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Research and Achievements in Real-Time and Embedded Systems, Intelligent Sensor Networks and Robotic Environments

Habilitation Thesis
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Contents

Abstract

This Habilitation Thesis presents some of the most important results of my post doctoral research activity, which has been carried on since 2005 at the Department of Computer and Software Engineering, Politehnica University of Timisoara.

A synopsis of my overall scientific and professional achievements is presented in the first chapter. During over 17 years of academic and research activity, I have gained a rich expertise in the following fields of interest: *real-time and embedded hardware/software systems, digital measurement and instrumentation, digital signal processing and multimedia, wireless sensor networks, digital telecommunication systems, collaborative robotic environments, and energy-efficiency and power management mechanisms*.

In these fields, I *published over 89 scientific works*, out of which, 8 articles appeared in high ranked journals indexed by the Thomson ISI database with impact factors, 20 papers in ISI-indexed proceedings of international conferences, and 22 works are indexed in other international scientific databases. The ISI-indexed papers cumulate a *total impact factor of 11.978*. The published works are *cited by more than 62 papers* published by other authors, out of which 28 are ISI-indexed.

I have also been actively involved in *more than 40 research and development projects and programs*, as director (13), manager (7) or team member. As project/program director or manager, I have been in charge of executing a *total value of over 0.8 Mil. EUR*.

My professional activity has been recognized by the academic and scientific community through several awards, distinctions and prizes, such as the *Eminent Young Researcher of Timisoara Prize and Medal*, from the National Authority for Scientific Research (ANCS), Romania, the *Eminent Researcher Prize*, from the Orizonturi Universitare Association, Timisoara, and *a total of 8 prizes*, won at 11 editions of the International Computers Contest for Students, "Hard&Soft" Suceava, as coach or advisor of the teams of students.

In Chapter 2, some of my most relevant post doctoral contributions to the field of *real-time and embedded systems* are presented. The first part describes a *full framework for inter-task communication and synchronization* on the HARETICK hard real-time operating kernel. The proposed mechanisms, including the persistent data structures for hard real-time task output parameters and guarded buffers for hard- to soft- real-time data exchange, provide a highly predictable, feasible and efficient inter-task communication support. Another research focus in this area has been to increase the scheduling performance (acceptance ratio) and flexibility of real-time embedded platforms, while preserving maximum execution predictability. As a solution, we proposed and validated the *H^2RTS hybrid hard real-time scheduling mechanism*. It combines the high predictability of a non-preemptive cyclic scheduler with the efficiency of a modified version of the Earliest Deadline First algorithm.

Advances and results, obtained by our research team in the field of *intelligent sensor networks*, are described in Chapter 3. The *CORE-TX* (*Collaborative Robotic*

Environments – The Timisoara Experiment) platform has been designed and implemented at prototype level, for the study and development of real-time systems, distributed artificial perception applications, intelligent sensor networks and collaborative robotic environments. The *PARSECS* (*Predictable ARchitecture for Sensor Communication Systems*) data communication system has been specifically designed and implemented to sustain, at low costs and complexity, the predictable communication of multiprocessor or distributed hard real-time systems.

In the field of *collaborative robotic environments*, several important contributions of our research team are discussed in Chapter 4. *A collaborative robotic alignment algorithm* has been developed as the first stage of some more complex robotic location management procedures. Further on, the *MTDOA* (*Modified Time-Difference-of-Arrival*) inter-robot distance measurement technique has been introduced and tested, yielding a worst case accuracy of 7.3 cm for inter-robot distances of up to 300 cm. To increase the accuracy and the performance of inter-robot distance measurement, the *CTOF* (*Combined Time-of-Flight*) method has been designed and implemented. By applying the Kalman filter to repetitive CTOF distance measurements, an accuracy of 1 cm can be achieved for distances of 300 cm between robots and without the need of fixed landmarks. Based on the previous results, a *location management and robotic positioning methodology* has been developed. The methodology relies on the collaborative inter-robot alignment and CTOF distance measurement techniques and employs the triangulation and the trilateration methods to determine the coordinates of a robotic and/or sensing node within a collaborative environment.

Chapter 5 covers some of the main contributions to the field of *energy efficiency and power management techniques*. We designed and tested a *software execution framework for measuring and evaluating power consumption signatures*, along with a set of *power consumption benchmarks*, with direct applicability in the power profiling of mobile systems and their multi-threading applications. A novel *methodology for online State-of-Health battery assessment* has also been developed and implemented, along with a fully functional *hardware/software battery management system (BMS)*, for resource-constrained Ni-MH battery powered embedded devices. The paper with the most relevant results of this research is currently being cited by more than 12 scientific articles, published by other authors in major journals or conference proceedings in the field.

The thesis is concluded by a set of principles and concrete elements of my scientific and academic development plan, as well as by the references used in this material, sorted in several distinct categories.

Rezumat

Teza de abilitare de față prezintă câteva dintre cele mai importante rezultate ale activității mele post-doctorale, desfăşurată începând cu anul 2005 în cadrul Departamentului Calculatoare, Universitatea Politehnica Timişoara.

O sinteză a propriilor realizări ştiințifice şi profesionale, de-a lungul întregii cariere, este cuprinsă în primul capitol. În cei peste 17 ani de activitate am acumulat o bogată experiență în următoarele domenii de interes: *sisteme hardware/software timp-real şi încorporate*, *sisteme de măsurare şi instrumentație, de prelucrare numerică a semnalelor şi multimedia*, *rețele de senzori fără fir*, *sisteme de telecomunicații numerice*, *medii colaborative robotice* şi *mecanisme pentru creşterea eficienței energetice şi a gestionării consumului*.

În aceste domenii am *publicat peste 89 lucrări ştiințifice*, dintre care 8 articole în jurnale prestigioase, indexate în baza de date Thomson ISI, cu factor de impact, 20 publicații în lucrările unor conferințe internaționale indexate ISI şi 22 de articole indexate în alte baze de date internaționale. Articolele indexate ISI *totalizează un factor de impact de 11.978*. Lucrările publicate sunt *citate în peste 62 de articole* publicate de alți autori în domeniu, dintre care 28 sunt indexate ISI.

Am fost implicat activ în *peste 40 granturi, proiecte şi programe CDI*, în calitate de director (13), responsabil (7) sau membru în echipa de cercetare. Ca director sau responsabil de proiect, am gestionat o *valoare totală de peste 0.8 milioane EUR*.

Recunoaşterea activității profesionale este ilustrată printr-o serie de premii, cum ar fi *Diploma şi medalia Tânărul Cercetător Eminent al Timişoarei*, acordată de Autoritatea Națională pentru Cercetare Ştiințifică (ANCS), România, *Diploma Cercetător Eminent*, acordată de către Asociația Orizonturi Universitare, Timişoara, precum şi *un total de 8 premii* câştigate la 11 ediții ale Concursului Internațional Studențesc de Calculatoare "Hard&Soft" Suceava, în calitate de coordonator al echipelor de studenți.

Câteva dintre cele mai relevante contribuții post-doctorale aduse în domeniul *sistemelor timp-real şi încorporate*, sunt prezentate în Capitolul 2. Este descris un *sistem-cadru de comunicație şi sincronizare inter-proces*, destinat nucleului de operare timp-real HARETICK. Mecanismele propuse, incluzând structurile persistente de date pentru parametrii de ieşire şi zonele tampon semaforizate pentru schimbul de date între procesele timp-real stricte şi lejere, oferă un suport de comunicație de înaltă predictibilitate, eficiență şi robustețe. O cercetare s-a concentrat asupra creşterii performanțelor de planificare (rata de acceptare) şi a flexibilității platformelor timp-real încorporate, menținând o predictibilitate maximă de operare. Ca soluție, am propus şi validat *mecanismul de planificare hibridă* H^2RTS. Acesta combină predictibilitatea unui planificator ciclic non-preemptiv, cu eficiența unei versiuni modificate a algoritmului "Earliest Deadline First".

În Capitolul 3 se prezintă rezultate obținute de către echipa noastră de cercetare în domeniul *rețelelor de senzori inteligenți*. Platforma complexă *CORE-TX*

(*Collaborative Robotic Environments – The Timisoara Experiment*) a fost realizată la stadiu de prototip, pentru studiul şi dezvoltarea sistemelor timp-real, a aplicaţiilor de percepţie artificială, reţelelor de senzori inteligenţi şi mediilor colaborative robotice. De asemenea, sistemul de comunicaţii de date *PARSECS* (*Predictable ARchitecture for Sensor Communication Systems*) a fost special proiectat şi realizat pentru a susţine, la un cost şi o complexitate redusă, comunicaţia predictibilă din cadrul sistemelor timp-real stricte de tip multi-procesor şi distribuite.

Contribuţiile aduse în domeniul *mediilor colaborative robotice* sunt discutate în Capitolul 4. Un *algoritm colaborativ de aliniere robotică* a fost dezvoltat ca o primă etapă a unor proceduri mai complexe de localizare. În continuare, a fost introdusă şi testată tehnica de măsurare a distanţelor inter-robot *MTDOA* (*Modified Time-Difference-of-Arrival*), rezultând o acurateţe, pentru cazul cel mai defavorabil, de 7.3 cm la distanţe inter-robot de 300 cm. În vederea creşterii acurateţei şi performanţelor obţinute anterior, a fost proiectată şi implementată metoda *CTOF* (*Combined Time-of-Flight*). Aplicând filtre de tip Kalman pentru măsurători CTOF repetitive, se poate obţine o acurateţe de 1 cm pentru distanţe inter-robot de 300 cm, fără a fi necesare puncte fixe de reper. Pe baza rezultatelor anterioare, echipa de cercetare a dezvoltat o *metodologie pentru localizare şi poziţionare robotică*. Metodologia utilizează algoritmul colaborativ de aliniere şi metoda CTOF de măsurare a distanţelor, implicând tehnici de triangulaţie şi trilateraţie pentru determinarea coordonatelor unui sistem robotic într-un mediu colaborativ.

Capitolul 5 cuprinde prezentarea contribuţiilor din domeniul *tehnicilor de creştere a eficienţei energetice şi de gestionare a consumului*. Echipa de cercetare a proiectat şi testat un *sistem-cadru pentru măsurarea şi evaluarea semnăturilor energetice*, precum şi un *set de referinţe de tip benchmark*, cu aplicabilitate directă în determinarea profilurilor energetice ale sistemelor mobile şi ale aplicaţiilor multi-fir ale acestora. De asemenea, a fost introdusă o nouă *metodologie de diagnosticare "la cald" a bateriilor*, împreună cu un *sistem hardware/software de gestionare a bateriilor* (*BMS*) complet funcţional, pentru dispozitive încorporate cu resurse limitate, alimentate cu baterii Ni-MH. Lucrarea în care am publicat cele mai relevante rezultate este citată până în peste 12 articole ştiinţifice publicate de alţi autori în jurnale şi la conferinţe de cel mai înalt nivel în domeniu.

Ultima secţiune a tezei cuprinde un set de principii şi elemente concrete ce compun planul personal de dezvoltare academică şi ştiinţifică, precum şi capitolul cu referinţele bibliografice, grupate pe categorii specifice.

1 Scientific and Professional Results: An Overview

1.1 Introduction and Fields of Expertise

I am currently a Professor Doctor engineer at the Department of Computer and Software Engineering (DCSE), Politehnica University of Timisoara Romania (http://dsplabs.cs.upt.ro/~micha). For over 17 years of didactic, scientific and research activity, I have gained a rich expertise in the following fields of interest:

- *Real-time and embedded hardware/software systems*
- *Digital measurement and instrumentation*
- *Digital signal processing and multimedia*
- *Wireless sensor networks*
- *Digital telecommunication systems*
- *Collaborative robotic environments*
- *Energy-efficiency and power management mechanisms*

In these fields, I published *over 89 scientific works*, as a main author (45) or co-author:

- 1 PhD Thesis and 3 PhD Reports
- 3 books and monographs, and 7 book sections or chapters
- 7 course support materials and 1 lab workbook, in hard copy or electronic versions
- 26 scientific articles in archival journals and periodicals
- 37 scientific papers in proceedings of national and international conferences
- 4 application notes, published by Motorola, Inc., USA.

Out of the published works, 8 articles appear in high ranked archival journals indexed by the Thomson ISI database with impact factors, 20 papers were published in ISI-indexed proceedings of international conferences, and 22 works are indexed in other international scientific databases, such as IEEE Xplore, INSPEC, Springer Link, Scopus, Compendex, ProQuest Central and DBLP.

The scientific papers published in ISI-indexed journals or conferences cumulate *a total impact factor of 11.978*. The relevance and impact of my scientific results in the field are also illustrated by a total number of *over 62 citing papers* published by other authors, out of which 28 are ISI-indexed. An overview of my ISI-indexed scientific profile is available on the ResearcherID database, at http://www.researcherid.com/rid/B-5581-2011.

For over 17 years I have been actively involved in *more than 40 research and development projects and programs*, as director (13), manager (7) or team member:

- 3 international R&D grants

- 25 national R&D grants
- 4 R&D contracts with industry
- 7 partnership programs
- 1 development project

As project/program director or manager, I have been in charge of executing a *total value of over 0.8 Mil. EUR*.

My PhD research activity has been carried out in the field of embedded and real-time hardware/software systems, at the Department of Computer and Software Engineering, Politehnica University of Timisoara (UPT), under the supervision of Professor Dr. eng. Vladimir Cretu. In 2005, I was given the *PhD title* (*Cum Laude* [P1]), with the Thesis "Design and Implementation of Real-Time Systems for Critical Applications of Digital Signal Acquisition and Processing". The main contributions of the PhD Thesis include:

- Development and demonstration of a homogenous set of models for real-time signals and tasks, based on an appropriate representation system for time. The "*ModX*" (*eXecutable MODule*) defines the periodic hard real-time tasks, which are scheduled and executed in a high priority, non-preemptive context.
- Adapted versions of the classical real-time scheduling algorithms Earliest Deadline First (EDF) and Minimum Laxity First (MLF), with focus on non-preemptive operation: *EDFNP* and *MLFNP*, respectively.
- Studies of the online operation of real-time schedulers, from the perspective of hardware (memory) limitations and the impact non-negligible execution times of task schedulers and dispatchers have on the overall system operation. Introduction and demonstration of two new online scheduling algorithms: *CEC-NPOS* and *PC-NPOS*.
- Development and demonstration of a fully predictable hard real-time scheduling technique, *FENP* (*Fixed Execution Non-Preemptive*), able to solve the classical problem of execution jitter in real-time systems.
- Extensive studies on the feasibility conditions and scheduling performance of the proposed techniques. Introduction of new necessity tests.
- Design and development of a prototype version of the *HARETICK* operating kernel (*Hard Real-Time Compact Kernel*), on Motorola DSP563xx embedded platforms. This kernel, used in conjunction with the FENP scheduling algorithm, is able, for instance, to generate multiple perfectly periodic (synchronous) signals, validating the models and techniques proposed by the thesis.

These results have been published in a monograph [M1], and in several journals and conference proceedings, including [A1] – [A4]. The thesis also gained an award from the Romanian Academy of Technical Sciences [P2].

1.2 Post Doctoral Research and Results

The high potential of the results obtained during my PhD research in the field, set the basis for an entire R&D direction in the Department of Computer and Software Engineering, under my supervision: *real-time and time-efficient techniques, with applications in embedded systems, digital signal processing, digital telecommunications, intelligent sensor networks and robotic environments*. The following paragraphs present a short summary of the most important results of my post doctoral research, while particular details will further be provided in the next chapters.

- The *OPEN-HARTS methodology* of real-time system modeling and design for critical applications has been further developed with funding from a series of national grants [G1], where I have been the manager of the research themes.
- A full *framework for inter-task communication and synchronization* on the HARETICK hard real-time operating kernel, has been developed, tested and validated [A21].
- The hard real-time scheduling techniques proposed in the PhD thesis have been continuously developed and extended. A *hybrid scheduling technique* has been studied and proposed as a solution to improve both the performance and flexibility of hard real-time scheduling algorithms [A37].
- New scheduling methods have also been introduced to increase the performance of *job-shop type applications* in automated factories, such as the semiconductor production facilities. These methods employ Petri nets, composite dispatching rules and evolutionary and genetic algorithms [A18], [A19], [A25], and have been developed with the support two R&D grants and contracts [G8], [G12].
- Based on a full set of requirements identified for mobile-oriented, multimedia applications [A32], a *real-time multiprocessor operating system* has been designed and implemented − the *MoviOS system* [A35]. *MoviOS* currently runs on the Movidius multi-core platform [G4] and features a special hierarchical scheduler to manage the application tasks scheduling and execution on such a platform. This scheduler is composed of a global, system-level scheduling module and a set of local, subsystem-level modules, allowing the proper handling of all the types of tasks specified by multimedia applications, i.e. hard-, soft- and non-real-time tasks.
- Research in the field of digital signal and image processing has also been intensively carried on. A *method and system for detecting frame compatible 3D content* has been developed to improve the stereographic image and video processing used mostly in television and 3D devices [G4]. The proposed method is based on edge processing of video frames, image projections calculation and 3D similarity analysis. The system is able to detect and display 3D Side-by-Side (SBS), 3D Top-and-Bottom (TAB) and 2D video content. These results have been filed at the national (OSIM, no. A00376/ 05.2012) [I1] and international (WIPO, no. PCT/RO2012/000010/05.2012) [I2] patent offices.

- A complex platform has been designed and implemented at prototype level, for the study and development of real-time systems, distributed artificial perception applications, intelligent sensor networks and collaborative robotic environments. The *CORE-TX* (*Collaborative Robotic Environments – The Timisoara Experiment*) platform [A9] has been set up with the support of an R&D Grant of Excellence [G2] and a subsequent grant [G3], and continues to serve as a key subject of scientific and PhD research [A6], [A7], [A12], [A13], Master's and Diploma projects [A22], [A23], [A30], at the Department of Computer and Software Engineering.
- A data communication system, called *PARSECS* (*Predictable ARchitecture for Sensor Communication Systems*) [A20], [A27], has been specifically designed and implemented to sustain, at low costs and complexity, the predictable communication of multiprocessor or distributed hard real-time systems, such as smart sensors or robotic devices. It is currently used to support the real-time communication of the modules and boards composing the CORE-TX Wireless Intelligent Terminal (WIT) nodes [A9], [M8], over their SPI backplane bus.
- Based on the CORE-TX platform and other robotic systems, such as the LEGO Mindstorms NXT, the complex topic of robotic positioning and location management has been addressed by our research team in the DSPLabs. A *collaborative robotic alignment algorithm* [A40] has been developed as the first stage of some more complex procedures, able to determine the relative distance between two mobile robotic systems and to accurately calculate their current location. This alignment algorithm provides a feasible solution to the impact misaligned transducers have on distance measurement methods based on signal directivity.
- The *MTDOA (Modified Time-Difference-of-Arrival) inter-robot distance measurement technique* [A26] proposed by our research team is based on the classical TDOA method with as set of additional improvements, to overcome several problems introduced by the unpredictable delays introduced by the wireless communication interfaces and protocols, generally used in robotic collectives and sensor networks. Synthetically, for inter-robot distances of up to 300 cm, the MTDOA performance is defined by a worst case accuracy of 7.3 cm and a maximum procedure duration of around 9 ms.
- To further increase the accuracy and the performance of inter-robot distance measurement, the *CTOF (Combined Time-of-Flight) method* [A26] has been designed and implemented. It proposes several improvements over other similar techniques, such as the MTDOA: it does not require additional robots or landmarks, and it is independent from the delays implied by the wireless communication interfaces of the robots. Our results indicate that the CTOF method, with its accuracy of 4.8 cm for distances of 300 cm and its linear behavior, outperforms the MTDOA and other distance measurement techniques, applied in state of the art location monitoring systems.
- An *improved version of the CTOF technique* [M7] in terms of accuracy has been further developed by our research team. By applying the Kalman filter to repetitive CTOF distance measurements, an accuracy of 1 cm can be

achieved for distances of 300 cm between robots, without the need of fixed landmarks.

- Based on the previous researches and results in the field, a *location management and robotic positioning methodology* [A38] has been developed in the DSPLabs by our team. This methodology relies on the collaborative inter-robot alignment and CTOF distance measurement techniques mentioned above, and employs the triangulation and the trilateration methods to determine the coordinates of a robotic and/or sensing node within a collaborative environment.
- In the field of energy efficiency and power management for embedded and real-time control and mobile systems, we designed and tested a *software execution framework for measuring and evaluating power consumption signatures* [A17], [M5], along with a set of *power consumption benchmarks* [A16]. They have direct applicability in the power profiling of mobile systems and their multi-threading applications, in the evaluation and calibration of power management solutions, application-related battery configuration and on-line battery monitoring.
- A *hardware/software power-aware device model* [A39] and an *energy consumption assessment and analysis framework* have been designed to enable the integrated development and analysis of both time-efficient and energy-efficient scheduling and operating mechanisms for real-time, power-aware embedded systems.
- A novel *methodology for online State-of-Health battery assessment* has been developed and implemented, along with a fully functional *hardware/software battery management system (BMS)*, for resource-constrained Ni-MH battery powered embedded devices [A31]. Currently, our paper, including the most relevant results of this research, has been cited by more than 12 scientific articles, published by other authors in major journals or conference proceedings in the field.

1.3 Head of the DSPLabs Research Group

Since 1995, I have been developing and coordinating the Digital Signal Processing Labs Timisoara (http://dsplabs.cs.upt.ro), together with Professor Dr. eng. Vladimir Cretu. Currently it is one of the most prominent labs of the department (http://www.rte.ie/news), leading the university R&D activities in the areas of interest previously mentioned in this section.

DSPLabs provides high level equipment and infrastructure support, mostly acquired through R&D grants and contracts [G1] – [G12], development projects [G13], or custom made by the teams in DSPLabs:

- intra-network of over 25 workstations and notebooks/laptops, 3 servers, several laserjet and deskjet printers, 1 scanner and network infrastructure (16 U rack, gigabit switches, WLAN access point, etc.);
- 5 professional lab instrumentation sets (oscilloscopes, power sources, signal generators and digital multimeters);

- development kits for embedded applications (various evaluation and development boards, emulators, debugging systems, programming environments, logic analyzers and universal programmers);
- 5 wireless sensor networks development kits (MICAz OEM Design Kit, MOTEWORKS Standard Edition License, various XBee and RF wireless communication modules);
- 11 robotic development kits (Lego Mindstorm NXT and Soccer Pro)
- 6 DSP application development systems (Analog Devices Blackfin DSP boards, VisualDSP++ development environment);
- specialized scientific computing and signal processing environment (MATLAB + SIMULINK Academic License);
- multimedia equipment (digital photo and video/HD cameras, stereo and surround/7.1 audio systems, high performance video projector);
- 10 digital telecommunication kits (custom made GSM/GPRS, WLAN, ZigBee and RF module –based development boards).

The DSPLabs research group consists of a core of 4 – 5 academic staff (currently: Dr. eng. Mihai Micea, Dr. eng. Vladimir Cretu, Dr. eng. Razvan Cioarga and eng. Dan Chiciudean) and an average of 10 – 16 students (undergraduate, master and PhD), who usually collaborate for more than 2 years to R&D projects in the lab.

Since 2007, I have been the technical PhD advisor of several PhD research programs within our department: Razvan Cioarga (Doctor since 2011), Mihai Fagadar-Cosma (Doctor since 2012), and Cristina Stangaciu (Certejan), Andrei Stancovici and Valentin Stangaciu (PhD students since 2011). A significant number of diploma and master projects had also been successfully carried out in the fields of interest mentioned above, under my direct supervision: *3 Master Theses and 6 Diploma Projects on average per year*.

The activity and results of the DSPLabs research group benefitted from a high level of attention and recognition [P7] – [P16].

DSPLabs is fully integrated into the Research Center in Computing and Information Technology (CCCTI, http://research.cs.upt.ro/), which concentrates all the research efforts and results of the Computer and Software Engineering Department staff into five main areas:

- Architectures and advanced computing systems
- Databases and artificial intelligence
- Real-time systems, robotics and digital signal processing
- Software engineering
- Mobile computing, sensor networks and embedded systems.

I have been serving as *deputy director of the CCCTI research center* since it has been set up and accredited at the university level, in 2011.

1.4 Initiator and Manager of Partnership Programs

In 1999, I initiated the "UPT – Motorola" Partnership Program and the Motorola DSP Applications Lab in Timisoara (DALT). This program lasted for 7 years, totaling over 55000 USD in financial and equipment support provided by the Motorola, USA, and has been a model followed by other similar partnerships throughout the university.

Based on the experience gained with this program, I am continuously interested in initiating and developing partnership programs with high-profile companies and academic structures:

- *Partnership with the Sensing and Modeling Research Lab (SMR) and BioMedical Instrumentation and Processing Research Laboratory (Bio MIP), University of Ottawa, Canada*, in the fields of sensor networks, digital instrumentation and signal processing, real-time systems and robotic environments, since 1998: common R&D projects, paper co-authoring (e.g. [A3], [A8], [A12], [A20], [A23], [A27], [A31]), and mobility actions. Contact persons: Prof. Voicu Groza – Director of the Bio MIP research group; Prof. Emil Petriu – Director of the SMR Lab and University research chair.
- *Partnership with the Image & Pervasive Access Lab (IPAL), Singapore*, in the field of digital image processing and medical imaging systems, initiated in 2005: 3 Diploma projects and 2 PhD programs successfully finalized under co-supervision from France and UPT. Contacts: Prof. Daniel Racoceanu – Lab co-director; Joo Hwee Lim – Lab co-director.
- *Partnership with the Department of Service Robotics, Catholic University of Lille (ISEN), France*, in the field of robotic systems, initiated in 2010: 4 staff and student mobility stages (EU Erasmus Lifelong Learning Programme), common project development and teaching exchanges. Contacts: Prof. Annemarie Kokosy – Head of the Service Robotics Department and President of the Research Council of the Catholic University of Lille.
- *Partnership with Alcatel-Lucent Romania*, in the fields of digital telecommunication systems and digital image processing applications, since 2000: development of the "Digital Telecommunications" undergraduate course at the Faculty of Automation and Computing, UPT, coordination of an R&D contract [G9], technical PhD advisor of eng. Mihai Fagadar-Cosma (Doctor since 2012), supervision of several Master and Diploma projects based on Alcatel specifications. Contacts: eng. Delia Golcea – Head of IT Software and Development Department; eng. Adrian Marina – Head of Alcatel University Timisoara; eng. Mihai Fagadar-Cosma – Project team manager.
- *Partnership with Advanced Clean Production Information Technology (acp-IT) S.R.L. Timisoara*, in the field of scheduling techniques for semiconductor production facilities, since 2006: coordination of an R&D contract [G8], scientific expert in a research grant [G12] and supervision of several Master and Diploma projects based on acp-IT specifications. Contact: eng. Laurentiu Maniu – Director of acp-IT Timisoara.

- *Partnership with Movidius S.R.L. Timisoara*, in the fields of digital image processing and real-time multiprocessor systems for multimedia, since 2010: partner project manager of a research grant supported by EU Structural Instruments [G4], co-author of a patent pending for invention [I1], paper publication [A32], [A35], supervision of several Master and Diploma projects based on Movidius specifications. Contact: Dr. eng. Valentin Muresan – Director of Movidius Timisoara.
- *Partnership with Continental Automotive Romania*, in the field of real-time operating systems and tools for automotive, initiated in 2013: coordination of an R&D contract [G7], setup of the "UPT – Continental RTS Group" research center in real-time automotive systems. Contacts: eng. Cristian Gavrilescu – Head of Continental Engineering Services Romania; Dr. eng. Virgil Ivaschescu – Leader Autosar Group.

I also maintain good collaborations involving paper co-authoring, common R&D projects and mobility actions with State University of New York, Stony Brook, USA (Prof. Alexandru Doboli), Salzburg Research, Austria (Prof. Ulrich Hofmann), Stefan cel Mare University of Suceava (Prof. Constantin Filote [G5], [G6]).

1.5 Manager of R&D Grants and Projects

During over 17 years of academic and scientific activity I have coordinated a significant number of R&D grants, contracts and projects as *director or principal investigator (17)*, and as *project or theme manager (6)*. The *total value executed as project director or manager is over 873462 EUR.*

Some of the most relevant examples of such projects are briefly summarized in the following paragraphs.

CORE-TX Project started in 2006, under my coordination and with financial support (~36000 EUR) from the Grant of Excellence, CEEX-ET-07/2006-2008 [G2]. Its main contributions include the design of a complex platform for the development and analysis of collaborative robotic environments and intelligent sensor networks [A9], [A13], and its use in studying emergent behavior patterns [A12], [A15], [M4]. The CORE-TX system has been developed at the stage of functional prototype, being used as a main support for a large set of further studies and projects (e.g. [G3]). It also opened new fields of research including PhD programs. I have been the technical PhD advisor for eng. Razvan Cioarga (Doctor since 2011) in the field of emergent behavior patterns in robotic collectives. Eng. Bogdan Ciubotaru (currently at Dublin City University) and eng. Bogdan Stratulat also started their PhD research on wireless networks with this project.

MELISSEVS Project continued the research started by CORE-TX in the field of collaborative robotic and intelligent sensor systems. The team has been led by Mihai Micea, with funding support (~225000 EUR) from the Exploratory Research Grant PN-II-ID-PCE-22/2007-2010 [G3]. It achieved the goal of developing MELISSEVS: an integrated Model for Representation of Collaborative robotic and Intelligent Sensor Systems in Environment Exploration and Supervision Applications. Some of the most interesting results included a methodology for modeling and evaluating emergent behavior control patterns [M6] with applications in robotic and sensor systems [A22], [A23], [A24], [A28], [A33], a predictable communication system for bus-based sensor networks [A27], models for sensor network and robotic environments support services [A26], [A30], [A34], [M8], and a battery management system for smart sensors [A31].

FALX-DACIAE Project approaches the fields of multimedia, mobile applications, multi-core architectures, digital image and video processing, real-time systems, parallel processing, compilers and software tools. The project has been executed during 2010 – 2012 as an R&D partnership between Movidius S.R.L. and Politehnica University of Timisoara. It has been financed through the POSCCE-499-11844 grant, by the European Regional Development Fund, European Social Fund and the Romanian National Authority for Scientific Research, ANCS (total value: ~506400 EUR) [G4]. The main goal was to research the various types of advanced software applications for state-of-the-art multi-core systems, with focus on the field of multimedia on mobile phones, and to develop appropriate semi-automatic tools and processes to increase the productivity of such applications. Some of the main results include:

- Models and implementations of hardware interface modules in a multiprocessor system-on-chip simulator
- Specification and requirements of a real-time multiprocessor operating system for multimedia applications [A32]
- An automatic application validation environment, *moviTest*
- A multi-core real-time and parallel operating system, *moviOS* [A35]
- A complete set of specialized software development tools: *moviSim* (multi-core simulator), *moviAsm* (assembler for the Sabre processor), *moviDebug* (application loader and debugger for the Movidius execution platforms), *moviCompile* (C and C++ compiler)
- A method and system for detecting frame compatible 3D content, filed at national (OSIM, no. A00376/05.2012) [I1] and international (WIPO, no. PCT/RO2012/000010/05.2012) patent offices
- 11 new jobs created for highly-qualified personnel.

1.6 Course Development and Teaching Activity

I have been collaborating with the Department of Computer and Software Engineering, UPT, since 1995, as an associate assistant. Successively, I occupied the following positions: teaching assistant (1997 – 2001), lecturer (2001 – 2006), associate professor (2006 – 2013) and full professor since 2013.

As an associate or teaching assistant I taught laboratory workshops which have been part of the undergraduate engineering curriculum of the Faculty of Automation and Computing: "Analiza si sinteza dispozitivelor numerice" ("Analysis and Synthesis of Digital Devices"), "Sisteme de achizitie numerica a semnalelor" ("Digital Signal Acquisition Systems"), "Discretizarea si prelucrarea numerica a semnalelor" ("Digital Signal Conversion and Processing") and "Tehnici de proiectare asistata de calculator" ("Computer Assisted Design Techniques"). I have also *developed the following lab workshops*:

- 1996 – 2000: "APND: Achizitia si prelucrarea numerica a datelor" ("Digital Data Acquisition and Processing"), 7th semester, 4th year BSc. in Computing, Faculty of Automation and Computing [M14] (*1 ISI-indexed citation*)
- 1997 – 2005: "PNS: Prelucrarea numerica a semnalelor" ("Digital Signal Processing"), 5th semester, 3rd year BSc. in Computing, Faculty of Automation and Computing
- 2002 – 2010: "ADSP: Advanced Digital Signal Processing", 1st/3rd semester, Master of Computer Engineering and Master of Information Technology, Faculty of Automation and Computing.

Starting from 2001, as a lecturer, I have been *authoring and teaching 3 courses*, which are part of the undergraduate engineering and Master's curricula of the Faculty of Automation and Computing, UPT:

- "PNS: Prelucrarea numerica a semnalelor" ("Digital Signal Processing"), 5th semester, 3rd year BSc. in Computing, Faculty of Automation and Computing [M10]
- "TD: Telecomunicatii digitale" ("Digital Telecommunications"), 7th semester, 4th year BSc. in Computing, Faculty of Automation and Computing [M12]
- "ADSP: Advanced Digital Signal Processing", 1st/3rd semester, Master of Computer Engineering and Master of Information Technology, Faculty of Automation and Computing [M11].

Since 2008, I have *developed 2 new courses*, which have been added to the undergraduate engineering and Master's curricula of the faculty:

- "SM: Sisteme multimedia" ("Multimedia Systems"), 8th semester, 4th year BSc. in Computing, Faculty of Automation and Computing [M13]
- "RT: Research Topics in Computer Systems / Information Technology", 1st/3rd semester, Master of Computer Engineering and Master of Information Technology, Faculty of Automation and Computing.

All the course lectures are presented using video-projected PowerPoint slides. Students are provided with the course support (course slides) in electronic or printed format. For this purpose I have been constantly publishing or updating a set of didactic materials, course support books and lab workbooks, in various editions [M10] – [M14].

1.7 Scientific Referee

As a recognition of my expertise in the fields of real-time and embedded hardware/software systems, digital measurement, instrumentation, signal processing, sensing and wireless sensor networks, digital telecommunication systems and collaborative robotic environments, I have been constantly invited to serve as referee, peer reviewer, session chair, member of the organizing committee or technical program committee for important scientific events, conferences or periodicals.

I am serving as a *peer reviewer* for a number of high ranked *archival journals*, most of them being indexed by Thomson ISI with impact factors, such as

- *Journal of Systems and Software*, Elsevier B. V., Amsterdam, The Netherlands, ISSN 0164-1212, (2013 – present)
- *IEEE Transactions on Instrumentation and Measurement*, IEEE, Instrumentation and Measurement Society, USA, ISSN 0018-9456, (2005 – present)
- *Electronics and Electrical Engineering*, Kaunas University of Technology, Kaunas, Lithuania, ISSN 1392-1215, (2009)
- *Scientific Bulletin of the UPT: Transactions on Automatic Control and Computer Science*, Politehnica University of Timisoara, Romania, ISSN 1224-600X, (2004 – 2008)
- *Advances in Electrical and Computer Engineering*, Stefan cel Mare University of Suceava, Romania, ISSN 1582-7445, (2001 – present).

I have been invited to serve as a *conference topic/session chair* to the following scientific events:

- *IEEE International Symposium on Applied Computational Intelligence and Informatics, SACI 2013, IEEE*, Timisoara, Romania, Special Session on PhD Student Research in Applied Informatics I, (2013, May)
- *IEEE International Symposium on RObotic and Sensors Environments, ROSE 2012*, IEEE, Instrumentation and Measurement Society, Magdeburg, Germany, Session – Intelligent Sensing and New Sensor Technologies, (2012, Nov)
- *International Congress on Computer Applications and Computational Science, CACS 2011*, International Research Alliance for Science and Technology (IRAST), Indonesia, Session 3 – Computer Networks and Communications, (2011, Nov)
- *International Conference of Technical Informatics, CONTI 2008*, Politehnica University of Timisoara, Romania, Section C-3 – Embedded Systems, (2008, Jun).

Since 1996, I have been a *member of the organizing committee* at national and international conferences, including:

- *IEEE International Symposium on Applied Computational Intelligence and Informatics, SACI 2013*, IEEE, Timisoara, Romania, (2013, May)
- *International Conference of Technical Informatics, CONTI*, Politehnica University of Timisoara, Romania, 2nd to 5th Editions (CONTI 1996, CONTI 1998, CONTI 2000 and CONTI 2002).

As a *member of the Technical Program Committee (TPC) and peer reviewer*, at several editions of national and international conferences:

- *IEEE International Conference on Virtual Environments: Human-Computer Interfaces and Measurement Systems, VECIMS*, IEEE, Instrumentation and Measurement Society: *VECIMS 2009*, Hong Kong, China (2009, May), *VECIMS 2010*, Taranto, Italy (2010, Sep), *VECIMS 2011*, Ottawa, Canada (2011, Sep), *VECIMS 2012*, Tianjin, China (2012, Jul)

- *IEEE International Workshop on RObotic and Sensors Environments, ROSE*, IEEE, Instrumentation and Measurement Society: *ROSE 2009*, Lake Como, Italy (2009, Nov), *ROSE 2010*, Phoenix AZ, USA (2010, Oct), *ROSE 2011*, Montreal, Canada (2011, Sep), *ROSE 2012*, Magdeburg, Germany (2012, Nov), *ROSE 2013*, Washington, USA (2013, Oct)
- *IEEE International Conference on Robotics and Automation, ICRA 2011*, IEEE, Robotics and Automation Society, Shanghai, China (2011, May)
- *IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications, CIVEMSA 2013*, IEEE, Instrumentation and Measurement Society, Milan, Italy (2013, Jul);
- *International Conference on Development and Application Systems, DAS*, Stefan cel Mare University of Suceava, Romania, 6th to 10th Editions (DAS 2002, DAS 2004, DAS 2006, DAS 2008 and DAS 2010).

I have also been invited in 2008 to serve as an *Expert Evaluator*, by the National Council for Academic Research (CNCSIS-UEFISCSU), Ministry of Education, Research and Innovation, Bucharest, Romania. In this capacity, I have evaluated a total of 15 applications for national R&D grant competitions.

1.8 Management and Administrative Experience

As an active member of the academic community, I have gained a significant management and administrative experience, at the department, faculty and at the university levels:

- *Elected member of the University Senate*, Politehnica University of Timisoara, Romania (2012 – present)
- *Elected member of the Faculty Council*, Faculty of Automation and Computers, Politehnica University of Timisoara, Romania (2008 – present)
- *Elected member of the Department Council*, Computer and Software Engineering Department, Politehnica University of Timisoara, Romania (2000 – present)
- *Studies Program Manager* for the Master of Information Technology, Faculty of Automation and Computers, Politehnica University of Timisoara, Romania (2008 – present)
- *Scientific Secretary of the Department*, Computer and Software Engineering Department, Politehnica University of Timisoara, Romania (2010 – present)
- *Member of the Master's Committee* for the Computer and Information Technology Domain, Computer and Software Engineering Department, Politehnica University of Timisoara, Romania (2009 – present)
- *Member of the Graduation Committee* for the Computer and Information Technology Domain, Computer and Software Engineering Department, Politehnica University of Timisoara, Romania (2008 – present)

- *Member of the Steering Committee*, Politehnica Timisoara Foundation, Romania (2010 – present)
- *Member of the Committee of R&D, Contracts, Doctoral Programs and Faculty Image*, Faculty of Automation and Computers, Politehnica University of Timisoara, Romania (2008 – present)
- *Department Public Image Manager*, Computer and Software Engineering Department, Politehnica University of Timisoara, Romania (2000 – present)
- *Member of the Central Board for Bachelor Entrance Examination*, Politehnica University of Timisoara, Romania (1996 – present).

1.9 Affiliations, Awards and Recognition

I have been affiliated to the two most prominent professional organizations in the field, since 2002: the *Institute of Electrical and Electronics Engineers* (*IEEE*) and *Association for Computing Machinery* (*ACM*).

The contributions and results achieved during over 17 years of activity in the field have been recognized by the academic and scientific community through several *awards, distinctions and prizes*, including:

- *Cum Laude Distinction*, Ministry of Education and Research, Bucharest, Romania, Order No. 3184/07.02.2005 (2005, Feb.) [P1], and *Best Doctoral Thesis of the Year 2004 Prize*, Romanian Academy of Technical Sciences, Timisoara Branch, Romania, (2006, Apr.) [P2], for the PhD. Thesis: "Design and Implementation of Real-Time Systems for Critical Applications of Digital Signal Acquisition and Processing"
- *Eminent Young Researcher of Timisoara Prize and Medal*, National Authority for Scientific Research (ANCS), Ministry of Education, Research and Innovation, Bucharest, Romania, (2006, Dec.) [P7]
- *Eminent Researcher Prize*, Orizonturi Universitare Association, Timisoara, Romania, (2006, Dec.) [P8]
- *Merit Award for 5 years* (2011 – present) [P3], *Merit Award for 1 year* (2010 – 2011) [P4], and *Merit Salary (annual)* [P5], Computer and Software Engineering Department, Faculty of Automation and Computers, Politehnica University of Timisoara, Romania (merit salary increase, granted on competition at the faculty/department level)
- *A total of 8 prizes*, won at 11 editions of the International Computers Contest for Students, "Hard&Soft", hosted by the "Stefan cel Mare" University of Suceava, as coach or advisor of the teams of students from the DSPLabs and the Faculty of Automation and Computing, Politehnica University of Timisoara: *2 First Prizes* (1999 [P16] and 2005 [P13]), *4 Second Prizes* (2000 [P15], 2002 [P14], 2007 [P12] and 2012 [P10]), *1 Special Prize* (2013 [P9]) and *1 Special Mention* (2012 [P11]).

2 Contributions to the Field of Real-Time and Embedded Systems

2.1 Framework for Inter-Task Communication and Synchronization on the HARETICK kernel

Further development of the HARETICK hard real-time compact kernel [A1], [A3], [A8], [A27], designed and implemented as a prototype during my PhD research, continues to remain a major field of interest.

A full *framework for inter-task communication and synchronization* on the HARETICK hard real-time operating kernel, has been developed, tested and validated [A21]. The research has been carried out by a team from the DSPLabs (Mihai V. Micea, Professor Vladimir Cretu, Dr. Razvan Cioarga, and PhD students Cristina Stangaciu and Valentin Stangaciu), in collaboration with a team from the University of Ottawa, coordinated by Professor Emil Petriu.

An important aspect of any operating system, inter-task communication and synchronization (ITCS) becomes a vital feasibility issue when real-time behavior of the system is required. Various types of ITCS mechanisms are implemented by most real-time operating systems and kernels [B1] – [B3]: flags, semaphores (POSIX, Ada95), mutexes and conditional variables (POSIX), conditional critical regions, monitors (Modula-1, Mesa, POSIX, RT Java), protected objects (Ada95), messages and mailboxes (POSIX, CHILL, Occam2, Ada95), priority inheritance and priority ceiling protocols [B4], etc. They all have specific problems (such as deadlocks, livelocks, priority inversion, and so on) and they also introduce some degree of non-determinism into the system. As an example, the Giotto system [B5] implements the ITCS mechanisms using "ports" and "guarded drivers" (which are atomic units of computation). To provide a degree of system predictability, these mechanisms must be scheduled along with the tasks, thus complicating the scheduling schemes.

HARETICK has been designed as a single-user, multitasking, real-time operating kernel, featuring two distinct task execution environments:

1) The hard real-time (HRT) task context, which has the highest priority and is based on non-preemptive scheduling and execution mechanisms
2) The soft real-time (SRT) task context, providing the necessary support for the execution of soft real-time (or regular) tasks in a classical, preemptive and priority-based manner.

In addition to these two types of tasks, any application will have an initialization task, which actually sets the required data structures, environment and task parameters, and starts the application.

Formally, the SRT tasks will be denoted here with L_j, $j \in \mathbf{N}$. As previously stated, they have a lower priority than the HRT tasks and can be preempted at any time by the HRT context. SRT tasks have non-restricted access to the application's global data area, along with any other application tasks.

On the other hand, the HRT tasks are modeled by the *ModX* (*eXecutable Module*) concept [A2], [A4], which specifies a modular, periodic, non-preemptive task, with firm temporal specifications:

$$M_i \equiv \langle \boldsymbol{T}, \boldsymbol{P}, \boldsymbol{S}, \boldsymbol{F} \rangle \, . \;\; i \in \mathbf{N} \tag{2-1}$$

where: $\boldsymbol{P} = \{\boldsymbol{P_{IN}}, \boldsymbol{P_{OUT}}, \boldsymbol{P_{GLB}}\}$ is the set of input, output and, respectively, global parameters of M_i, $\boldsymbol{S} = \{\boldsymbol{S_{IN}}, \boldsymbol{S_{OUT}}\}$ is the set of input and output signals which M_i interacts with, $\boldsymbol{F}$ is the task instruction code (its functional specification), and

$$\boldsymbol{T} = \left\{ T_{pr}^{M_i}, T_{ex}^{M_i}, T_{dl}^{M_i}, T_{dy}^{M_i}, N^{M_i} \right\} \tag{2-2}$$

represents the set of temporal parameters of M_i, in their respective order: period, execution time, deadline, delay of execution during each period, and execution count. The execution time is considered a constant value equal to the task WCET (Worst Case Execution Time) resulting from the offline program timing analysis.

The inter-task communication and synchronization mechanisms proposed and developed for the HARETICK kernel are based on the main features of the SRT and HRT task models presented above. For instance, the HRT tasks can accommodate very well periodic and atomic operations, which will be executed with the highest precedence within the system.

To further detail the proposed ITCS mechanisms, an example application will be introduced and briefly described. The application implements a relatively generic data communication and processing system on the HARETICK kernel. Figure 2-1 depicts the general design and specifications of this application. The communication driver (considered here a synchronous interface) is handled by three HRT tasks: `M_Comm_LVL1_RxTx` implements the synchronous reception and transmission of a word of data (Level 1 protocol), while `M_Comm_LVL2_Rx` and `M_Comm_LVL2_Tx` handle the reception and, respectively, the transmission of an entire frame (Level 2 protocols), using finite-state automata for frame encapsulation and processing.

Data processing is handled within the SRT context, mainly by the `L_Filter_Proc` task. It processes in-place the data provided in a buffer, which is referred by the input parameter. Additionally, the SRT context contains the tasks which provide the application level communication protocol (Level 3): `L_Comm_LVL3_GetFrame`, a non-blocking task which copies the received frame data from the Level 2 buffer to the buffer referred by the input parameter, and its transmission counterpart, `L_Comm_LVL3_SendFrame`.

As a classical model has been used for the SRT tasks, the ITCS mechanisms within the SRT context are also based on classical, traditional techniques. At the HRT level, inter-task communication between ModXs is based on the particular model defined for this type of hard real-time tasks. Since they implement periodic and atomic operations, the need for specific synchronization mechanisms has been eliminated, along with the issues related to concurrent access control to shared resources. Information exchange between the HRT tasks is supported by the input, output and global parameters, which define the $\boldsymbol{P}$ set of the ModX in (2-1).

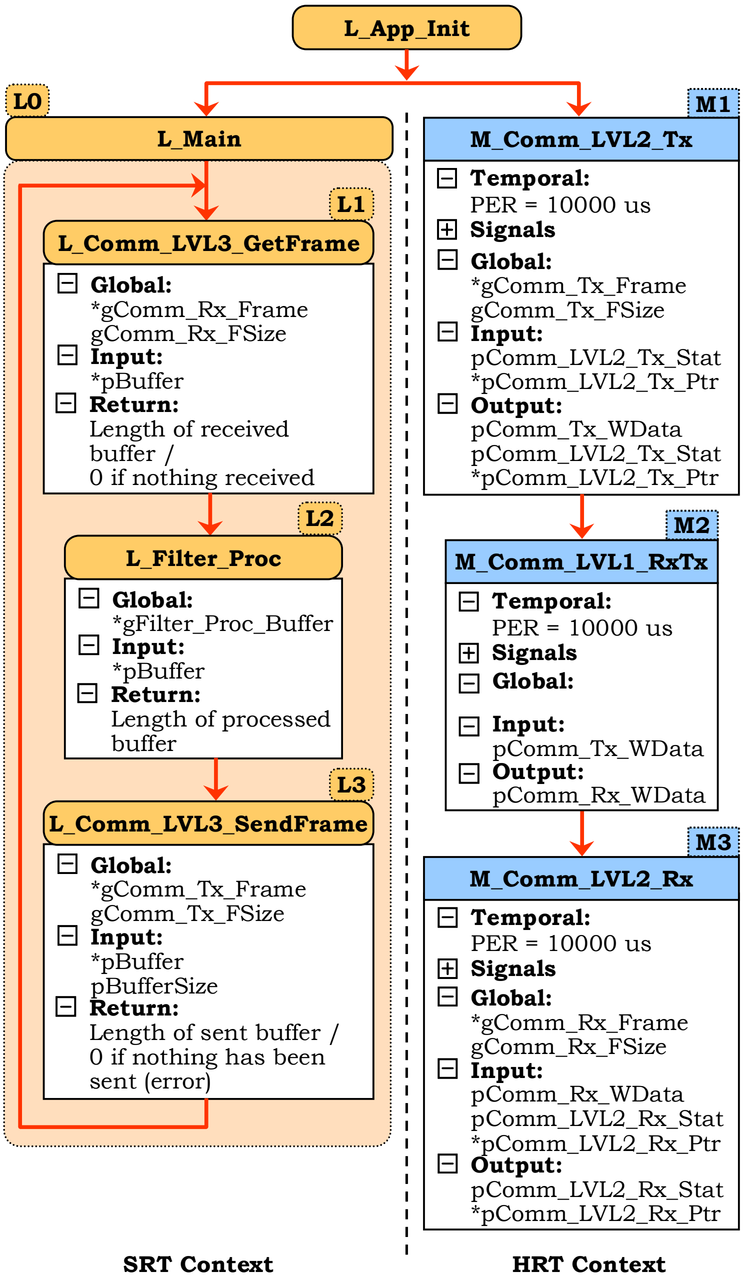

Figure 2-1. Specifications of the data communication and processing application (source: [A21]).

Figure 2-2 depicts the HARETICK memory map with the data and program structures allocated for the HRT tasks of the example application. The output parameters of each ModX, as well as the global data area, are implemented to keep their respective values over time, until updated (persistent data structures). The output parameters can be modified only by their respective tasks.

On the other hand, the input parameters are volatile data structures and must have a direct correspondence with an output parameter of another HRT task (*direct* *data dependence*), or of the same task (*circular data dependence*). At each start of an execution instance, any ModX will copy into its input parameters the current values of the corresponding output parameters. An example of direct data dependence is `pComm_Tx_WData`, which is an output parameter of the `M1` ModX (`M_Comm_LVL2_Tx`) and an input parameter of `M2` (see Figure 2-1). Through this data dependence, `M2` gets a new word of data from the transmit frame built by `M1`, to send it over the communication interface, on each execution cycle. Since the ModXs are periodic tasks, they are able to transmit to propagate their own status information from one execution instance to another, using the circular data dependence feature of this ITCS mechanism. Such a *circular parameter* is `pComm_LVL2_Rx_Stat` for the ModX `M3`, used to keeping track of the current status of the data frame at reception.

The application initialization task (`L_App_Init` in our example), executed prior to all other application ModXs, is key also from the proposed ITCS perspective, being in charge of setting initial values for the above presented categories of parameters.

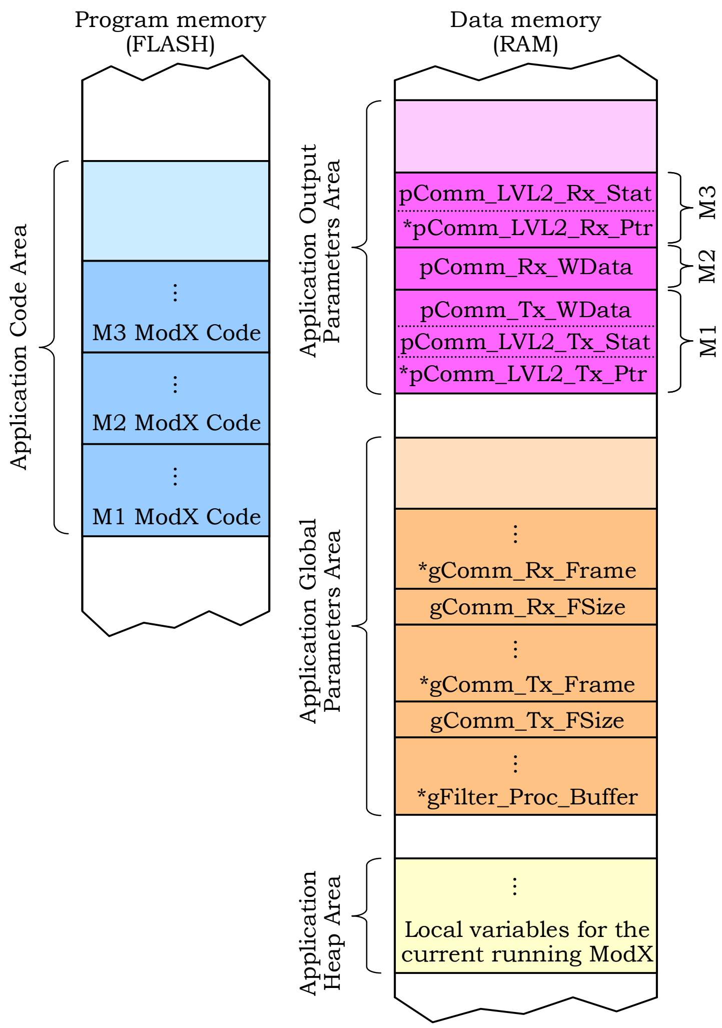

Figure 2-2. HARETICK data and program memory map for the application HRT tasks (source: [A21]).

The most difficult problem of the HARETICK inter-task communication and synchronization mechanism is to ensure the correct communication between the HRT and the SRT contexts. The former execution context cannot be interrupted and has also precedence over the SRT context. As a result, a SRT task can be interrupted at any moment by a ModX, without even having any indication on the occurrence of such an event. Therefore, classical ITCS techniques, such as semaphores, flags, messages, monitors and conditional critical regions, cannot be applied to this case.

A solution to this problem is to basically consider the communication between HRT and SRT tasks as a master-slave type of exchange, with the HRT task as manager (i.e. it manages the communication process). The information exchange will be accommodated by the so-called *guarded* (or *flagged*) *buffers*.

Figure 2-3 illustrates the operating principles of this mechanism, considering a data frame from another peer, which has just been received by the `M3` ModX (`M_Comm_LVL2_Rx`) and is in the process of being retrieved by the SRT task `L1` (`L_Comm_LVL3_GetFrame`), to be further processed (see Figure 2-1). The *guarded buffer* structure supporting this particular ITCS example consists of two globally declared parameters – the `gComm_Rx_Frame` buffer and the `gComm_Rx_FSize` variable (see Figure 2-2). This variable will act as a guard (flag), under the following rule:

a) when it is zero (meaning also that the frame buffer is empty), ModX `M3` will have exclusive access over the ITCS data;

b) otherwise, any other non-zero value indicates exclusive access of the SRT task `L1` over the frame buffer.

In the example under consideration here, the ITCS mechanism operates according to the following steps:

- During each of its execution instances, ModX `M3` receives a new word of data from the frame sent by the other peer, and inserts it into the `gComm_Rx_Frame` buffer, while the `gComm_Rx_FSize` flag remains reset. While the entire data frame has not yet been received by `M3`, it will have exclusive access to the data buffer. This step is represented with (1) and (2) in Figure 2-3.
- When `M3` encounters an *End of Frame* type of word at reception, it calculates the final length of the frame (λ in Figure 2-3) and writes this value into the guard parameter. As a result, the exclusive access to the ITCS data structures will be transferred to the `L1` task (step (3) in Figure 2-3).

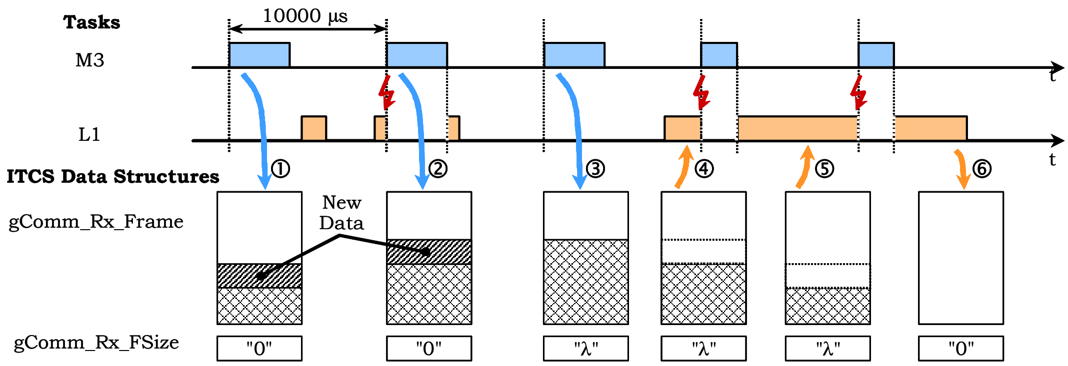

Figure 2-3. HRT-SRT inter-task communication principle (source: [A21]).

- Upon its next activation, `L1` notices the non-zero value of the flag and starts to copy the received data frame from the buffer. This step is illustrated with (4) and (5) in Figure 2-3, which also depicts some execution instances of ModX `M3` during this interval. `M3` interrupts the task `L1`, checks the flag and recognizes the exclusive access of `L1` over these ITCS data structures (thus, these execution instances of `M3` will be shorter than the previous ones, as seen in Figure 2-3).
- When `L1` finishes copying the data from the buffer, it resets the flag (`gComm_Rx_FSize = 0`), thus releasing its lock on the ITCS structure. This operation will be one of the final instructions of the `L1` code, as it is equivalent to the commit operation of a shared database access transaction (step (6) in Figure 2-3).

This ITCS mechanism has been tested and validated on various applications implemented on embedded platforms running the HARETICK kernel. Such an application is the SPI (Serial Peripheral Interface) communication interface developed for the WIT (*Wireless Intelligent Terminal*) nodes [A9] of the CORE-TX platform [G2]. Based on a modular design, the WIT nodes consist of a motherboard, with central processing and control functions, and several daughter boards, each having specialized functions required by wireless sensor networks and robotic environments: wireless communication, data acquisition, robotic mobility, power management, and so on. The motherboard and the daughter boards are interconnected through a real-time SPI backbone.

Two versions of SPI have been implemented and tested, using the HARETICK kernel and the proposed ITCS mechanisms: half-duplex and full-duplex SPI. The motherboard is the SPI master and the daughter boards are SPI slaves, in both versions. The master is in charge of generating the serial synchronous bit clock and cyclically polling the slaves for data exchange. The main implementation parameters of the half-duplex SPI application are presented in Table 2-1.

The operation of the tasks belonging to the HRT and SRT contexts of the target platforms has been captured and measured. For the SRT tasks, their code has been modified to toggle an output line at the beginning of each execution.

Table 2-1. Implementation parameters of the half-duplex SPI application.

Parameter	Value
Synchronous serial bit clock frequency	1.8 MHz
Feasible SPI bitrate achieved	800 bps
Period: Reception ModX	3333.33 μs
Period: Transmission ModX	10000 μs
Execution time: HRT Scheduler (HSCD) + Executive	224 μs
Execution time: Reception ModX + Executive	14 μs
Code size: Reception ModX	12940 Bytes
Code size: Transmission ModX	12656 Bytes
Data size: Reception ModX	14176 Bytes
Data size: Transmission ModX	13964 Bytes

The execution of the HRT tasks have been tracked with the help of the system hard real-time dispatcher (HDIS), which has been programmed to toggle another output line before and after the execution of a ModX.

An example capture and measurement of the operation of the SPI reception tasks is illustrated in Figure 2-4. Channel 1 (top) captured the Layer 3 SPI reception SRT task, while two consecutive executions of the SPI reception ModX appear on Channel 2 (bottom). The second execution of the ModX is shortly followed by an execution of the HRT context scheduler, HSCD. The scope time base has been configured at 500 µs. As a result, the period of the SPI reception HRT task has been measured at a value of around 3333 µs, which corresponds to the value specified at the application design phase (Table 2-1).

The mechanisms designed to provide communication and synchronization support for tasks operating within both soft real-time (or classical) and hard real-time contexts, have been successfully implemented and validated. A set of applications have been tested on HARETICK-based platforms. The measurements and performance evaluations confirmed the correct behavior of the applications, according to the design specifications, from both the processing as well the timing perspectives. The proposed ITCS mechanisms, including persistent data structures for ModX output parameters and guarded buffers for HRT-SRT data exchange, proved to be feasible as well as efficient.

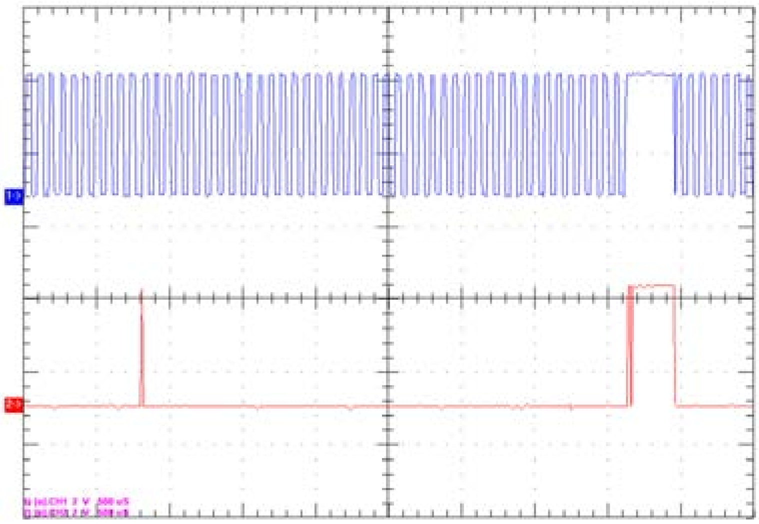

Figure 2-4. Measurement of the Layer 3 Reception SRT task (top), the SPI Reception ModX and the HSCD hard real-time scheduler (bottom) (source: [A21]).

2.2 Hybrid Scheduling Techniques to Improve the Efficiency of Highly Predictable Real-Time Systems

One of the key directions of interest in my post doctoral research has been to improve the performance of OPEN-HARTS methodology for design, analysis and execution of hard real-time applications, proposed in the PhD Thesis.

In this field, the main research focus has been to increase the scheduling performance (acceptance ratio) and flexibility of real-time embedded platforms, while preserving maximum execution predictability. The research team which I have coordinated, including Professor Vladimir Cretu, PhD student Cristina Stangaciu and PhD student Valentin Stangaciu, proposed and validated the *H^2RTS hybrid scheduling mechanism* [A37], which combines the high predictability of a non-preemptive cyclic scheduler with the efficiency of a modified version of the Earliest Deadline First algorithm.

Current real-time task execution support systems can be categorized [B6], [B7] in either (a) highly predictable and reliable, but not flexible, based on hard real time scheduling algorithms, or (b) very flexible, but with relatively low predictability. Most executives and operating kernels in the first category are still custom designed to guarantee correct behavior even under worst operating conditions [B7], [B8]. A notable example from the second category is POSIX. The task scheduling mechanisms provided by this standard are round robin and a fixed preemptive priority [B9]. As a result, the system allows high flexibility for task allocation and execution, but at the expense of predictability.

Hybrid scheduling techniques have been previously proposed. Dobrin, Fohler and Puschner investigate in [B10] a method to "translate the off-line schedules into task attributes for fixed priority scheduling". Its disadvantage is the increase of the total number of tasks by splitting them into instances, which can generate priority assignment conflicts. The method also uses time target windows, which reduce the granularity for task scheduling and execution. Burns, Wellings and Zhang discuss in [B11] a hybrid scheduling technique based on the Earliest Deadline First (EDF) and the Fixed Priority (FP) algorithms on preemptive execution scenarios. The system can reach a higher scheduling efficiency, while also the FP tasks feature some degree of predictability. Nevertheless, the execution jitter, common to all the preemptive scheduling techniques, remains an open issue to this approach, too. Another hybrid scheduling method is proposed in [B12]. It divides the tasks into several sets, based on some common features. The tasks within each set are then scheduled with a distinct algorithm, while the system also features a global scheduler. On the other hand, this method is presented only as a principle, without providing any concrete scheduling combination.

The *H^2RTS Hybrid Hard Real-Time Scheduler* we propose considers a standard model of a mono-processor real-time system $\boldsymbol{S}$, consisting of N statically defined tasks τ_i, which are characterized by typical timing parameters:

$$\boldsymbol{S} = \{\tau_i \equiv (T_i, C_i, D_i) \mid i = 1..N\} \qquad (2\text{-}3)$$

such that T_i is the period of task τ_i (or the minimum inter-arrival time of its jobs, if it is a sporadic task), C_i is the computational cost (the worst-case execution time among all jobs issued by τ_i) and D_i is its relative deadline (assumed to be at most equal to the period, i.e. $D_i \le T_i$).

H^2RTS will split the hard real-time tasks set $\boldsymbol{S}$ into two distinct execution/scheduling contexts:

1) The "*FENP context*", which contains the tasks requiring perfectly synchronous operation and, implicitly, the lowest jitter.

   These tasks, part of the $\boldsymbol{S}^{FENP}$ subset, will be executed with the highest priority in the system and without admitting preemptions from any other task (non-preemptive execution). The FENP (Fixed Execution Non-Preemptive) algorithm [A8] is employed to schedule the tasks in this context.

   Examples of tasks of this type are found in critical or hard real-time applications, which require perfectly synchronized interactions with the environment, e.g. various periodic signal generators [A8], data communication systems with synchronous operation [A20], [A27], and real-time support for wireless sensor networks [A41], [M8].

   In such applications, cyclic schedulers and especially their non-preemptive versions, such as the FENP algorithm, provide a set of key advantages, such as simplicity, high operating predictability and the lowest possible task execution jitter. Yet, an important drawback is their lack of flexibility, e.g. when the time behavior of a task (such as the period) needs to be changed, it will require the feasibility re-analysis of the entire application.

2) The "*MEDF context*" (Modified EDF) contains the remaining hard real-time tasks in $\boldsymbol{S}$, which specify execution deadlines but do not require perfectly synchronous operation.

   To increase both the flexibility and the performance of the entire system in terms of processor utilization, the tasks in the $\boldsymbol{S}^{MEDF}$ subset will be dynamically scheduled with a modified version of the classical EDF (Earliest Deadline First) technique [B7], [B13], such that the system predictability remains unaffected.

   The tasks in the MEDF context will be executed without preemptions from any other task, except from the tasks in the higher priority FENP context. The preemption restriction avoids issues commonly found in the case of dynamic, preemptive scheduling algorithms: complex context switching support, resource access contentions, priority inversion, expensive inter-task communication and synchronization mechanisms, and so on.

Additionally, the tasks with soft real-time specifications, or without any timing requirements, will be scheduled and executed within a third context, the "*BGND context*" ("Background"). This context has the lowest priority and employs traditional multitasking/multi-threading scheduling and dispatching techniques.

Formally, the H^2RTS hybrid scheduling technique can be specified by the following equations [A37]:

$$\begin{cases} \boldsymbol{S} \equiv \left\{ \boldsymbol{S}^{FENP}, \boldsymbol{S}^{MEDF} \right\} \\ \text{a system of } N = m + n \text{ hard real-time tasks} \end{cases} \tag{2-4}$$

$$\begin{cases} \boldsymbol{S}^{FENP} \equiv \{\mu_1, \ldots, \mu_i, \mu_{i+1}, \ldots, \mu_m\} \\ \mu_i \equiv (\varphi_i, T_i, C_i) \;.\; i = 1..m \\ T_i \le T_{i+1} \\ s_{i,k+1} = s_{i,k} + T_i = \varphi_i + kT_i \;,\; \forall \mu_i \in \boldsymbol{S}^{FENP}, k \in \mathbf{N} \end{cases} \tag{2-5}$$

$$\begin{cases} \boldsymbol{S}^{MEDF} \equiv \{\varepsilon_1, \ldots, \varepsilon_j, \varepsilon_{j+1}, \ldots, \varepsilon_n\} \\ \varepsilon_j \equiv (T_j, C_j, D_j) \;.\; D_j \le T_j,\; j = 1..n \\ T_j \le T_{j+1} \\ s_{j,k_j+1} = \max(t, k_j T_j), \text{ where:} \\ \qquad j \,\middle|\, \forall p \ne j, (k_j T_j + D_j - t) \le (k_p T_p + D_p - t) \\ \qquad \text{and } k_j, k_p \in \mathbf{N} \end{cases} \tag{2-6}$$

The hard real-time task system, scheduled with the H^2RTS algorithm, is defined in (2-4). Here, it is also shown the partitioning of the hard real-time tasks into the subset of perfectly synchronous tasks, $\boldsymbol{S}^{FENP}$, and the subset of tasks which will be dynamically scheduled with the MEDF technique.

The next subsystem of equations, (2-5), specifies the FENP component of the H^2RTS hybrid scheduler. The $\boldsymbol{S}^{FENP}$ subset is composed of a total of m perfectly periodic hard real-time tasks, μ_i, characterized from the temporal perspective by the period T_i (also considered as deadline), the computational cost C_i and the start time of the first execution instance (offset), φ_i. These tasks are arranged within the $\boldsymbol{S}^{FENP}$ subset in non-decreasing order of their periods. The scheduling principle is formally specified as follows: the start time of the next instance (k + 1) of μ_i is computed by adding the period T_i to the start time of the current instance, $s_{i,k}$.

Subsystem (2-6) specifies the MEDF component of H^2RTS. The temporal parameter D_j represents the deadline of the MEDF task ε_j. The scheduling algorithm is based on the current decision time, t, which can only occur upon the completion of any MEDF task, when the next task will have to be selected for scheduling. The next scheduled task, with the index j, will satisfy the following conditions:

a) it is ready for execution, i.e. it has not been already executed within its period (the last executed instance of ε_j is k_j)
b) its absolute deadline is the closest to t among all the other MEDF tasks which are also ready.

After selecting the next task to be executed (ε_j), its start time will either be the current moment (t), or, if the current period has not elapsed yet, the start of its next period (k_jT_j).

Figure 2-5 illustrates an example of H^2RTS task scheduling and execution within the three contexts defined by the proposed method. The execution of the MEDF task ε_j is interrupted by the higher priority FENP task μ_i and, after the completion of the latter one, the execution context of ε_j is restored. When ε_j finishes, the MEDF scheduling component selects ε_p to be executed at the moment it will become ready (i.e. at the beginning of its next period). During the idle intervals of FENP and MEDF contexts, the processor will be allocated to the background tasks (the BGND context). To accommodate the timely execution of the hard real-time tasks scheduled within the FENP and MEDF contexts, two system timers will be used, to issue corresponding interrupts.

The hashed rectangles which frame the execution of μ_i in Figure 2-5 represent the prefix and, respectively, the suffix components of the FENP context dispatcher module, with the main roles of launching μ_i and programming $TIMER_0$ to issue an interrupt when the next FENP task is scheduled. The hashed rectangles on the MEDF context representation have similar functionalities, and additionally, include the MEDF scheduling component itself, which calculates and selects the next MEDF task to be scheduled.

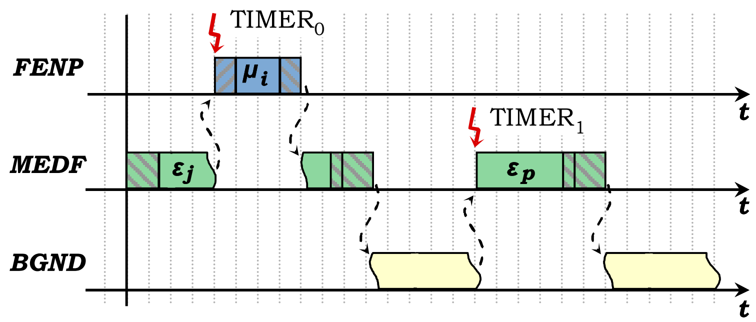

Figure 2-5. Example of H^2RTS task scheduling and execution (source: [A37]).

An extensive set of simulations has been performed to assess the performance of the proposed hybrid scheduling technique, taking into account various configurations of hard real-time task sets. The number of tasks within each subset, i.e. m for $\boldsymbol{S}^{FENP}$ and n for $\boldsymbol{S}^{MEDF}$, has been specified to different values. Each task set has been randomly generated based on a uniform distribution for the periods (T_i) and execution costs (C_i) of the tasks in the set, while also enforcing various processor utilization factors for each task subset:

$$U = \sum_{i=1}^{N} \frac{C_i}{T_i} \qquad (2\text{-}7)$$

Figure 2-6 shows the schedulability ratio (success ratio, SR) versus the processor utilization factor, specified by (2-7), for simulation sets of $N = 10$ hard real-time tasks which define the system $\boldsymbol{S}$ in (2-4). Two extreme configurations have been considered:

a) All the tasks are FENP tasks ($m = 10$, $n = 0$). In this case, the hard real-time task scheduling is performed only by the FENP component of the H^2RTS algorithm.

b) Half of the tasks are FENP and half are MEDF tasks ($m = n = 5$). This is considered also an extreme case, as hard real-time tasks which require a perfectly synchronous operation are, usually, much fewer than the other hard real-time tasks ($m << n$).

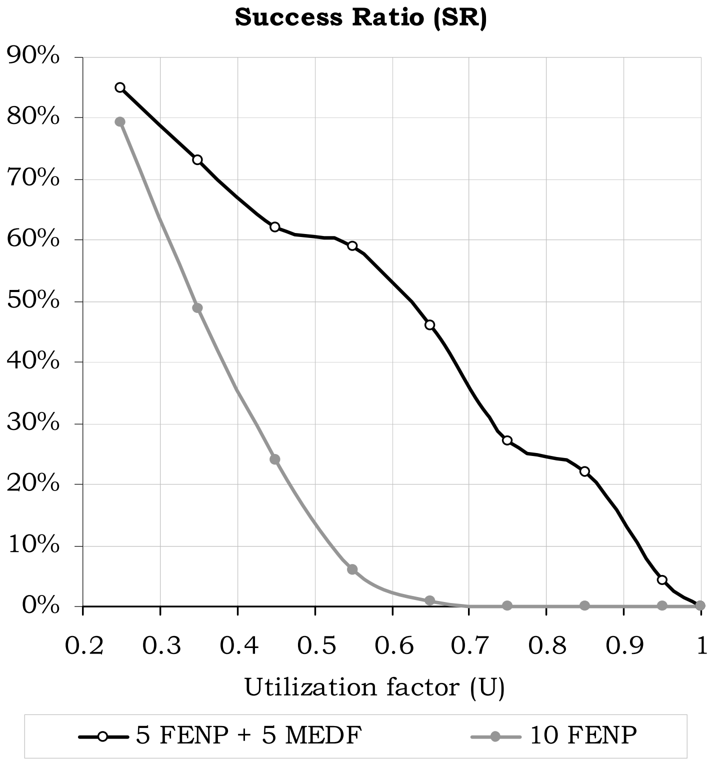

Figure 2-6. Performance of the H^2RTS hybrid scheduling, compared to the FENP algorithm (source: [A37]).

The simulation results confirm a much better efficiency of the proposed H^2RTS hybrid algorithm as compared to using only cyclic schedulers such as the FENP technique, especially when the system is loaded towards its full capacity (i.e. at higher values of processor utilization factor).

Test applications and experiments have also been conducted to assess the predictability of the H^2RTS method. The CORE-TX platform [A9], [A20], [M8] has been used to analyze and measure the timing behavior of its wireless communication system and of the real-time tasks involved at system and application level. Worst-case communication has been considered for the XBee modules, i.e. transactions with the maximum amount of data, to use the maximum capacity of the corresponding buffers.

Figure 2-7 depicts an example logic analyzer caption of the task execution and timing measurements performed during the tests performed on the CORE-TX XBee-based wireless communication modules, running the H2RTS hybrid scheduling on the HARETICK real-time kernel [A1], [A3], [A8], [A27]. The execution of the *SPI* and *XBee_FENP* tasks, which are included within the $\boldsymbol{S}^{FENP}$ subset, can be observed in this figure as being framed by the dispatcher modules (*HDIS_PRE* and *HDIS_SUF*), as theoretically discussed and presented in Figure 2-5. Further on, the execution of *XBee_EDF*, which is an MEDF task, is interrupted by the *SPI* task and then resumes after the latter one finishes (i.e. its corresponding HDIS_SUF finishes).

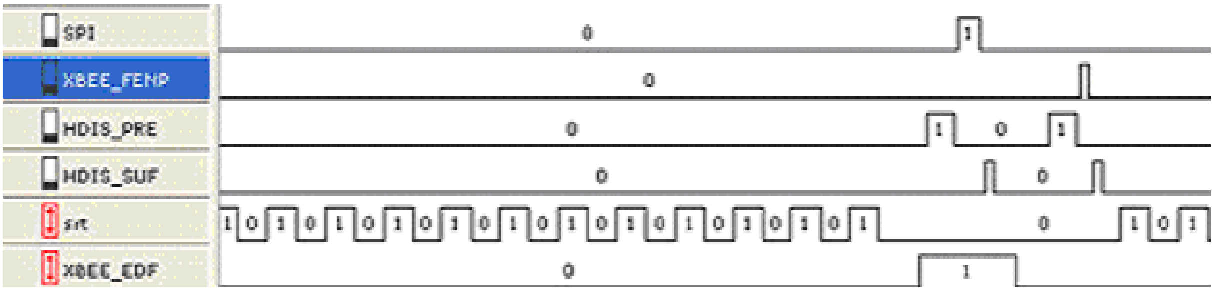

Figure 2-7. Caption of task execution and timing measurement for the wireless communication system (source: [A37]).

All the tests, experiments and measurements confirmed the full predictability and timeliness of the communication system, according to the specifications and parameters set at the design and analysis phase.

As a result, the proposed H^2RTS hybrid hard real-time scheduling technique provides a fully predictable and an efficient operating environment. Its FENP scheduling component is able to execute with the lowest possible jitter the hard real-time tasks with perfectly synchronous operating requirements. Furthermore, by moving the rest of the hard real-time tasks in the system (i.e. the tasks which do not need perfectly periodic execution cycles) into the more efficient MEDF context does increase the overall system performance in a significant manner, while still able to provide hard timing guarantees.

3 Advances and Results in the Field of Intelligent Sensor Networks

3.1 CORE-TX: Collaborative Robotic Environments – The Timisoara Experiment

To support complex studies and development techniques on real-time systems, distributed artificial perception applications, intelligent sensor networks and collaborative robotic environments, the CORE-TX platform [A9] has been designed and implemented at prototype level by a core research team composed of Professor Vladimir Cretu, and PhD students Dan Chiciudean, Razvan Cioarga and Bogdan Ciubotaru, under my coordination. The research and development activities have been consistently supported by a national Grant of Excellence [G2] and a subsequent national R&D grant [G3]. Since 2006, the CORE-TX platform has continue to serve as a key subject of scientific and PhD research [A6], [A7], [A12], [A13], Master's and Diploma projects [A22], [A23], [A30], at the Department of Computer and Software Engineering.

Intelligent sensor networks represent a new instrument which can be called "macro-scope" [B14]. This instrument permits real-time monitoring and interaction with physical phenomena and processes, with a much better precision that can be obtained with traditional control and monitoring instruments. Currently, a large number of applications and pilot projects are being developed in the field of intelligent sensor networks [B15] – [B17], including:

- Seismic activity monitoring and depth measurement, using a sensor network equipped with seismometers (UCLA Department of Earth and Space Sciences / Center for Embedded Networked Sensing)
- System to assist Alzheimer patients, as part of an experimental smart house from Intel Oregon campus (Intel Research)
- Detection and tracking of vehicles and personnel in battlefield areas: DARPA NEST project developed at MacDill Air Force Base (Ohio State University).

A large variety of platforms providing support for such intelligent sensing applications as mentioned above have also been proposed in the field. From the size and scale points of view, the intelligent sensor network platforms can be classified in four categories [B18]:

- *Gateway-type platforms*, which are composed of a few gateway nodes of medium to large sizes (>10 cm^3), hosting complex applications such as databases and web interfaces. Such an example platform is Stargate [B19].

- *High-bandwidth sensing platforms*, are based on tenth of high-bandwidth, medium-sized nodes (1÷10 cm^3) which usually acquire and process multimedia streams such as video and acoustic signals. Imote2 [B20] is a platform in this category.
- *Generic sensing platforms*, consist of hundreds of general sensing (door, window, temperature, motion) and communication relay nodes of medium to small sizes (< 10 cm^3). Crossbow's Mica2 and MicaZ [B21] belong to this platform class.
- *Specialized sensing platforms*, are composed of hundreds to thousands of special-purpose, low bandwidth sensor nodes or advanced radio-frequency tags, with small sizes (~ mm^3). Examples of such platforms are the Spec [B18], Smart dust systems [B15], [B22], or Spray Computers [B23].

On the other hand, current technology also permits the design and implementation of a large variety of low-cost robots with autonomous intelligence. At the same time, a large number of replicas of a single robot, suited for a set of particular applications, can be built. Research in collaborative environment, robots communities and emergent behavior represents a relatively new domain of high interest in the field [B25], [B26].

Various robotic platforms are constantly being developed and proposed as basis for collaborative environments [B24], [B29]. Examples in this field include the K-Robots, developed by the K-Team Corporation [B27], iRobot Swarm platform [B28], Lego Mindstorms, Palm Pilot Robot Kit (PPRK) from Carnegie Mellon University [B29], and the Swarmanoid Project [B30]. The iRobot Swarm environment, for instance, consists of tenths of charging stations and navigational beacons, and over 100 SwarmBots, equipped with sensors, communication and human interface devices, a camera, batteries and two drive motors [B28]. Its operating software is designed to feature a set of "behaviors" which run concurrently and control the SwarmBot sensing, actuator, mobility and communication processes. On the other hand, the Swarmanoid project proposes a distributed robotic system of heterogeneous, small, autonomous robots, able to dynamically connect and co-operate to reach various goals in a real-life 3D environment. There are mainly three categories of such robots in a Swarmanoid system [B30]:

- Eye-bots, capable of flying and attaching themselves to the ceilings, with the main role of sensing and providing an overview analysis of the environment
- Hand-bots, capable of climbing walls and vertical surfaces, to handle various target objects within the environment
- Foot-bots, specialized in moving on the floor and transporting other bots or various objects.

Our research team focused on combining the two types of platforms described above, i.e. intelligent sensor networks and robotic collectives. The CORE-TX system (COllaborative Robotic Environment – the Timisoara eXperiment) [A9], is composed of a set of static or mobile autonomous sub-systems, supervised by a particular, central node with special functions, which are interconnected through a wireless communication environment. Its architecture is based on advanced principles derived from complex, distributed digital systems: functional abstraction, modularity, re-configurability, flexibility and reliability. Formally, the CORE-TX model is structured on three main layers of abstraction (see Figure 3-1):

- Perception and operation layer
- Collaborative communication layer
- Background control and supervision layer

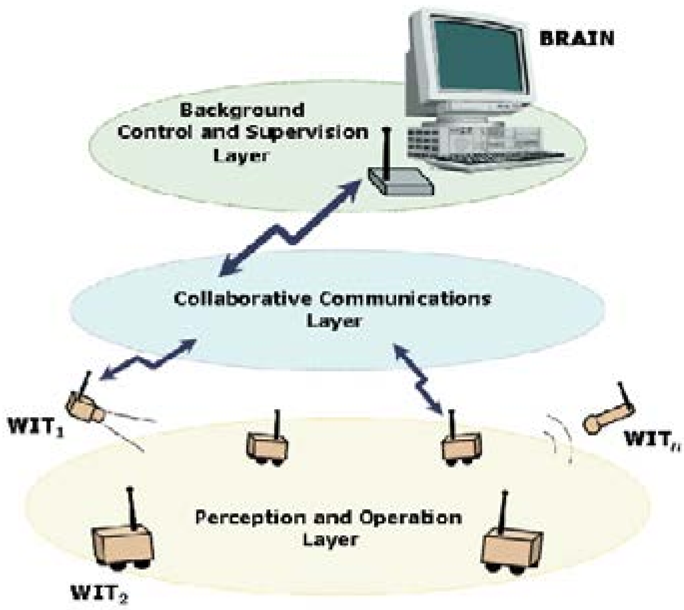

Figure 3-1. CORE-TX layered model architecture (source: [A9]).

CORE-TX interacts with the environment through the *operation and perception layer*, which consists of a set of autonomous embedded devices with perception (intelligent sensors) and/or operating functions (mini-robots). These devices, called *WIT*s (Wireless Intelligent Terminals), have a modular, multi-board design, as presented in Figure 3-2. The architecture of a WIT is based on a motherboard and up to 15 daughter boards, interconnected through a synchronous peripheral interface (SPI) backplane bus. Each daughter board is specifically designed to perform a set of particular, closely related, functions of the WIT node, such as wireless communication, power management, sensing, mobility, and so on. The most common modules of a WIT are as follows:

- BAM (Base Processing Module) or Mainboard, is the core element of the WIT node, serving as central processing and control module, responsible for the general behavior of the node.
- COM (Communication Module), is the daughter board which manages the communication of the WIT with the rest of the system and its interconnection to the second layer of the CORE-TX model, the Collaborative communication layer. By default, this module implements the ZigBee wireless standard (IEEE 802.15.4), based on the X-Bee PRO modules.
- POM (Power Management Module), includes the battery pack of the WIT, its recharging circuits and state-of-health estimation logic, as well as hardware

and software components for real-time monitoring of the power consumption for each of the boards composing the WIT.

- SEM (Perception/Sensor Module), contains the sensing devices of the WIT, such as temperature sensors, SONAR transducers, infrared devices, accelerometers, electronic compass and so on. This daughter board also includes the corresponding analog-to-digital and digital-to-analog conversion logic and data pre-processing.
- ROM (Support and Operation / Robotic Module), manages the mobility and actuation functions of the mobile WITs. It consists of a robotic platform with driver motors and corresponding control logic, hardware and software components for mobility and location management. It can also include optional actuators, such as a robotic arm, for manipulating and interacting with the environment.

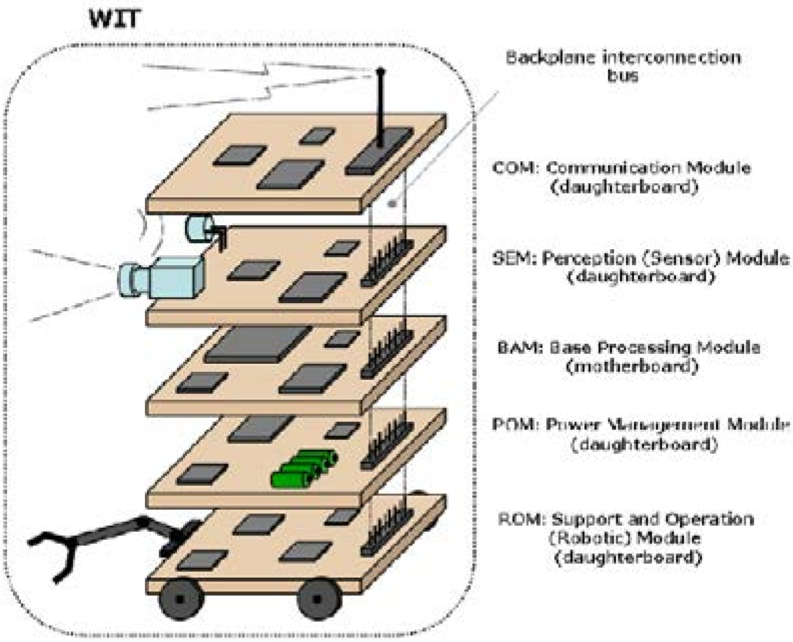

Figure 3-2. Modular architecture of the WIT.

The *collaborative communication layer* provides the support and protocols required by all the nodes of the CORE-TX platform to exchange information in a co-operative manner. Currently, this layer is based on the ZigBee/IEEE 802.15.4 wireless standard, with particular adaptations of the medium access and routing protocols to support high accuracy time synchronization [A30] and real-time message transactions [A41], [M8]. A dynamic, ad-hoc network architecture is used, with a multi-hop configuration and a cluster-based hierarchy [A6]. This type of architecture is required by two main considerations:

a) Some of the nodes are mobile/robotic WITs, which can dynamically enter or leave the radio coverage area at any time.

b) Most of the network nodes have limited, battery-type, power supplies. As a result, the system must cope with nodes exiting due to power failure, or with nodes entering various power saving states.

Therefore, the routes are updated regularly and have a limited lifetime. Multi-hop communication is useful when the CORE-TX is deployed over wide areas, where not all the WITs have direct links with each other. In such cases, some individual nodes can be configured by the system as simple communication relays [A13].

The *background control and supervision layer* consists mainly of the BRAIN subsystem (Background Robotic Activity Induction Node), which is a supervisor software system that coordinates all activities taking place inside the CORE-TX environment. It is designed to provide the following key functions:

- Specification, analysis and development of particular behavior patterns for the whole collaborative system [A7], [A22], [A23], [A28], [A33], [M6]
- Reconfiguration / auto-configuration of the whole collaborative environment through "auto-discovery" and "plug-and-play" techniques
- General coordination of the CORE-TX system through behavior induction directives ("background induction"), using a formal language, *eBML* [A12], [A15], specifically designed to describe various behavior patterns of individual WITs and of the system in general
- General monitoring and supervision of the CORE-TX platform through specific techniques of distributed status querying and through individual activity reports, gathered continuously from the WITs
- Network data extraction, correlation, fusion and visualization [A34], analysis of the system state and its behavior tendencies
- Interface with the user/system operator, providing a real-time, intuitive, visual and interactive environment for processing the commands and presenting the network information.

Currently, the CORE-TX platform is implemented at prototype level. A set of WIT nodes have been developed (see also Figure 3-3 and Figure 3-4), based on the ARM7TDMI-S core architecture (Philips LPC2xxx microprocessor families), both for their motherboard, and for the specialized daughter boards.

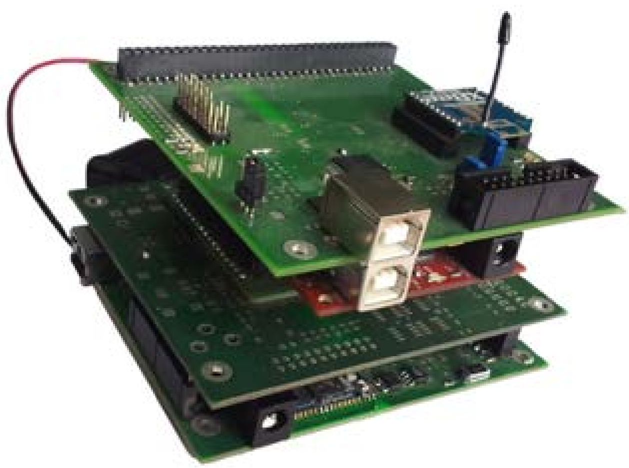

Figure 3-3. Minimal configuration of a static WIT prototype (sensor node).

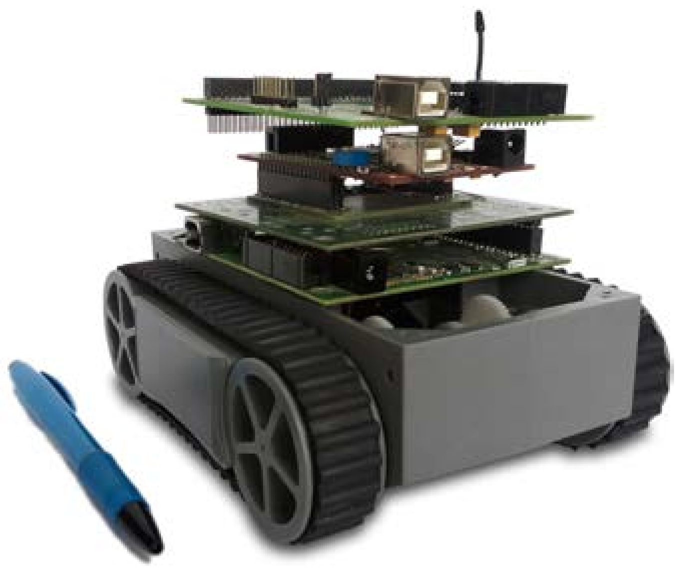

Figure 3-4. Minimal configuration of a mobile WIT prototype (robotic node).

The HARETICK real-time operating kernel [A1], [A3], [A4], [A8], [A21], has been ported and installed on each module of the WITs, providing maximum operating predictability for the specialized, real-time applications developed with the OPEN-HARTS methodology [A2], [M1], for each of these targets. The communication layer is currently based on the XBee PRO modules featured by the COM boards of the WITs, thus implementing the ZigBee / IEEE 802.15.4 wireless standard. The BRAIN system is currently implemented on a PC workstation, which is directly connected to a WIT COM board as an interface to the CORE-TX communication layer. Currently, the BRAIN features an interpreter for the formal behavior pattern modeling language, eBML, an integrated environment simulator application which can also interact with the real-life WITs, and a user interface module.

3.2 Predictable Data Communication System for Smart Sensors in Hard Real-Time Applications

Real-time data communication with direct application in embedded systems, smart sensor networks and robotic environments is a major field of interest in my post-doctoral research activity. A data communication system, called *PARSECS* (*Predictable ARchitecture for Sensor Communication Systems*) [A20], [A27], has been specifically designed and implemented to sustain, at low costs and complexity, the predictable communication of multiprocessor or distributed hard real-time systems, such as smart sensors or robotic devices. This research has been carried out by a team composed of Professor Vladimir Cretu, teaching assistant Dan Chiciudean and students Gabriel Carstoiu and Lucian Ungurean, under my coordination and in close collaboration with Professor Voicu Groza from University of Ottawa, Canada.

Predictability of operation is a key design and implementation problem for hard real-time systems, covering also the aspects of information exchange and communication in such systems. From this perspective, the existing real-time communication techniques can be divided into two main categories: *asynchronous* (or *event-triggered*) and *synchronous* (or *time-triggered*).

Asynchronous communication protocols are based on heuristic approaches, global network communication schedules and medium access contention avoidance and recovery mechanisms. As a result, hard real-time communication predictability still remains an open issue. Examples of such protocols include the CAN (Controller Area Network) bus [B31], intensively used in automotive applications, RT Ethernet [B32], Black-Burst [B33], RI-EDF (Robust and Implicit Earliest Deadline First) [B34], Byteflight [B35], and Profibus [B36].

Time-triggered communication protocols feature a better predictability for data communication. Their physical layer supports synchronous data transactions, while in many cases, the medium access of the nodes is managed through specific scheduling algorithms embedded into their protocol stacks. A relevant example in this category is the time-triggered architecture, TTA, and protocol family, TTP/A and TTP/C [B37]. TTP/C provides a scalable and fault tolerant solution, at the expense of the implementation complexity of the node, though. At a lower cost, TTP/A still maintains the communication predictability, but its performance can be surpassed by other equivalent solutions. FlexRay [B38], [B39], is a hybrid system which combines the time-triggered concepts for hard real-time transactions, with the flexibility of the asynchronous Byteflight protocol for soft real-time exchanges. On the other hand, its high performance and reliability imply complex hardware and highly efficient scheduling mechanisms to be designed, both at the application and at the message exchange levels, thus resulting in an overall increase of the costs. The TTCAN standard [B40] implements a time-triggered variant of the CAN protocol, allowing both time-triggered and event-triggered message transactions. On the other hand, it provides a lower level of fault-tolerance as compared to the TTP or FlexRay protocols, for example. As a common approach of this class of protocols, TDMA-based techniques are used to assign distinct time slots to individual nodes and to provide guarantees on bounded delivery times for message transactions [B41], [B42]. However, ensuring correct synchronization and operating predictability at node level still remains an important issue.

PARSECS (*Predictable ARchitecture for Sensor Communication Systems*) is an architecture specifically designed to meet a set of key requirements regarding inter-component data communication interfaces for smart sensors and multiprocessor hard real-time systems environments:

a) Simplicity, at moderate transfer rates: the interface should rather have a low complexity, instead of providing a very high data transfer rate which, in many cases, is not a priority in sensing environments
b) Multiple peers: a large number of applications require data transactions between more than two peers
c) Timeliness of communication: accurate timing is an important requirement in hard real-time applications involving smart sensors
d) Predictability of operation: predictable behavior must be guaranteed regarding the operation of hard real-time systems, as well as their data exchanges

e) Reliability: the communication system should provide handshaking and error handling mechanisms to ensure data reliability
f) Low cost: the hardware and software components of the communication system should be kept as low as possible.

PARSECS proposes an architecture which provides high predictability, *up to the application level* of each node, for data communication. Consequently, it states a set of particular specifications at two main levels:

1) A hard real-time operating environment for the applications hosted by each node of the system
2) A predictable data communication interface to interconnect the nodes.

The first component of the PARSECS specifications can be fully provided by the HARETICK real-time operating kernel [A1], [A3], [A4], [A8], [A21], developed during my PhD. research. The HARETICK kernel is able to guarantee that all the system and application hard real-time tasks will meet, under worst–case assumptions, all their temporal specifications. Using a periodic, non-preemptive scheduling and execution model for the hard real-time tasks, and employing time-triggered (polling) techniques to interact with the external signals and events, HARETICK is also able to ensure the lowest possible task jitter, a key feature for systems and transactions operating under synchronous principles.

For the second key component of the PARSECS specifications, a communication interface has been designed, based on a synchronous, full-duplex, bus-type physical layer, which interconnects multiple communicating peers in a master-slave configuration of nodes. Such an interface is the SPI (Serial Peripheral Interface) which is commonly integrated as a native peripheral by a large variety of microcontrollers and processors and has the advantage of being a low cost solution for smart sensors and embedded multiprocessor systems.

In such a configuration, the master node issues the clock signal and manages the bus synchronization. Based on a carefully designed local schedule, the master node also initiates all data transactions on the bus by cyclically polling and selecting each slave node. This schedule can be statically (offline) calculated, taking into account the general communication requirements of each slave node, or can be dynamically adjusted, during system operation. Therefore, the PARSECS architecture proposes a flexible TDMA-type of medium access control (MAC). Information exchanges over the network are controlled and processed by a simple and efficient, four-layered protocol stack, as presented in Figure 3-5.

In the following paragraphs, the main characteristics of each layer of the PARSECS protocol will be briefly presented and discussed.

Layer 1: Physical Interface Control

Layer 1 performs the physical interface control, and operates the data transmission and reception at word level. Layer 1 must be synchronous with the operation of the communication interface and, therefore, its corresponding tasks must be executed on a carefully scheduled, time-triggered basis. The hard real-time execution environment of the HARETICK kernel can provide the operating support required by Layer 1 tasks. The functional diagram of the protocol is depicted in Figure 3-6.

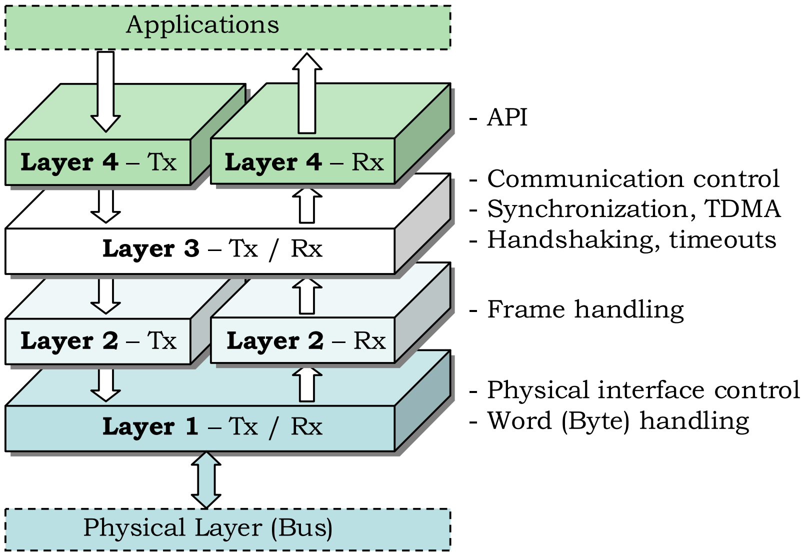

Figure 3-5. PARSECS communication protocol stack (source [A27]).

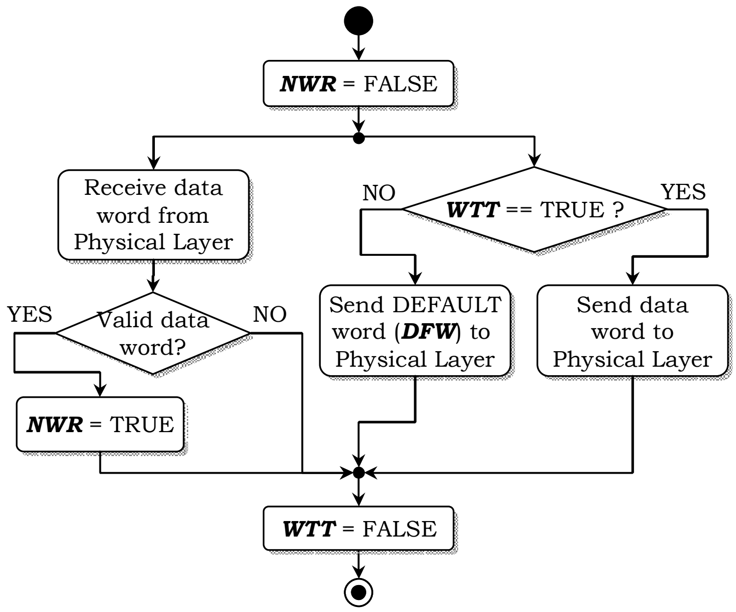

Figure 3-6. Functional diagram of Layer 1 protocol (source [A27]).

On synchronous, full-duplex communication interfaces, the master driving the clock line initiates the communication with any slave, within a well-specified time slot. During this interval, it sends any available data to the corresponding slave and, simultaneously, receives data from the slave. In many synchronous interface implementations, including the SPI, a node (either master or the currently polled slave) is required to send a "dummy" or "default" word in the case it does not have valid data to transmit. This word is denoted with *DFW* in Figure 3-6. *NWR* denotes the "New Word Received" flag, set by Layer 1 to indicate to Layer 2 the reception of a new word, and *WTT* is the "Word to Transmit" flag. It is set by Layer 2 when a new word needs to be transmitted and is reset back by Layer 1 after having it successfully sent over the physical interface.

The length of the data words conforms to the hardware specifications of the physical layer of the particular communication interface. The usual values are either 8, or 16 bits.

Layer 2: Frame Handling

Layer 2 protocols handle the frame structures and the peer-to-peer frame exchange. At this level, two variants of protocols have been developed as components of the PARSECS system:

- PARSEC-P is based on packet frame structures, to provide reliable support for predictable, time-triggered data transactions over the network
- PARSEC-M uses message-type frames and provides stream communication capabilities to the system, i.e. long data message (stream) transactions, of lower importance and reduced reliability requirements.

The frame structure of a packet for the PARSEC-P version, depicted in Figure 3-7, consists of a header, a data payload of a maximum length and a trailer. The header is composed of a *Start of Frame* (SOF) and the *Payload Length* (LEN) words, while the trailer consists of a 2-byte cyclic redundancy code (CRC) to increase the communication reliability, taking especially into account the applications of smart sensing and sensor networks. As a result, the total packet size L_F for a payload of m data words of b bits each, can be derived as

$$L_F = 2 + m + \left\lceil \frac{16}{b} \right\rceil \; . \; m \le 2^b - 1 \qquad (3\text{-}1)$$

where $\lceil x \rceil$ ("ceiling") denotes the smallest integer greater than or equal to x. Our implemented prototype of PARSEC-P interface uses words of 1 byte (b = 8) and, consequently, the maximum payload length is limited to 255 bytes. The ANSI CRC polynomial of 16th order, $x^{16} + x^{15} + x^2 + 1$, has been used for packet level error detection and correction.

PARSEC-M uses a simpler structure for the message-type frames (see also Figure 3-8): escaped data word sequences as payload of variable length, delimited by the *Start of Frame* (SOF) and *End of Frame* (EOF) special words, respectively. A third protocol word, *Escape* (ESC), is used to mark data words with the same value as the special ones.

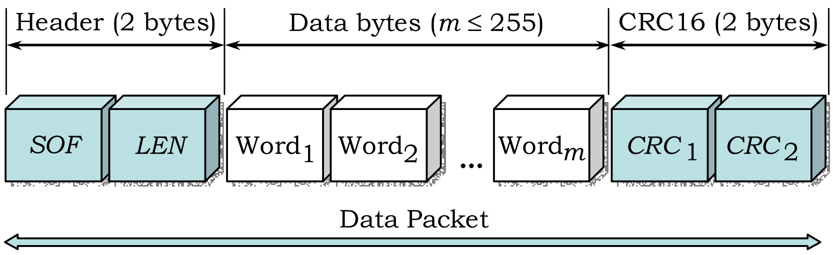

Figure 3-7. PARSEC-P packet frame structure (source [A27]).

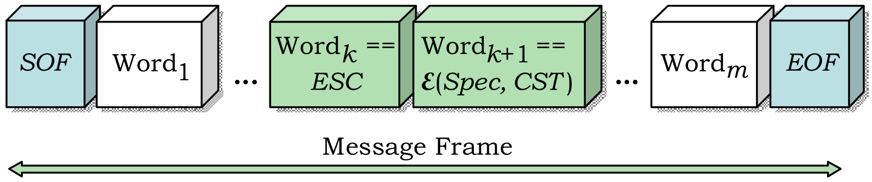

Figure 3-8. PARSEC-M message frame structure (source [A27]).

In the case a data word has the value of a special word (denoted here by *Spec*), it will be replaced in the message payload with an ESC word, followed by a word with the value ε(*Spec*, *CST*), where *CST* is a predefined constant and ε is an involution, i.e. a function with the following property:

$$\varepsilon \circ \varepsilon = \varepsilon(\varepsilon(x, y)) = x \text{, or } \varepsilon(x, y) = \varepsilon^{-1}(x, y) \quad (3\text{-}2)$$

Due to this property, the same function can also be applied at reception, both to decode the escaped data and to check for transmission errors. Such an involution is, for example, the XOR function, used in the PARSEC-M prototype implementation.

In the case of escaped data methods, the frame length, L_F, depends both on the number of data words to be transmitted, m, and on their actual values. In the worst case, each data word has a value identical to a special frame word (SOF, EOF, CST or ESC). As a result, the total message length is lower and upper bounded by

$$m + 2 \leq L_F \leq 2m + 2 \quad (3\text{-}3)$$

Layer 2 protocols are implemented by two distinct finite-state automata, one for the reception and decoding of a frame, and the other for encoding and transmitting of a frame. They will operate synchronously with the Layer 1 routines. These automata pairs have distinct implementations for the PARSEC-P and PARSEC-M versions of frames. Figure 3-9 exemplifies the PARSEC-P Layer 2 packet receive automaton, while the Layer 2 message transmit automaton of PARSEC-M is depicted in Figure 3-10. The following flags have been used for managing the operating states and to communicate with the adjacent layers:

- *NFR* (New Frame Received), set by the Layer 2 Rx automaton to indicate to Layer 3 protocols a new frame has been successfully received and decoded
- *RFE* (Rx Frame Error), set by Layer 2 to indicate to Layer 3 the Rx buffer allocated for the reception of the current frame is not available or has been overrun, resulting in an erroneous reception
- *FRIP* (Frame Reception in Progress), internal state flag of the Layer 2 Rx automaton
- *NWR* (New Word Received), set by Layer 1 to indicate to Layer 2 the reception of a new word
- *WTT* (Word to Transmit), set by Layer 2 when a new word needs to be transmitted; reset by Layer 1 after having it successfully sent over the physical interface
- *FTT* (Frame to Transmit), set by Layer 3 when a new data frame needs to be transmitted; reset by Layer 2 after the successful transmission of the frame
- *FTIP* (Frame Transmission in Progress), internal state flag of the Layer 2 transmission automaton.

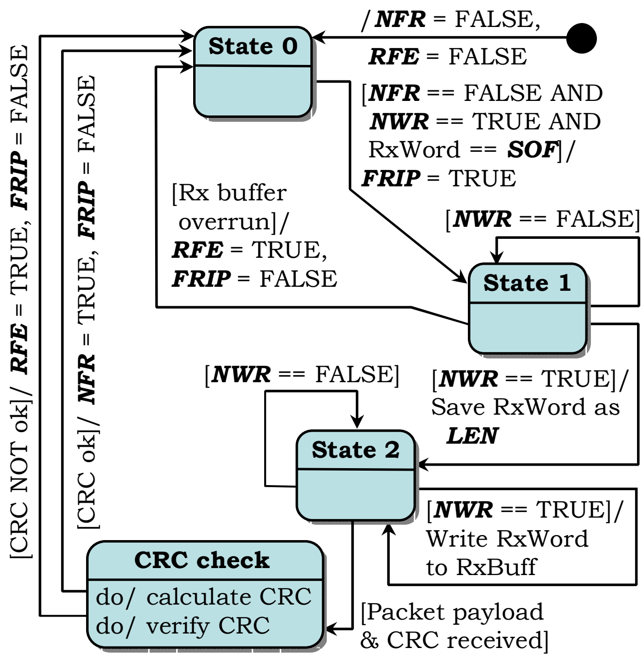

Figure 3-9. Layer 2 packet receive automaton (source [A27]).

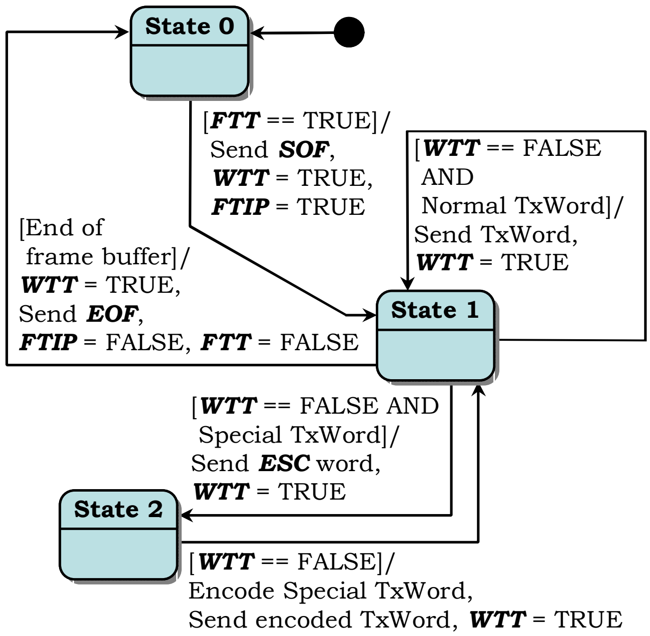

Figure 3-10. PARSEC-M Layer 2 message transmit automaton (source [A27]).

Layer 3: Communication Control

Protocols of this layer are in charge of the overall control of the communication, especially from three main perspectives: synchronization, reliable data exchange with handshaking and timeouts, and multi-peer master-slave communication using flexible TDMA techniques.

As an initialization of the system, the synchronization occurs prior to any exchange of valid data over the interface. It is initiated by the master node with each slave, consecutively. As a result, all the protocol automata will be initialized, and some of the basic parameters of the communication will be transmitted by the master to all the slave nodes (e.g. the maximum frame length, in words, for the current configuration).

Data exchange over the bus is also controlled by the Layer 3 protocols in a predictable and reliable manner, based on timeouts and handshaking techniques. As a result, any transaction over the communication interface will have known lower and upper time bounds, which can be further used by real-time applications to estimate the temporal behavior of the overall system. The various possible scenarios of exchanges between the master (*M*) and any slave nodes (S_i, S_{i+1}, etc.) are depicted in Figure 3-11. In the first case, neither the master nor the slave node (here, S_i) have valid data to transact, and the master is polling this node during its corresponding TDMA timeslot. As a result, an "Empty Timeslot" occurs, in which both the master and the slave node are sending a "default/dummy word" (*DFW*) over the bus. The scenario in which the master has valid data to send but the corresponding slave does not, is represented in Figure 3-11 with the combination (a) + (c): *M* sends its data frame (while S_{i+1} answers with default words, *DFW*s). Afterwards, the master polls the slave node for the acknowledge frame (*M* sends *DFW*s to enable S_{i+1} to send the *ACK* or *NACK* frame). At this point, if the master does not receive either a valid *ACK* or a *NACK* frame from S_{i+1}, its Layer 3 protocols will generate an APP_TOUT (Application Timeout) error, to notify the application layer. A third type of transaction is represented by the case when the master *M* has no valid data to send, while the slave does. This corresponds to the combination (b) + (d) in Figure 3-11 and, this time, *M* will send its acknowledge frame to S_{i+1}. The case in which both the master and the slave nodes transmit valid data and, afterwards, their corresponding acknowledge frames, is depicted in Figure 3-11 as the combination (a) + (d). As an observation, the scenario (b) + (c) during the "Full Timeslot" in Figure 3-11 is actually equivalent to the first case discussed above, which corresponds to the "Empty Timeslot" situation.

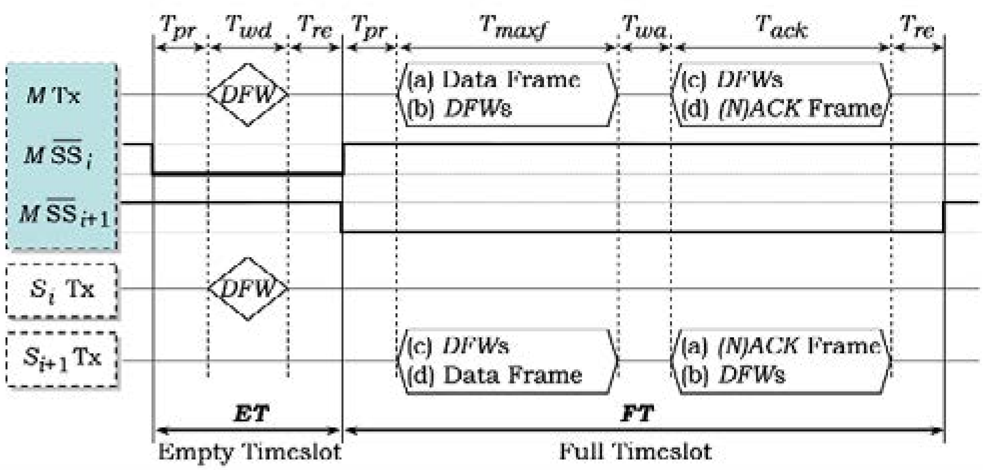

Figure 3-11. Scenarios of PARSECS data exchange with handshake.

Layer 3 protocols also implement and control the multi-peer master-slave communication through flexible TDMA (FTDMA) or classical TDMA mechanisms, which specify a pre-defined time interval, called timeslot, allocated to the communication between the master and each slave nodes, in turns. Their main focus is to provide highly predictable frame exchanges over the communication interface. As a result, the application on each slave will know exactly the time intervals when it can transact information over the interface. There are several techniques to improve bandwidth utilization of classical TDMA, while preserving communication predictability. One method, used in our prototype PARSECS implementation, is to allocate uneven timeslots, directly proportional to the estimated average data rates needed by the applications on each node. The "Empty Timeslot", which is much shorter than the normal timeslots, can also be used in various implementations of flexible TDMA techniques, in a way which is similar to the Byteflight [B35] and FlexRay [B38], [B39] protocols.

Layer 4: Application Interface

As the interface (API) of the PARSECS system to the applications running on each node, Layer 4 provides a set of specific functions and configuration parameters.

On the slave nodes, the API consists of:

- A configuration function (`CommConfig`), which reads the current communication parameters (such as the maximum length of the frames, in words) from the master node during the initial synchronization phase
- A reception function (`CommRx`), with the following parameters: receive data buffer (`*RxData`) and size (`*RxLength`)
- A transmission function (`CommTx`), with the transmit data buffer (`*TxData`) and size (`TxLength`) as parameters.

Additionally, the API receive and transmit functions on the master node have a parameter identifying the slave node related to the data to be transacted.

A thorough timing analysis of the information transactions over the communication interface is of key importance to providing a high level of predictability for the PARSECS system. As also depicted in Figure 3-11, the total length of a Full Timeslot which accommodates any of the previously discussed types of transactions can be calculated as a sum of the following time intervals:

$$FT = T_{pr} + T_{maxf} + T_{wa} + T_{ack} + T_{re} \tag{3-4}$$

The time intervals in (3-4) will be briefly presented and discussed in the following paragraphs, based on a real-life implementation of the PARSECS communication system for the Wireless Intelligent Terminals (WITs) of the CORE-TX platform [A9], [G2]. As detailed in the previous subsection, all the modules (i.e. the motherboard and the daughter boards) of a WIT are interconnected through an SPI backplane bus. Their own real-time operating predictability is supported by the HARETICK compact kernel [A1], [A3], [A4], [A8], [A21]. The WIT motherboard is the SPI master and each daughter board is an SPI slave. They all implement the first three layers of the PARSECS protocols as a single hard real-time task (*ModX*) [A2], as shown in Figure 3-12. This SPI ModX is scheduled and executed on each module with a period denoted as $\mathcal{T}_{SPI}$.

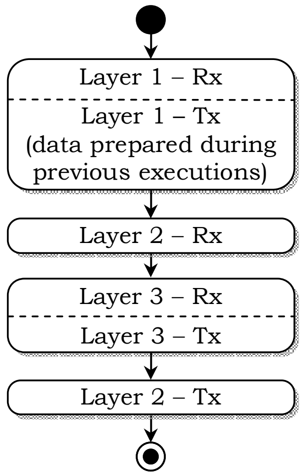

Figure 3-12. SPI ModX execution cycle (source [A27]).

Based on the execution period of the PARSECS SPI ModX, $\mathcal{T}_{SPI}$, all the time parameters in (3-4) can be calculated and further on, validated through experimental measurements. To provide the highest level of communication predictability, these parameters are calculated considering worst case operating scenarios.

T_{pr} *Transmission prepare time* is the interval starting when the application needs to send data over the interface, until the first word is ready to be sent to the physical layer.

In the worst case, the SPI ModX needs three execution periods (see also Figure 3-12) to accomplish this: (1) protocol automata switch to the frame transmit states, (2) the Layer 2 transmit automaton encodes the frame with the data to be sent, and (3) Layer 2 notifies Layer 1 the frame to be transmitted, through the WTT flag. This parameter does not depend on the length of the payload or on the type of protocol frame (packet or message):

$$T_{pr} = 3\mathcal{T}_{SPI} \tag{3-5}$$

T_{wa} *Time to wait for acknowledge* elapses, in the worst case, three execution instances of the PARSECS ModX (set Layers 2 and 3 to transmit states, evaluate if received frame is correct, and prepare transmission of ACK/NACK frames).

This parameter also does not depend on other external factors:

$$T_{wa} = 3\mathcal{T}_{SPI} \tag{3-6}$$

T_{ack} *Time of acknowledgement* depends on the length of the ACK/NACK special frames.

In the case of the PARSEC-P protocol, the acknowledgement packet is composed of five words (*SOF*, *LEN*, *ACK/NACK*, CRC_1 and CRC_2):

$$T_{ack} = 5\mathcal{T}_{SPI} \tag{3-7}$$

For the PARSEC-M protocol, the total length of the acknowledgement message is three words (*SOF*, *ACK/NACK*, *EOF*):

$$T_{ack} = 3\mathcal{T}_{SPI} \tag{3-8}$$

T_{re} *Time to notify results* is needed by the PARSECS protocols to notify the application with the results of the currently completed transaction.

This interval is of a single execution instance of the protocol ModX:

$$T_{re} = \mathcal{T}_{SPI} \tag{3-9}$$

T_{maxf} *Time of transmitting a frame of maximum length* is the only parameter directly affected by the maximum length m_{max} of the payload. For each word to be transmitted over the physical layer, an execution period of the PARSECS ModX is required. This parameter also depends on the type of protocol frame, i.e. packet or message.

In the case of the PARSEC-P protocol, based on (3-1) and considering the protocol word of 8 bits length (b = 8),

$$T_{maxf} = \left(2 + m_{max} + \left\lceil \frac{16}{8} \right\rceil\right)\mathcal{T}_{SPI} = (m_{max} + 4)\mathcal{T}_{SPI} \quad . \quad m_{max} \leq 255 \tag{3-10}$$

In a similar way and based on (3-3), we calculate this parameter for the PARSEC-M message-based protocol, in the worst case scenario:

$$T_{maxf} = (2m_{max} + 2)\mathcal{T}_{SPI} \quad . \quad m_{max} \leq 255 \tag{3-11}$$

Taking into account the above timing analysis, the maximum length of the Full Timeslot interval can be determined by replacing the values from (3-5) − (3-11) into (3-4). Thus, the Full Timeslot for a maximum length PARSEC-P packet frame is

$$FT_{PKT} = (3 + 3 + 5 + 1)\ \mathcal{T}_{SPI} + (m_{max} + 4)\ \mathcal{T}_{SPI} = 271\mathcal{T}_{SPI} \tag{3-12}$$

while, in the case of PARSEC-M message frames

$$FT_{MSG} = (3 + 3 + 3 + 1)\ \mathcal{T}_{SPI} + (2m_{max} + 2)\ \mathcal{T}_{SPI} = 522\mathcal{T}_{SPI} \tag{3-13}$$

The results of the extensive tests and experiments performed on the prototype implementation of PARSECS validate both the correct operation of the protocols, as well as the highly predictable behavior of the communication system, according to the theoretical timing analysis. The experiments have been conducted in various configurations of 1 + n nodes, i.e. 1 master and n slave nodes, where n varies from 1 to 4, both for the packet and message based protocols, and using several values for the execution period of the PARSECS ModX. Some of the most interesting experimental results obtained for the packet-based PARSEC-P and the message-based PARSEC-M protocols are depicted in Figure 3-13 and Figure 3-14, respectively. At a certain value of the $\mathcal{T}_{SPI}$ period, the actual, measured transfer rates approach the ideal limit asymptotically as the frame length increases, while at the same time, the timeslot length has a linear, monotonically ascending evolution. Therefore, an optimal communication performance can be obtained when using data lengths of 64 to 128 bytes: the actual data rate for message frames will be at 46.51% ÷ 47.76% of the ideal data rate (as compared to a maximum of 50% which can be obtained in the worst case), and for the packet frames at 78.95% ÷ 88.57% of the ideal rate (from 100% which could be obtained).

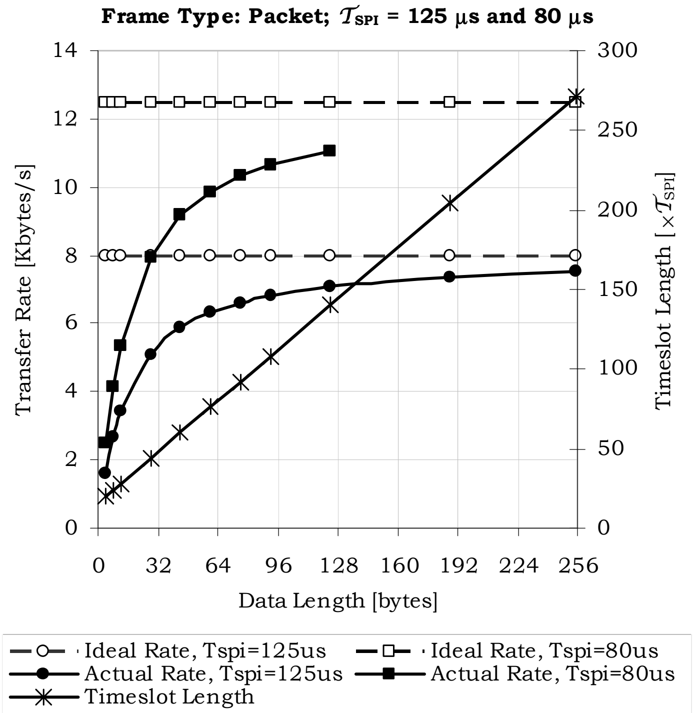

Figure 3-13. Measurements of main communication parameters for the PARSEC-P protocol, at $\mathcal{T}_{SPI}$ = 125 µs and $\mathcal{T}_{SPI}$ = 80 µs (source [A27]).

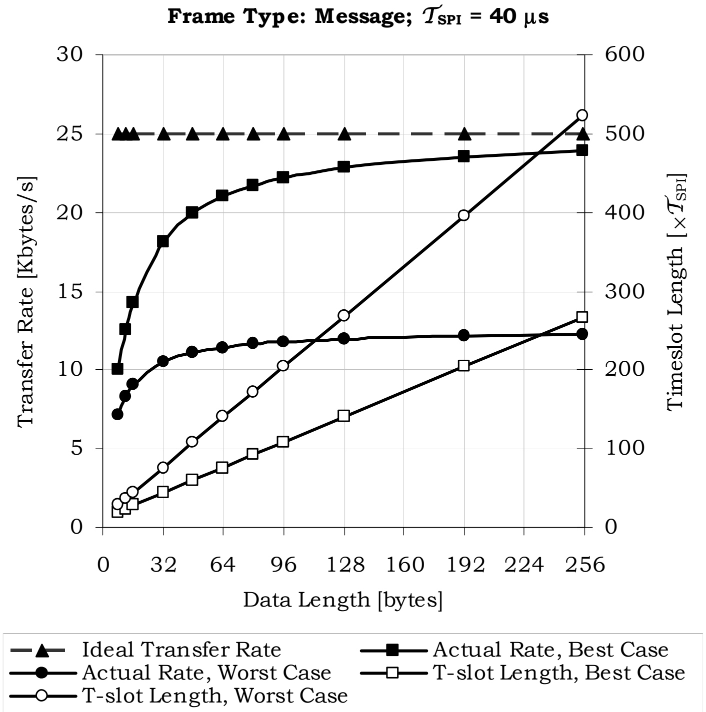

Figure 3-14. Experimental results for the PARSEC-M protocol, at $\mathcal{T}_{SPI}$ = 40 µs (source [A27]).

Another important performance parameter with respect to the communication predictability is the *jitter*. At the physical layer, the jitter is mainly generated by the differences between the time instants the PARSECS ModX writes the data to be transmitted into the SPI interface registers and the moments they are actually sent over the line. A maximum jitter of 0.87 μs has been measured for the PARSEC-P protocol packets of 128 bytes total length, with a $\mathcal{T}_{SPI}$ period of 80 μs. Thus, the maximum measured jitter is 0.0085% (corresponding to the theoretical transmission duration of the packets, of T_{fr} = 10240 μs). As a result, this type of jitter can be considered negligible.

On the other hand, although capable of higher transfer rates, the message-based PARSEC-M protocol introduces a significantly higher jitter. This type of jitter appears as the difference between the Full Timeslot durations in the worst case (i.e. each data word identifies a special frame word to be escaped) and in the best case (no data word is identical to a special word). Figure 3-14 also illustrates these two situations. The upper bound of the jitter for a given payload length of *m* words can be derived from (3-3) and (3-11), to

$$MJ_{\max}(m) = (2m + 2)\mathcal{T}_{SPI} - (m + 2)\mathcal{T}_{SPI} \quad (3\text{-}14)$$

As resulting from (3-14), the communication jitter in the case of the PARSEC-M protocol is directly dependent on the payload (frame) length. Nevertheless, it can be accurately predicted by considering the worst case, according to the previous timing analysis. In turn, this approach leads to using only at most half of the ideal transfer rate which could be obtained. The packet format transactions of PARSEC-P protocol do not have this problem.

A set of comparative performance analysis has been performed for the PARSEC-P protocol, against existing similar, relevant real-time communication solutions. The comparison considers a bus-type network topology, which interconnects several nodes, such that a full TDMA communication cycle consists of 4 timeslots. Three representative protocols have been chosen, each operating at their maximum transfer rates:

- *FlexRay* [B38], [B39], using the static segment for the communication of the four nodes, at 10 Mbps,
- *TTP/A* [B37], with a multi-partner data communication round configured for 1 master and 3 slave nodes, operating at 50 kbps, and
- *LIN* (Local Interconnect Network), with 1 master and 3 slaves, communicating at 20 kbps.

Due to its special feature which allows duplex communication between the master and a slave on each TDMA timeslot, the PARSEC-P system has been evaluated in a configuration of 5 nodes (1 master and 4 slave nodes). The SPI ModX period is set to 40 μs, thus giving a raw bitrate of 200 Kbps, for 1 byte per data word (although the capability of the SPI bus is 1.843 Mbps).

Figure 3-15 presents the comparative evaluation of the response time of the communication systems considered. The response time is defined as the minimum time interval necessary for one node (master) to poll all the other nodes. Figure 3-16 depicts the analysis of the communication efficiency at frame level, defined as the percentage ratio between the raw bitrate of the network for the payload transacted during the 4 timeslots, versus the overall bitrate required at frame level.

The experimental results show that the FlexRay system has the best figures at almost all performance parameters (except for the efficiency at frame level), while also operating at the highest interface bitrate. On the other hand, it is by far the most complex and expensive (e.g. it uses the SPI interface as one of the options to connect the FlexRay Bus Driver device to the node host controller). The PARSEC-P protocol has the best efficiency results, at the lowest costs, and outperforms the other two analyzed protocols, TTP/A and LIN.

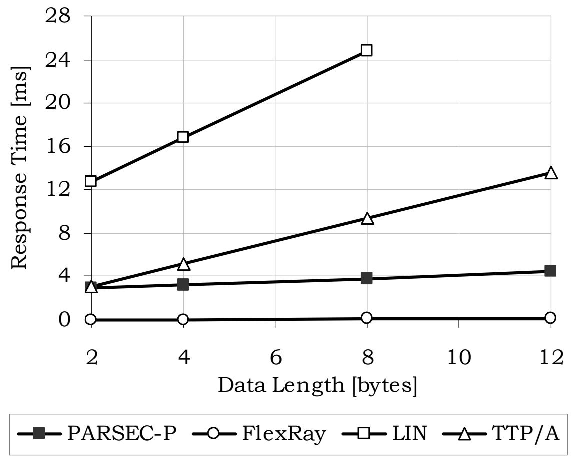

Figure 3-15. Comparison of the response time (source [A27]).

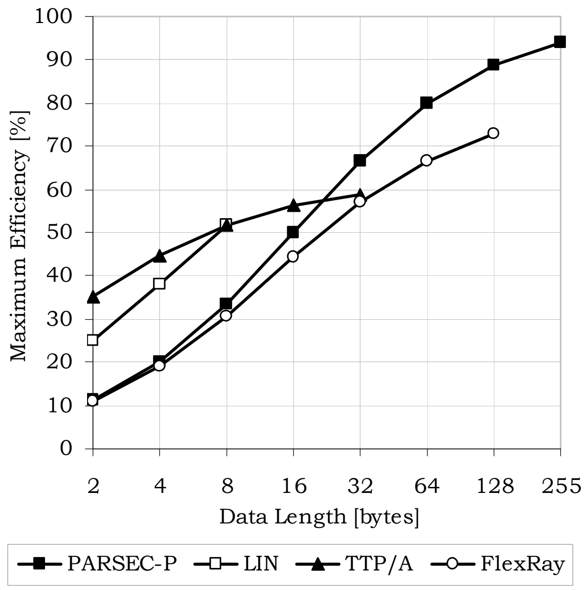

Figure 3-16. Analysis of communication efficiency (source [A27]).

4 Contributions to the Field of Collaborative Robotic Environments

A key field of interest of my post-doctoral research activity is *collaborative robotics*, with particular focus on several topics of high importance, such as

- robotic mobility management [A22], [A24], [A28],
- collaborative robotic platforms [A9], [A30], [G2], [G3],
- collective and emergent behavior patterns [A12], [A15], [A23], [A33], [M6],
- location management and robotic positioning [A38],
- collaborative robotic alignment techniques [A40],
- collaborative distance measurement [A26], [M7], and
- improving wireless sensor network performance with mobile nodes [A13].

The complex topic of robotic positioning and location management has been addressed by a research team composed of Professor Vladimir Cretu, PhD student Andrei Stancovici, MSc. student Sinziana Indreica, under my coordination and in close collaboration with Professor Voicu Groza from University of Ottawa, Canada. This research started during the development process of the CORE-TX platform [A9], with additional support from R&D grants [G2] and [G3]. We focused on the problem of autonomous and collaborative alignment, distance measurement, and positioning techniques for mobile robotic systems, under the following set of design and functional constraints:

a) indoor operation,
b) independence of fixed landmarks,
c) robustness and accuracy,
d) energy efficiency, and
e) low cost and complexity.

Robotic positioning and location management are aspects of high importance for the operation of autonomous, mobile robotic systems, with direct applicability in a large variety of fields, such as manipulation in difficult or dangerous areas, rescue operations, industrial robotics, environment monitoring, and space exploration. The approaches found in the literature can be classified as absolute or relative localization techniques, using fixed landmarks (beacons), active or passive landmarks, or based only on the mobile robots in the system.

The absolute localization techniques based on GPS (Global Positioning System) [B43] can provide the current position of a receiver from multiple transmitters (e.g. satellites), based on the Time-of-Flight (TOF) method. Nevertheless, such solutions can only be used outdoors and are expensive. An indoor version of the GPS system, discussed in [B44], consists of two receivers as fixed reference points and a transmitter which uses both ultrasonic and radio frequency signals. The distance from the transmitter to a receiver is calculated based on the delay between the received RF signal and the ultrasound waves. The two resulting distances are then used to calculate the location of the transmitter, through geometrical formulas. A Linear Kalman Filter is also used to minimize the errors and noise occurring in the measurements of the ultrasound signal.

Another relevant approach based on fixed landmarks is the Cricket Indoor Location System [B45]. It is able to operate in closed environments (e.g. indoors), based on at least three preinstalled ultrasonic transmitters and by combining radio-frequency and ultrasonic signals to calculate their Time-Difference-of-Arrival (TDOA). It has a good accuracy (1 ÷ 3 cm), but at the costs of system complexity and initial setup process. Furthermore, the location of the mobile robots will be available only within the environment defined by the range of the fixed landmarks. Using the power level of the received radio signal is proposed in [B46], to calculate the distance to the transmitter, based on the ZigBee protocol (IEEE 802.15.4). This system reaches a relatively poor accuracy, in the range of meters (2 ÷ 3 m).

The Building Positioning System [B47] proposes a technique similar to the GPS or the Cricket systems, with four fixed transmission beacons, to determine the position of a mobile device. Its accuracy is in the range of centimeters (approx. 5 cm), but the system has the common shortcomings of fixed landmark location approaches.

Several localization methods, based on passive landmarks, employ recognizing special features and geometric shapes within the environment. On one hand this type of landmark recognition is difficult, and, additionally, it requires a large database to store the landmarks as they are discovered [B48].

Hagisonic StarGazer [B49] is a location system for mobile robots, based on the analysis of infrared rays which are reflected by a passive landmark with a unique ID. First, the IR transmitter on the robot sends infrared beams to the fixed landmark attached to the ceiling of the room. The infrared rays are reflected from the landmark and reach the Stargazer, mounted on the robot. Based on a CMOS camera, Stargazer estimates the angle of incidence of the reflected IR waves and the distance between the robot and the landmark. Finally, geometric methods use these parameters to calculate the position of the robot in the room. The accuracy of the system can reach approximately 2 cm. The system can carry out 20 measurements per second. Its drawbacks are the high price and the reduced coverage area, ranging from 2.5 to 5 m.

Localization solutions based on relative landmarks have also been proposed, including the REWL system [B50], PhotoBeacon [B51] and the trilateral localization method, described in [B52]. Common problems of such techniques are poor adaptation to the environment, speed, scalability, accuracy, cost and fault tolerance.

4.1 Collaborative Robotic Alignment Algorithm

Ultrasonic signal is frequently used for distance calculation, due to its good directivity and convenient propagation speed. In robotic environments, Time-of-Arrival (TOA) and Time-Difference-of-Arrival (TDOA) methods employ ultrasonic devices, or a combination of ultrasonic and higher speed (e.g. radio frequency) signals, respectively, to detect and avoid obstacles or to measure the relative distance between two mobile robots [B53].

To increase the accuracy of distance measurements between two ultrasonic transducers, they must be properly aligned, i.e. they must face each other, along the straight line in between. As a result, the ultrasonic wave will fall inside the main reception lobe of the transducer, as close as possible to its peak. The impact misaligned transducers have on distance measurement is described in [B54], which show that the acceptable alignment angle must not deviate more than 10 degrees from the common direction.

The proposed robotic algorithm, [A40], is the first stage of a more complex procedure, which determines the relative distance between two mobile nodes (WITs) of the CORE-TX platform [A9], with the final goal to calculate the location of the nodes.

To support the location management of the WITs, their Perception/Sensor Module (SEM) has been specifically designed with an extension turret, containing two ultrasonic transducers (see Figure 4-1). Another important part of the module is the coprocessor ATxmega128A1 (Atmel Corporation), used for fast, multi-channel data acquisition and processing operations. It integrates a high performance 16 channel ADC along with multiple resources, such as 4 DMA channels, 8 timers, 24 PWM channels, 4 SPI interfaces and a large set of I/O ports. The extension turret is equipped with two similar transducers, used for both transmitting and receiving ultrasonic signals. The BPU-1640IOAH12 device (Bestar Electronics) has been selected, due to its convenient features, which include low cost, bidirectional operation, nominal frequency of 40 kHz, and maximum input voltage of 120 Vpp. To speed up the alignment process, these transducers are mounted back to back at 180 degrees on a rotating platform. The servo motor is a TowerPro SG-50 (Tower Pro) with the following specifications: weight 5 g, dimensions 21.5 × 11. 7 × 25.1 mm, speed 0.1 s/60 degrees (at 4.8 V), supply voltage 4 ÷ 6 V. The servo motor is driven by a PWM signal with a period of 20 ms and a variable duty cycle. Rotation is between 0 (minimum pulse duration) and 180 degrees (maximum pulse duration).

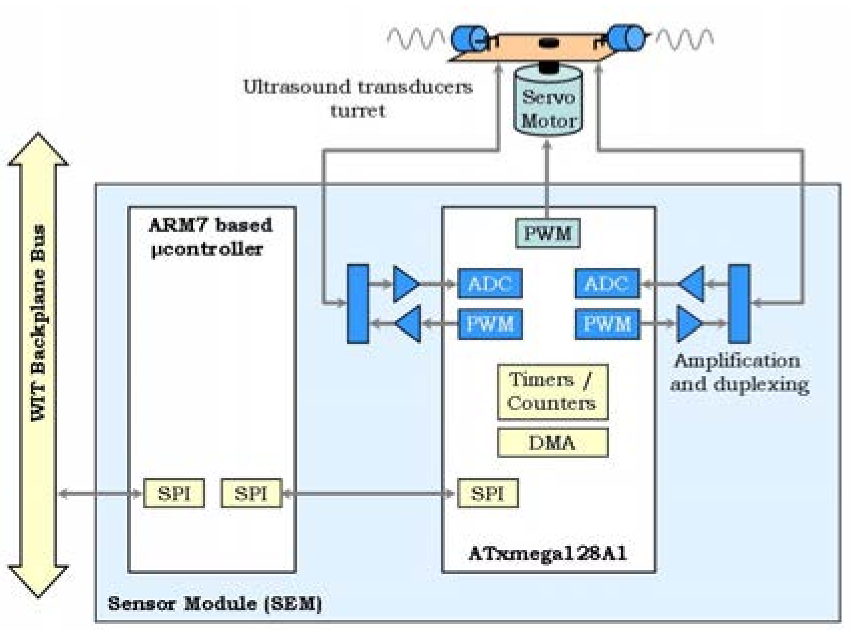

Figure 4-1. WIT Perception/Sensor Module with the ultrasound turret extension.

The proposed design, based on a turret support for the ultrasonic transducers, has several advantages when compared to other designs. On one hand, the rotation of the entire robot, during the alignment process, is avoided. As a result, the inherent positioning errors are eliminated, while the power consumption of the system is also significantly reduced. The increase of the alignment accuracy, at a higher process speed, is another advantage of this solution.

Correct alignment means the ultrasonic transducers of the robots are facing each other, as close as possible to the straight line between them (see Figure 4-2). The alignment algorithm uses a set of key parameters and angles describing the position and orientation of each WIT, with respect to its local reference system (Figure 4-3):

- α_{12} is the angle between the orientation axis (Ox_1) of the first robot (W_1) and the direct line between the two robots;
- φ_1 is the angle defined by the Ox_1 axis and the ultrasonic sensor axis of W_1;
- α_{21} is the angle between the orientation axis (Ox_2) of the second robot (W_2) and the direct line between W_1 and W_2;
- φ_2 is the angle defined by the Ox_2 axis and the ultrasonic sensor axis of W_2.

Therefore, the ideal alignment scenario is when

$$\alpha_{12} = \varphi_1 \ \wedge \ \alpha_{21} = \varphi_2 \tag{4-1}$$

In this case, the alignment error is 0.

The alignment procedure is based on the continuous measurement of the Sonar acoustic intensity, while using the wireless communication interface of the robots for the exchange of the required commands and messages. The alignment is initiated and coordinated by one of the robots, which will be the master (W_M), while the other robot, the slave (W_S), executes the commands received from the master through the wireless link. The master will operate in the Sonar receive mode and the slave in Sonar transmit mode. As the turrets of the two robots rotate, the master calculates the average strength of the ultrasonic signal received from the slave, at each rotation step of 1 degree. If W_M senses an increase of this average signal strength, from the previous rotation step, it will continue the procedure until a decrease will be encountered. Then, the two robots will change the rotation directions of their turrets to return to the previously detected maximum.

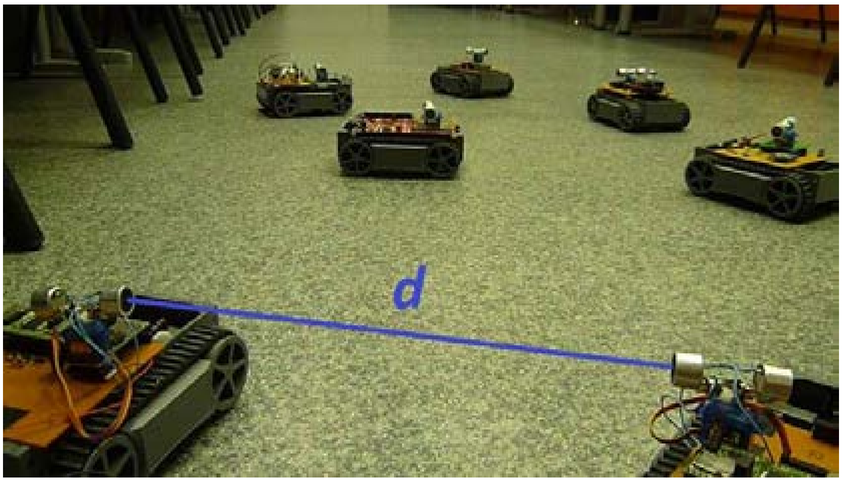

Figure 4-2. Inter-robot alignment process (source [M7]).

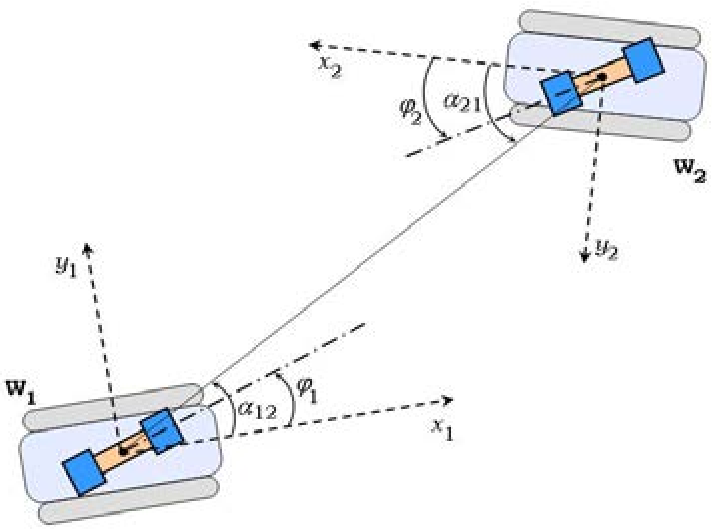

Figure 4-3. Main parameters of the alignment process (source [A40]).

The robotic alignment algorithm is presented in Code Listing 4-1. It starts with reading a predetermined number of ultrasound samples from the ADC. Next, the measured values are optimized by finding the peak amplitude of each period, applying a Kalman filter to reduce the noise (from the environment and from the measurement process) and comparing the results with each other to determine a global maximum. This global maximum (`Max_val`) is further used as the amplitude of the signal in the next steps. If the algorithm is not in the final phase of the process (`Pre_align != 0`), it determines the trend of the received ultrasound signal: if two consecutive increases are detected (Line 9 in Code Listing 4-1), `Flag_inc` is set and if there has been a previous decrease, the current stage of the algorithm is finished. On the other hand, if there are two consecutive decreases (Lines 14 and 15 in Code Listing 4-1), the direction of rotation changes and, if `Flag_inc` is set, `Flag_inc` will also be set.

In the last phase of the alignment (`Pre_align == 0` at Line 22 in Code Listing 4-1), the algorithm traces back the position with the highest measured values. Thus, if it detects an increase of the measured signal and the current value is greater than or equal to the stored peak, the process ends and the transducers are considered aligned. If, instead, a decrease is detected, the rotation direction is changed. In all cases, if the process does not end, the flow of the algorithm goes back to ADC readings.

An extensive set of experiments have been conducted in the DSPLabs to validate the proposed alignment technique, using the robotic system of the CORE-TX platform. The experimental setup consisted in several mobile robots (see, for example, Figure 4-2), out of which two of them were randomly chosen to perform the alignment and the distance calculation procedures for each experiment. The robots have been placed at a distance ranging from 100 mm to 3000 mm and, for each 100 mm in this range, a set of over 50 pairs of measurements have been performed. Before each measurement, the robots have been oriented in random directions with respect to each other.

Code Listing 4-1. Robotic alignment algorithm.

```
1:   Pre_align = 3

2:   repeat
3:     ADC read
4:     Find max sample per period
5:     Apply Kalman filter
6:     Find max sample per degree

7:     if (Pre_align != 0)
8:       Max_val = global max value

9:       if (double amplitude increase)
10:        Flag_inc = TRUE
11:          if (Flag_dec == TRUE)
12:          Pre_align = Pre_align - 1
13:        end if

14:      else                          // Amplitude not increased.
15:        if (double amplitude decrease)
16:          if (Flag_inc == TRUE)
17:            Flag_dec = TRUE
18:          end if
19:          Change turret rotation
20:        end if
21:      end if

22:    else                            // Pre_align == 0. Final stage
                                       //  of the alignment algorithm.
23:      if (amplitude increase)
24:        if (Amplitude >= Max_val)
25:          break;                    // End condition of alignment.
26:        end if

27:      else                          // Amplitude not increased.
28:        if (amplitude decrease)
29:          Change turret rotation
30:        end if
31:      end if
32:    end if
33:  end repeat
```

Figure 4-4 presents several periods of the raw received ultrasonic signal, at the input of the ADC, after being amplified (see Figure 4-1). This step can be identified at Line 3 in Code Listing 4-1. Further on, the signal peaks (which occur every 25 μs) are extracted and interpreted as the received Sonar signal (Line 4 in Code Listing 4-1). As depicted in Figure 4-5, this pre-processed Sonar signal contains a relatively significant amount of noise, which can be reduced by applying a Kalman filter (Figure 4-6).

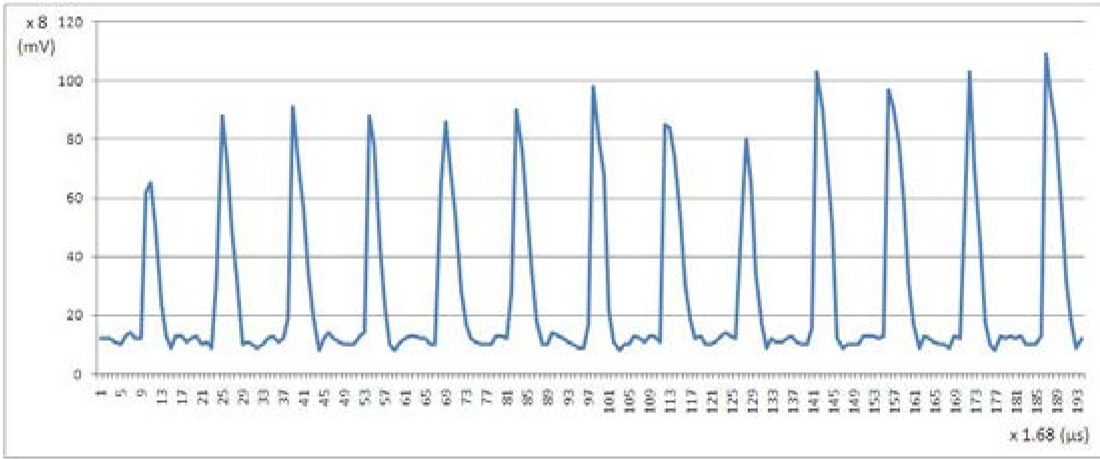

Figure 4-4. Received ultrasonic signal, after amplification (source [M7]).

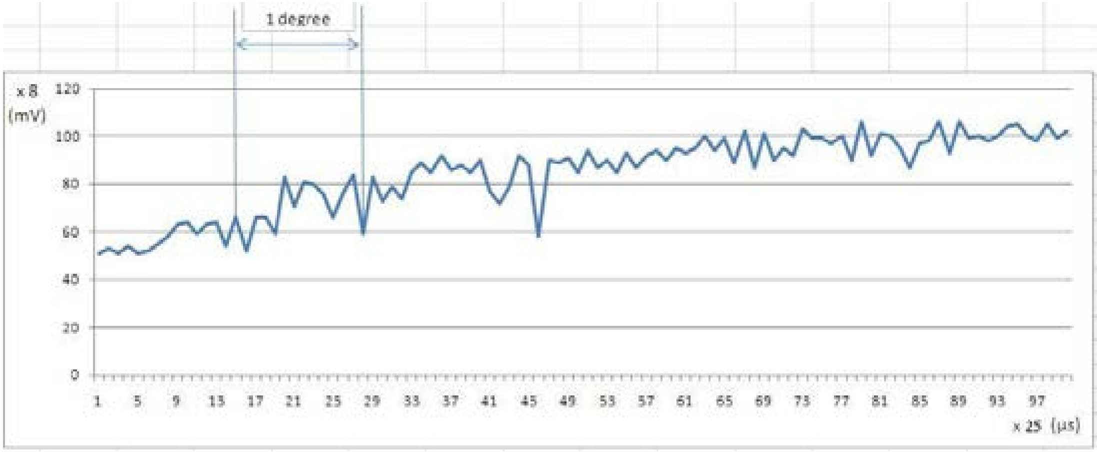

Figure 4-5. Received ultrasonic signal, after extracting its peaks (source [M7]).

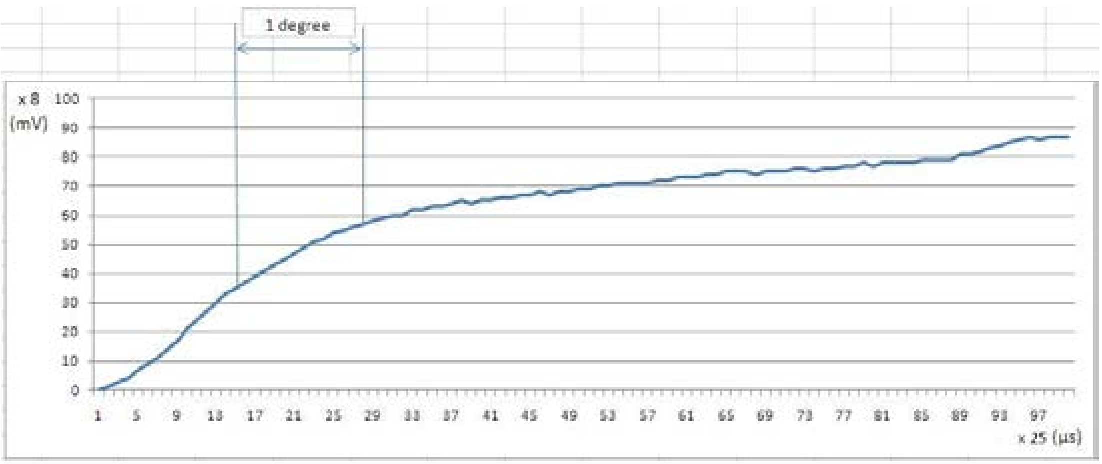

Figure 4-6. Received ultrasonic signal, after Kalman filtering (source [M7]).

The results for a full scan of the ultrasonic transducer, i.e. a rotation of 180 degrees, are presented in Figure 4-7, both with and without applying the Kalman filter. The target robot is detected between 93 and 135 degrees, with a maximum of the Sonar signal occurring at approximately 116 degrees.

Figure 4-8 presents some of the most interesting experimental results for the alignment process. The accuracy varies even for the same distance between the robots, due to the frequent changes in the rotation of the turrets and to the different time instances the transmitted ultrasonic signal is acquired. With few exceptions, the alignment correction angle remains lower than 10 degrees. The results presented in Figure 4-8 also show the improvement of the alignment accuracy with the increase of the distance between the two robots.

Time is also a key parameter for the effectiveness assessment of the alignment process. To speedup the evaluation of the proposed algorithm and to include a larger range of scenarios, a custom designed simulator has been implemented, called *SimAllign*, using the C# programming language and the Windows Presentation Foundation framework.

SimAllign provides a graphical user interface with multiple configuration possibilities and an output area to visualize and evaluate the behavior of the simulated robots. The user interface has the possibility to model and draw the robots, to add a new robot, select an "active robot" (the master, W_M, for the alignment process), move the "active robot", select the rotation speed of the transducer turrets of each robot, and to visualize the entire alignment process. The time base of the simulations is provided by a special purpose timer, which has to be accurate and fast. Furthermore, due to the fact that the position of the transducer turrets must be tracked at 1 degree accuracy, an acceptable resolution for the time will range between 1 and 10 ms tick, which usually is a challenge for Windows-based applications. As a result, for a good accuracy, the values for the alignment time cannot be used individually, but as an average of multiple similar results [A40].

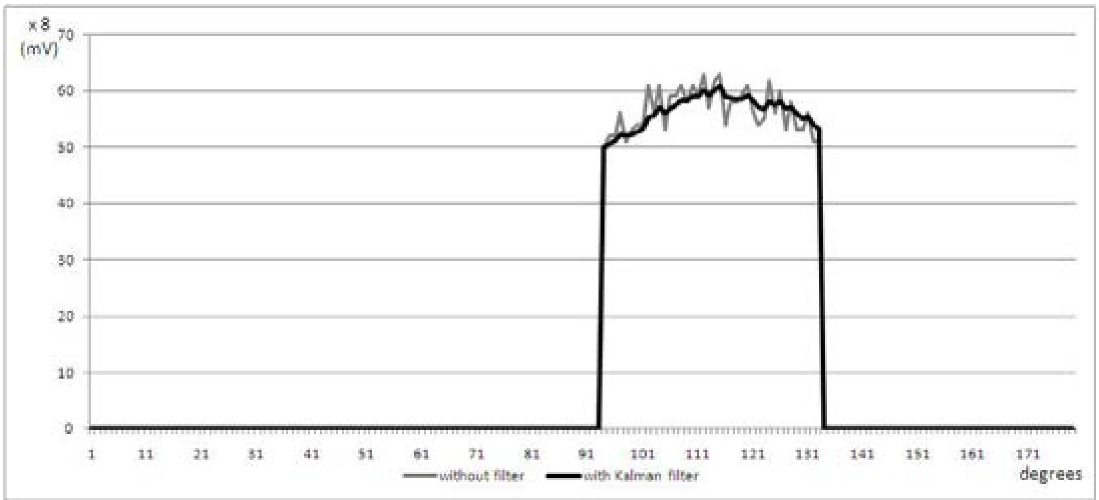

Figure 4-7. Received (pre-processed) ultrasonic signal for a 180 degree rotation (scan) of the transducer (source [M7]).

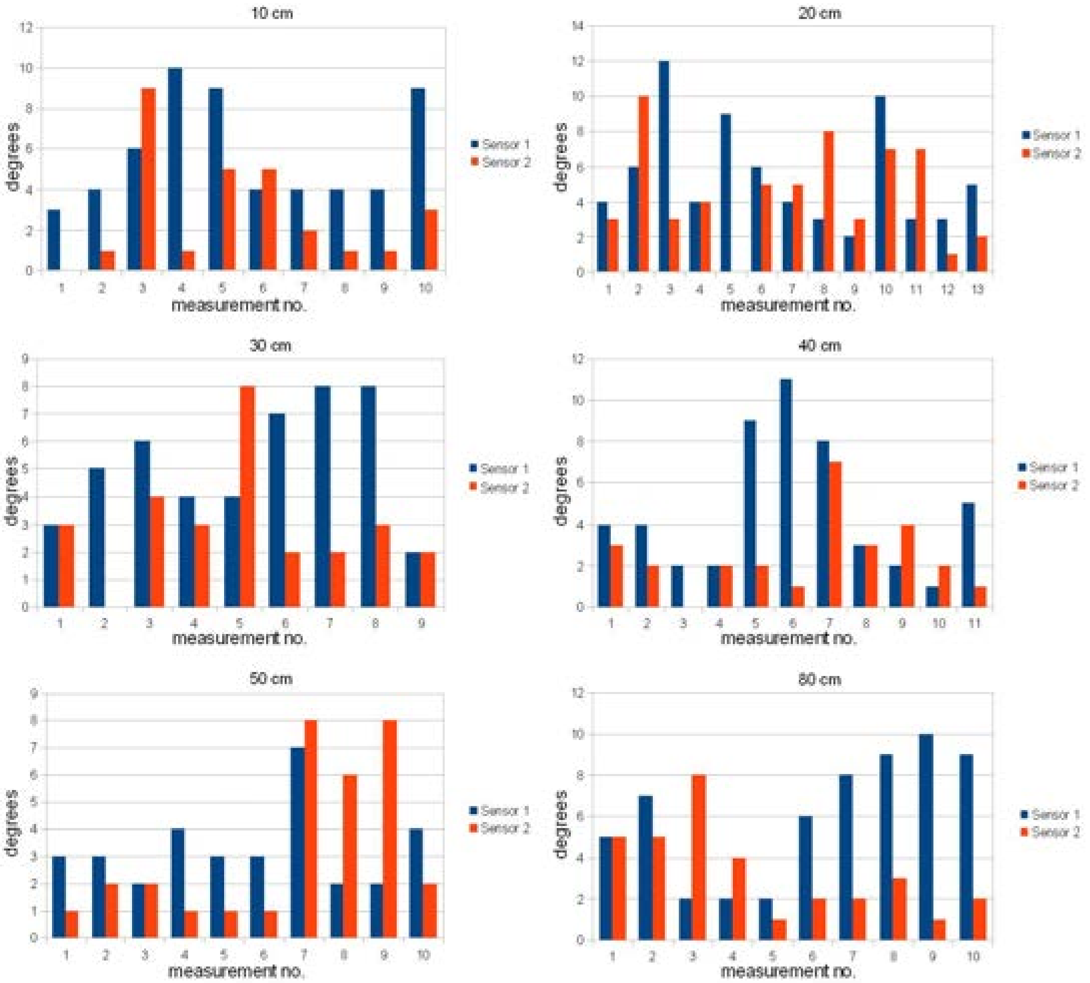

Figure 4-8. Maximum variation of the correction angle for the experimental alignment procedure, at various distances between robots (source [M7]).

The simulation scenarios basically consider the alignment of two robots, W_1 and W_2 (see also Figure 4-3), where W_1 is the reference robot and W_2 is positioned in 8 different start positions (denoted with t_1 to t_8 in Figure 4-9). Table 4-1 shows a summary of the simulation results, using an average value for the alignment times. Extensive simulations have also been performed using different rotation speed ratios for the transducer turrets of the robots, during the alignment process. Figure 4-10 depicts the alignment times for the following speed ratios (W_1/W_2): 1/1 (upper left diagram), 2/1 (upper right), 3/1 (bottom left) and 4/1 (bottom right). As resulting from the simulations, the optimal ratio is 2/1 [A40].

Table 4-1. Simulation results for the alignment time averages.

	Alignment time averages [ms]			
	t_2	t_3	t_6	t_7
Same rotation direction of turrets	379	741	382	767
Opposite rotation direction of turrets	728	426	723	448

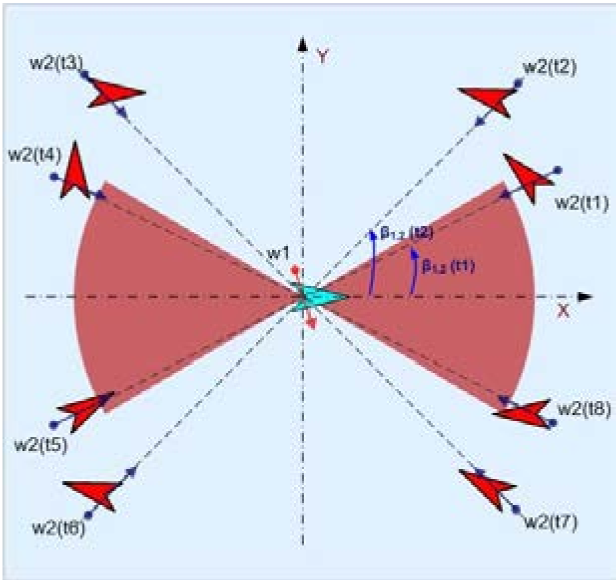

Figure 4-9. Simulation scenarios for the alignment performance evaluation.

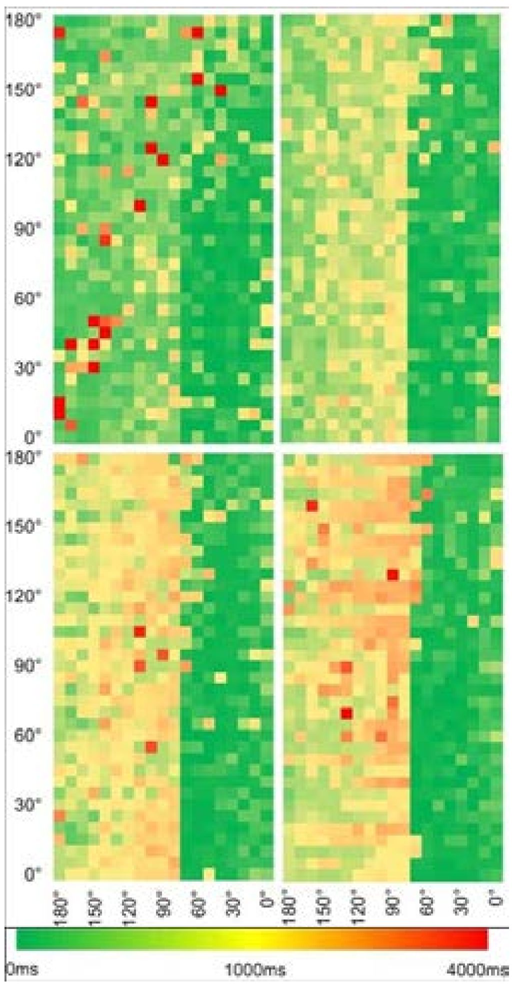

Figure 4-10. Alignment times for different turret speed ratios: 1/1 (upper left diagram), 2/1 (upper right), 3/1 (bottom left) and 4/1 (bottom right).

4.2 MTDOA Inter-Robot Distance Measurement Technique

Based on the classical Time-Difference-of-Arrival method, our research team has developed and tested an inter-robot distance measurement technique, called *MTDOA* (Modified TDOA) [A26]. This method adds a set of improvements, to overcome some the problems which generally occur when using several wireless communication interfaces. This is especially the case of communication interfaces with a consistent protocol stack, such as the ZigBee protocol (IEEE 802.15.4), used in our CORE-TX robotic platform. In such cases, there are important delays and time jitter introduced by the protocol stack, both during transmission and reception, which will corrupt the TDOA results. Moreover, the transmission delays are significantly longer than the reception counterparts and have also a much larger standard deviation. As a result, the MTDOA technique focuses only on wireless reception for the two robots involved in the distance measurement process.

The operating principle of the MTDOA method is based on the proposed inter-robot alignment technique described in the previous section, as a prerequisite. As seen in Figure 4-11, when robot R_1 needs to determine its distance to another robot, R_2, it initiates first the alignment procedure, as the master, with R_2, which becomes the slave. After R_1 is correctly aligned with R_2, it will search for a third robot, R_C, to play the temporary role of MTDOA coordinator. The communication is carried out using the wireless interfaces of the robots. Further on, R_C sends a wireless message indicating the start of distance measurement procedure. At the instance of its reception, R_2 sends an ultrasonic signal burst towards R_1 while, *at approximately the same moment*, R_1 starts counting the time elapsed until the reception of the ultrasonic signal. This delay is directly proportional to the distance between the two robots.

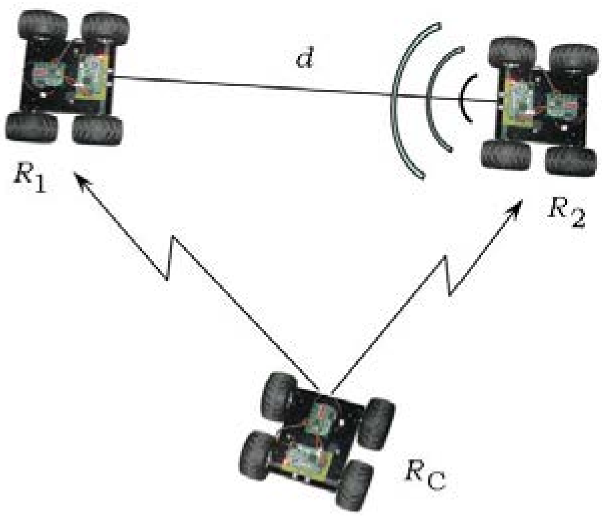

Figure 4-11. Principle configuration for the MTDOA method (source [A26]).

The term "at approximately the same moment" has been used above due to the possible variations of the time needed for different robots to receive and process the message over the wireless interface protocol stacks. The upper bound for these time variations, denoted here with θ_W, can be empirically established. Consequently, the distance d between R_1 and R_2 results as

$$d = c_{air}(\Delta t - \theta_W) \tag{4-2}$$

where c_{air} = 343.4 m/s is the velocity of acoustic waves in air at room temperature and normal pressure, Δt is the time elapsed from the moment R_1 receives the radio message from R_C until the reception of the ultrasonic signal from R_2, and θ_W is the maximum value of the message reception delays at the wireless interface.

A large number of experiments and tests has been conducted in the DSPLabs by our research team, to evaluate the performances of the proposed MTDOA distance measurement technique. The experimental setup consisted in three mobile robots, out of which two of them were randomly chosen to perform the distance calculation for each experiment. The robots have been placed at a distance ranging from 100 mm to 3000 mm and, for each 10 mm in this range, a set of over 50 pairs of measurements have been performed. Before each measurement, the robots have been positioned in random directions with respect to each other, to also verify the robot alignment procedure discussed in the previous section.

The difference between the packet reception times for the XBee modules of the two robots involved in the distance measurement procedures has been measured with a logic analyzer. This difference varies randomly each time, mostly due to the operation of the XBee modules and their corresponding protocol stack. We obtained a maximum value of θ_W = 86 µs, which corresponds to a distance measurement error of 30 mm. Table 4-2 and Figure 4-12 present the experimental results obtained for the MTDOA technique. A statistical analysis of the data, in terms of maximum absolute and relative errors, has also been performed, as shown in Figure 4-13. The maximum absolute error, which has a value of 7.3 cm, has been obtained when the two robots were positioned at a distance of 100 cm from each other.

Table 4-2. Distance measurement results for the MTDOA method (source [A26]).

Real distance [mm]	Measured distance [mm]			Procedure duration [µs]
	Min	Average	Max	
100	36	71	101	559
200	164	198	243	929
300	281	324	358	1296
400	394	423	470	1584
500	494	522	554	1872
600	546	602	661	2105
700	674	705	736	2405
800	789	817	855	2731
900	882	919	966	3028
1000	937	1003	1073	3273
2000	1931	1983	2046	6127
3000	2948	2978	3023	9024

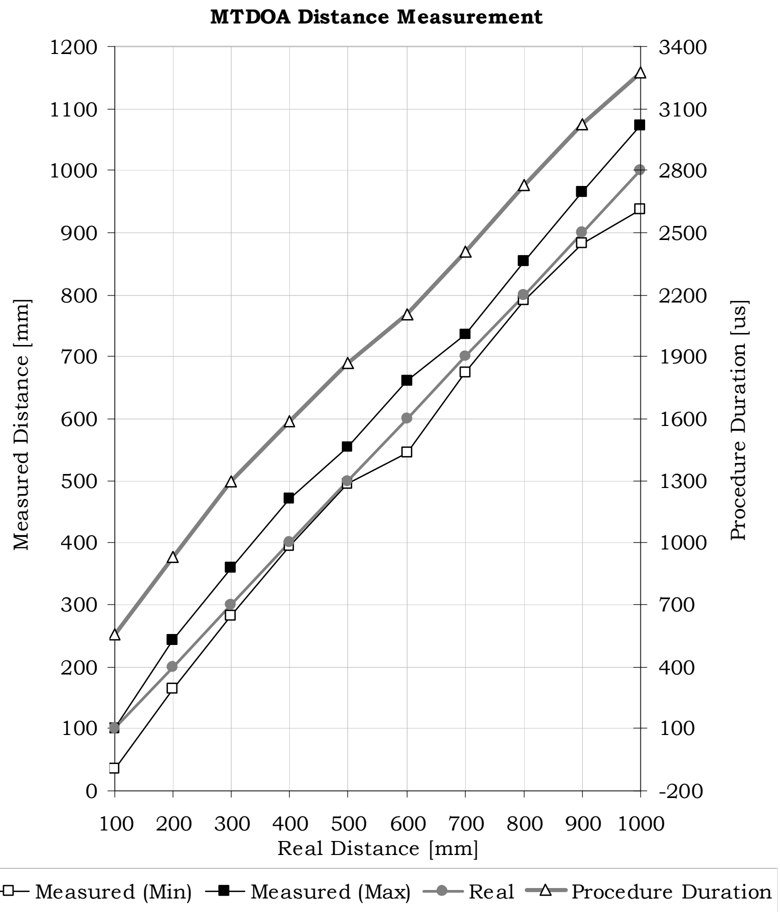

Figure 4-12. MTDOA measured distance and procedure duration vs. real distance (source [A26]).

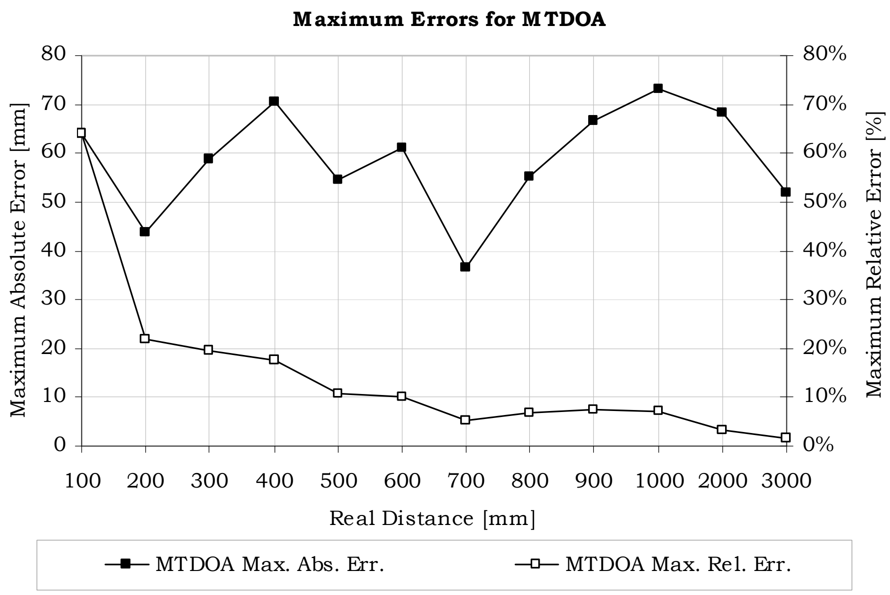

Figure 4-13. Maximum absolute and relative errors for the MTDOA method.

The measurement results and error analysis show that, although the MTDOA method generates relatively high absolute errors, the average follows closely the real distance and has a linear evolution, after the corresponding calibration adjustments. Moreover, the maximum relative errors tend to decrease with the measured distance. This is another indication of the predominant contribution of the XBee operating delays which influence the results.

Synthetically, for inter-robot distances of up to 3000 mm, the MTDOA performance is defined by a worst case accuracy of 7.3 cm and a maximum procedure duration of around 9 ms, thus allowing a theoretical rate of 111 measurements per second.

An improvement to this technique could be to perform multiple measurements for a particular position of the robots, and, if the results differ significantly, to repeat the process.

4.3 CTOF Inter-Robot Distance Measurement Method

A second distance measurement method has been proposed by our research team, to further increase the accuracy and the performance of this important component of robotic mobility management. CTOF, Combined Time-of-Flight, is derived at its principle from the classical TOF techniques [A26], [M7]. From the beginning it proposes several procedural improvements over the MTDOA method:

a) CTOF does not require an additional third robot as coordinator, and
b) it does not depend on the delays implied by the wireless communication interfaces of the robots.

The operating principle of the CTOF method is illustrated in Figure 4-14. The procedure is initiated by robot R_1, by sending a "START" wireless message (denoted with "WMes 1" in Figure 4-14) to its peer, R_2. Robot R_2 acknowledges this message and starts its part of the procedure with the "SONAR REQ" message, while simultaneously launching its own Sonar Receive Task. As a response to the "WMes 2" message, R_1 starts the Sonar Transmit Task and activates the timer (Δt) which will measure the duration of the entire procedure. Upon receiving the ultrasound signal, R_2 activates a delay timer with a predefined value, δ_U, which is empirically determined to cover the total duration of the ultrasonic transmission from R_1. After the δ_U delay, R_2 sends a "SONAR START" message to the first robot and starts a second timer, with a value δ_W empirically established to cover the maximum communication delay over the wireless link and the corresponding interfaces. Upon receiving the "SONAR START" message, R_1 launches its Sonar Receive Task. After the δ_W timer expires, R_2 starts its Sonar Transmit Task and sends the corresponding ultrasonic signal towards R_1.

Finally, when R_1 receives the signal, it stops the timer to produce the Δt period. As a result, the Δt interval contains the two predefined delays, δ_U and δ_W, and twice the propagation delay of the ultrasound signal, from R_1 to R_2 and backwards.

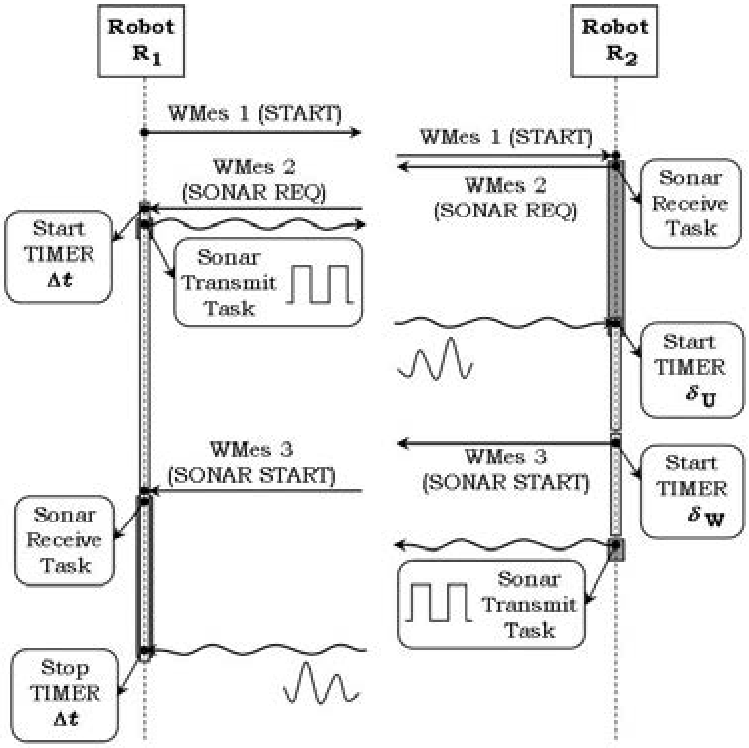

Figure 4-14. Operating principle of the CTOF method (source [A26]).

Based on these three components of the Δt period, i.e. δ_U, δ_W and the propagation delay, the distance between robots R_1 and R_2 can be calculated as

$$d = \frac{c_{air}(\Delta t - \delta_U - \delta_W)}{2} \tag{4-3}$$

where c_{air} is the velocity of the ultrasound waves in air, at room temperature and normal pressure (c_{air} = 343 m/s).

As the ultrasonic bursts are detected at reception using a threshold-based method and taking into account the fact that the ultrasonic measurements are not perfectly linear, we introduced an additional calibration offset in (4-3), to improve the detection accuracy:

$$d = \frac{c_{air}(\Delta t - \delta_U - \delta_W - \theta_{UC})}{2} \tag{4-4}$$

The θ_{UC} parameter in (4-4) is the ultrasonic signal calibration offset and has an experimentally determined value. In our experiments, θ_{UC} has been established at a value of 290 μs.

To evaluate the performance of the proposed CTOF method, a set of experiments has been conducted in the DSPLabs. In a similar way as in the case of the previously discussed MTDOA technique, the experimental setup consisted in three mobile robots, out of which two of them have been placed at distances ranging from 100 mm to 3000 mm. For each 10 mm in this range, a set of over 50 pairs of measurements have been performed. Table 4-3 and Figure 4-15 present the experimental results obtained for the CTOF procedure.

Table 4-3. Distance measurement results for the CTOF technique (source [A26]).

Real distance [mm]	Measured distance [mm]			Procedure duration [µs]
	Min	Average	Max	
100	92	96	99	20849
200	199	201	207	21461
300	298	300	303	22037
400	401	404	410	22643
500	504	508	515	23249
600	604	607	612	23825
700	700	706	710	24402
800	803	807	813	24990
900	906	911	916	25596
1000	1013	1019	1026	26225
2000	2024	2033	2043	32130
3000	3018	3031	3047	37943

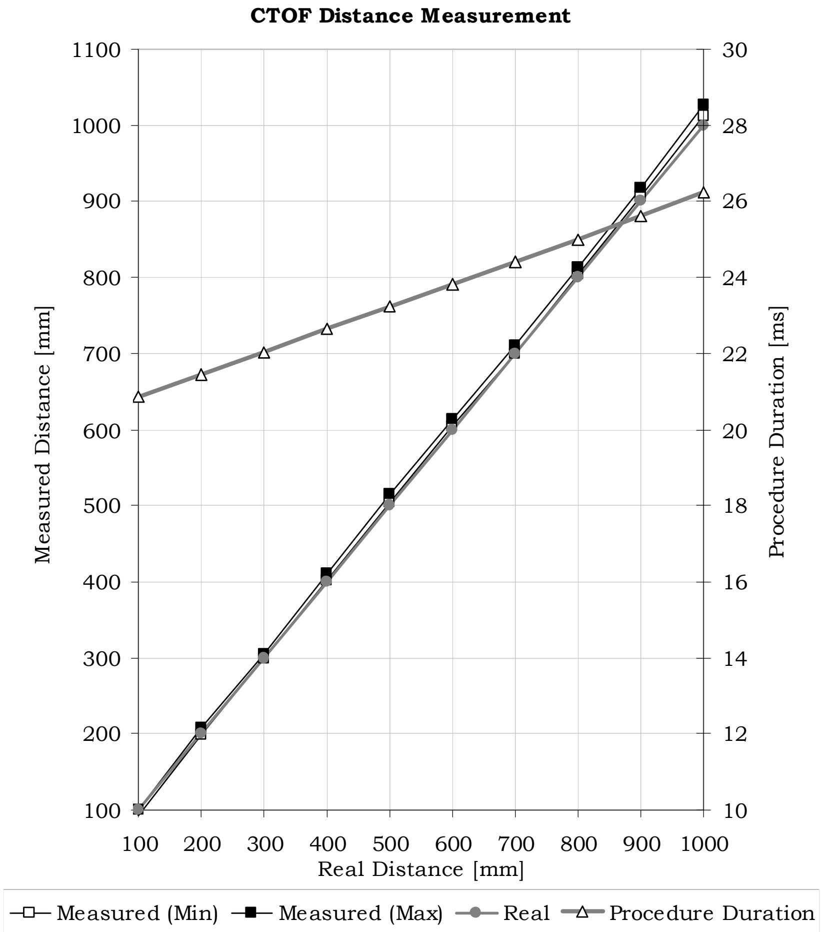

Figure 4-15. CTOF measured distance and procedure duration vs. real distance (source [A26]).

Figure 4-16 presents a comparative statistical data analysis for the CTOF and MTDOA distance measurement techniques, in terms of maximum absolute and relative errors. As expected, the CTOF method behaves much better than the MTDOA procedure. After the necessary calibrations, its measurement characteristics are linear and follow very closely the real distance. The corresponding maximum errors have also a natural evolution, as seen in Figure 4-16. This is a direct consequence of the independence of this technique from the random delays introduced by the wireless modules. The maximum absolute error has been reached when the two robots were positioned 300 cm apart from each other, and had a value of 4.8 cm.

Overall, the experimental results indicate that the CTOF method, with its accuracy of 4.8 cm for distances of 3 m and its linear behavior, outperforms the MTDOA and other similar techniques which are applied in state of the art location monitoring systems. The only drawback is the procedure duration, which is roughly four times longer in the case of CTOF as compared to the MTDOA method. Nevertheless, at its maximum duration of 38 ms, the procedure allows a theoretical rate of 26 measurements per second.

To further improve the accuracy of the CTOF distance measurement method, a Kalman filter has been applied to various numbers of repetitive measurements for the same distance to be determined. Some comparative distance evaluation results, with and without filtering, are exemplified in Figure 4-17, for a real distance of 1000 mm between the two robots. The results are very good in terms of accuracy, as can be seen from Table 4-4.

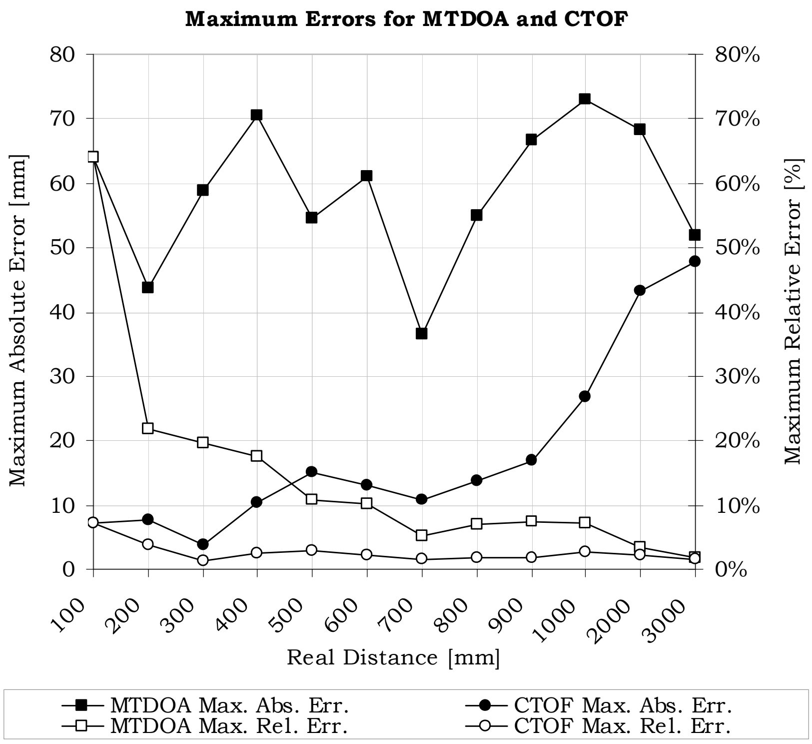

Figure 4-16. Comparative statistical data analysis for the CTOF and MTDOA methods (source [A26]).

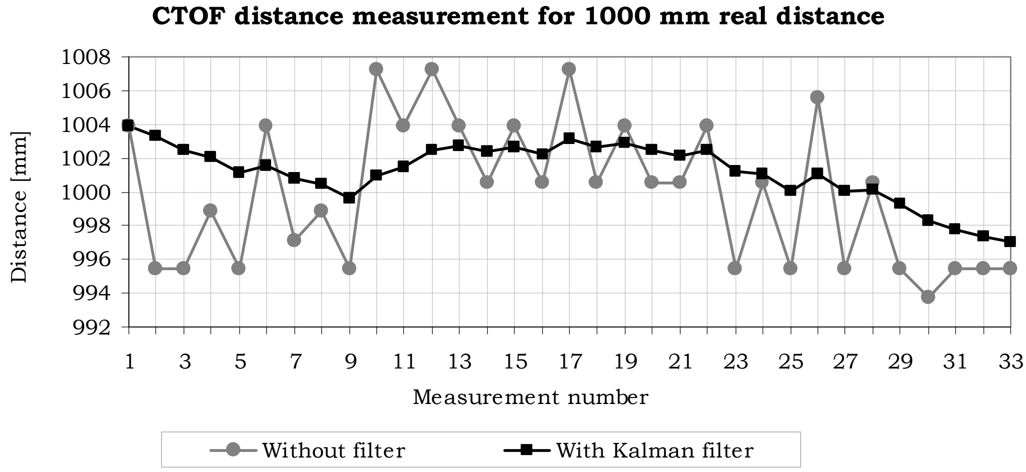

Figure 4-17. CTOF distance measurements with and without Kalman filtering, for a distance of 1000 mm between robots.

Table 4-4. Distance measurement results for the CTOF method with Kalman filtering (source [M7]).

Real distance [mm]	Measured distance [mm]			Procedure duration [µs]	Error reduction with filtering [%]
	Min	Average	Max		
100	98	100	101	208 ÷ 688	66
200	198	200	205	215 ÷ 708	29
300	298	300	301	220 ÷ 727	62
400	397	399	401	226 ÷ 747	50
500	498	500	508	232 ÷ 767	63
600	598	599	601	238 ÷ 786	68
700	697	699	703	244 ÷ 805	19
800	796	800	802	250 ÷ 825	56
900	897	899	901	256 ÷ 845	56
1000	997	1001	1004	262 ÷ 865	49
2000	1997	2002	2006	321 ÷ 1060	40
3000	2993	3000	3006	379 ÷ 1252	57

As resulting from the experiments, an accuracy of 1 cm can be achieved for distances of 3 m, with the proposed CTOF method and by applying the Kalman filter to repetitive distance measurements, without the need of fixed landmarks. The disadvantage is the time of measurement, which increases for repetitive measurements. From the experiments we conclude that the system provides optimal results for approximately 10 repetitive measurements.

4.4 Collaborative Localization Methodology for Autonomous Robots

Based on the previous researches and results in the field, a location management and robotic positioning methodology has been developed in the DSPLabs by our team [A38]. In particular, this methodology heavily relies on the collaborative inter-robot alignment and the CTOF distance measurement techniques, which have been presented in the previous sections.

Formally, the methodology considers a network composed of *n* robotic and/or sensing nodes

$$\mathbf{W} = \{w_i(d_i, r_i) \mid i = 1..n\} \tag{4-5}$$

where d_i is the ultrasonic range and r_i, the wireless communication range of node w_i. At any time instance t, the network in (4-5) is partitioned into the following subsets:

$$\mathbf{W}(t) = \{w_1, \mathbf{S}(t), \mathbf{U}(t)\} \tag{4-6}$$

The first type of nodes in (4-6) is the *coordinator node*, w_1, which is set up and configured at the deployment and initialization phases of the network. Among other important functions, it will establish the *home reference system* for the relative positioning of the other nodes in the network. **S**(*t*) is the subset of *settled nodes*, or *satellites*, at the instance *t*. The satellites are the nodes for which their location has been determined at time *t*, relative to the home reference system, based on this methodology. **U**(*t*) is the subset of *unknown nodes*, i.e. nodes with unknown location at the moment *t*. The main goal of the localization system is to allow the unknown nodes to estimate their position within the network and, thus, to reduce **U** towards a void subset, at a certain moment τ:

$$\mathbf{W}(0) = \{w_1, \varnothing, \{w_2, w_n\}\} \longrightarrow \mathbf{W}(\tau) = \{w_1, \{w_2, w_n\}, \varnothing\} \tag{4-7}$$

Based on the ultrasonic and the wireless ranges of each node w_i (d_i and r_i, respectively), the methodology defines a particular set of color zones and lists:

- *Green zone* defines the area of ultrasonic range for w_i, area of radius d_i. The *green list* contains all the other nodes located into the green zone of w_i, at some time instance. With any node within its green list, w_i can perform the specific alignment [A40] and distance measurement procedures [A26], [M7], proposed by our research team and briefly described in the previous sections.
- *Yellow zone* is the wireless communication range of w_i, defined by the radius r_i. Similarly, the *yellow list* contains all the other nodes located into the yellow zone of w_i, at some moment.
- *Red zone* and the *red list* contain all the other nodes which are not in the other two zones and lists, respectively, relative to a particular node w_i, at a certain time instance.

Each node w_i has its *local system* of Euclidean coordinates, defined by the pair $(x_i, y_i) \in \mathbf{R}^2$. This local x_iOy_i system is directly related to the current position and orientation of w_i: the origin is the geometric center of node w_i and the Ox_i axis lies over the orientation direction of w_i. The *home reference system*, xOy, established at the coordinator node level (w_1), is added by this methodology to the total of n local reference systems during system initialization. The home reference system is used by the network to translate the position coordinates and the orientation angles of the settled nodes (satellites) from their local systems of reference.

A special purpose property of localization of the nodes is introduced by this methodology. The *localization confidence*, $\xi \in \mathbf{N}$, measures the significance and reliability of the position coordinates of a network node. All the unknown nodes have the location confidence $\xi = 0$ and, as a particular node gains a higher confidence value, its coordinates are considered more significant in the overall localization methodology.

An overview of the basic phases of the proposed methodology will be outlined in the following paragraphs, using as a case study the robotic environment depicted in Figure 4-18. The scenario in this figure considers a network of six robotic nodes, out of which w_6 is currently moving (from moment t_1 to t_3).

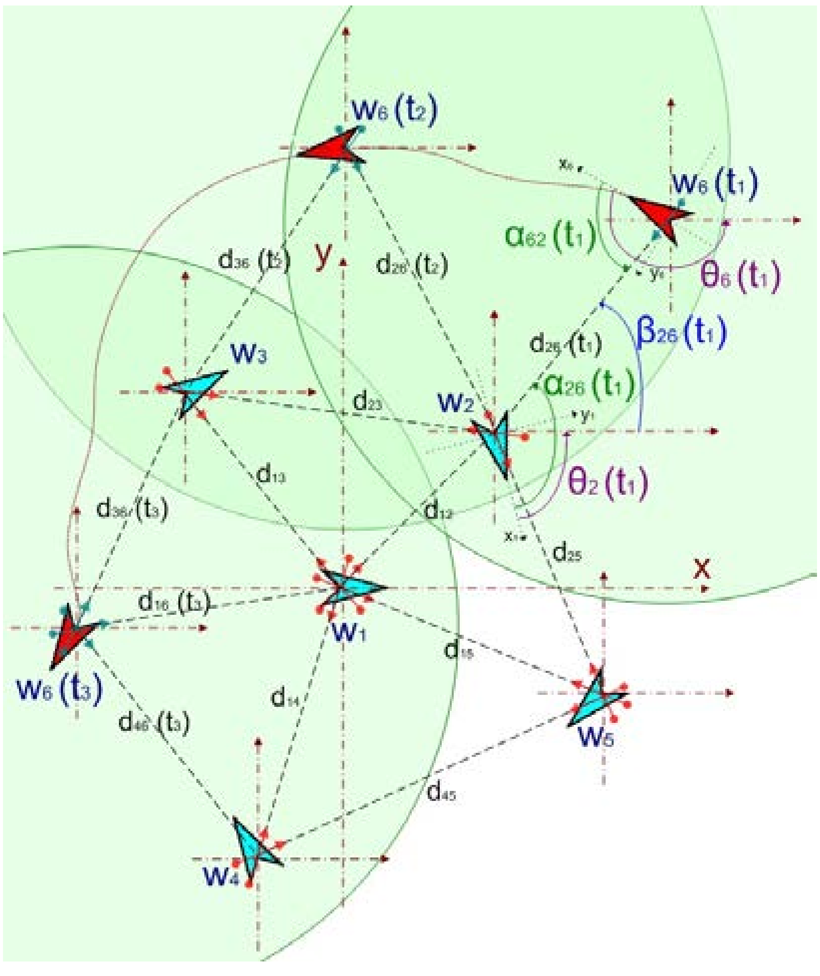

Figure 4-18. Case study robotic environment for the collaborative localization methodology (source [A38]).

a) System initialization

Generally, in applications such as rescue operations, manipulation in dangerous environments, space exploration and probing, where location management has an important role, there are a set of requirements to initialize and calibrate the localization system.

During this phase, robot w_1 is set as a coordinator node and the home reference system *xOy* will be established according to the position and the orientation of w_1.

b) Localization of an unknown node

Any robot entering the network (through deployment and power up or by moving within the network range) starts to send a broadcast wireless message to discover all robots in the system. For example, w_2 in Figure 4-18 is initially an unknown node. It will send broadcast messages and, upon receiving the acknowledgment from w_1, it sends a message to w_1 requiring the localization procedure.

The localization of w_2 starts with the alignment process, followed by the angle estimation and distance measurement procedures. These operations will be started only if w_1 and w_2 are within each other's green lists (within their respective ultrasonic ranges).

Further on, the position of w_2 is determined in both local and home reference systems. If the entire process terminates successfully, its location confidence is set to $\xi = 1$ and w_2 becomes a satellite node.

c) Angle estimation

With θ_i, we denote the angle needed to translate the local reference system of w_i into the home reference system of the network. Thus, θ_i actually defines the orientation angle of w_i. Further on, with α_{ij}, we denote the angle between the local reference system of w_i and the straight line from w_i to w_j (see Figure 4-18 for exemplification). Translating α_{ij} to the home reference system, we obtain the β_{ij} angle. This angle is an important component of the localization system, because it will be used by the position computation and also by the localization algorithm.

Angle estimation can only be performed in green zones and it results as a component of the inter-robot alignment procedure. Figure 4-18 shows an example on how robots w_2 and w_6 calculate the angles used for localization.

d) Distance measurement

Distance measurement between two nodes, w_i and w_j, is performed if the nodes are within each other's green lists and is based on the MTDOA or CTOF techniques described in the previous sections.

Based on our measurements and evaluations, in scenarios where the procedure duration is not a critical issue, the best choice would be the CTOF method with Kalman filtering for a set of 10 repetitive measurements.

e) Node localization with the triangulation method

The triangulation method can be used to determine the coordinates (x_j, y_j) of an unknown node w_j, based only on the position of a satellite node w_i and on the following two parameters: (i) the distance d_{ij} between w_i and w_j, and (ii) the estimated angle β_{ij} of the straight line between the two nodes relative to the home reference system. The equation system for calculating the (x_j, y_j) pair of coordinates depends on the Cartesian quadrant which delimits the value of β_{ij}:

$$\begin{cases} \text{I} & \begin{cases} x_j = d_{ij}\cos\beta_{ij} \\ y_j = d_{ij}\sin\beta_{ij} \end{cases} & ,\ \beta_{ij} \in \left[0, \frac{\pi}{2}\right) \\ \text{II} & \begin{cases} x_j = -d_{ij}\cos(\pi - \beta_{ij}) \\ y_j = d_{ij}\sin(\pi - \beta_{ij}) \end{cases} & ,\ \beta_{ij} \in \left[\frac{\pi}{2}, \pi\right) \\ \text{III} & \begin{cases} x_j = -d_{ij}\cos(\beta_{ij} - \pi) \\ y_j = -d_{ij}\sin(\beta_{ij} - \pi) \end{cases} & ,\ \beta_{ij} \in \left[\pi, \frac{3\pi}{2}\right) \\ \text{IV} & \begin{cases} x_j = d_{ij}\cos(2\pi - \beta_{ij}) \\ y_j = -d_{ij}\sin(2\pi - \beta_{ij}) \end{cases} & ,\ \beta_{ij} \in \left[\frac{3\pi}{2}, 2\pi\right) \end{cases} \tag{4-8}$$

Since the triangulation method has a relatively low accuracy, it is used as the first step of the localization methodology, to determine the approximate location of an unknown node, based on a single satellite node. Figure 4-18 exemplifies such a triangulation scenario, for the position of robot w_6 at moment t_1. Here, $w_6(t_1)$ uses the satellite node w_2 to determine its position, with a low level of confidence, $\xi = 1$.

f) Node localization with the trilateration method

The trilateration method is used to increase the localization accuracy of a node w_k, once its position has been estimated through the previous method, i.e. the triangulation. To apply this technique, the unknown node must rely on at least two satellite nodes, w_i and w_j, which are present in its green list and with which it has performed the alignment and distance measurement procedures.

Trilateration is based on the distances between w_k and the two satellites, i.e. d_{ik} and, respectively, d_{jk}. It determines with relatively high accuracy the coordinates of the two intersection points of the circles having their respective centers at the coordinates of w_i and w_j, with the radius d_{ik} and d_{jk}, respectively:

$$\begin{cases} \{(x_i, y_i), d_{ik}\} \\ \{(x_j, y_j), d_{jk}\} \end{cases} \tag{4-9}$$

Finding the intersection points of the circles defined in (4-9) is equivalent to solving the following system:

$$\begin{cases} (x_k - x_i)^2 + (y_k - y_i)^2 = d_{ik}^2 \\ (x_k - x_j)^2 + (y_k - y_j)^2 = d_{jk}^2 \end{cases} \tag{4-10}$$

Out of the two resulting positions, the correct solution will be the pair of coordinates (x_k, y_k) which are closer to the values obtained through the triangulation method.

Examples of trilateration scenarios are depicted in Figure 4-18 for the positions of robot w_6 at the time instances t_2 and t_3, by using two satellites (w_2 and w_3) and three landmarks, respectively (coordinator node w_1, and satellites w_3 and w_4).

Extensive tests and experiments have been conducted by our research team to evaluate the performances of this methodology. Most of the experimental setups followed the general configuration depicted by Figure 4-18: robot w_1 is configured as the coordinator node, $w_2 - w_5$ are configured as satellite nodes and w_6 is the unknown node, performing the localization methodology described above.

Table 4-5 presents the worst error case measurements for the scenario of $w_6(t_1)$, when it uses the trilateration method to calculate its position, based on a single satellite node, w_2. Several measurements have been performed at various distances between the two robots. The CTOF method has been employed for determining the distance, with Kalman filtering of repetitive measurements. As seen from Table 4-5, the localization errors increase significantly with the real distance.

At moment t_2, node w_6 can be localized by applying the trilateration method with respect to other two robots: w_2 and w_3 (satellite nodes). The location of w_6 has been determined for different distances to see if the error increases with the distance. The experimental results are presented in Table 4-6.

Similarly, at instance t_3, robot w_6 measures its coordinates using trilateration with respect to w_1, w_3 and w_4. In this case, two pairs of coordinates with relatively close values are obtained. The final position is computed through arithmetic averaging. This approach is efficient when there are two location results with the same confidence number. Otherwise, the result with the highest confidence number is selected, to achieve a better performance in terms of execution time. In our approach the confidence number will be increased by 1 when the localization uses trilateration with three landmarks, considering that the location error is reduced by applying the arithmetic average. This, however, is not very efficient in execution time, as can be observed from Table 4-6. The measurement errors, however, have been marginally improved, as compared to the previous scenarios.

Table 4-5. Localization results with the triangulation method (source [A38]).

Real distance [mm]	Measurement results (worst error case)		
	Distance with CTOF and Kalman filtering [mm]	**Maximum procedure duration [ms]**	**Maximum error for triangulation based localization at time t_1 [mm]**
100	98	688	17
200	205	708	43
300	298	727	42
400	397	747	77
500	508	767	70
600	598	786	94
700	697	805	110
800	796	825	138
900	897	845	157
1000	1004	865	227
2000	2006	1060	488
3000	2993	1252	783

Table 4-6. Localization results with the trilateration technique (source [A38]).

Real distance [mm]	Trilateration based localization at time t_2 (using two satellites)		Trilateration based localization at time t_3 (using three satellites)	
	Worst error measurement [mm]	Alignment and distance measurement duration [ms]	Worst error measurement [mm]	Alignment and distance measurement duration [ms]
100	2.32	6212	2.01	9318
200	5.76	6252	4.98	9378
300	2.31	6290	2.00	9435
400	3.48	6330	3.01	9495
500	9.24	6370	7.98	9555
600	2.32	6408	2.10	9612
700	3.48	6446	3.08	9669
800	4.64	6486	4.01	9729
900	3.48	6526	3.00	9789
1000	4.63	6566	4.00	9849
2000	6.94	6956	6.00	10434
3000	8.11	7340	7.01	11010

5 Energy Efficiency and Power Management Techniques

As the current embedded and real-time control systems impose increasingly stringent requirements of small size and low power consumption, their energy efficiency and power management became problems of key interest for the worldwide scientific and engineering communities.

Finding solutions to several important problems in this field has been another major area of interest in my postdoctoral research activity. Some of the main results to which I have been contributed as a coordinator or member of several research teams in the field, include:

- Development of a software execution framework for power consumption profiling of multi-threading mobile applications [A17], [M5], along with a set of power consumption benchmarks for mobile devices [A16], as a member of a research team consisting of dr. eng. Dacian Tudor, A/Prof. dr. eng. Horatiu Moldovan, Lect. dr. eng. Sebastian Fuicu, PhD students Silvia Copi-Crisan and Florin Maticu, and coordinated by A/Prof. dr. eng. Marius Marcu.
- Design of a hardware/software power-aware device model [A39] and an energy consumption assessment and analysis framework for real-time, energy efficient embedded systems, as coordinator of a research team which included Professor Vladimir Cretu, PhD student Cristina Stangaciu and several diploma and master students.
- Development of a novel methodology for online State-of-Health battery assessment and implementation of a hardware/software battery management system for resource-constrained Ni-MH battery powered embedded devices [A31], as coordinator of a research team composed of eng. Lucian Ungurean and eng. Gabriel Carstoiu, and in close collaboration with Professor Voicu Groza from University of Ottawa, Canada.

A brief description of the above mentioned contributions to the field of energy efficiency and power management techniques is provided in the following sections.

5.1 Framework and Benchmarks for Power Consumption Profiling of Mobile Devices and Applications

Power consumption of mobile computing systems is in general a very complex problem [B55], each physical component having its own consumption profile which depends mostly on the types of operations it executes. Therefore, in conjunction with the hardware subsystem, the software application layer has an important influence on the power consumption [B56] of the system. Furthermore, although most researchers in the field agree that mobile multi-core systems will be able to provide a significant increase of system performance at reasonable power consumption [B57], this area is currently still in its infancy. One of the main challenges of multi-core systems is task scheduling [B58], [B59]. There still is a significant gap between the state of the art scheduling algorithms, the capabilities of multi-core architectures and power consumption optimization.

The main objective of our research team has been to create an application framework [A17], [M5], which allows the execution of different types of threads (by using multiple thread libraries), to measure their power consumption on mobile devices, and to use specific power benchmarks to evaluate and compare their consumption profile [A16].

The general architecture of the proposed application framework is depicted in Figure 5-1. It has a modular structure based on several abstraction layers. The lower layer consists, at the operating system level, of a set of *monitor drivers* for the various hardware modules included in the process of energy consumption optimization: CPU, battery, wireless chipset, main-board chipset, the memory etc. For example, the *battery monitor* acquires real-time battery-related measurements, the *CPU monitor* gathers specific processor-related parameters such as load and temperature, and the *wireless monitor* handles information regarding the wireless communication bandwidth, data rates and signal strength (RSSI).

Next, the *power framework core* reads the available measurements from the monitor drivers and calculates the energy consumption of the running applications. It communicates with external modules through an *application interface* (API), using specific energy consumption control messages. The framework core and its API are used to implement adaptable, power-aware mobile applications.

At the application level, the *workload generator* has been designed to generate and manage the workload threads. It allows the user to create and run multiple algorithmic interactions, including multithreading algorithms such as the producer-consumer problems, on different types of threads (based on various thread libraries, such as the POSIX Pthreads for Win32 and BOOST Threads).

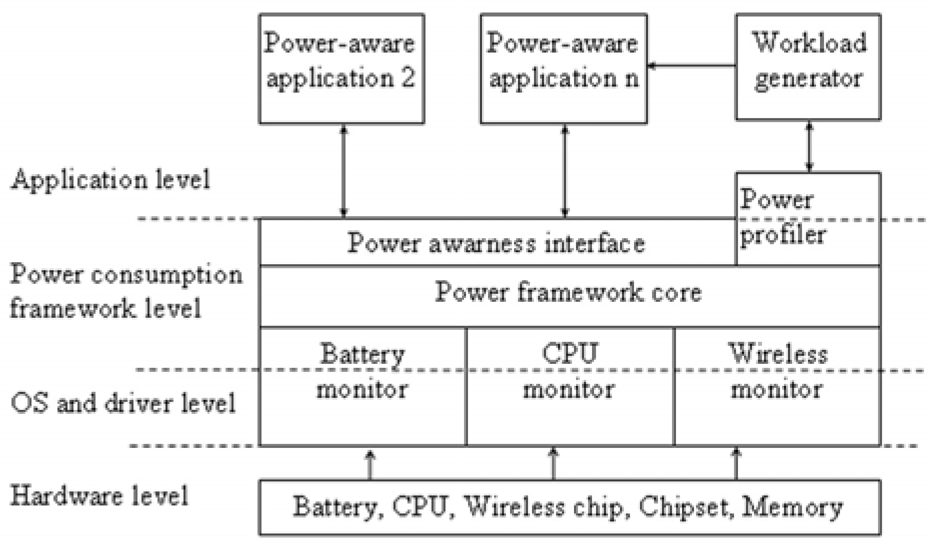

Figure 5-1. General architecture of the application framework (source [A17]).

Another important component of the proposed framework is the *power profiler*, which, on one hand, is responsible for gathering and logging the power consumption data from the other framework modules, for offline analysis. On the other hand, this module is also used for application power consumption profiling, based on predefined patterns. The following profile categories have been currently considered in the application framework prototype, which can be further extended in the future:

- Wireless profile − typically used by applications performing wireless communication tasks. This profile defines parameters such as download rate, upload rate and radio signal strength (RSSI)
- CPU profile − typically used by applications which involve any kind of data processing. The main parameters specified by this profile are: thread IDs, thread priorities, thread wait state time and thread/core mapping (function which maps the threads to processing cores, in case of multi-core systems).

The applications are registering to one or more such profiles, depending on their underlying tasks.

A set of experiments have been conducted based on the proposed application framework to evaluate the power consumption of different components of a mobile multi-core device in specific multi-threading applications. The experiments focused to cover several important aspects of multi-threaded applications: CPU power consumption, memory power consumption, thread-library power consumption, single-core and dual-core power consumption, and single-, dual- and quad- threaded power consumption. Each experiment has been executed for an interval of 30 minutes, within the same environmental conditions. Three mobile hardware platforms have been used in our tests:

- Fujitsu-Siemens LOOX T830 and Qtek 8310 smartphones
- Fujitsu-Siemens LOOX N560 PocketPC
- Fujitsu-Siemens laptop, with Intel Pentium IV dual core mobile processor, running at 2000 MHz, and 512 MB RAM.

We used the concept of power benchmark profiling in the experiments. The power benchmark has been derived from the general computing benchmarking [B60], which has been extended with a special metric − the power consumption [B61], [M5]. A power benchmark is able to evaluate the way a certain type of workload affects the power consumption of a module, related to its idle state consumption. The power benchmark will be composed of three distinct intervals:

- *Idle mode interval* (T_1), when the hardware component is not executing anything and also, the power saving mechanisms are prevented to occur
- *Workload phase* (T_2), when the module is executing a workload-type of application, e.g. the SPEC CPU200 [B62]
- *Release interval* (T_3), elapsed while the component returns to the idle power consumption mode. Similarly to T_1, during this interval, the module is not executing any task and the power saving mechanisms are also blocked.

Full real-life examples of such power benchmarks are the experimental results represented in Figure 5-2, which show the consumption of the mobile microprocessor under different categories of workload: integer, memory type and floating point operations. Minor differences can only be noticed between these power consumption patterns. The three time intervals previously presented can also be observed in Figure 5-2: T_1 between 0 s and ~500 s, T_2 between ~500 s and ~1000 s, and T_3 after ~1000 s.

Significant differences between power consumption profiles resulted from the experimental set which evaluates the single-threaded execution of the same workload algorithm, at different CPU load percentages, as seen in Figure 5-3. From the experimental results it follows that the overall processor load has a higher impact on the power consumption patterns than the type of computations.

In another set of experiments, the power consumption signatures have been measured and evaluated, considering the execution of the same algorithm workload on different numbers of threads. The dual core mobile processor laptop has been used as the experiment platform. Figure 5-4 presents the resulting profiles for the idle case versus workload execution on one, two and four threads. In the latter two cases, both processor cores have been used. Consequently, a noticeable increase in power consumption appears when compared to the single thread case, which employs only one core.

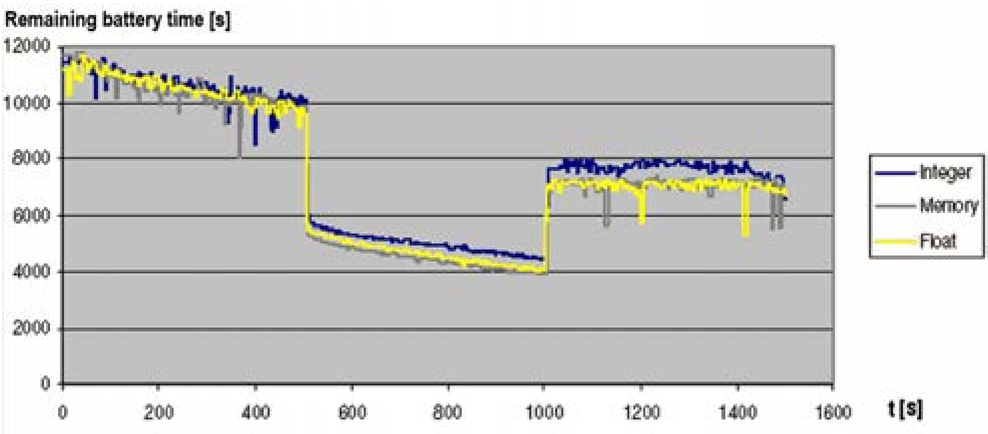

Figure 5-2. Power consumption signatures of the CPU, at different types of workloads (source [A16]).

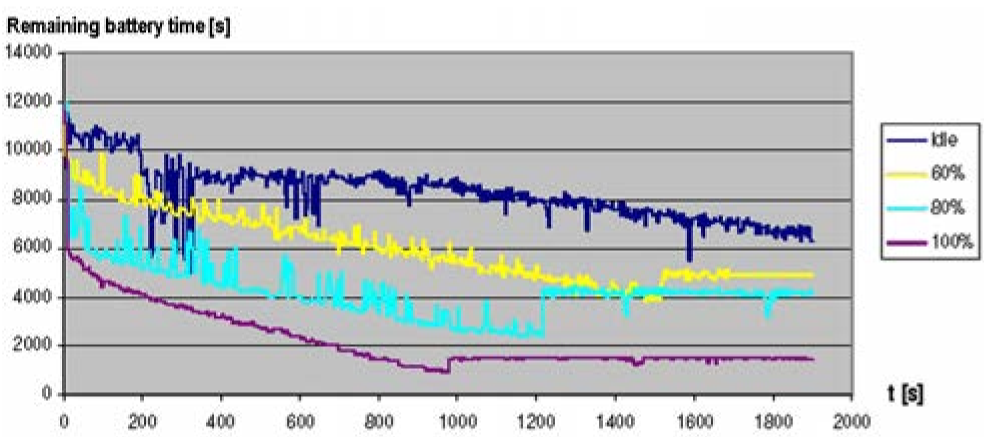

Figure 5-3. Power signatures of the same workload, at different CPU loads (source [A16]).

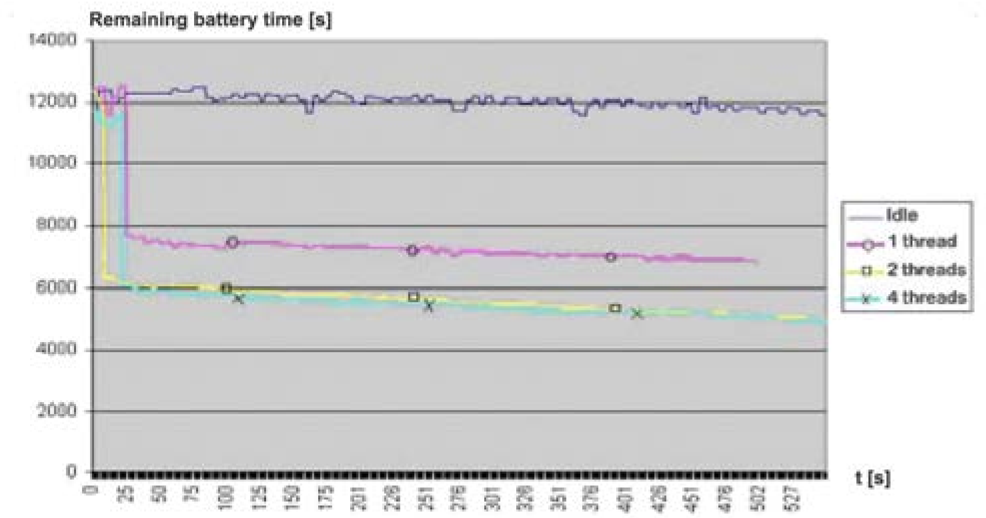

Figure 5-4. Power consumption signatures of the same workload, at different thread counts (source [A17]).

Based on the proposed framework, we showed how multithreading applications influence the power consumption of the single-core and multi-core battery powered, mobile devices. Three of the most commonly used multithreading libraries have been tested with this framework, i.e. Win32 threads, Boost threads and PThreads. We also obtained a large set of power benchmarks for various hardware components of a mobile device, software modules and types of workloads. They have direct applicability in the power profiling of mobile systems and their applications, in the evaluation and calibration of power management solutions, application-related battery configuration and on-line battery monitoring.

5.2 Battery Management System and Methodology for Online State-of-Health Assessment

Our research team in the DSPLabs has developed a complete battery management system, which can be used either stand-alone, or as part of Ni-MH battery powered embedded devices [A31]. The battery management system (BMS) is based on a novel methodology for online evaluation and prediction of the battery State-of-Health (SoH). Our solution provides in-system charging of the attached battery pack, State-of-Charge (SoC) calculation and SoH prediction of the remaining number of cycles or the remaining useful life (RUL), as defined by [B63].

Ni-MH batteries feature a lower cost compared to Lithium-ion (Li-Ion) based solutions in many applications. Ni-MH technology provides a high storage capacity (up to 2700 mAh for standard AA cells) and high energy density. It uses environmental friendly chemical elements, and features good charging and discharging rate capabilities [B64]. Another advantage of Ni-MH batteries worth mentioning is the good tolerance to fast charging (using charging currents up to 1 C). On the other hand, the main disadvantage of this technology is its low robustness related to extreme conditions which affect the battery storage capacity and therefore its performance [B65]. Another problem remains the self discharge rate which is not negligible but it can be quantified and used in calculations.

All these advantages favor the usage of Ni-MH cells in battery powered embedded systems which are resource-constrained in terms of size, processing power and battery capacity. Notable examples of such systems are smart sensor nodes used in monitoring and surveillance applications.

State of Charge (SoC) is an important parameter for all battery powered devices. It is used to indicate the remaining operating time for the current discharge cycle or, during the charging phase, the remaining time until the batteries are charged. Although many methods exist for SoC indication [B64], [B66], [B67], the most widely studied and most used ones include the following:

- coulomb counting, which can be implemented on all battery types and has a relatively low complexity;
- impedance spectroscopy, which can also be generally used, but is expensive to implement;
- fuzzy logic approaches, which can provide accurate estimates but present large memory requirements;
- Kalman filters, which are robust and adaptable to multiple battery types, but require a complex battery model and are difficult to implement.

Among the multiple ways in which SoC can be defined, the most commonly accepted definition is the maximum remaining useful capacity stored in the battery pack. SoC can also be described as a percentage value relative to the nominal capacity of the battery pack, expressed in Ampere-hours (Ah):

$$SoC(t) = \frac{Q_{\text{nom}} - \int_0^T I(t)dt}{Q_{\text{nom}}} \cdot 100 \qquad (5\text{-}1)$$

where, the state of charge, denoted by $SoC(t)$, can hold a value from 0 to 100, Q_{nom} is the nominal capacity, and $I(t)$ is the current flowing to/from the battery pack. This current has a positive value in the charging phase and a negative value during discharge.

Our proposed estimation algorithms need accurate SoC measurements as inputs; therefore, we developed an adaptation of the mixed algorithm for SoC determination, described in [B67]. The applications targeted by our BMS design will use currents in the range of 200 to 1000 mA. In the field of battery engineering, this range corresponds to an interval of 0.1 to 0.5 C of a 2000 mAh battery pack, for which the rated discharge current of 1 C is equal to 2000 mA. As a consequence, according to [B65], the maximum available SoC does not depend on the charge or discharge current applied to the batteries. To ease the implementation as part of an embedded BMS and to shorten the testing times necessary to identify its parameters, a simplified first order Randle model has been considered for the Ni-MH batteries, as shown in Figure 5-5.

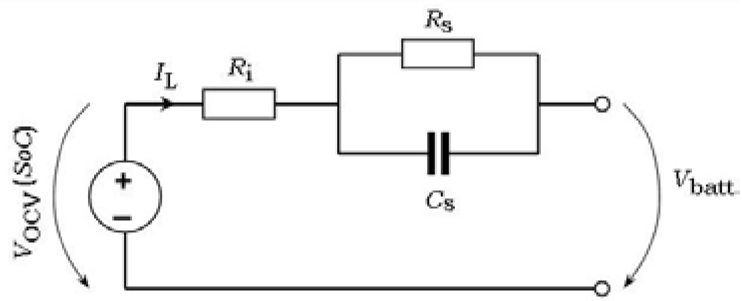

Figure 5-5. Proposed electrical model for the Ni-MH battery (source [A31]).

In this model, the battery terminal voltage V_{batt}, is expressed considering the load current, I_L, as a function of the battery open circuit voltage $V_{OCV}(SoC)$. The battery overpotential ($V_{OCV}(SoC)$ - V_{batt}) is modeled by the voltage drop across its internal resistance R_i, and the response to a step current signal is handled by the parallel R_s-C_s group:

$$V_{batt}(t) = V_{OCV}(SoC) - I_L\left(R_i + R_s\left(1 - e^{\frac{-t}{R_s C_s}}\right)\right) \tag{5-2}$$

where t represents the elapsed time of the current charge/discharge cycle. In the Laplace domain, (5-2) can be represented with the following relation:

$$V_{batt}(s) = V_{OCV}(SoC) - I_L\left(R_i + \frac{R_s}{1 + s\,R_s C_s}\right) \tag{5-3}$$

The relations (5-2) and (5-3) link the directly measurable parameters, V_{batt} and I_L, to the model parameters and the open current voltage (OCV). These relations will be used by the BMS software implementation to periodically recalculate the model parameters as needed.

The State of Health (SoH) is a metric which indicates the current condition of a battery with respect to the reference condition of a new battery. SoH determination is not a simple task, involving in most cases multiple parameters, including cycle numbers, accurate SoC determination, etc. [B63], [B68]. There is a strong dependency between SoH and both the battery and the type of applications running on the battery powered device. A simple SoH estimation approach, presented in [B69], is based on the stored maximum capacity function, C_k, for some charge/discharge cycle, k.

Our research focused on improving this paradigm by introducing curve modeling and estimation based on polynomial regression. The resulting algorithm is relatively simple and well suited for consumer smart chargers with low computational resources. A least-square approach is proposed to implement the second order polynomial regression, which estimates the C_k function as

$$C_k = ak^2 + bk + c \tag{5-4}$$

where k is the current charge/discharge cycle of the battery pack, and $a < 0$. The constraint imposed to a ensures a better curve approximation, because of its monotonically decreasing part.

Consider a battery operating scenario with a total of n charge/discharge cycles completed up to the current moment. The maximum capacity value C_k for each successive battery cycle can be estimated with least-square algorithms by solving the following system of equations:

$$\begin{cases} a\sum_k k^2 + b\sum_k k + cn = \sum_k C_\mathrm{k} \\ a\sum_k k^3 + b\sum_k k^2 + c\sum_k k = \sum_k kC_\mathrm{k} \\ a\sum_k k^4 + b\sum_k k^3 + c\sum_k k^2 = \sum_k k^2 C_\mathrm{k} \end{cases} \quad . k = \overline{1,n}\,,\ n \geq 3 \tag{5-5}$$

The system in (5-5) can be solved using a simple algorithm, such as Cramer's. It consists of computing the following determinants:

$$\Delta = \begin{vmatrix} \sum_k k^2 & \sum_k k & n \\ \sum_k k^3 & \sum_k k^2 & \sum_k k \\ \sum_k k^4 & \sum_k k^3 & \sum_k k^2 \end{vmatrix}, \quad \Delta_\mathrm{a} = \begin{vmatrix} \sum_k C_\mathrm{k} & \sum_k k & n \\ \sum_k kC_\mathrm{k} & \sum_k k^2 & \sum_k k \\ \sum_k k^2 C_\mathrm{k} & \sum_k k^3 & \sum_k k^2 \end{vmatrix} \tag{5-6}$$

$$\Delta_\mathrm{b} = \begin{vmatrix} \sum_k k^2 & \sum_k C_\mathrm{k} & n \\ \sum_k k^3 & \sum_k kC_\mathrm{k} & \sum_k k \\ \sum_k k^4 & \sum_k k^2 C_\mathrm{k} & \sum_k k^2 \end{vmatrix}, \quad \Delta_\mathrm{c} = \begin{vmatrix} \sum_k k^2 & \sum_k k & \sum_k C_\mathrm{k} \\ \sum_k k^3 & \sum_k k^2 & \sum_k kC_\mathrm{k} \\ \sum_k k^4 & \sum_k k^3 & \sum_k k^2 C_\mathrm{k} \end{vmatrix}$$

The resulting values of the a, b, and c parameters in (5-4) can be derived with:

$$a = \frac{\Delta_\mathrm{a}}{\Delta}\,,\ b = \frac{\Delta_\mathrm{b}}{\Delta}\,,\ c = \frac{\Delta_\mathrm{c}}{\Delta} \tag{5-7}$$

To easily calculate the sums in the determinants of (5-6), the following recurrent formulae, suited for embedded implementation, can be used:

$$S_{\mathrm{k}+1} = S_\mathrm{k} + (k+1)\,,\ S_{(\mathrm{k}+1)^2} = S_{\mathrm{k}^2} + (k+1)^2\,,\ \text{etc.} \tag{5-8}$$

With the polynomial function in (5-4), we can compute the first cycle, m, for which the SoH is considered 0%, i.e. the discharged capacity is under a threshold value, denoted as $F \cdot C_{\mathrm{nominal}}$. The value of m is obtained by solving the inequality:

$$am^2 + bm + c < F \cdot C_{\mathrm{nominal}} \tag{5-9}$$

Since $a < 0$, m becomes:

$$m = \left\lfloor \frac{-b - \sqrt{b^2 - 4ac}}{2a} \right\rfloor \tag{5-10}$$

where $\lfloor x \rfloor$ (floor) represents the largest integer less than or equal to x.

This SoH estimation principle adopted for integration in the BMS is based on previously stored measurements of the total available discharge capacity of the battery pack. As a consequence, we proposed two methods for SoH estimation using the available battery data and the number of elapsed battery cycles:

a) *History-based algorithm* for SoH estimation
This method is based on the observation that the typical Ni-MH cell discharge curve presents a relatively constant decreasing curve over its expected lifetime [B70]. The algorithm uses the entire charge-discharge history of the battery, up to the current cycle. The accuracy of the SoH estimation will increase as more inputs are used.

b) *Time-window algorithm* for SoH estimation
Considering that n is the current battery cycle, then the measured capacities of the previous $n - 1$ cycles (C_1 through C_{n-1}) will be used to estimate the remaining u useful cycles. As the number of the battery cycles advances, so do both boundaries of the considered time window, providing the estimation algorithm with a moving time-window of the previous $n - 1$ cycles.
Among the advantages of this approach, we can note that in the case of a new battery pack, $n << u$, and therefore, relatively few logged discharge cycle data are needed to estimate the remaining useful life. Our experimental results show that a number of up to u = 60–70 future cycles can be estimated by considering only n = 25 recorded discharge capacities.

Considering the two proposed SoH estimation techniques, the BMS designer can choose the best suited implementation, based on such factors as: nominal cell capacity, the number of cells/pack and the available computing power and memory storage (for keeping the measured battery capacity logs). Such an embedded battery management system has been designed and implemented by our research team in DSPLabs, as the Power Management Module (POM) of the Wireless Intelligent Terminal nodes (see also Figure 3-2), which compose the CORE-TX intelligent sensor and robotic platform [A9].

The WIT the *Power Management Module* has several important functions:

- to supply power to the WIT,
- to manage the intelligent charging and discharging of the node battery pack,
- to increase the life and state of health of the battery pack,
- to measure and manage in real time the overall power consumption of the node, and of each individual module of the WIT, as well,
- to provide the system parameters of the battery to the upper levels of the WIT system power management (SPM) software.

Management of the power consumption through the POM module is based on accurate measurements of voltage, current and temperature values. The temperature is measured using a TMP101 sensor (Texas Instruments) and the voltage by using a 10 bit SAR ADC (integrated into the Philips Semiconductors LPC213x ARM-based microcontroller). A high side monitor schematic has been implemented for measuring the current on a particular load channel, which corresponds to an individual module (board) of the WIT, as depicted in Figure 5-6. The variable resistor R_s denotes the resistive load. The $R_1 - R_2$ line is a resistor divider which adapts the voltage to the ADC channel. As the ADC input has very high impedance, its current draw is in the order of µA. The AD8551 op-amp draws 750 µA. The power consumption of the shunt resistor (which has the highest power profile in the schematic) is proportional to the current through the load and has a maximum value of 500 mW, considering a 0.5 Ω shunt and the maximum load current of 1000 mA. This power figure can be reduced by decreasing the value of the shunt resistor.

Figure 5-7 depicts the general architecture of the power management software, as a key part of the WIT POM board implementation. This modular embedded application ensures three layers of functionality:

- Battery State Manager (APPL layer): measurement, storing and processing of the main battery parameters; handling of the communication protocol with the system power management (SPM) software, which is hosted by the WIT motherboard (Base Processing Module, BAM, in Figure 3-2).

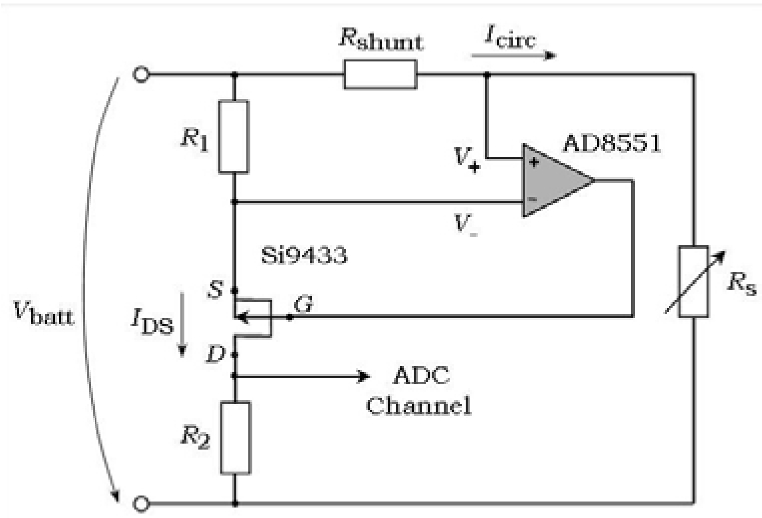

Figure 5-6. High side current monitor schematic of the POM module (source [A31]).

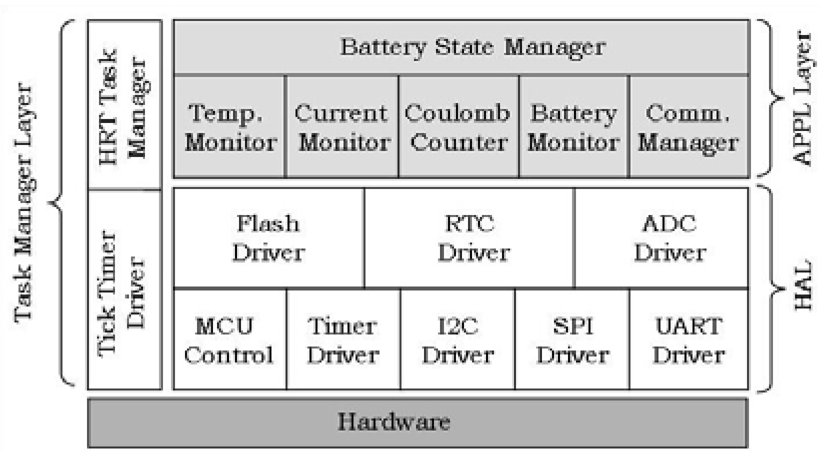

Figure 5-7. Layered architecture of the power management software (source [A31]).

- Task manager layer: provides the scheduling and execution of the hard real-time (HRT) tasks, according to the HARETICK (Hard REal-TIme Compact Kernel) model [A1], [A3], [A4], [A8], [A21].
- Hardware abstraction layer (HAL): contains the drivers and interfaces of the microcontroller unit (MCU) and board peripherals.

The estimation software component, which is part of the battery state management layer, handles both the estimation of the remaining operating time of the current discharge cycle, as well as the proposed SoH prediction algorithms. As previously discussed, the prediction of the SoH, or of the remaining useful life (RUL) of the battery pack, is achieved by first calculating the polynomial coefficients via the parabolic regression, and then by solving the second order inequality of (5-9). The implementation of the proposed SoH estimation algorithm, to calculate the number of RUL cycles (n_{RUL}), is presented in Code Listing 5-1. Here, n denotes the current number of measured battery cycles and n_{min}, the minimum number of cycles necessary for the startup of the algorithm. The value of n_{min} is equal to the size of the moving time-window, defined by the SoH estimation algorithms.

Considerable care has been taken to solve in an efficient way the required tradeoffs between the implementation complexity of the proposed methods and the available computing resources of the target embedded platform. Moreover, one of the most important requirements for the BMS software is that its components must be executed within hard real-time constraints, while also minimizing the system power consumption. For all these reasons, the SoH estimation algorithms have been implemented using all available optimizations, to reduce their execution time and memory footprint.

Code Listing 5-1. Remaining useful life estimation algorithm.

```
while not (battery cycle completed) do
  wait
end while
increment n
if n >= nmin do
  Calculate Sum1, Sum2, ..., Sum7 with (5-8)
  Calculate Delta1, Delta2, Delta3
  Calculate Delta
  Calculate Delta4, Delta5, DeltaA
  Calculate Delta6, DeltaB
  Calculate Delta7, DeltaC
  // Scaling of Delta, DeltaA, DeltaB, DeltaC
    Delta = Delta /128
    a = (DeltaA / Delta) left shifted 20 bits
    b = (DeltaB / Delta) left shifted 20 bits
    c = (DeltaC / Delta) left shifted 20 bits
  Solve (5-9) and calculate m according to (5-10)
  nRUL = m - n
end if
```

For example, we studied the best methods of calculating the four third-order determinants in (5-6), such as to favor additions and subtractions over multiplications. We have chosen the method of recursive expansion in cofactors using the first row, over the classical Sarrus or triangle rules. With this technique, a total of 12 second-order determinants will be generated. Further on, we have noticed that only 7 of the second-order determinants are distinct (`Delta1` through `Delta7` in Code Listing 5-1), yielding a significant reduction of the required calculations.

Extensive experimental evaluations and tests have been performed in the DSPLabs on the implemented BMS prototype / POM module. For this purpose, two sets of data have been considered. The first set contains the estimated values for the cycle in which the battery capacity drops under a certain fraction of its nominal capacity, value for which the SoH is considered 0%. This value is specific to each type of battery and can usually be found in the manufacturer documentation. The second set of data contains the real cycle number for which the capacity reaches the terminal SoH value specified earlier. The two SoH estimation algorithms have the following configurations:

- for the time-window algorithm, the estimation is made using the values recorded in the last 25 and last 30 cycles (i.e. the window size is $W = 25$ and $W = 30$ cycles), and
- for the history-based technique, the estimation is made based on all the recorded values, up to the current cycle.

The data has been obtained from cycling two types of Ni-MH battery packs: GP batteries with a nominal capacity of approximately 2400 mAh and aged Sanyo batteries designed for 2200 mAh. A factor of 80% of the nominal capacity is considered in our experiments to be the threshold for reaching the terminal SoH. Our experimental data shows the respective condition occurs at the 85-th cycle for the GP pack and at the 69-th cycle for the Sanyo pack.

The cycling of the batteries through multiple charge and discharge phases has been accomplished using an automated test framework, based on the Power Management Module (POM) prototype. The batteries have been configured in packs of two cells connected in series, at a nominal voltage of 2.4V. The average discharge current for the GP battery packs has been 210 mA or 0.09 C (at the rated capacity of 2400 mAh) and 420 mA or 0.19 C (at the rated capacity of 2200 mAh) for the Sanyo packs. In the charge mode, a total of 2300-2600 mAh have been supplied to the battery pack in each cycle, using the constant current charging strategy and terminating the charge at the activation of one of the classical termination techniques, such as the "V plateau" [B71]. In discharge mode the battery pack has been automatically switched to supply a programmable resistive DC load, using specialized hardware embedded into the POM board, to simulate the typical current consumption of a WIT.

Several approaches have been used to evaluate the performance of the proposed SoH estimation algorithms. On one hand, the maximum discharge capacities for the tested battery packs have been recorded and the cycle number at which the 0% SoH point is reached has been measured. The comparative graph of this evaluation is shown in Figure 5-8. The cycle number represents the number of the test cycles elapsed since the start of the experiment and not the absolute discharge cycle of the pack since first use. On the other hand, the experimental results obtained with the implemented prototype have been compared against the theoretical results obtained from executing the algorithms in a Matlab environment.

Figure 5-9 and Figure 5-10 present the experimental results obtained for the GP and the Sanyo batteries, respectively, when compared to the theoretical, Matlab simulations. As shown in Figure 5-9, the history based algorithm estimation errors approach zero from the 60th execution cycle. However, the algorithm occasionally produces gross estimation errors, visible for example between cycles 35 and 50. A solution to improve the robustness of the estimation is to filter out the measurement results, at the application level. In the case of the Sanyo batteries, we can observe from Figure 5-10 that the initial estimation errors are smaller when compared with Figure 5-9, but the algorithm prediction accuracy is maximized starting approximately from the 55th cycle. Another important observation is that the proposed SoH estimation approach is viable even for aged battery packs.

The root-mean-square-deviation (RMSD) of the prototype implementation in the case of GP battery tests is depicted in Figure 5-11. The maximum deviation from the theoretical results has a value of 10.5 cycles and corresponds to the shortest time-window approach.

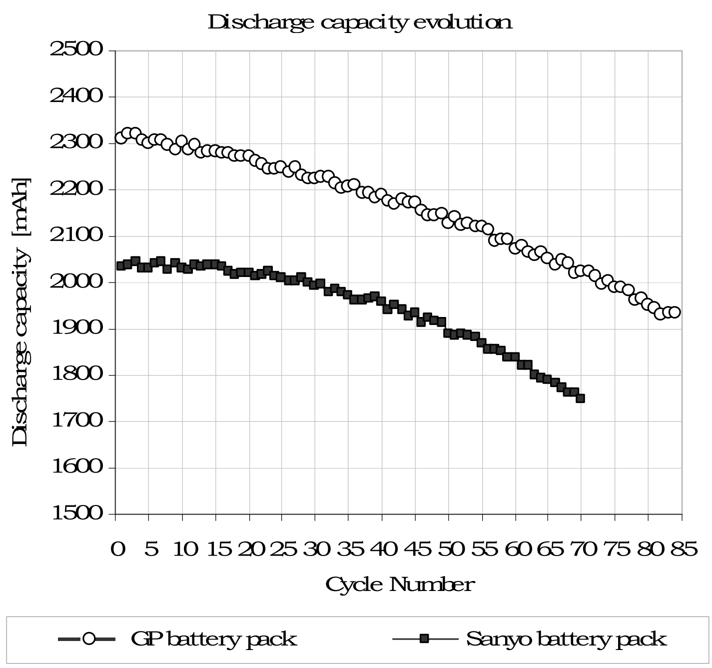

Figure 5-8. Discharge capacity evolution of the GP and Sanyo battery packs (source [A31]).

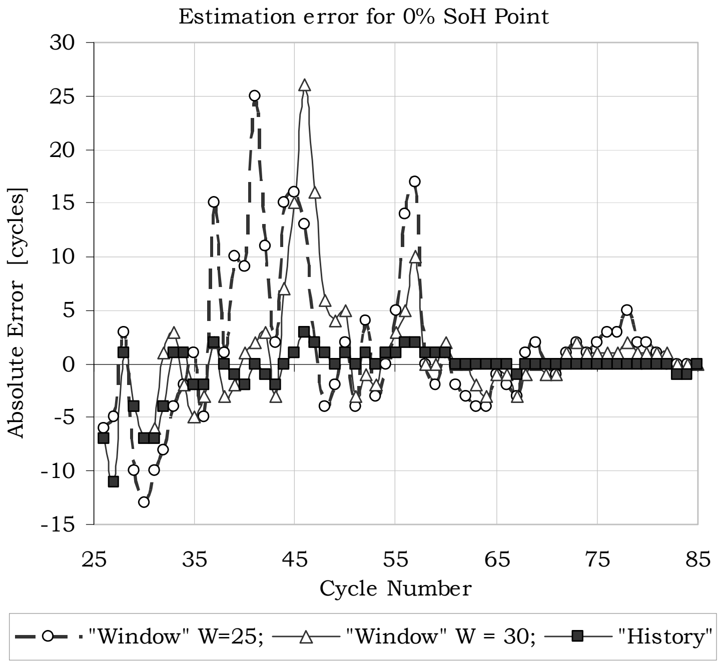

Figure 5-9. Absolute estimation errors for the GP battery pack (source [A31]).

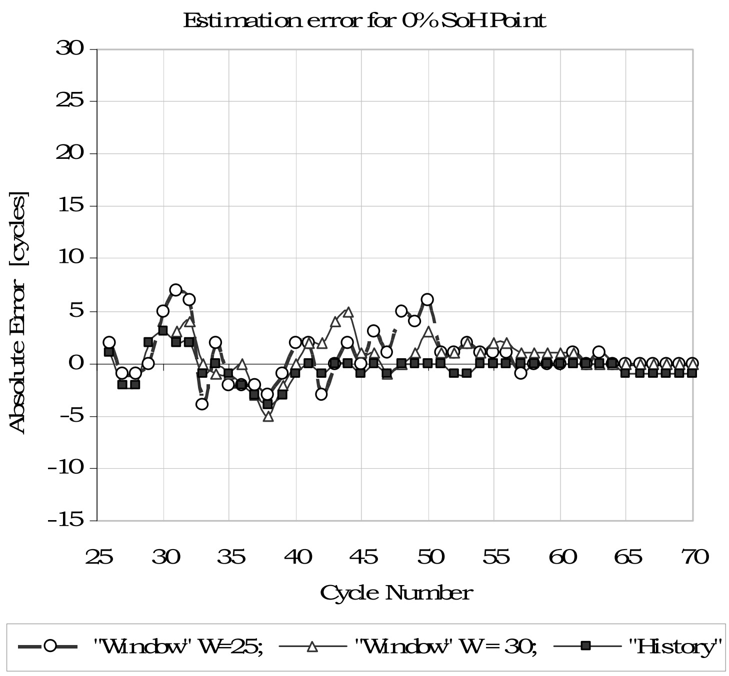

Figure 5-10. Absolute estimation errors for the Sanyo battery pack (source [A31]).

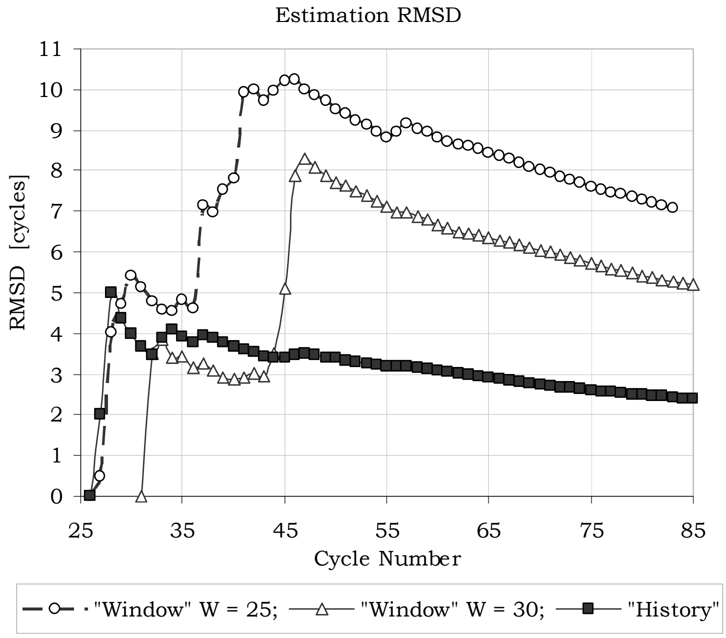

Figure 5-11. Estimation RMSD for the GP battery pack
(source [A31]).

Comprehensive evaluations have also been made regarding the embedded resource requirements of the software components of our BMS implementation.

i) Memory footprint

Table 5-1 shows the memory requirements of the SoH estimation software module in comparison with the total memory footprint required by the BMS software. To provide increased flexibility to the system designer, the implementation contains the routines for both types of algorithms. The three rows represent the comparison metrics: the total ROM (or Flash memory) used for code storage, the ROM used for constant data and the total RAM for runtime data storage.

The evaluation results clearly point out the low memory overhead of our implementation of the SoH estimation algorithms, which also include all the necessary optimizations, mentioned in the previous paragraphs.

ii) Power consumption

The hardware design of the entire BMS has been done with special care to address this key problem. PMOS gates have been integrated on board as switching devices for the charge current, and low power and high efficiency buck boost regulators have also been used. For this BMS implementation, the minimum available CPU frequency (14.745 MHz) is used. The BMS CPU time is around 31%, yielding a total power consumption of 13.95 mW.

iii) Real-time behavior

A series of tests have been carried out to evaluate whether the computation times of the BMS software components are bounded within the real-time boundaries specified by the system operation. The CPU frequency has been modified in steps, starting from 14.745 MHz up to 58.980 MHz. The window size of the SoH estimation algorithm has also been varied, from W = 25 to W = 40 cycles, in order to assess the evolution of the execution times and to provide the system designer a range of possible solutions, in the CPU frequency and window size domains.

We have noticed that the maximum execution times do not exceed 550 μs even in the worst case, i.e. at 14.745 MHz. This proves that the SoH algorithms add little to the real-time constraints of the system, allowing for more relaxed timing configurations.

Another set of tests have been conducted to compare the history based and the time-window algorithms, emphasizing the effect of the recursive accumulation optimization introduced by (5-8). A fixed CPU frequency of 29.490 MHz has been considered and we have varied the window size as in the previous test. The results, presented in Figure 5-12, show that the history based algorithm features a significant improvement of processing times, due to the fact that the summation terms are only calculated once (at the 25th cycle) and the subsequent calculations rely on recursive accumulation, which is more computationally efficient.

Table 5-1. Memory requirements of the BMS and the SoH estimation module (source [A31]).

Memory type	BMS footprint [Bytes]	SoH module footprint [Bytes]	SoH module / BMS footprint [%]
Code ROM	35936	3034	8.44
Constant ROM	2056	32	1.56
Data RAM	8624	176	2.04

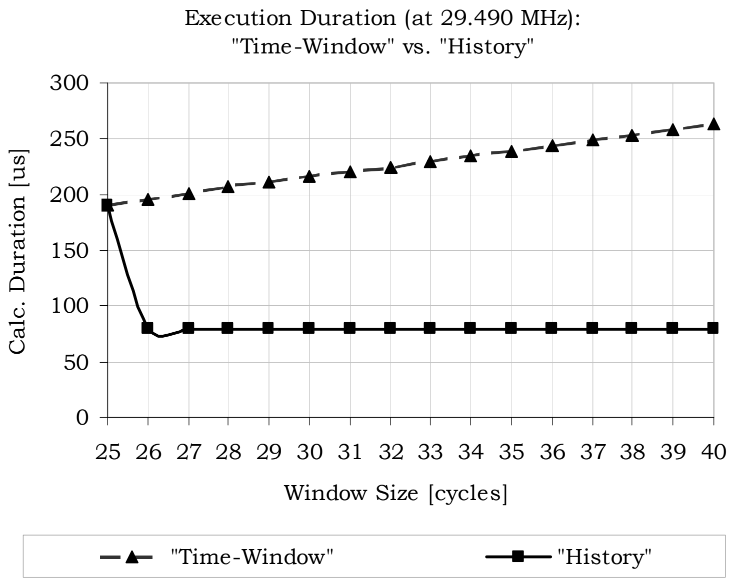

Figure 5-12. Execution times comparison of time-window and history-based SoH estimation approaches (source [A31]).

The two proposed battery SoH estimation algorithms, based on the least squares regression technique, have been successfully implemented and tested as a complete BMS solution for the CORE-TX WIT Power Management Module (see Figure 5-13). The results of our extensive tests show that the history based algorithm ensures a more accurate estimation than the time-window method, although both types present a very good accuracy of estimation, starting from approx. 50% of the remaining useful life of the battery.

It is also worth mentioning that the scientific article with the most relevant results of this research has been published in 2011 by the prominent journal *IEEE Transactions on Instrumentation and Measurement*, [A31]. Currently, our paper is being cited by more than 12 scientific articles, published by other authors in major journals or conference proceedings in the field, as summarized in Table 5-2.

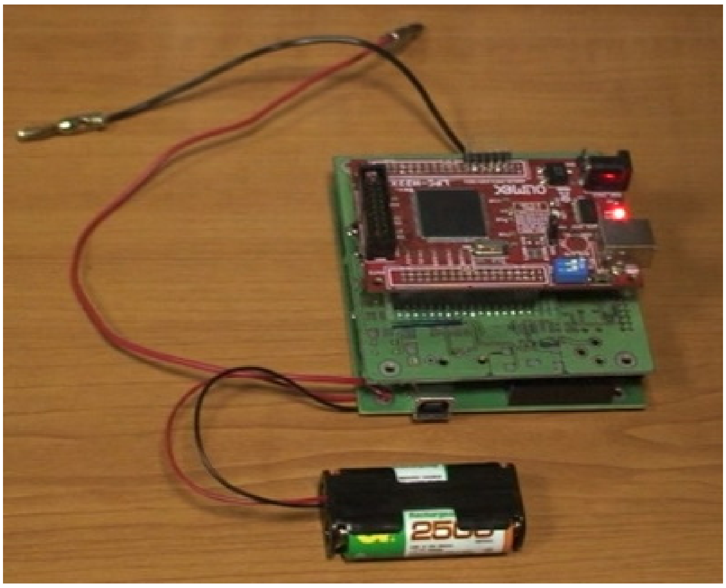

Figure 5-13. Prototype implementation of the BMS system.

Table 5-2. Most relevant citations for [A31].

#	Citing paper	Visibility of citing paper
1	M. Landi, G. Gross, "Measurement Techniques for Online Battery State of Health Estimation in Vehicle-to-Grid Applications", *IEEE Trans. Instrum. Meas.*, DOI: 10.1109/ TIM.2013.2292318, 2014. [In print].	Impact Factor: 1.357
2	J. Yu, "Health Degradation Detection and Monitoring of Lithium-Ion Battery Based on Adaptive Learning Method", *IEEE Trans. Instrum. Meas.*, DOI: 10.1109/TIM.2013.2293234, 2014. [In print].	Impact Factor: 1.357
3	W. Waag, C. Fleischer, D.U. Sauer, "Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles", *J Power Sources*, 258, Elsevier, 2014, pp. (321 - 339).	Impact Factor: 4.675
4	L.C. Stevanatto, V.J. Brusamarello, S.Tairov, "Parameter Identification and Analysis of Uncertainties in Measurements of Lead–Acid Batteries", *IEEE Trans. Instrum. Meas.*, 63 (4), IEEE, 2014, pp. (761 - 768).	Impact Factor: 1.357
5	G. Ablay, "Online Condition Monitoring of Battery Systems With a Nonlinear Estimator", *IEEE Trans. Energy Convers.*, 29 (1), IEEE, 2014, pp. (232-239).	Impact Factor: 2.427
6	A. Moldovan, S. Weibelzahl, C. Hava Muntean, "Energy-Aware Mobile Learning: Opportunities and Challenges", *IEEE Commun. Surv. Tutor.*, 16 (1), IEEE, 2014, pp. (234 - 265).	Impact Factor: 4.818
7	Y. Xing, E.W.M. Ma, K. Tsui, M. Pecht, "An ensemble model for predicting the remaining useful performance of lithium-ion batteries", *Microelectron. Reliab.*, 53 (6), Elsevier, 2013, pp. (811 - 820).	Impact Factor: 1.137
8	M. Shahriari, M. Farrokhi, "Online State-of-Health Estimation of VRLA Batteries Using State of Charge", *IEEE Trans. Ind. Electron.*, 60 (1), IEEE, 2013, pp. (191 - 202).	Impact Factor: 5.165
9	Y. Xing, E.W.M. Ma, K. Tsui, M. Pecht, "Influence of Parameter Initialization on Battery Life Prediction for Online Applications", *Int. Conf. Electron. Packaging Technol.*, IEEE, China, 2012, pp. (1043 - 1047).	ISI Proceedings
10	M. Yatsui, H. Bai, N. Cramer, et al., "Evaluation of the impact of the different charging algorithms on the lead-acid batteries lifetime", in *Proc. IEEE ITEC*, USA, 2012, pp. (1 - 4).	IEEEXplore, INSPEC
11	Y. Xing, E.W.M. Ma, K. Tsui, M. Pecht, "A Case Study on Battery Life Prediction Using Particle Filtering", in *Proc. IEEE PHM*, China, 2012.	IEEEXplore, INSPEC
12	C. Chen, M. Pecht, "Prognostics of lithium-ion batteries using model-based and data-driven methods", in *Proc. IEEE PHM*, China, 2012.	IEEEXplore, INSPEC

6 Scientific and Academic Development Plan

The evolution of my personal scientific and research activity has been and continues to be guided by a set of general principles, which I consider essential to the development of a high profile scientist:

- R&D activity is a key component of the academic career. One's own scientific contributions in the field, along with the most recent results reported by other experts, must provide the main source of information for the didactic process
- Curiosity and the investigative spirit, hard work, and a drop of inspiration, are the main factors which generate remarkable results in science. All these factors, except for the latter, can be controlled and amplified
- Maintaining a continuity and a constant rhythm of the research activity, along with the honest publication of the relevant results, are also key aspects for a successful scientific career
- Positive applicability of the research results, their beneficial contribution and impact on society and environment in the near future, must be high priority concerns for the scientist
- R&D grants and projects are key factors which help consolidating the research teams and raising their professional level, while also providing important financial support to the academic activities in general
- PhD research must be regarded as an essential scientific activity for the academic environment and, thus, it must be supported and used with even higher interest and efficiency
- Students who can be involved for longer intervals (over 2 years) in projects developed within the university have higher chances to become valuable researchers in the future.

The main areas of my planned research activity are, on one hand, of major interest for the scientific and technologic communities worldwide. On the other hand, they coincide with the fields in which I have accumulated a significant scientific expertise along the years:

- *Digital signal acquisition and processing, measurement and instrumentation*
- *Real-time and embedded systems*
- *Intelligent sensor networks*
- *Collaborative robotic environments*
- *Digital telecommunication systems*
- *Energy efficiency and power management of digital systems*.

One of my objectives with top priority for the near future is to start supervising PhD activities and to involve high quality PhD students in the research fields mentioned above, as key members of the DSPLabs team. This objective derives from my conviction that PhD activity represents research at its highest level, if properly guided and supported. Since 2007, I have been involved in the technical coordination of several PhD students, at the Department of Computer and Software Engineering: Răzvan Cioargă (Doctor since 2011), Mihai Făgădar-Cosma (Doctor since 2012), Cristina Stângaciu (Certejan), Andrei Stancovici and Valentin Stângaciu (PhD students since 2011).

Initiating R&D grants and projects, as well as attracting financial support for the scientific and academic activities, are of a constant concern to me. Without interruption since 2005, I have been actively coordinating research and development projects and grants (9 grants coordinated as director, principal investigator, project or research theme manager [G1] – [G9]), as well as new project proposals. My plan is to continue and even intensify these important activities.

For the near future, my scientific and research plan includes the following topics and project proposals:

Real-time and embedded systems

The OPEN-HARTS methodology of developing and analyzing real-time systems for critical applications [G1], created during my PhD research, continues to remain one of my major fields of interest. As part of this methodology, the real-time operating kernel HARETICK will be implemented on a set of embedded platforms, intelligent sensors and robotic systems within the DSPLabs.

INVERTA, the integrated real-time application development and analysis environment, will also be extended and implemented, from its current state of functional prototype, to become a complete, integrated and fully usable application. Main collaborators: Professor Vladimir Crețu and PhD. student Cristina Stângaciu.

Intelligent sensor and mobile robotic networks

Research in these fields will be continued, mainly by further developing and extending the CORE-TX platform (Collaborative Robotic Environment – the Timisoara Experiment) [G2], [G3].

A consequent set of projects and research topics will derive hereby and will involve the entire DSPLabs team. Some of the most important topics are briefly presented below.

Energy efficiency and power management of real-time digital systems

We will focus on developing an integrated solution to model in details and to measure and analyze the energy consumption of embedded systems. This framework will also combine specially designed real-time task scheduling techniques to provide a highly efficient operation of the system, from the perspectives of timing behavior and energy consumption, as well.

Main collaborators in this area: PhD. student Cristina Stângaciu, T/Assist. eng. Dan Chiciudean, M.Sc. eng. Lucian Ungurean and MSc. eng. Gabriel Cârstoiu.

Energy efficient, real-time communication systems for sensor networks

Our research will be conducted towards efficient communication solutions, which combine the real-time data exchange capabilities with the optimization of energy consumption. Main collaborators: PhD. student Valentin Stângaciu and A/Prof. Dr. eng. Dan Pescaru.

Network-level power management mechanisms

Research on this topic will focus on combining specific distributed control techniques with emergent system models and patterns, to provide global-level power management solutions for sensor networks. Main collaborator: Lect. Dr. eng. Răzvan Cioargă.

Collaborative robotic environments

We will further develop the R&D results of grant [G3]. The integrated model MELISSVS will be extended with new specific services and functionalities for robotic collectives. Main collaborators: PhD. student Andrei Stancovici, Lect. Dr. eng. Răzvan Cioargă and T/Assist. eng. Dan Chiciudean.

Based on the rich experience gained over the years in starting and developing scientific, R&D and academic partnerships in the field, I intend to continue and even amplify these actions. Several examples of collaborations planned for the near future:

- *Setup of the "UPT-Continental RTS Group"*. I am currently coordinating the setup of a research group in the field of automotive real-time operating systems and applications, in collaboration with Continental Automotive. It will be mainly based on a kernel of academic staff and will also involve teams of PhD., Master's and undergraduate students in research and development projects on this topic. The research group will have the structure of a R&D center and will collaborate closely with experts from the Continental company (eng. C. Gavrilescu, Dr. eng. V. Ivăşchescu);
- *Launching of a research partnership with the Service Robotics Department at ISEN Lille, France*. The partnership will cover R&D activities in the field of industrial and service robotics. We plan to start with the specification and development of a modular hardware/software architecture for mobile robots used in applications which involve consistent interactions with human personnel. Main collaborator: Professor A-M. Kokosy, ISEN Lille;
- *Development of the current partnership with the Movidius Company*. New projects will be developed in close collaboration with Movidius in the area of multi-core real-time systems for digital signal, image and video processing, and multimedia applications. Main collaborator: Dr. eng. V. Mureşan.

As with the scientific and research activity, there is a set of principles guiding my academic and teaching work, for over 17 years since I had the privilege of becoming a staff member of the Department of Computer and Software Engineering:

- One of the main roles of an academic staff member is to teach and train the students, to contribute to their final, decisive stages of education, to help them become top level engineers, intellectuals of high professional and human value, elite members of our society. Therefore, the teaching activity must be regarded at least as important as the research and scientific activities
- Additionally, there is the quality of being a model, an example for the generations of students we are interacting with. Therefore, the exemplar

professional and moral profile, punctuality, reliability, diligence are key attributes of the academic profession

- Students, as an essential element of the academic environment, must be regarded as real partners in academic activities, including courses and lectures, laboratory workshops and R&D projects. Therefore, students must be involved as much as possible, and in the most collaborative way, in such activities
- Student feedback is to be considered a key factor to the constant improvement of the scientific and technical level of the didactic support and the teaching act
- The academic staff must continuously improve and update the corresponding didactic support, based on the latest results of personal research and of other experts in the field
- Staff in the engineering universities must also update and develop the infrastructure of the corresponding laboratories, by attracting financial support for state of the art equipment, tools and documentation
- Students must be encouraged and guided in participating to various extracurricular R&D projects, professional and scientific contests, and partnerships with other specialized organizations
- Of major importance to maintaining the professional connections with the scientific and academic networks in the field is to permanently communicate and collaborate with other experts in the field, from one's own university or from external institutions and companies.

Several concrete elements regarding my academic development plan for the near future will be briefly presented next.

The support for the "*Research Topics*" course (Master on Information Technology and Master on Computer Engineering) will be extended with a new section on measurements, experimental results processing in research, statistical approaches, and results representation and visualization. The "*Advanced Digital Signal Processing*" course (Master IT and Master CE) will also be extended with several new chapters on adaptive digital filter design, adaptive LMS algorithms and their practical applications.

New laboratory workshops are under development for the "*Digital Telecommunications*" course ("Telecomunicații digitale", 4th year undergraduates on Computers and Information Technology – CTI). The workshops will focus on wireless communication systems, and the GSM and GPRS mobile telecommunication standards, using the specialized hardware platform recently developed within the DSPLabs by the team coordinated by PhD. students Valentin Stângaciu and Cristina Stângaciu, and T/Assist. eng. Dan Chiciudean.

Several new courses have also been recently proposed and introduced into the study programs provided by the Faculty of Automation and Computing: "*Data Transmission, Coding and Compression*" (Master CE) and "*Robotic Systems*" (Master CE). The corresponding course and lab support are currently under development, in close collaboration with DSPLabs team members PhD. student Valentin Stângaciu, Lect. Dr. eng. Răzvan Cioargă and T/Assist. eng. Dan Chiciudean.

Within the partnership with the Movidius Company, ongoing for over 4 years in the field of digital signal, image and video processing and multimedia systems, we have been planning to develop a new course module on "*Computational Photography*". It will consist of a set of lectures on digital photography preprocessing and digital technologies in photo and video cameras. The resulting support will be used to extend the "*Multimedia Systems*" (4th year undergraduates in CTI, Romanian and English programs) and "*Advanced Digital Signal Processing*" courses (Master CE and Master IT). The module also includes a set of application workshops, based on specialized image processors and photo cameras, provided by Movidius.

As a result of over 17 years of activity within the Department of Computer and Software Engineering, the Digital Signal Processing Labs Timisoara (DSPLabs) are currently considered among the best equipped and the most updated laboratories in the department. DSPLabs provide the necessary support for the lab workshops and projects of over 6 courses from the Faculty of Automation and Computing curricula. Such efforts, to continuously improve and update the laboratory infrastructure, will be made in the future with the same resolution. I am focused on attracting financial support particularly from infrastructure development projects and grants, such as [G13], as well as from other R&D grants and contracts with consistent infrastructure budget, such as [G2], [G3], [G5] and [G6].

Based on the rich experience gained and the very good results obtained over the years, I will continue to consider a priority attracting good and dedicated students towards activities and projects hosted by the faculty. I am convinced that, in most cases, such activities, which involve students over a relatively longer period (1-2 years), provide them with a richer and more diverse experience than a premature full-time job within companies. For instance, the large majority of DSPLabs team alumni are currently either academic staff, or high-level professionals on management positions at various international companies.

I will also encourage and guide student involvement in professional contests, such as the *Microsoft Imagine Cu*p (2 teams qualified in the grand finals) and *"Hard&Soft" International Computers Contest for Students, Suceava* (since 1999, the student members of the DSPLabs team participating to such contests have been winning *2 First Prizes* [P13], [P16], *4 Second Prizes* [P10], [P12], [P14], [P15], and *2 Special Prizes* [P9], [P11]).

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7.3 Relevant R&D Grants, Contracts and Projects

[G1] Vladimir Cretu (Director), Mihai V. Micea (*Research themes manager*), Mircea Stratulat, Mircea Popa, Marius Marcu, et al., "OPEN-HARTS: Modelarea, proiectarea si dezvoltarea sistemelor timp-real pentru aplicatii critice de achizitii de semnal, prelucrare si control digital incorporat", ("OPEN-HARTS: Modeling, Design and Development of Real-Time Systems for Critical Applications of Digital Signal Acquisition and Processing, and Embedded Control"), *CNCSIS R&D Grant*, A-717/**2005 - 2007**, Research Theme 7/2005, 9/2006, and 9/2007, CNCSIS, Romanian Ministry of Education and Research, Bucharest. Contracts 27688/14.03.2005, A1/GR181/19.05.2006 and GR76/23.05.2007. Total value: ~19600 EUR. [Online: http://dsplabs.cs.upt.ro/grants/openharts/].

[G2] Mihai V. Micea (*Director*), Ioana Sora, Dan Chiciudean, Razvan D. Cioarga, Bogdan Ciubotaru, "CORE-TX: Sisteme timp-real incorporate in aplicatii complexe de perceptie artificiala distribuita, medii colaborative robotizate si retele de senzori inteligenti" ("CORE-TX: Real-Time Systems Embedded in Complex Applications of Distributed Artificial Perception, Collaborative Robotic Environments and Intelligent Sensor Networks"), *R&D Grant of Excellence*, CEEX-ET-07/**2006 - 2008**, UEFISCSU, Romanian Ministry of Education and Research, Bucharest, Romania. Contract 1437/28.03.2006. Total value: 126000 RON (~ 36000 EUR). [Online: http://dsplabs.cs.upt.ro/grants/coretx/].

[G3] Mihai V. Micea (*Director*), Vladimir I. Cretu, Dan Chiciudean, Razvan D. Cioarga, Bogdan Stratulat, "MELISSEVS: Dezvoltarea si analiza unui model integrat de reprezentare a sistemelor colaborative robotice si de senzori inteligenti in aplicatii de explorare-supraveghere de mediu" ("MELISSEVS: Development and Analysis of an Integrated Model for Representation of Collaborative Robotic and Intelligent Sensor Systems in Environment Exploration and Supervision Applications"), *R&D Grant, PNCDI II, Program 3 - Ideas*, ID-22/**2007 - 2010**, CNCSIS, Romanian Ministry of Education and Research, Bucharest, Romania. Contract 58/01.10.2007. Total value: 731000 RON (~ 225000 EUR). [Online: http://dsplabs.cs.upt.ro/grants/melissevs/]

[G4] Valentin Muresan (Director), Mihai V. Micea (*UPT Partner project manager*), Alexandru Amaricai-Boncalo, Oana Amaricai-Boncalo, Gheorghe Guran, Andrei Tanase, Valentin Stangaciu, et al., "FALX DACIAE: Unelte si Procese de Dezvoltare SW pentru Aplicatii Multimedia Avansate pe Arhitecturi Multi-Core pentru Telefoane Mobile" ("FALX DACIAE: SW Development Tools and Processes for Advanced Multimedia Applications on Mobile Phone Multi-Core Architectures"), *POSCCE-A2-O2.1.1 R&D Grant*, POSCCE-499-11844/**2010 - 2012**, EU - Structural Instruments, ANCS - The Romanian National Authority for Scientific Research, Bucharest, Romania. Contract 133/04.06.2010. Total value: 2126766 RON (~ 506400 EUR). Value, UPT Partner: 1143416 RON (~ 272300 EUR). [Online: http://www.falx-daciae.ro/]

[G5] Constantin Filote (Director), Mihai V. Micea (*UPT Partner project manager*), Vladimir I. Cretu, Mircea Stratulat, Claudia Micea, Florian Miclea, Razvan D. Cioarga, et al., "FILOLET: Sistem novativ de monitorizare a calitatii energiei electrice bazat pe transformarea wavelet in vederea cresterii eficientei energetice a consumatorilor industriali" ("FILOLET: Wavelet Innovative Power Quality Monitoring System with Respect to Industrial Consumers Power Efficiency Increase"), *R&D Grant, PNCDI II, Program 4 - Partnerships*, PDP-4339/**2008 - 2011**, CNMP, Romanian Ministry of Education, Research and Innovation, Bucharest, Romania. Contract 22-137/01.10.2008. Total value: 2191000 RON (~ 595000 EUR). Value, UPT Partner: 250000 RON (~ 68000 EUR).

[G6] Constantin Filote (Director), Mihai V. Micea (*UPT Partner project manager*), Vladimir I. Cretu, Mircea Stratulat, Claudia Micea, Florian Miclea, Razvan D. Cioarga, et al., "SICRAMAS: Sistem inteligent de conducere neliniara robust-adaptiva dupa fluxul rotoric a actionarilor cu motoare asincrone" ("SICRAMAS: Intelligent System for Non-Linear, Robust-Adaptive, Rotoric Flow Based Control of Asynchronous Electrical Machines"), *R&D Grant, PNCDI II, Program 4 - Partnerships*, PDP-2306/**2007 - 2010**, CNMP, Romanian

Ministry of Education, Research and Innovation, Bucharest, Romania. Contract 71-065/18.09.2007. Total value: 2140000 RON (~ 641000 EUR). Value, UPT Partner: 260000 RON (~ 78000 EUR).

[G7] Mihai V. Micea (*Director*), Martin R. Reidel, "CESSAR Configuration and Generation Tool - Release 2013c, 2014a, 2014b", *R&D and Execution Contract*, CESSAR_CT/**2013 - 2014**, Continental Automotive Romania SRL., Timisoara, Romania. Contract 13/24.02.2012, Aad. 5/23.09.2013. Total value: 12548.8 EUR.

[G8] Mihai V. Micea (*Director*), Vladimir I. Cretu (Co-director), Artur Kuczapski, Mihai Novac, Horia Ciocarlie, "PERL: Modelarea si simularea echipamentelor de productie automata si tehnici de planificare a productiei in industria semiconductorilor" ("PERL: Modeling and simulation of Automatic Production Equipments and Process Scheduling Techniques in Semiconductor Manufacturing"), R&D and Execution Contract, **2007**, Advanced Clean Production Information Technology SRL. (acp-IT), Timisoara, Romania. Contract 612/28.02.2007. Total value: 27194 RON (~ 8400 EUR).

[G9] Mihai V. Micea (*Director*), Vladimir I. Cretu (Co-director), Delia Golcea, Mihai Fagadar-Cosma, Cosmina Chise, et al., "Geodata Platform: Aplicatie pentru manipularea informatiilor geografice - GIS" ("AURORA Geodata Platform: Application for Handling Geographical Information - GIS"), *R&D and Execution Contract*, **2007**, Alcatel-Lucent Romania SA., Timisoara, Romania. Contract 751/08.10.2007. Total value: 16738 RON (~ 5100 EUR).

[G10] Attila Bilgic (Director), Vladimir I. Cretu (UPT Partner project manager), Horia Ciocarlie, Marius Marcu, Mihai V. Micea, Calin Jebelean, Dacian Tudor, et al., "ICT-eMuCo: Embedded Multi-Core Processing for Mobile Communicating Systems", *FP7 STREP R&D Grant*, FP7-ICT-216378/**2008 - 2010**, CORDIS, European Union. Contract 216378/01.02.2008. Total value: 4.58 Mil. EUR. Value, UPT Partner: 147000 EUR. [Online: http://www.emuco.eu/]

[G11] Andras Hajdu (Director), Marius Marcu (UPT Partner project manager), Vasile Gui, Mircea Popa, Mihai V. Micea, Alexandru Amaricai-Boncalo, Razvan D. Cioarga, et al., "MobileAssistant: Cross border academic development of an image-based recommendation system for regional educational purposes", *HURO-1001-283-2.3.1 Grant*, HURO-1001-283-2.3.1/**2012 - 2013**, EU - European Regional Development Fund (ERDF), Budapest, Hungary. Total value: 184460 EUR. Value UPT: 89202 EUR. [Online: http://www.mobileassistant.ro/]

[G12] Laurentiu Maniu (Director), Vladimir I. Cretu (UPT Partner project manager), Mihai V. Micea, et al., "MERLIN: Platforma IT de Modelare, Simulare, Planificare si Optimizare a Productiei Automatizate in Industria Semiconductorilor" ("MERLIN: IT Platform for Modeling, Simulation, Scheduling and Automatic Production Optimization in Semiconductor Industry"), *R&D Grant, PNCDI II, Program 5 - Innovation*, PDP-1262/**2008 - 2011**, CNMP, Romanian Ministry of Education, Research and Innovation, Bucharest, Romania. Contract 198/12.09.2008. Total value: 2546000 RON (~ 710000 EUR). Value, UPT Partner: 152782 RON (~ 42500 EUR).

[G13] Mihai V. Micea (*Director*), Vladimir I. Cretu, Dan Chiciudean, Razvan D. Cioarga, Bogdan Ciubotaru, "DSPLABS: Dezvoltarea laboratorului multidisciplinar de prelucrare numerica a semnalelor, multimedia, telecomunicatii digitale, retele de senzori si robotica" ("DSPLABS: Development of the Multidisciplinary Laboratory for Digital Signal Processing, Multimedia, Digital Telecommunications, Sensor Networks and Robotics"), *Development Project, License Laboratories Program*, AC-11/**2007 - 2008**, Romanian Ministry of Education, Research and Innovation, and Politehnica University of Timisoara, Romania. Total value: 344759 RON (~ 100000 EUR).

7.4 Patents Pending for Inventions

[I1] Cormac Brick, Andrei C. Cosma, Demis Diaconescu, Mihai V. Micea, Valentin Muresan, Cristian G. Olar, "System for detecting frames with 3D compatible content, comprises frame receiving circuit connected through bus to a memory unit, memory unit for storing processed data and central processing unit", *Patent pending for invention*, RO127932-A0, Oficiul de Stat pentru Inventii si Marci (OSIM), Bucharest, Romania, 30.10.**2012**, International Patent Classification (IPC): H04N-013/00; G06T-015/00. [IP Owner: Movidius SRL, Timisoara, Romania]. [Indexed: Derwent Innovations Index, Thomson Reuters].

[I2] Cormac Brick, Andrei C. Cosma, Demis Diaconescu, Mihai V. Micea, Valentin Muresan, Cristian G. Olar, "Method for detecting frame compatible three-dimensional (3D) content in video stream of TV, involves processing projection series, and processing final comparisons such that viewable images are displayed", *Patent pending for invention*, WO2013180590-A1, World International Property Organization (WIPO), Geneva, Switzerland, 05.12.**2013**, International Patent Classification (IPC): H04N-013/00. [IP Owner: Movidius SRL, Timisoara, Romania]. [Indexed: Derwent Innovations Index, Thomson Reuters].

7.5 Relevant Monographs, Book Chapters and Didactic Materials

[M1] Mihai V. Micea, "Proiectarea sistemelor timp-real pentru aplicatii critice" ("Design of Real-Time Systems for Critical Applications"), *Editura Orizonturi Universitare*, Timisoara, Romania, **2005**, 175 pg., ISBN 973-638-222-2.

[M2] Mihai V. Micea, "Prelucrarea numerica a semnalelor in domeniul timp", in *Colectia Prelucrarea Semnalelor, Editura Politehnica*, Timisoara, Romania, **2009**, 254 pg., ISBN 978-973-625-927-2.

[M3] Mircea Popa, Anca S. Popa, Vladimir I. Cretu, Mihai V. Micea, "Centralized Management System for Mobile Communications with Pocket PCs", in *Innovations and Advanced Techniques in Computer and Information Sciences and Engineering*, section 58, Tarek Sobh (Eds.), Springer Science and Business Media, Dordecht, The Netherlands, Jun., **2007**, pp. (327 - 332), ISBN 978-1-4020-6267-4, DOI: 10.1007/978-1-4020-6268-1_58. [Indexed: ISI Web of Science, Thomson Reuters].

[M4] Razvan D. Cioarga, Mihai V. Micea, Bogdan Ciubotaru, Vladimir I. Cretu, Dan Chiciudean, "Emergent System for Information Retrieval", in *Artificial Intelligence and Innovations 2007: From Theory to Applications (IFIP Series)*, volume 247, section 44, Christos Boukis, Aristodemos Pnevmatikakis, Lazaros Polymenakos (Eds.), Springer Science and Business Media, Boston, USA, Sep., **2007**, pp. (409 - 417), ISBN 978-0-387-74160-4, DOI: 10.1007/ 978-3-642-10817-4_16. [Indexed: Springer Link, Springer Science + Business Media].

[M5] Marius Marcu, Dacian Tudor, Sebastian Fuicu, Mihai V. Micea, Silvia Copil-Crisan, Florin Maticu, "Power Characterization of Multi-Threading Mobile Applications", in *New Aspects of Computers*, volume 2, N. E. Mastorakis, V. Mladenov, Z. Bojkovic, D. Simian, S. Kartalopoulos, A. Varonides, et al. (Eds.), WSEAS Press, Heraklion, Greece, Jul., **2008**, pp. (583 - 588), ISBN 978-960-6766-85-5, ISSN 1790-5109. [Indexed: ISI Web of Science, Thomson Reuters].

[M6] Razvan D. Cioarga, Mihai V. Micea, Vladimir I. Cretu, Daniel Racoceanu, "Emergent Behavior Control Patterns in Robotic Collectives", in *Lecture Notes in Artificial Intelligence (LNAI)*, volume 5928, section 16, Ming Xie, Youlun Xiong, Caihua Xiong, Honghai Liu, Zhencheng Hu (Eds.), Springer Berlin Heidelberg, Singapore, Singapore, Dec., **2009**, pp. (165 - 173), ISBN 978-3-642-10816-7, ISSN 0302-9743, DOI: 10.1007/978-3-642-10817-4_16. [Indexed: ISI Web of Science, Thomson Reuters].

[M7] Mihai V. Micea, Andrei Stancovici, Sinziana Indreica, "Distance Measurement for Indoor Robotic Collectives", in *Mobile Robots - Control Architectures, Bio-Interfacing, Navigation, Multi Robot Motion Planning and Operator Training*, section 16, Janusz Bedkowski (Eds.), InTech, Rijeka, Croatia, Dec., **2011**, pp. (353 - 372), ISBN 978-953-307-842-7.

[M8] Mihai V. Micea, Valentin Stangaciu, Cristina Stangaciu, Constantin Filote, "Sensor-Level Real-Time Support for XBee-Based Wireless Communication", in *Advances in Intelligent and Soft Computing (AISC)*, volume 145, section 20, Ford L. Gaol, Quang V. Nguyen (Eds.), Springer Berlin Heidelberg, Berlin, Germany, Jan., **2012**, pp. (147 - 154), ISBN 978-3-642-28307-9, DOI: 10.1007/978-3-642-28308-6_20. [Indexed: ISI Web of Science, Thomson Reuters].

[M9] Mihai Fagadar Cosma, Vladimir I. Cretu, Mihai V. Micea, "Dense and Sparse Optic Flows Aggregation for Accurate Motion Segmentation in Monocular Video Sequences", in *Lecture Notes in Computer Science (LNCS),* volume 7324, section 25, Aurelio Campilho, Mohamed Kamel (Eds.), Springer Berlin Heidelberg, Aveiro, Portugal, Jun., **2012**, pp. (208 - 215), ISBN 978-3-642-31294-6, ISSN 0302-9743, DOI: 10.1007/978-3-642-31295-3_25. [Indexed: ISI Web of Science, Thomson Reuters].

[M10] Mihai V. Micea, "Introducere in prelucrarea numerica a semnalelor: Suport de curs" ("Introduction to Digital Signal Processing"), 2-nd Edition, Politehnica University of Timisoara, Romania, Oct., **2007**, 174 pg. [Print Order 350].

[M11] Mihai V. Micea, "Advanced Digital Signal Processing: Slide Support", Politehnica University of Timisoara, Romania, Sep., **2007**. [Online: http://dsplabs.cs.upt.ro/~micha/courses/ADSP/support/index.html].

[M12] Mihai V. Micea, "Telecomunicatii digitale moderne: Suport de curs" ("Modern Digital Telecommunications: Course Support"), 3-rd Edition, Politehnica University of Timisoara, Romania, Apr., **2008**, 138 pg. [Print Order 270].

[M13] Mihai V. Micea, "Multimedia Systems: Curs Support", Politehnica University of Timisoara, Timisoara, Romania, Sep., **2010**. [Online: http://dsplabs.cs.upt.ro/~micha/courses/MS/support/index.html].

[M14] Mihai V. Micea, "Sisteme de achizitie numerica a datelor: Indrumator de laborator" ("Digital Data Acquisition Systems: Lab Workbook"), Politehnica University of Timisoara, Romania, Sep., **2000**, 182 pg. [Print Order 270]. [***Times cited: 1***].

7.6 Prizes, Awards and Recognition

[P1] *PhD Cum Laude Distinction*, Ministry of Education and Research, Bucharest, Romania, Order No. 3184/07.02.2005, PhD. Thesis: "Design and Implementation of Real-Time Systems for Critical Applications of Digital Signal Acquisition and Processing", Feb. **2005**.

[P2] *Best Doctoral Thesis of the Year 2004 Prize*, Romanian Academy of Technical Sciences, Timisoara Branch, Romania, Apr.**2006**.

[P3] *Merit Award (5 years)*, Computer and Software Engineering Department, Faculty of Automation and Computers, Politehnica University of Timisoara, Romania, Merit salary increase, granted for 5 years based on competition at the faculty/department level, 01.Jan.**2011** - **present**.

[P4] *Merit Award (1 year)*, Computer and Software Engineering Department, Faculty of Automation and Computers, Politehnica University of Timisoara, Romania, Merit salary increase, granted for 1 year based on competition at the faculty/department level, 01.Jan - 31.Dec.**2010**.

[P5] *Merit Salary (annual)*, Computer and Software Engineering Department, Faculty of Automation and Computers, Politehnica University of Timisoara, Romania, Merit salary

increase, granted annually based on competition at the faculty/department level, 01.Oct.**1998** - 31.Dec.**2009**.

[P6] *Special Award of the Jury*, Scientific Student Communication Session, Computer and Software Engineering Department, Politehnica University of Timisoara, Romania, title of the project: "A Client-Server Approach of a Library Database Management in UNIX", Jun.**1995**.

[P7] *Eminent Young Researcher of Timisoara Prize and Medal*, National Authority for Scientific Research (ANCS), Ministry of Education, Research and Innovation, Bucharest, Romania, Dec.**2006**.

[P8] *Eminent Researcher Prize*, Orizonturi Universitare Association, Timisoara, Romania, Dec.**2006**.

[P9] *Special Prize*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 20th Edition, as adviser of the Timisoara 3 team, 19-26.May.**2013**.

[P10] *Second Prize*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 19th Edition, as adviser of the Timisoara 1 team, 13-20.May.**2012**.

[P11] *Special Mention*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 19th Edition, as adviser of the Timisoara 2 team, 13-20.May.**2012**.

[P12] *Second Prize*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 14th Edition, as first coach of the team of Timisoara, 21-26.May.**2007**.

[P13] *First Prize*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 12th Edition, as first coach of the team of Timisoara, 16-21.May.**2005**.

[P14] *Second Prize*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 9th Edition, as first coach of the team of Timisoara, 20-25.May.**2002**.

[P15] *Second Prize*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 7th Edition, as coach of the team of Timisoara, 15-20.May.**2000**.

[P16] *First Prize*, "Hard&Soft" International Computers Contest for Students, Stefan cel Mare University of Suceava, Romania, 6th Edition, as coach of the team of Timisoara, 17-22.May.**1999**.