable work was done to advance design tools to tackle the above problems. For a description of key technical aspects involved in the development of advanced schemes for single and multiple vehicle control, the reader is referred to [2], [3], [4], [6], [7], [8], [10], [11], [12], [17], [18], [19], [20], [33], [34], [35]. See also [13], [14], [15], [22], [23], [25], [26], [28], [29], [30], [31], [32], [36], and the references therein for an overview of the state of progress in the area.

The results obtained so far hold potential for application. To the best of our knowledge, some of the work reported is pioneering in that it effectively addresses explicitly time-varying communication networks with temporary failures and latency in the transmissions, and logic-based communications aimed at reducing the amount of discrete-time data to be transmitted among the vehicles. The results obtained were instrumental in defining, together with the GREX partners, a library of Single and Multiple Vehicle Primitives (MVPs) for motion control that are described in the next section.

3.2 Single and Multiple Vehicle Primitives

The work envisioned in the scope of the GREX project aims at affording system designers the tools to develop, using a "bottom-up" approach, the modules that are needed to implement a true Multi Vehicle Mission Control System for a fleet of autonomous vehicles.

Based on the mission scenarios and the general architecture for multiple vehicle cooperation described in the previous sections, a set of Multiple Vehicle Primitives (MVPs) for coordinated motion control were developed. The definition of the primitives and the algorithms for their implementation take into account the fact that the vehicles considered have complex dynamics, exhibit large parameter uncertainty, are often underactuated, and must perform well in the presence of unknown, shifting ocean currents. During the first part of the project, the attention was focused on the development of primitives enabling the following tasks:

- Point Stabilization, Path Following, and Trajectory Tracking of single marine vehicles with complex dynamics.
- Path Planning for multiple vehicles.
- Cooperative Path Following of multiple vehicles.
- Cooperative Target Following and Cooperative Target Tracking of multiple vehicles.
- Cooperative Manoeuvring in the presence of tight communication constraints by exploiting recent research results on Networked Control Systems.
- All of the above in the presence of sensor and actuator faults.

In what follows we provide a brief description of each of the tasks listed above and point out relevant bibliography that describes the motion control algorithm solutions developed by the ISR/IST team.

Point Stabilization (also referred to as *Go to Point*) refers to the problem of steering a vehicle to a point with a desired orientation (in the absence of currents), or simply to a desired point without a desired orientation (in the presence of currents). The algorithms derived are reported in [4] and [6].

Path Following. In this task, the objective is to steer a vehicle towards a path and make it follow that path with an assigned speed profile. Notice that there are no explicit temporal specifications, that is, the vehicle is not required to be a certain point at a desired time. Rather, what is relevant is for the vehicle to traverse the path, albeit with a speed that may be path dependent. Algorithms are reported in [2], [17], [33], and [34].

Trajectory Tracking. In contrast with the Path Following objectives, what is now required is that the vehicle track a desired temporal/spatial trajectory. Timing constraints become important for this task. In practice, trajectory tracking systems are harder to design (when compared with Path Following systems) and may yield "jerky" maneuvers and large actuator activity. This is because of tight temporal constraints; see [5] and [9]. In this respect, Path Following strategies usually lead to more benign maneuvers. However, there are instances in which one is forced to adopt trajectory tracking strategies (for example, when one wishes to investigate a phenomenon that is strongly time-dependent). Algorithms are summarized in [2].

Path Planning for Multiple Vehicles. Multiple vehicle path planning methods build necessarily on key concepts and algorithms for single vehicle path following. However, they go one step further in that they must explicitly take into account such issues as inter-vehicle collision avoidance and simultaneous times of arrival. See [21] and the references therein.

The literature on path planning is vast and the methodologies used are quite diverse. Classical methodologies aim at computing feasible strategies off-line that minimize a chosen cost criterion. More recently, new methodologies have come to the forum where the objective is to generate paths on-line, in response to environmental data, so as to optimize the process of data acquisition over a selected area. In the scope of GREX we focused on the problem that arises when multiple vehicles are scattered in the water and it is required that they safely reach the starting location of a cooperative mission with a desired formation pattern and assigned terminal speeds (Go-To-Formation manoeuver). The cost criteria of interest may include minimizing travel time or energy expenditure. The key objective was to obtain path planning methods that are effective, computationally easy to implement, and lend themselves to real-time applications.

The techniques that we developed for multiple vehicle path planning are based upon and extend the work reported in [24] for unmanned air vehicles. See [20] and [21] for recent work on the subject, with applications to autonomous marine vehicles. Explained in intuitive terms, the key idea exploited is to separate spatial and temporal specifications, effectively decoupling the process of spatial path computation from that of computing the desired speed profiles for the vehicles along those paths. The first step yields the vehicles' spatial profiles and takes into consideration geometrical constraints; the second addresses time related requirements that may include, among others, initial and final speeds, deconfliction in time, and simultaneous times of arrival. Decoupling the spatial and temporal constraints can be done by parameterizing each path as a set of polynomials in terms of a generic variable τ and introducing a polynomial function $\eta(\tau)$ that specifies the rate of evolution of τ with time, that is, $d\tau/dt = \eta(\tau)$. By restricting the polynomials to be of low degree, the number of parameters used during the computation of the optimal paths is kept to a minimum. Once the order of the polynomial parameterizations has been decided, it becomes possible to solve the multiple vehicle optimization problem of interest (e.g., simultaneous time of arrival under specified deconfliction and energy expenditure constraints) by resorting to any proven direct search method; see [27].

Cooperative Path Following. In this case, a fleet of vehicles is required to track a series of pre-defined spatial paths, while holding a desired formation pattern at a desired "formation speed". The implementation of the corresponding MVP calls for the execution of a path following algorithm for each of the vehicles, together with a synchronization algorithm that changes the nominal speeds of the vehicles so as to achieve the desired temporal synchronism. The algorithms used are described in [3], [7], [10], [11], [17], [18], [19], and [34] and take into account explicitly the topology of the inter-vehicle communication network.

Cooperative Target Following (CTF) and Cooperative Target Tracking (CTT). The CTF and CTT tasks enable a group of vehicles to follow (in space) and track (in space and time) a moving target, respectively. The CTF refers to the situation where the group of vehicles follows the path traversed by the target, without stringent temporal constraints. This is done by "observing" the target motion, extracting from it a spatial reference path, and following it. No further objective is attempted, and the distance between the group of vehicles and the target is left uncontrolled. As an example, we cite the situation where a manned vessel leads ("shows the way" to) a group of marine craft through a harbour area where obstacles are present. By observing the motion of the manned vessel, the group of vehicles learns a safe path across the harbour and follows it accurately ("doing by imitation"). The CTT is similar to CFT, except that it is now required for the group of vehicles to maintain a desired along-path distance from the target. Instead of traversing the path defined by the target "at leisure", the group of vehicles is required to adjust its overall speed so as to keep a desired distance to the target. These two problems are far from trivial in the case when the trajectory to be tracked is not available apriori, but is instead defined implicitly by the unknown motion of a target vehicle. Interestingly, enough, both problems can be solved by converting them into an equivalent path following problem. This is done by having at least one vehicle in the formation "observe the motion" of the target and fit a parameterized path to it over a short, receding time window. The parameters of the consecutive segments of paths thus obtained are then broadcast to the other vehicles, and a coordinated path following algorithm executed.

Cooperative Manoeuvring in the Presence of Tight Communication Constraints. This task refers to the problem of developing MVPs for Cooperative Path Following and Cooperative Target Following and Target Tracking in the presence of varying communication topologies, communication losses, and delays. The latter is especially relevant in view of the small speed of propagation of sound in the water. Solutions are proposed in [3], [18], and [19]. In [3], the solutions address explicitly the fact that underwater communications occur at discrete intervals of time, thus reducing drastically the frequencies at which the vehicles communicate. As far as we could ascertain, previous work along these lines is not available in the literature for multiple underwater vehicle control. The new solution adopted borrows from related work in networked control and holds potential for further refinement aimed at striking an adequate balance between performance and energy spent to communicate.

4 Simulation Results

In this section we show results of simulations that illustrate the performance that can be achieved with the motion control algorithms mentioned before. The simulations were done using the Networked Marine Systems Simulator (*NetMarsyS*), a software suite developed at ISR/IST in the scope of GREX to simulate different types of cooperative missions involving a variable number of heterogeneous marine craft, each with its own dynamics, see [35]. The high level of detail with which the environment can be modeled affords end-users the tools that are necessary to take into account both the effect of water currents on the vehicle dynamics as well as the delays and environmental noise that affect underwater communications. The simulation kernel developed so far paves the way for future developments aiming at incorporating more sophisticated acoustic communication models and communication protocols, together with interfaces to allow seamless distributed software and hardware-in-the-loop simulation.

The *NetMarsyS* interface is divided into four main areas: mission environment, mission specifications, vehicles, and output interface. The mission environment area includes three different menus: water current, coordination strategy (which defines the inter-vehicle communication topology), and communication channel. The mission specifications area includes a list of possible missions to be executed, e.g. Cooperative Path Following and Cooperative Target Tracking. The area devoted to vehicles contains a file with a number of different vehicle blocks (kinematics and dynamics). Here, the user can choose the number and the type of vehicles in the formation. Finally, an output interface enables the visualization of mission results and the creation of videos from the simulations.

The simulator has been instrumental in evaluating the efficacy of selected algorithms for motion control of marine vehicles. By incorporating blocks that emulate the actual software code that is implemented on-board the different vehicles, the simulator has also been a valuable tool to evaluate the software for the implementation of MVPs, and in fact has played a key role in the preparation for the first series of field tests in the Azores, in the Summer of 2008.

An illustrative 3D example

We now illustrate the application of the results in [3] to coordinate three AUVs moving in three-dimensional space.

The AUVs are required to follow paths of the form $p_{di}(\gamma_i)=[c_i \cos(2\pi/T\gamma_i+\phi_d),\ c_i \sin(2\pi/T\ \gamma_i+\phi_d),\ d\ \gamma_i\ ]$, with $c_1 = 20m$, $c_2 = 15m$, $c_3 = 25m$, $d = 0.05m$, $T=400$, and $\phi_d = -3\pi/4$. The initial positions are $p_1 = (10m, -15m, -5m)$, $p_2 = (5m, 0m, 0m)$, $p_3 = (20m, -25m, 5m)$. The vehicles start at rest and the normalized reference speed was set

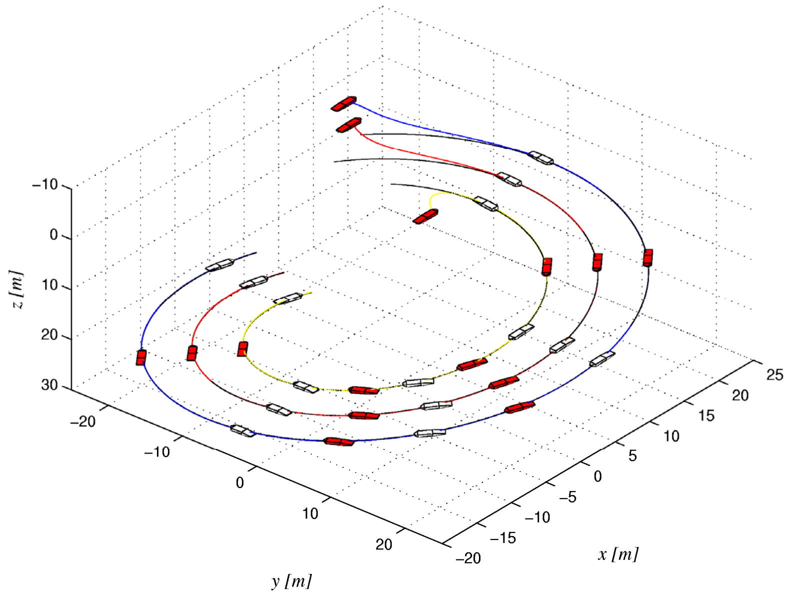

Fig. 3. Coordinated path-following of 3 AUVs, with logic-based communication.

to v_r = *1m/s.* The vehicles are also required to keep a formation pattern that consists of having them aligned along a straight line in the plane. Furthermore, AUV 1 is allowed to communicate with AUVs 2 and 3, but the latter two do not communicate between themselves directly. To further illustrate the behaviour of the proposed co-operative path-following control architecture, we also force the following scenario: from *t=150s to t=250s*, AUV 1 is only capable of following its path with $d\gamma_1/dt = 0.5$. Fig. 3 shows the trajectories of the AUVs and Fig. 4 the evolution of the overall path-following error $\Sigma | p_i - p_{di} |$, coordination error $|\gamma_1-\gamma_2| + |\gamma_1-\gamma_3|$, and the communication signal σ. The signal $\sigma \in \{0,1\}$ indicates, by switching its value, when communications occur. Before *t=150s*, the vehicles adjust their speeds to meet the formation requirements and the coordination errors converge to zero. Note the reduced number of communications exchanged during that period. In fact, the vehicles only need to communicate a few times during the transient phase. When AUV 1 is forced to slow down from $t \in [150, 250]$ (without transmitting explicitly to its neighborhoods its new reference velocity), the communication rate increases in order to keep the coordination error bounded.

5 Experimental Results

In July 2008 the first series of GREX field tests took place at Horta, Faial, in the archipelago of the Azores. The tests were instrumental in bringing together the different partners to perform hardware and software integration and paved the way for full development of the tools that are needed for multiple vehicle cooperative control and navigation.

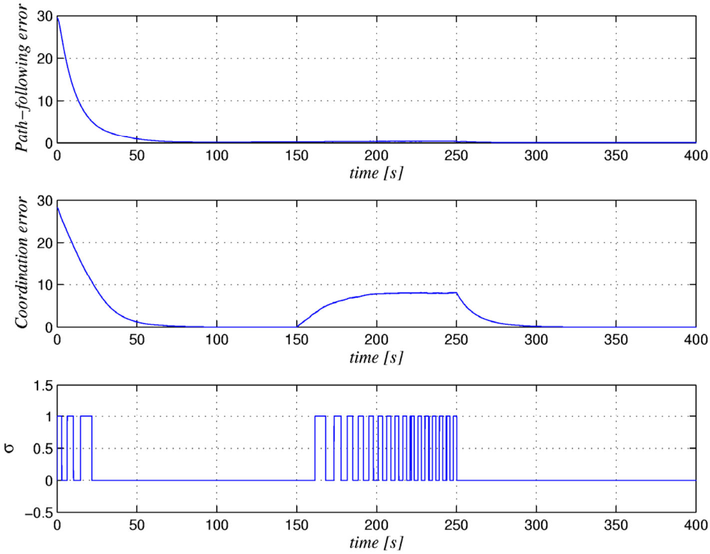

Fig. 4. Path-following error, coordination error, and communication signal σ.

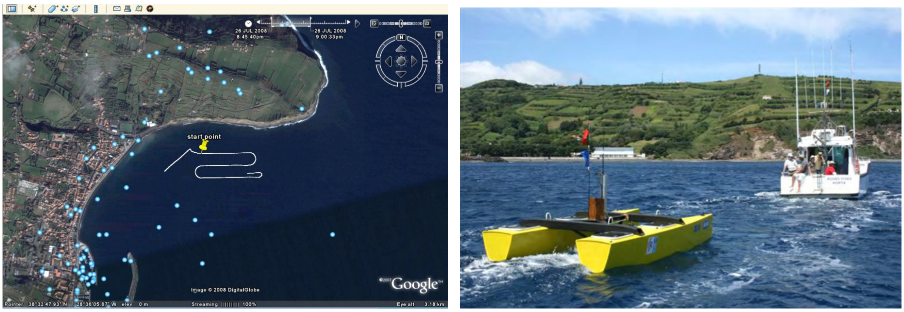

Fig. 5. a) Results of the first GREX mission at sea with the DELFIMx: Going-to and Following a Lawn-Mowing Maneuver; **b)** The DELFIMx ASV (left) and the manned vessel Aguas Vivas.

It was early decided that one of the tests would involve two surface vehicles undergoing joint motion: the Aguas Vivas manned vessel and the DELFIMx autonomous surface vehicle equipped with a dedicated GREX computer, both shown in Fig. 5.b. The DELFIMx is an autonomous surface craft that was designed and built at the Instituto Superior Tecnico, Lisbon, Portugal. It is a small Catamaran *4.5m* long and *2.4m* wide, with a mass of *380kg*. Propulsion is ensured by three-bladed propellers driven by electrical motors. The maximum speed of the vehicle with respect to the water is *3.0m/s*. The vehicle is equipped with on-board resident systems for navigation, guidance and control, and mission control. Navigation is done by integrating motion sensor data obtained from an attitude reference unit, a Doppler Log unit, and a DGPS (Differential Global Positioning System). Transmissions between the vehicle and its support vessel, or between the vehicle and a control center installed on-shore are achieved via a radio link with a range of 10km. The vehicle has a wing shaped central structure that is lowered during operations at sea. Installed at the bottom of this structure is a low drag body that can carry acoustic transducers, including those used to communicate with submerged craft.

Two vehicles primitives were executed with success: Path Following (PF) and Target Following (TF). Fig. 5.a shows a lawnmowing PF maneuver executed by DELFIMx. To test the Target Following primitive, the AGUAS VIVAS manned vessel underwent arbitrary motion at sea while transmitting its GPS position to DELFIMx, see Fig. 5.b. Based on the GPS information received, DELFIMx identified online, using a path fitting algorithm, the path segments traversed by Aguas Vivas (line segments or segments of arcs identified over short receding time windows) and followed these paths at a set speed by invoking repeatedly the PF primitive. As a consequence, DELFIMx maneuvered well along the overall path "defined by" Aguas Vivas, not known a priori. The results of this maneuver are shown in Fig. 6. The tests proved extremely important in evaluating the performance of the algorithms developed for path following and target following, the aerial communication channel between Aguas Vivas and DELFIMx, and the efficacy of the software/hardware architecture adopted within the project, namely that of the GREX computer installed onboard the DELFIMx.

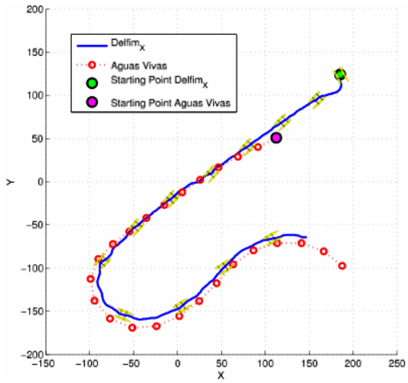

Fig. 6. Experimental results of the DELFIMx performing a target following maneuver in the Azores, PT.

6 Conclusions and Future Work

This paper gave a brief overview of some of the theoretical and practical issues that arise in the process of developing advanced motion control systems for cooperative multiple autonomous marine vehicles (AMVs). Many of the problems addressed were motivated by challenging scientific mission scenarios defined in the course of the EU GREX project, entitled Coordination and Control of Cooperating Heterogeneous Unmanned Systems in Uncertain Environments. A general architecture for cooperative autonomous marine vehicle control in the presence of time-varying communication topologies and communication losses was proposed. The architecture implementation relies on a number of Single and Multiple Vehicle Primitives, the development of which was rooted in solid control theory. The algorithms developed were fully tested in simulation using the NetMarSyS - Networked Marine Systems Simulator - developed by ISR/IST. The same simulator was used to do hardware in the loop simulations prior to tests at sea, in the Azores, in the Summer of 2008. The field tests were instrumental in evaluating the performance of the algorithms developed for path following and target following, the aerial communication channel between Aguas Vivas and DELFIMx, and the efficacy of the software/hardware architecture adopted by the project team.

Future work will address the testing of other Multiple Vehicles Primitives (including Go-To-Formation and Cooperative Target Tracking) and the definition of a final set of integrated tests at sea, followed by their execution in the Azores in the Fall of 2009. From a theoretical standpoint, two main lines of research are envisioned: i) cooperative navigation exploiting non-conventional geophysical-based navigation systems, and ii) in-depth study of the constraints imposed by the underwater channel and underwater communication protocols.

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Wireless Sensor Networks: Standards and Driving Forces

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Abstract. The paper will provide a state-of-the-art report of Wireless Sensor Networking technologies, including ZigBee, WirelessHART, LowPower Bluetooth and others. The main advantages and drawbacks of these technologies will be described, focusing on application-driven requirements. Special focus will be put on standardization activities in the areas of WSN design itself, as well as domain-specific WSN-related standards (Energy, Industry, Healthcare and Environmental). A review of application frameworks will also be provided, including OS-level platforms (TinyOS, Contiki OS).

1 Introduction

Following a period of relative stagnation, Wireless Sensor Networks now enjoy time of rapid growth, facilitated by renewed interest in conservative resource consumption and increasing usage of service infrastructures. Applications of WSN adopted now in many areas, including Energy, Industry, Healthcare, Environmental Monitoring and others. Among numerous advantages, provided by Wireless Sensor Networks, a special emphasis can be put on possibility to create systems, optimized for environment and thus consuming less of resources, easily deployable and offering non-intrusive behavioral characteristics.

Introduction of WSN into the real life applications is following a number of trends, including industrial efforts for standardization of technologies, governmental activities to promote certain application scenarios, scientific research in the areas of technological platforms for WSN (including radio data transmission, communication network architectures and protocols, energy harvesting techniques, etc.). In this paper, we will try to sketch a global picture of WSN technologies and applications from a point of view of industrial adopters.

2 Communication Technologies

Wireless Sensor Network communication technologies include results of research and development activities in the areas of radio communication, networking protocols, software architectures and platforms. Development and standardization of WSN is driven by several communities, including:

1. Internet community

2. Industrial associations
3. Technology groups

Often, standards development is going in similar directions and some standards overlap significantly in purpose and/or approach to implementation. Therefore knowledge of existing WSN options, taking into account technical and marketing aspects, is essential to select the right approach for a project or product.

2.1 IEEE 802.15.4

IEEE 802.15.4 is one of the most promising standards for Wireless Personal Area Networks (WPAN). It is available since 2003 and serves as a basis for several higher level protocols, including ZigBee, WirelessHART and 6LoWPAN. IEEE 802.15.4 [1] defines physical and MAC layers (including security) and supports star and peer-to-peer topologies. Data transfer rate is up to 250 kb/s. Supported bands and modulations are changing depending on a standard version (2003, 2006 and 2007 versions available), but the most common is 2.4 GHz band with 16 channels. IEEE 802.15.4 can be used “as is” only for very simple applications].

2.2 6LoWPAN

IPv6 over Low power WPAN (6LoWPAN) is IETF working group, aiming to bring IP networks (IPv6) and sensor networks together. The problem with integration of IP and sensor networks is in significant overhead of IP protocol headers, which are not suitable for IEEE 802.15.4 networks (with 127 bytes data frame). 6LoWPAN WG has completed IETF RFC 4944 [2], defining a way for transmission of IPv6 packets over IEEE 802.15.4 networks, basically using stateless headers compression. Usage of IP is promoted by IP for Smart Objects (IPSO) Alliance as a native way for integration of sensor networks and smart objects with existing IT infrastructure.

2.3 ZigBee

ZigBee Allience is an industrial association, developing and promoting ZigBee protocol standard [3]. ZigBee protocol is a layer above IEEE 802.15.4, which provides networking layer with support for different architectures, including star, tree and most interesting – mesh topology. ZigBee specification is a mature one, first version released in 2004 and used by some commercial products. Special focus of the Alliance is on application level standardization, i.e. definition of standard interfaces for different application domains, including Home Automation, Smart Energy, Building Automation, Health Care and others.

2.4 Wireless HART

HART is an industrial protocol for communication between field instrumentation and host systems. Wireless HART is a part of HART 7 Specification [4], and as ZigBee, provides extension over IEEE 802.15.4 layers with industrial specifics, such as necessity for real-time operations. It defines communication network structure and necessary components, such as Network Manager. Wireless HART uses channel hopping TDMA protocol with 10 ms communication slots. HART specification includes also application level elements, such as definition for formats of diagnostic information, which are applicable for Wireless HART devices also.

2.5 ISA100

ISA100 Wireless Compliance Institute aims to define a complete set of industrial wireless standards. One of these standards, ISA100.11a [5], is covering wireless process control applications. From the maturity point of view, it is rather new (2008) and very similar to Wireless HART from the technical perspective. This is also based on IEEE 802.15.4-2006, uses channel hopping to increase robustness and provides star topology for better response time and mesh topology for reliable communication. Very interesting particularity of this standard is that it provides inter-networking routing and frame format in accordance to IETF RFC 4944. Special attention is also paid to interoperability with other families of standards (ZigBee, Wireless HART, etc.).

2.6 Bluetooth Low Energy

Development of Bluetooth Low Energy is currently ongoing and specification is planned in the beginning of 2009. It is based on Nokia Webree and targeted to similar applications as IEEE 802.15.4; advantage of Bluetooth Low Energy is availability and cost of radio hardware (existing Bluetooth radios can be used in many cases). However, applicability of this standard is limited to consumer devices, i.e. industrial scenarios are not covered.

2.7 Other Solutions

There are many other solutions exist on a market, most of them proprietary and targeted to certain specific applications. The list includes, but not limited to Z-Wave (the main competitor to ZigBee), KNX RF, EnOcean and others. Often development of particular technology is driven mostly by one company, and this makes investments into this technology rather risky.

3 Wireless Sensor Platforms

Wiireless Sensor Platforms are hardware/software solutions to enable development of WSN applications. These solutions usually have very special architecture due to application requirements, i.e. include very low-power hardware (this means low performance and small amount of memory) and low overhead software components, including OS, drivers, protocol stacks, application services, etc. Usually, platforms are centered around particular operating system, which is adopted for WSN needs.

3.1 TinyOS

TinyOS is an open source component-based operating system, designed for embedded Wireless Sensor Networks. TinyOS is written on nesC, a dialect of C designed for sensor applications with limited resources. Due to openness, portability and component architecture, TinyOS used in many projects and some ZigBee stack implementations use it as an underlying platform. However, TinyOS networking model is not standard and without usage of some common protocol is more suited for research activities, rather then industrial applications. Another limiting factor is usage of nesC language – with all simplicity it is a new programming language to learn by developer.

3.2 Contiki OS

Contiki OS is another open source embedded platform for WSN applications. It is implemented in C and similar to TinyOS, provides a broad spectrum of supported hardware architectures, system modules and user tools. Very interesting particularity of Contiki is IP networking stack, which actually led to IETF standard development and IPSO Alliance creation. Contiki also used by Freaklabs FreakZ open source ZigBee stack implementation project, so it has potential to cover both most perspective WSN networking directions.

3.3 Linux

Linux is traditionally considered as a backbone for a modern networking infrastructure. In our days it is not only adopted in server equipment, but also used in network appliances, such as routers, media streaming centers, etc. In the same time it is selected by some manufacturers as a platform for mobile handsets. From author point of view, this makes Linux an ideal platform for gateways between wireless sensor networks and traditional network infrastructures, including computer and mobile networks. The main blocking factor is the absence of proven implementations of WSN protocols for Linux operating system. However, this situation is being changed by Linux-ZigBee SourceForge.net project, which aims to develop a ZigBee (and more generally – LoWPAN) protocols stack for Linux kernel.

4 Application Domains

Adoption of Wireless Sensor Network technologies is driven by application requirements. There are some "natural" areas where need in WSN obvious – for example home automation, environmental monitoring or tracking applications. Other applications are "triggered" by specific governmental actions; a good example here is smart metering technology.

4.1 Energy (Metering)

Advanced Metering is a very hot topic in US and Europe, due to governmental plans to update electricity grid and facilitate energy saving technologies. Electricity metering, is not connected directly to WSN topic, however there is a synergy with home automation, which could bring significant benefits by enabling smart meters to communicate with in-house smart appliances, for example to schedule or control energy consumption. This was understood by ZigBee Alliance and triggered development of Smart Energy profile. However, state-level standards for metering are not yet developed, so it is not clear if WSN will be adopted at the end as an enabler technology for Advanced Metering Infrastructures.

4.2 Industry (Manufacturing)

Wireless technologies in industrial automation are adopted rather slowly due to significant products lifecycle and conservative approach to engineering. This area has many specific requirements for reliability and real-time operation; main standardization activities are done by International Society of Automation. However advantages of WSN for industry are so significant, that 2 of most mature WSN standards (Wireless HART and ISA100.11a) are targeting industrial process control applications.

4.3 Health Care

In healthcare industry, most of the advantages of Wireless Sensor Networks are usually connected to "personalized healthcare" concept. Development of standards in this area is mostly driven by Continua Health Alliance, defining technologies and interoperability requirements for the industry. There are specific requirements for healthcare applications, mostly in the area of security and reliability of operation. However from technology point of view, mostly common approaches and standards are adopted, for example careful attention is paid to possibility of mobile technology integration with healthcare services, and this means usage of Bluetooth (at the time of writing, evaluation and selection of wireless technology by Continua was still in progress).

4.4 Environmental Monitoring

This is a native application of Wireless Sensor Networks and it has a lot of attention from research community. However, there are no significant moves to define common standards in this area, probably due to significant diversity of possible use cases. For example, wireless sensor networks are adopted for pipeline infrastructures monitoring, dikes, bridges and pollution control.

5 Conclusions

Wireless Sensor Networks standardization process is rapidly progressing, driven by introduction of new application scenarios, market forces and governmental regulation activities. The number of already published standards, often for similar (or same) applications, raises concern for interoperability of different networking technologies. Usage of common platforms for networking infrastructure may help to overcome this potential problem and help to create single world wide “Internet of Things”.

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