A NEW EXPERIMENT IN RESEARCH ON HYBRID SYSTEMS: THE CENTER OF EXCELLENCE DEWS

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Abstract: The Architectures and Design of Embedded controllers, Wireless interconnect and System-on-chip Center of Excellence (DEWS) was established in 2001 under the auspices of the Ministry of University and Scientific Research of the Italian Government. Its goals are to foster research in a number of important topics that are the foundation of novel applications of electronic technology. In particular, DEWS research has been focused on these topics:

- embedded controllers, their mathematical underpinnings (hybrid system analysis and synthesis);
- design methodologies for embedded software and systems-on-chip;
- automotive electronic system design;
- wireless sensor networks for environment monitoring;
- electrical motors.

Keywords: Hybrid systems, Embedded systems, Embedded software, Automotive electronics, Wireless sensor networks, Electrical motor control.

1. INTRODUCTION

Embedded systems, i.e., electronic systems that are non user programmable and are integrated with the physical dimensions of the device that hosts them, are becoming the main driver for the evolution of the electronics industry in all its aspects. Automotive electronics, airplane controllers, cell phones, appliances, and industrial plants are but a few examples where embedded systems are essential. Embedded systems design must satisfy a number of constraints on performance, safety and power consumption while trying to minimize cost and time-to-market: a challenge that is increasingly difficult to meet.

The design of embedded systems today is still a craft and not a science. However, given the challenges that increased complexity, safety requirements, time-to-market and cost pose to the design community, research has to be funded and supported to improve the methodology and the tools for embedded system design. Embedded systems today are heterogeneous systems, i.e. systems that consist of diverse components. Mechanical, electrical, analog, digital, hardware, software, continuous time, discrete time, synchronous and asynchronous components must co-exist and play together in a consistent fashion. The theory for this is still in its infancy. In the embedded controller domain, hybrid systems have received attention as interesting mathematical objects to analyze and design in particular transportation systems such as automobiles, helicopters and airplanes.

Recently there has been a flurry of funding initiatives in the United States and in Europe to foster the advance of design methods and tools for embedded systems, from the design of algorithms, to the selection of a platform to support the algorithms, from the design of software that implements the algorithms, to the selection of communication protocols. Distributed fault-tolerant systems, wireless networks, sensors and actuators networks, safety-critical hard real time systems are common key words in call for proposals from funding agencies.

This paper presents the activities of the Center of Excellence for Research DEWS (Architecures and Design of Embedded controllers, Wireless interconnect and System-on-chip (http://www.

diel.univaq.it/dews), an experiment in setting up a research agenda and a group for addressing the problems posed by embedded system design from theory to applications with special attention to problems that can be cast in the domain of hybrid systems in Italy.

DEWS was set up at University of L'Aquila to respond to a call for proposal by the Italian Ministry of Education and Scientific Research for National Centers of Excellence in Research. After a review process involving international experts, the final selection included DEWS among the Centers to be financed by the Ministry. Its overall long-term objective is to develop an embedded system design methodology to balance production costs with development time and cost in view of performance and functionality considerations. This over-arching objective consists of several subordinate macro objectives that are articulated in work-packages, organized in a matrix structure where the "horizontal" work-packages are methodological foundations and the "vertical" ones are applications. The rationale for this organization is that design methodologies are difficult, if not impossible, to develop in abstraction. Strong design drivers are needed to validate assumptions, to measure efficiency and to discover pitfalls of the proposed approaches. The application domains make heavy use of the methodology developed in the horizontal work-packages. The long-term objective is to propagate this design methodology as widely as possible within the application domains by demonstrating in the short term its power on a series of real test cases.

In addition to the funding provided by the Italian Government, DEWS is supported by two European IST Projects: HYBRIDGE (Distributed Control and Stochastic Analysis of Hybrid Systems supporting Safety Critical Real-Time Systems Design) and COLUMBUS (Design of Embedded Controllers for Safety Critical Systems). A main feature of the COLUMBUS project is the close interaction between EU and US teams.

2. THEORETICAL FOUNDATIONS

The research agenda is articulated in five work-packages: two cover foundations and theory work ((i) hybrid system control and (ii) architecture-function co-design) and cut across the three others that are embedded system applications in automotive electronics, wireless networks and electrical motors.

2.1 Hybrid System Control

Hybrid systems are mathematical models that contain both discrete and continuous time components. As such, the class of hybrid control problems is extremely broad (it contains continuous control problems as well as discrete event control problems as special cases). Hence, it is very difficult to devise a general yet effective strategy to solve them. In particular, emphasis has been placed on solving problems with safety specifications, described by giving a set of "good" states within which the controlled hybrid system should evolve. Ensuring safety is a non trivial task. Methods for *reachability analysis*, which consists of computing the set of all reachable states of the hybrid system and then checking that no "bad" state belongs to the reachable set, have been developed and procedures for solving problems with safety specifications have been proposed (see e.g. (Berardi *et al.*, 2000), (Lygeros *et al.*, 1999) and (Tomlin *et al.*, 1998)). However, the efficient computation of reachable sets remains a difficult and open problem.

Research in the area of hybrid systems addresses significant application domains to develop further understanding of the implications of the hybrid model on control algorithms and to evaluate whether using this formalism can be of substantial help in solving complex, real-life, control problems (see e.g. (DiBenedetto and Sangiovanni-Vincentelli, 2001), (Greenstreet and Tomlin, n.d.) and the references therein).

Hybrid systems can be used to model complex systems using abstractions to eliminate unnecessary details. In addition, in the design of digital controllers, it is important to model both the plant and the controller to assess the properties of the control system. In this case, plants are in general modeled as continuous systems, while digital controllers are discrete systems.

An application that has benefited greatly from this modelling paradigm is the design of embedded controllers for transportation systems. In particular, the design of electronics systems for cars has been cast in the hybrid domain. In the automotive domain, electronics has become the driving innovation engine. Daimler Chrysler executives pointed out that 90% of future innovative content in a car will come from electronics. In addition, because of the strategic role electronics is taking in the automotive market place, the amount of electronic subsystems present in a car is rapidly increasing creating a noteworthy impact on costs (more than 30% of the cost of manufacturing a high-end car such as a BMW Series 7 is estimated to be for electronics) and pressure on the supply chain to deliver better products faster. The peculiarity of automotive electronics is the conjugation of its distributed nature (more than 80 processor-based subsystems are connected together inside the body of a car), the safety critical aspects of some of these subsystems and the cost pressure. Avionic systems share with automotive the first two concerns but not the last. These needs together with the market size make the automotive application a particularly appealing design driver. In particular, power-train control is one of the most interesting and challenging problem in embedded system design. The test of the quality of our approach will be the design from conception to implementation of industrial-strength embedded controllers for power trains. In particular, our link to Magneti Marelli and ST Microelectronics through PARADES (a European Group of Economic Interest located in Rome and supported by Cadence, Magneti Marelli and ST Microelectronics) is essential for this task.

Another application of hybrid modelling in transportation systems that can potentially improve the quality of present solutions is the design of Air-Traffic Management systems. The objective of Air-Traffic Management is to ensure the safe and efficient operation of aircrafts. The stress placed on the present systems by the ever increasing air traffic has forced the authorities to plan for an overhaul of ATM to make them more reliable, safer and more efficient. A move in this direction requires more automation and a more sophisticated monitoring and control system. Automation and control require in turn a precise formulation of the problem. In this context, variables that can be measured or estimated have to be identified together with safety indices and objective functions. To make things more complex, the behavior of ATM depend critically on the actions of humans who control the operations that are very difficult to observe, measure, model, and predict.

The European IST Project HYBRIDGE (http://www.nlr.nl/public/hosted-sites/hybrid/) aims at improving substantially the quality of the systems in use today by applying modern control theories and algorithms to the problem. In particular, stochastic hybrid systems seem particularly well suited to model the operation of an ATM system.

Deterministic hybrid systems have been the topic of intense research in recent years. By contrast, relatively few classes of stochastic hybrid processes (dynamical systems that in addition to continuous and discrete dynamics also allow probabilistic phenomena) have been studied in detail. Even though deterministic hybrid models can capture a wide range of behaviours encountered in practice, stochastic features are very important in modelling, because of the uncertainty inherent in most real world applications. All stochastic hybrid processes proposed thus far can capture different classes of dynamics, depending on the applications they were developed to address. The most important difference between the models lays in where the randomness is introduced. Some models allow diffusions to model continuous evolution, while others do not. Likewise, some models force transitions to take place from certain states, others only allow transitions to take place at random times (e.g. using a generalised Poisson process), while others allow both. An important part of our work is to classify all approaches and compare them in terms of their mathematical properties and expressiveness. This classification and comparison is essential to push the state-of-the-art towards a more solid understanding the issues surrounding the use of stochastic hybrid models. In the ATM application, this understanding will help in modelling the various non deterministic aspects of the system and, in particular, human behavior.

2.2 Architecture-Function Co-design

This work-package covers a methodology that has been proposed as a cornerstone in embedded system design and that is aimed at improving substantially the way a system is conceived and implemented.

Orthogonalization of concerns, i.e., the separation of the various aspects of design to allow more effective exploration of alternative solutions, is an essential paradigm for this methodology (Sangiovanni-Vincentelli, 2002). In particular, it is important to clearly separate:

· Function (what the system is supposed to do) and architecture (how it does it);

· Communication and computation.

The mapping of function to architecture is an essential step from conception to implementation.

In the recent past, there has been a significant attention in the research and industrial community to the topic of Hardware-Software Co-design. The problem to be solved is coordinating the design of the parts of the system to be implemented as software and the parts to be implemented as hardware blocks, avoiding the HW/SW integration problem that has marred the electronics system industry for so long. When considering the great deal of electronic components that will be living very close to each other, it is essential to limit both EM emissions and EM susceptibility. A long-term objective is to devise numerical techniques for analysis and design of EMC compliant circuits at board, package and chip level.

The IST Project COLUMBUS of the European Community is focused on evolutions of the foundational work on architecture-function co-design and brings together three European Institutions (University of Cambridge, INRIA and University of L'Aquila) with two US Institutions (University of California at Berkeley and Vanderbilt University) who are among the world leaders in the area of embedded software design. In particular, the group is looking at design methodologies rooted on platform-based design (Sangiovanni-Vincentelli, 2002) that deals with various levels of abstraction in a uniform and rigorous fashion. In this domain, the COLUMBUS teams look at comparing various mathematical models for hybrid and heterogeneous systems and at recommending one for adoption as a standard for the community to build upon. In addition, design flows for application areas will be proposed that are based on the theoretical work centered around models of computation and their properties.

COLUMBUS is one of the first experiments of research across the Ocean that receives support from the European Commission and from the NSF for the American side. There is an interesting parallel between DEWS and CHESS, the Center for Hybrid and Embedded Systems, of University of California Berkeley. CHESS is more focused on the embedded software problem while DEWS is more focused on the control aspects and on the application domain but they share a common view of the important research problems that need to be solved thus giving solid foundations to the collaboration.

3. TARGET APPLICATION AREAS

In our opinion, theory and methodology in engineering need a strong experimental component to verify the assumptions and the power of the techniques. Design drivers for our embedded system design efforts come from a set of applications that have industrial and intellectual relevance. In particular, we focused on automotive electronics (see e.g. (Balluchi *et al.*, 2000), (Balluchi *et al.*, 2001), (Balluchi *et al.*, 1999)) because of the importance of the application domain to the European economy, on wireless sensor networks (see e.g. (Colantonio *et al.*, 2001), (Graziosi and Santucci, 2002), (Iacobucci and DiBenedetto, 2002), (Santucci *et al.*, 2000)) because of the impact these systems are going to have on the overall situation of semiconductor and electronic system industry, and on electrical motors (see e.g. (Parasiliti *et al.*, 2002), (Parasiliti *et al.*, 2001)) because of the pervasiveness of this application to an industrial landscape that is favoring the use of small electrical motors in all kinds of embedded system applications.

3.1 Automotive Electronics

To support the automotive design chain, a new design flow has to be put in place. The importance of clean interfaces and unambiguous specifications will be essential. In addition, the thorny issue of IP protection and property has to be addressed. In the automotive domain, this is even more important as the supplier chain is deeper than in other industrial segments.

The methodology we are working on at DEWS in collaboration with PARADES, includes three main steps: algorithm specification, virtual prototyping, and physical prototyping. We assume the designers, given an informal specification of the (sub)-systems, are able to specify the requirements in some (semi)-formal way (e.g. UML). The overall behavior (functional network) and architecture net-list of the distributed system constitutes the output of this phase.

The approach can be summarized as follows:

· Use of sophisticated hybrid models and algorithms with guaranteed formal properties for power-train control, to minimize emissions and maximize comfort;

· Use of a virtual platform, for system testing and prototyping (hardware/software architecture) via simulation;

· Use of virtual models of the application software and the target hardware/software architecture (bus controllers, CPUs, RTOS schedulers, communication protocols) to create a virtual prototype of the entire distributed application. The application software models are imported from other tools, or can be authored within the system. The architectural models are developed within the tool (e.g. the communication protocol model is the subject of further chapters) using a standard C++ API;

· Use of virtual models of the environment, complex human-machine interactions, and test-benches that provide the stimuli to the system under testing - the models are either imported from other tools such as Mathworks/Simulink or authored within the system.

3.2 Wireless Sensor Networks

The application area of DEWS that today is receiving most attention is the one that deals with the design of Wireless Sensor Networks. Wireless Sensor Networks have the potential of improving our living conditions and global energy consumptions by a quantum leap. Consider the management and optimization of environmental control systems in large office buildings. A distributed building monitor and control approach may greatly improve the living conditions for the population of the building, resulting in improved thermal comfort, improved air quality, health, safety, and productivity. It can also dramatically reduce the energy needed to condition the space. The same environmental control network could easily hook into the disaster mitigation system and provide building monitoring as well as information distribution in case of emergency. From a technology-development point of view, developing this network requires a combination of micro-sensor technology, low power signal processing and computation, and low-energy/low-cost wireless links. Developing design guidelines for each specific aspect and, at the same time, a global design approach at a higher level of abstraction is indeed an ambitious goal.

Another important application of Wireless Sensor Networks is environment monitoring. Pollution, fire, out-of-range temperature can all have a major negative impact of the environment causing the loss of property, natural resources and even lives. Since fires and pollution often originate in remote and hard-to-reach locations, sensors that can monitor the environment continuously and relay the information so collected to stations that can alert operators about hazardous conditions, have a strategic importance. In DEWS, we are exploring collaborations with regional authorities about devices and wireless networks for water quality and highway structures such as bridges and tunnels.

The capability of producing micro-sensors such as the Berkeley Smart Dust opens new vistas on health monitoring for the elderly and the chronically ill. Italy is the nation with the highest rate of population decrease in the world. The challenges posed by an increasingly aging population for health care organizations are worrisome. Wireless networks could continuously relay data about physical conditions of patients who are carrying out their normal life outside the hospital infrastructure, lowering costs and improving service quality. This application is still under consideration because of the impacts on legislature and ratification of devices and infrastructures.

Finally, these networks could be used to monitor the stability of historical buildings that may suffer serious damages for the aging of their construction material or for weather conditions. Italy is famous for the great number of buildings and monuments that have historical and artistic value and we believe that this technology can have a significant impact on conservation and on preventing irreparable damages to the heritage of a large fraction of western culture.

3.3 Electrical Motors

Electrical motors are present everywhere and their evolution is likely to make it possible to extend their use in other areas where they are still not common. Electrical motors come in different forms, e.g., induction motors, permanent magnet synchronous motors (both brush-less AC and DC) and reluctance motors. Each has a preferred domain of application according to its performance, cost and energy consumption characteristics. In any case, their dissemination has been possible by the adoption of on-board micro-controllers that have made it feasible to control accurately the behaviour of the motors and to optimise their performance. Micro-controllers offer more and more performance with decreasing costs. To fully exploit their potential, sophisticated control algorithms can now be used even for mundane applications such as washing machines and refrigerators. Indeed, the home appliance industry traditionally considered low-tech, is evolving into a high-tech industry where integrated circuits and control algorithms play a more and more important role. In this work-package, the objective is to provide the much-needed coupling between the architecture of electrical motors, the application characteristics and the available technology.

4. INDUSTRIAL RELATIONS

An important objective of the Center is to develop a novel approach to industry-University relations. Much has been written about the difficulties that University and industry have found collaborating on projects that have a measurable impact on society in Europe and, in particular, in Italy. In the US, while still difficult to conjugate the industrial needs and the University aspirations, several joint research projects have yielded important innovations that pervaded markets and yet resulted in important theoretical contributions. One of the objectives of the Center is to start developing similar working conditions in Italy. Important electronics companies active both nationally and internationally have been involved since the very beginning to keep us in tune with the industrial reality of our Country. The Team has excellent relationships with research centers in Italy and abroad that have been very helpful in identifying problems and solutions beyond our human and infra-structural resources.

Small and medium industry in traditional economics sectors will have to face the problem of electronic infusion in their products. Embedded controllers of increasing power and complexity will be inserted in every device for the house, the office, the environment and the car. Hence, the methods studied in the Center will allow our industrial infrastructure to remain competitive in view of an ever-increasing competition.

5. INTERNATIONAL COLLABORATIONS

DEWS is built upon the principle that relevant research in today's economic climate can only be done by polling the international research communities. In particular, our research activities are tightly linked to the research work at the University of California at Berkeley, where a subset of our researchers have spent significant amount of time, at PARADES in Rome, and at the location of our EU partners:

- for HYBRIDGE: National Aerospace Laboratory (NL), University of Cambridge (UK), Università di Brescia (I), National Technical University of Athens (Gr), University of Twente (NL), Eurocontrol Experimental Centre (F), Centre d'Etudes de la Navigation Aérienne (F), AEA Technology (UK), INRIA (F), BAE Systems (UK);
- for COLUMBUS: INRIA (F), University of Patras (Gr), University of Cambridge (UK), University of California at Berkeley (US), Vanderbilt University (US).

Other relevant collaborations are with UWB research group at Università di Roma "La Sapienza" and the RF research group at Università di Roma Tor Vergata.

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