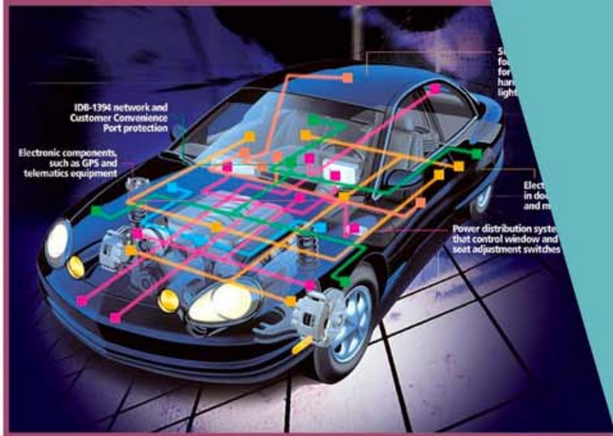

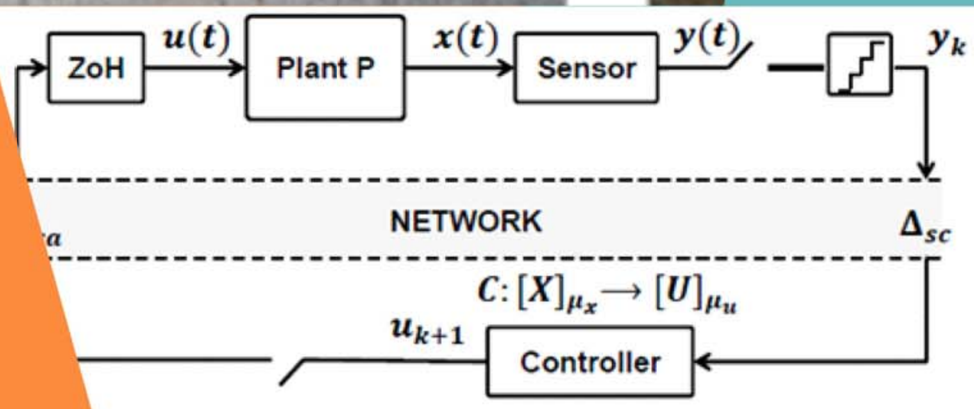

Center of Excellence for Research DEWS

Research Activity Report
Years 2015-2018

Summary

Contents

Activity Overview

DEWS started its operations in 2001 after the Ministry of Scientific Research and University awarded grants for the formation of centers of excellence on a competitive basis. DEWS was among the very first organizations that proposed research on the use of networks of sensors, controllers and actuators to solve societal scale problems such as health, disaster recovery, transportation systems, and education. Since its inception, DEWS has addressed a cross-section of information and communication technology domains by activating research activities that anticipated the themes at the core of the Horizon 2020 vision.

DEWS promotes interdisciplinary cooperation to address the integration of computing, communication, electronics and control that is at the basis of the Cyber-Physical Systems domain. In particular, the focus of DEWS in the last three years has been on distributed, possibly heterogeneous, control systems based on multi-processing, wireless communication and advanced sensor technology.

In this report, we first summarize the main activities pursued during the period 2015-2018. Then, we describe in more detail the research directions and outcomes.

Research Strategy 2015-2018

DEWS research organization has continued to be structured into the same six research areas as in the past three years, where applications are vertical lines and methodologies, tools and models are horizontal lines (see Fig. 1).

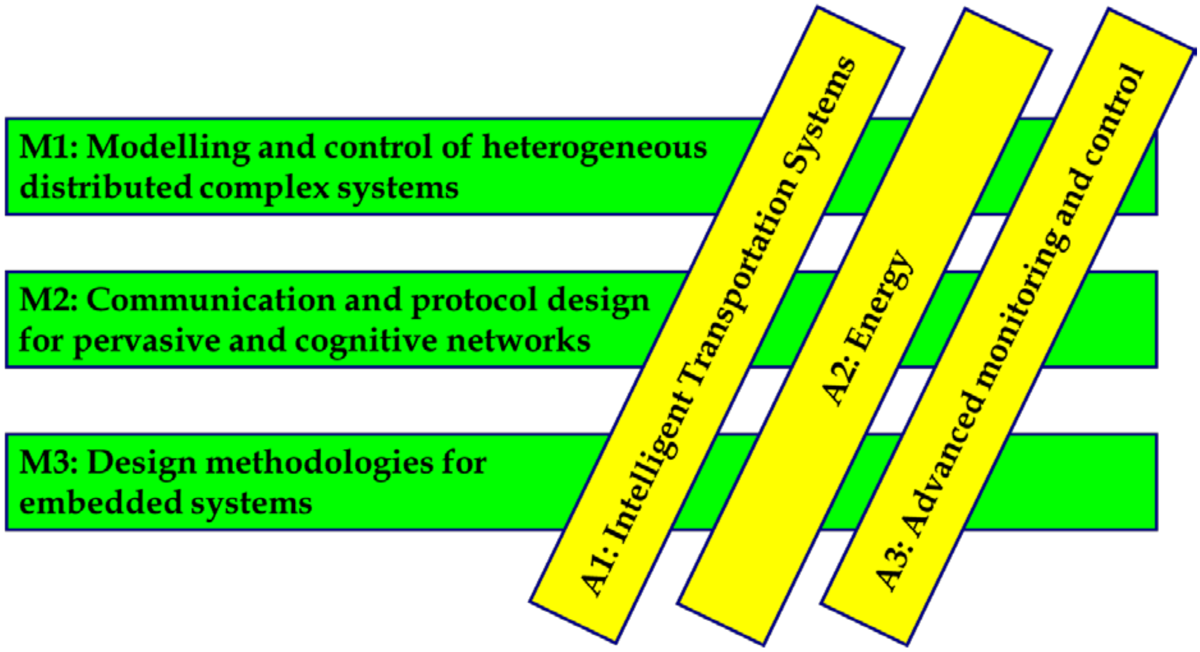

Figure 1: DEWS methodological and applicative research areas.

Methodologies and Technologies:

- M1: Modelling and control of heterogeneous distributed complex systems (Leader: M.D.Di Benedetto)
- M2: Communication and protocol design for pervasive and cognitive networks (Leader: F. Santucci)

- M3: Design methodologies for embedded systems (Leader: V. Cortellessa)

Research Areas M1, M2 and M3 are foundational, they are aimed at developing new methodologies for the design of complex embedded systems and communication paradigms for their mutual interaction. In particular, M1 provides the mathematical methodologies and tools for control, design and formal verification of networked heterogeneous control systems; M2 provides fundamental methodologies for networked systems architectures and design; M3 provides the fundamental background on models, metrics and tools for embedded systems development.

Applications:

- A1: Intelligent Transportation Systems (Leader: S. Di Gennaro)
- A2: Energy (Leader: E. De Santis)
- A3: Advanced monitoring and control (Leader: F. Graziosi)

Research Areas A1, A2 and A3 are orthogonal to the Foundational Areas M1, M2 and M3, each covering an application specific research domain.

Labs

From the start, DEWS created the DEWSLab, a laboratory for the design and implementation of wireless sensor networks using products developed by Memsic (ex Crossbow) and Texas Instruments. The lab has been configured as a "testbed" for innovative solutions related to routing and coding algorithms and it is used as a web service to allow remote access to interested parties. Since 2005, DEWS has also been chosen by the FP7 Network of Excellence HYCON as the node of the European Embedded Control Institute (http://www.eeci-institute.eu) Networked Control Systems Laboratory (NCSlab).

Education

In 2012, DEWS was awarded a grant to set up an Advanced ICT School on pervasive computation, communication and control systems. This initiative gained enthusiastic support from industry because of its goal of connecting the ICT research and industry communities. This award was supported by OCSE and had a number of important outcomes, in particular it allowed the establishment of the ICT PhD school offered by the Department of Information Engineering and Computer Science (DISIM) of the University of L'Aquila. During the reporting period, the participation has grown up to 31 students who are presently enrolled, 12 among them from the international community.

All students are encouraged to spend at least six months during their PhD in a foreign institution to enlarge their research horizons. This becomes mandatory to obtain a European or International PhD degree.

As member of the European Embedded Control Institute (EECI), DEWS offers each year PhD courses in L'Aquila, in the context of the EECI Graduate School on Control. In particular, the following modules were organized:

- EECI GSC, 21-24 March, 2016, "Tools for nonlinear control, Lyapunov function, positivity, applications", Frédéric Mazenc (INRIA, Paris-Saclay, France)
- EECI GSC, 4-8 April, 2016, "Cyber-Physical systems control: Algebraic and Optimization techniques", Raphaël Jungers (Université Catholique de Louvain, Belgium)

- EECI-GSC, 5-9 February, 2018: Time-delay and sampled-data systems, Emilia Fridman (TelAviv University, Israel) and Pierdomenico Pepe (University of L'Aquila, Italy)

All modules have been attended by a minimum of 20 students coming from all over Europe. For 2019, the course "Hybrid control design" has already been planned to be given in L'Aquila from 13 May to 17 May 2019 by Ricardo Sanfelice (University of California at Santa Cruz, California, USA).

DEWS signed a Joint Doctoral Degree agreement with the *Royal Institute of Technology* (KTH, Stockholm, Sweden) and with the *Centro de Investigación y Estudios Avanzados* (CINVESTAV, Instituto Politécnico National, Campus Guadalajara, Mexico). The doctoral candidates carry out their activities under the responsibility and the guidance of thesis advisors from each of the two universities. The two advisors act in all respects as academic mentors for the doctoral candidate. The joint doctoral degree allows candidates to obtain a PhD degree from each of the co-advising universities.

The international agreement with EECI, signed for the establishment of a Path-to-Excellence master Program (PEP), has the objective of increasing the value of the education of Master students, who deserve and are interested in deepening knowledge activities and cultural integration. The mission of PEP is to provide high-profile scholars combining in-depth disciplinary knowledge from their MSc program in Automatic Control, Computer Engineering, Telecommunication and Electronics with interdisciplinary skills that are needed in advances in Cyber Physical Systems. The PEP curriculum consists of educational activities that are added to the normal student curriculum. PEP is supervised by a Scientific Committee composed of three members, two members of the University of L'Aquila and one member nominated by the EECI. The Scientific Committee selects the students that are admitted to the PEP in each academic year among the applicants to the Master of Science Program in Automatic Control and Computer Engineering, the Master of Science Program in Telecommunications and the Master of Science Program in Electronics at University of L'Aquila. Students enrolled in the PEP are required to perform specific activities, agreed upon by the Scientific Committee, including internships at foreign participating Institutions and participation in recommended international activities and courses.

The Scientific Committee certifies the successful completion of the requirements for the PEP upon analysis of the activities of each student every year. At the end of the program, EECI and DEWS deliver a certification of accomplishment.

The PEP has proven to facilitate the participation of the master students in joint research projects. In the next years, the PEP will be used as a first tool for building a closer collaboration between DEWS and the nearby PhD School of the Gran Sasso Science Institute (GSSI). This will help in leveraging the complementarity of research and education activities of DEWS and GSSI, as suggested by the International Advisory Board.

Academic and industrial collaborations

As a consequence of the participation to high-level EU funded research projects and of exchanges of researchers/PhD students, DEWS has established strong research collaborations with some of the most prestigious universities and research centers in the world such as the University of California at Berkeley, the University of California at Los Angeles, the University of California at Santa Barbara, the University of Pennsylvania, the Royal Institute of Technology (KTH, Stockholm), the Technical Universities of Delft and Eindhoven, Ecole Centrale-Supélec (Paris), the Center for Automotive Research (CAR, Ohio State University), the National Aerospace Laboratory (NLR, Netherlands). The worldwide academic and industrial collaboration network of DEWS is depicted in Figure 2.

In particular, DEWS signed formal cooperation agreements with the University of California at Berkeley (UCB, US) at the beginning of its operation, which involve the mutual exchange of researchers and students working on joint projects. An agreement with the "Antonio Ruberti Institute on Systems Analysis and Computer Science" (IASI-CNR, Italy) is under way.

DEWS has ongoing collaborations with multinational companies such as Leonardo (Chieti, Florence, Genoa, Pomezia - Italy), Intecs (Pisa – Italy), Pure Power Control (Pisa - Italy), Tekne (Chieti - Italy), Thales Alenia Space (L'Aquila and Rome - Italy), LFoundry Marsica (Avezzano - Italy), Terna (Roma – Italy), ITACO (Roma - Italy), Telecom Italia (Rome – Italy), RoTechnology (Roma - Italy), and the partners of EU and national research and industrial projects. In this context DEWS has been planning and managing projects of significant complexity, as well as spin-off an engineering company (WEST AQUILA, http://www.westaquila.com).

DEWS has been very active in the establishment of the PhD School in ICT, offered by the Department of Information Engineering and Computer Science (DISIM). The PhD School is intended also as a fundamental environment for improving cooperation between companies and universities/research centers.

Figure 2: DEWS worldwide collaboration network.

Projects

The Center DEWS is self-sustained. Its activities have been supported by the participation in several research and industrial international projects. The following list shows some details about the current and some past DEWS research projects.

European Research Projects (2015-2018)

AFARCLOUD: *Aggregate Farming in the Cloud* (ECSEL-JU RIA-2017)

Project in negotiation phase, responsible: Dr. Luigi Pomante

FITOPTIVIS: *From the cloud to the edge - smart IntegraTion and OPtimization Technologies for highly efficient Image and VIdeo processing Systems* (ECSEL-JU RIA-2017)

Project in negotiation phase, responsible: Dr. Luigi Pomante

AQUAS (2017-2020): *Aggregated Quality Assurance for Systems* (ECSEL-JU RIA-2016). There is an ever increasing complexity of the systems we engineer in modern society, which includes facing the convergence of the embedded world and the open world. This complexity creates increasing difficulty with providing assurance for factors including safety, security and performance - particularly for safety critical systems such as the transportation, aerospace and the industrial control domains. In this project we will focus on the following: safety/security/performance to be considered together, during the overall life cycle of our products; flexibility across domains; consolidate the industrial market by reducing costs and increasing system quality and maintaining compliance with more and more exacting standards; improved tool features and capabilities

Total cost of the project: 15.512.787,89 €

DEWS cost: 450.000 € - DEWS funding: 292.500 € (MIUR)

Responsible: Dr. Luigi Pomante

MEGAM@RT2 (2017-2020): *MegaModelling at Runtime - scalable model-based framework for continuous development and runtime validation of complex systems* (ECSEL-JU RIA-2016). European industry faces stiff competition on the global arena. Electronic Components and Systems become more and more complex, thus calling for modern engineering practices to be applied in order to better tackle both productivity and quality. Model-based technologies promise significant productivity gains, which have already been proven in several studies and applications. However, these technologies still need more enhancements to scale up for real-life industrial projects and to provide more benefits in different contexts. The ultimate objective of improving productivity, while reducing costs and ensuring quality in development, integration and maintenance, can be achieved by using techniques integrating seamlessly design time and runtime aspects. Industrial scale system models, which are usually multi-disciplinary, multi-teams and serving to several product lines have to be be exploited at runtime, e.g. by advanced tracing and monitoring, thus boosting the overall quality of the final system and providing lessons-learnt for future product generations. MegaM@Rt2 brings model-based engineering to the next level in order to help European industry reducing development and maintenance costs while reinforcing both productivity and quality. To achieve that, MegaM@Rt2 will create a framework incorporating methods and tools for continuous development and runtime validation to significantly improve productivity, quality and predictability of large and complex industrial systems. MegaM@Rt2 addresses the scalability challenges with advanced megamodelling and traceability approaches, while runtime aspects will be tackled via so-called "models@runtime", online testing and execution traces analysis.

Total cost of the project: 15.000.763 €

DEWS cost: 475.000 € - DEWS funding: 308.750 € (MIUR)

Responsible: Prof. Vittorio Cortellessa

SAFECOP (2016-2019): *Safe Cooperating Cyber-Physical Systems using Wireless Communication* (ECSEL-JU RIA-2015). SafeCOP (Safe Cooperating Cyber-Physical Systems using Wireless Communication) will establish a safety assurance approach, a platform architecture, and tools for cost-efficient and practical certification of cooperating cyber-physical systems (CO-CPS). SafeCOP targets safety-related CO-CPS characterized by use of wireless communication, multiple stakeholders, dynamic system definitions, and unpredictable operating environments. In this scenario, no single stakeholder has the overall responsibility over the resulted system-of-systems; safe cooperation relies on the wireless communication; and security and privacy are important concerns. Although such CO-CPS can successfully address several societal challenges, and can lead to new applications and new markets, their certification and development is not adequately addressed by existing practices. SafeCOP will provide an approach to the safety assurance of CO-CPS, enabling thus their certification and development. The project will define a platform architecture and will develop methods and tools, which will be used to produce safety assurance evidence needed to certify cooperative functions. SafeCOP will extend current wireless technologies to ensure safe and secure cooperation. SafeCOP will also contribute to new standards and regulations, by providing certification authorities and standardization committees with the scientifically validated solutions needed to craft effective standards extended to also address cooperation and system-of-systems issues. SafeCOP brings clear benefits in terms of cross-domain certification practice and implementations of cooperating systems in all addressed areas: automotive, maritime, healthcare and robotics. The advantages include lower certification costs, increased trustworthiness of wireless communication, better management of increasing complexity, reduced effort for verification and validation, lower total system costs, shorter time to market and increased market share.

Total cost of the project: 11596484,13 €

DEWS cost: 428.288,80 € - DEWS funding: 171.315,52 (ECSEL-JU), 107.072,20 € (MIUR)

Responsible: Dr. Luigi Pomante

CASPER (2014-2019): *User-centric MW Architecture for Advanced Service Provisioning in Future Networks* (H2020-MSCA-RISE-2014). The current paradigm in service provisioning to future communication networks lacks thorough end-to-end interpretation from the quality viewpoint, while the end-users'/customers' profiles and preferences are mostly not taken into account. The subjective perception of a provided service, known as Quality of Experience (QoE), is one of the most important factors for a user's decision on retaining the service or giving it up, and the key parameter for enabling advanced customer experience management (CEM). The main objective of CASPER is to combine academic and industrial forces towards leveraging the expected benefits of QoE exploitation in future networks. In particular, CASPER will exploit the most recent approaches in communication networks, such as the Software Defined Networking (SDN) and the Network Functions Virtualisation (NFV), to design and implement a middleware architecture for QoE-driven service provisioning. The cornerstone of this effort will be a carefully-planned inter-sectorial secondment program for *Experienced Researchers* (ERs) and *Early Stage Researchers* (ESRs). Under this program, CASPER is expected to foster the exchange of knowledge and strengthen the collaboration among academia and industry through a bidirectional knowledge-sharing approach.

Total cost of the project: 1.080.000 €

DEWS cost: 27.000 € - DEWS funding: 27.000 € (EU)

Responsible: Dr. Luigi Pomante

EMC^2 (2014-2017): *Embedded multi-core systems for mixed criticality applications in dynamic and changeable real-time environments* (ARTEMIS-JU 2013). EMC^2 project, funded by Artemis-JU AIPP, has just started (April 2014). It focuses on the industrialization of European research outcomes and builds on the results of several previous ARTEMIS, European and National projects. It provides the paradigm shift to a new and sustainable system architecture which is suitable to handle open dynamic systems. EMC^2 is part of the European Embedded Systems industry strategy to maintain its leading edge position by providing solutions for: dynamic adaptability in open systems, utilization of expensive system features only as service-on-demand in order to reduce the overall system cost, handling of mixed criticality applications under real-time conditions, scalability and utmost flexibility, full scale deployment and management of integrated tool chains, through the entire lifecycle. The main contributions of DEWS will be related the development of a MW for service interoperability support, to provide contribution to the definition and the integration of innovative design space exploration approaches and, in collaboration with Thales Alenia Space Italy, to perform the evaluation of different multi-core architectures on FPGA platforms and related development methodologies and tool chains (including RTOS and/or Hypervisor) in order to assess their suitability for space (i.e. satellite) mixed-criticality applications, opening new application domains to the use of multi-cores.

Total cost of the project: about 100.000.000 €

DEWS cost: 93.750 € - DEWS funding: 15.656 € (ARTEMIS JU), 45.281 € (MIUR)

Responsible: Dr. Luigi Pomante

CRAFTERS (2012-2015): *ConstRaint and Application driven Framework for Tailoring Embedded Real-time Systems* (ARTEMIS-JU 2011). This project brings to bear a holistically designed ecosystem, from application to silicon, for real-time, heterogeneous, networked, embedded many-core systems. The ecosystem is realized as a tightly integrated multi-vendor solution and tool chain complementing existing standards.

Total cost of the project: 17.861.802 €

DEWS cost: 518.400 € - DEWS funding: 86.573 € (ARTEMIS-JU), 172.627 € (MIUR)

Responsible: Dr. Luigi Pomante

VISION (2010-2015): *Video-oriented UWB based Intelligent Ubiquitous Sensing* (FP7 "Ideas" Specific programme ERC Staring Grant 2009). VISION will develop an innovative infrastructure aiming at strengthening future wireless sensor networks (WSN) with the capability of supporting intelligent services for ubiquitous sensing, with particular emphasis on real-time 3D video sensing.

Total cost of the project: 1.173.680 €

DEWS cost: 120.342 € - DEWS funding 120.342 € (EU)

Responsible: Dr. Luigi Pomante

PRESTO (2011-2014): *ImProvements of industrial Real Time Embedded SysTems development process* (ARTEMIS-JU 2010). PRESTO aims at improving test-based embedded systems development and validation, while considering the constraints of industrial development processes.

Total cost of the project: 8.662.934 €

DEWS cost: 518.400 € - DEWS funding: 86.573 € (ARTEMIS-JU), 172.627 € (MIUR)

Responsible: Dr. Luigi Pomante

HYCON2 (2010-2014): *Highly-complex and networked control systems* (EU FP7 NoE). HYCON2 is a four-year project coordinated by CNRS. It aims at stimulating and establishing a long-term integration in the strategic field of control of complex, large-scale, and networked dynamical systems. It focuses in particular on the domains of ground and aerospace transportation, electrical power networks, process industries, and biological and medical systems. The FP7 NoE HYCON2 provided its vision on the challenges of future for systems and control science technology in the Position Paper on Systems and Control in FP8.

Total cost of the project: 4.905.855 €

DEWS cost: 332.926 € - DEWS funding 273.000 € (EU)

Responsible: Prof. Maria Domenica Di Benedetto

National Research Projects (2015-2018)

GRETA (2013-2016): *GREen TAgs and sensors with utrawideband identification and localization capabilities* (MIUR). This project is concerned with innovative solutions and disruptive technologies aimed at the realization of a distributed system for identification, localization, tracking and monitoring in indoor scenarios, based on ecofriendly materials, where the tags must be: i) localizable with sub-meter precision even in indoor scenarios and in the presence of obstacles, ii) small-sized (flat, with an area in the order of a few square centimeters) and working without cumbersome batteries, iii) made with recyclable materials, to be integrated in goods, clothes and packings. Ultra-wideband (UWB) localization techniques are fundamental enablers and rely on environmental energy gathering, together with passive transmission techniques based on backscattering modulation and tag circuitry based on "green electronics".

Total cost of the project: 1.652.824 €

DEWS cost: 211.740 € - DEWS funding: 148.217 € (MIUR)

Responsible: Prof. Fortunato Santucci

SMILING (2012-2015): *SMart In home LIviNG: Tecnologie innovative per la sensoristica e l'automazione dedicate alla Domotica* (RIDITT 2009). The project aims at realizing a laboratory for knowledge and technology transfer from the research to the world of industries focusing on advanced automation and sensing technologies for the home automation domain.

Total cost of the project: 1.999.687,5 €

DEWS cost: 501.250 € - DEWS funding: 250.625 € (MISE)

Responsible: Dr. Luigi Pomante

Former Research Projects

CASA+: *Integrated domotic platform for enabling autonomy of disabled people*. The project started in 2010 and it is funded by AIPD (No profit association for disabilities) and Vodafone Foundation. The research is focused on developing smart and non-intrusive solutions for networking, tracking and user interfaces to help people with disabilities to carry out basic daily life operations. A test bed has been developed in cooperation with WEST Aquila srl.

ESSOR: *European Secure SOftware Radio programme*. (MP-IST-083-04). ESSOR is a major European research program in SDR, supported by several european countries and led by major industrial manufacturers, whose main objectives are to strengthen European autonomy on a crucial technological area, federate European industries activities to support production equipment and support development of open standards. The focus is on developing mobile ad-hoc networks (MANETs) with a large number of nodes (hundreds) that are able to operate in harsh environments. Activities of this project have been carried out in the frame of the Radiolabs Consortium.

MAREA: *Mathematical approach towards resilience engineering in ATM*. SESAR WP-E: the aim of MAREA project tis to provide the formal methodology to address the new SESAR 2020 concepts of operation, at present under study by the air traffic management systems' experts at EUROCONTROL.

IntelliCIS: *Intelligent Monitoring, Control and Security of Critical Infrastructure Systems (*COST Action IC0806). The main objective of the Action is to develop innovative intelligent monitoring, control and safety methodologies for critical infrastructure systems, such as electric power systems, telecommunication networks, and water distribution systems. The work done by DEWS is concerned with architecture and development of an Intrusion Detection System (IDS) in wireless sensor networks (WSN). The logic design is based on a WPM (Weak Process Model) based approach to model system behavior and a lightweight modified Viterbi algorithm to detect all possible behavioral patterns; alarms are generated according to scores associated to each pattern. The architecture design is agent-based, where the dynamic portion of IDS logic (i.e., the part specific to cluster heads in a dynamical WSN topology) is implemented through mobile agents, while the static part (i.e., the part shared by all nodes) resides directly on nodes and is implemented through SW modules embedded into a middleware platform. SW development was based on the Agilla middleware, wherein several improvements were made, e.g., porting of the platform on TinyOS 2.x.

iFly: *Safety, Complexity and Responsibility based design and validation of highly automated Air Traffic Management*. EU FP6 STREP, 2007-2011: In the last years the ATM community research trend is to direct large airborne self-separation research projects to situations of less dense airspace. iFly aims at fostering this transition through a systematic exploitation and further development of the advanced mathematical techniques that have emerged within the HYBRIDGE project of EC's 5th Framework Programme. iFly research intent is to establish an upper bound on traffic levels for which airborne self-separation is safe. For en-route traffic, iFly has the objective to develop an advanced control design for airborne self-separation within the SESAR framework. The goal is to accommodate a three- to six-fold increase in current en-route traffic levels. The approach is to develop an overall validation plan which incorporates safety analysis, complexity assessment and pilot/controller responsibilities together with an assessment of ground and airborne system requirements.

PAR2010: *Analisi dei Sistemi di Supervisione, Controllo e Protezione per Reattori Nucleari di Nuova Generazione*. MISE. The Italian Ministry of Economic Development (Ministero dello Sviluppo Economico, MISE) and the Italian Agency for new technologies, energy and sustainable economy (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, ENEA) established an agreement to grant financial assistance for the execution of the three-year plan of research and development of general interest to the "National Electric System". In particular, ENEA has signed a research contract on the theme "Analysis of core instrumentation and simulation" under the area "Nuclear Fission: Methodologies for analysis and verification of nuclear projects fueled by pressurized water". The themes developed under this collaboration agreement between ENEA and DEWS, focus on the supervision, control and protection for pressurized water nuclear reactors of new generation.

DISTRETTO ABRUZZO: *Wireless Networks and Advanced Platform for Smart Agriculture*. Funded by Ministry of Research (MIUR, 2007-2011) and Selex Communications. The aim of this project is to define and develop a platform relying on wireless sensor networks for constant and energy efficient environment monitoring oriented to support advanced practices in the food chain. The project has led to a test-bed development.

IRMA: *Impulse Radio for Multimedia Applications*. Research Contract with Thales Communications in the frame of a project funded by the Italian Ministry of Defense (MD). The project was concerned during the first two phases (2006-2010) with definition and validation of an UWB physical layer for integrated communications, positioning and multi-static radar scanning. The third phase was concerned with the development of a demonstrator (HUMANET) that involves our startup WEST Aquila srl.

PRIN 05: *Forecast and control systems for landslides: local sensor distributed networks integration, monitoring techniques and hydro-geological models*. MIUR, 2006-2007. The research project aims at combining locally deployed sensors and remote sensing for acquisition of a multitude of physical parameters that are directly or indirectly related to those phenomena that may determine landslides events in unstable slopes. If compared to currently employed techniques, the proposed method is characterized by the use of advanced technologies such as remote sensing e dense wireless sensor networks: thus, a large set of measurements can be performed and collected, and then used to feed advanced models and algorithms, with the ultimate goal of performing more reliable and economic forecast tools.

HYCON: *Hybrid Control: Taming Heterogeneity and Complexity of Networked Embedded Systems*. EU FP6 NoE, 2004-2008: The objective of the NoE HYCON is establishing a durable community of leading researchers and practitioners who develop and apply the hybrid systems approach to the design of networked embedded control systems that are found, for example, in industrial production, transportation systems, generation and distribution of energy, communication systems. Hybrid systems provide a scientific paradigm to systematically address the analysis, modelling, simulation, synthesis, and optimisation of digital controllers for physical plants that communicate directly or via networks with other computerized systems and with human users and supervisors. HYCON aimed at a major advancement of the methodology for the design of such systems and their application in power management, industrial controls, automotive control and communication networks. The long-lasting result was the establishment of a European Embedded Control Institute (EECI) that is a worldwide focal point for hybrid and embedded systems research. The network contributed significantly to bridge the gap between traditional control engineering and embedded system design.

HYBRIDGE: *Distributed Control and Stochastic Analysis of Hybrid Systems Supporting Safety Critical Real-Time Systems Design*. EU FP5 STREP, 2002-2005: HYBRIDGE was a project within the 5th Framework Program IST-2001-IV.2.1 (iii) (Distributed Control), funded by the European Commission under contract number IST-2001-32460. The 21st century finds Europe facing a number of remarkable changes, many of which involve large complex real-time systems the management and control of which undergoes a natural trend of becoming more and more distributed while at the same time the safety criticality of these systems for human society tends to increase. However good the control design for these systems will be, humans are the only ones carrying responsibility for the operational safety. This implies that control system designs for safety critical operations have to be embedded within sound safety management systems such that the level of safety stays under control of humans. The objective of HYBRIDGE was to develop the methodologies to accomplish this, and to demonstrate their use in support of advanced air traffic management design. In addition to direct application to air traffic management, these contributions formed the nucleus for further research and development into a complex, uncertain system theory, and into application of this theory to distributed control of other real time complex systems such as communication, computer and power networks.

PRIN02: *Methods for the design of embedded controllers for hybrid systems. MIUR, 2003-2004*. The aim of this project is about bridging the dichotomy between functional design and implementation. To achieve this goal, we drew on the theory of hybrid system control with safety specifications and the principles of platform-based design. In this method, the design process is decomposed into a sequence of steps that involve different levels of abstraction (platforms) related by a refinement relation. The choice of the layers of abstraction and of the corresponding parameters is essential for the quality of the final solution of the design problem. Platforms for the embedded control design problem were defined in terms of their parameters and appropriate cost functionals introduced. The design of the engine control unit for automotive applications was considered for illustrating the advantages of the proposed method.

COLUMBUS: *Design of Embedded Controllers for Safety Critical Systems*. EU FP5 STREP, 2002-2004: The design of embedded systems deals with the implementation of a set of functionalities satisfying a number of constraints ranging from performance to cost, emissions, power consumption and weight. The choice of implementation architecture implies which functionality will be implemented as a hardware component and which as software running on a programmable component. The design of embedded hardware and software poses a number of problems that cannot be addressed by traditional methods. These include hard constraints on reaction speed, memory footprint, power consumption, and, most importantly, the need to verify design correctness. The latter is a critical aspect of embedded systems since several application domains, such as transportation and environment monitoring, are characterized by safety considerations that do not arise in traditional, PC-like software applications. In this project we developed design methods and tools for embedded systems in safety critical applications.

DEWS Organization

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Marco	Santic	DISIM
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Francesco	Smarra	DISIM
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Luca	Benvenuti	Sapienza Univ. di Roma
Domenico	Bianchi	Udanet
Alessandro	Borri	IASI (CNR)
Bernardino	Castillo Toledo	CINVESTAV
Riccardo	Cespi	(Alumni)
Maurizio	Colizza	West Aquila
Dario	De Leonardis	Sapienza Univ. di Roma
Marco	Di Renzo	CNRS
Piergiuseppe	Di Marco	Ericsson Research
Fabio	Federici	UTRC - Ales
Gabriella	Fiore	Jaguar (Coventry, UK)
Carlo	Fischione	KTH
Giovanni	Girasole	ELDOR
Tarek	Kabbani	Università de Surrey
Marco	Lepidi	Università di Genova
Ivano	Malavolta	
Giovanni	Palombo	IASI (CNR)
Pasquale	Palumbo	IASI (CNR)
Jorge	Pires Guerra	Federal University of Bahia
Marco	Pugliese	Metroweb
Jorge	Rivera	CINVESTAV
Paolo	Serri	Thales Alenia Space
Stefano	Tennina	West Aquila

Ubaldo	Tiberi	Volvo
Humberto	Valadez Rangel	(Alumni)
Fabio	Salice	Università Roma 3
Marco	Carli	Università Roma 3
Yuriy	Zacchia Lun	IMT (Lucca)

Research activity (2015-2018)

In this section, the results obtained in the reporting period in the following horizontal and vertical research lines are illustrated.

Methodologies and Technologies:

M1: Modeling and control of heterogeneous distributed complex systems

M2: Communication and protocol design for pervasive & cognitive networks

M3: Design methodologies for embedded systems development

Applications:

A1: Intelligent transportation systems

A2: Energy

M1: Modeling and control of heterogeneous distributed complex systems

M1 research activities provide the basic mathematical methods and tools for analysis and control of complex heterogeneous Networked Embedded Control Systems. The growing relevance of Networked Embedded Control Systems is sustained by the evolution of enabling technologies such as embedded systems and networks. Embedded systems are computing systems designed to perform one or more dedicated functions often with real-time constraints. Embedded systems are present in all aspects of everyday life, from automotive to avionics systems, from white goods to consumer electronics.

The research lines pursued in M1 include hybrid and non-linear systems theory, decentralized control/observability/diagnosis, and networked embedded control. In this report we emphasize the following activities, the first two being characterized by an interdisciplinary approach: i) the development of correct-by-design methods to address controller synthesis for Networked Embedded Systems, taking into account non-idealities at the implementation layers.; ii) analysis of critical observability, diagnosability and predictability not only for finite state machines, or networks of them, but also for continuous and hybrid systems; iii) analysis and control of stochastic linear systems; iv) application of hybrid systems techniques to the control of chemical processes.

Formal methods for the analysis and control of Cyber-Physical Systems

In this section we report the results we obtained in the following research directions:

1. Control of Cyber-Physical Systems via discrete abstractions
2. Analysis of observability, diagnosability and predictability of finite-state machines, of networks of finite state machines and of hybrid systems

Control of Cyber-Physical Systems via discrete abstractions

Discrete abstractions of continuous and hybrid systems have been the topic of intensive study in the last twenty years from both the control systems and the computer science communities. While physical world processes are often described by differential equations, digital controllers and software and hardware are usually modeled through discrete/symbolic processes. During the years, the heterogeneity of these mathematical models has posed interesting and challenging theoretical problems that must be addressed to ensure the formal correctness of control algorithms in the presence of non-idealities at the implementation layers. From the synergistic collaboration of researchers in the control systems and computer science communities, a novel and sound approach has recently emerged, which is termed "Correct-by-Design Embedded Control Software". This research line can be roughly described as a three-step process, as shown in Figure M1.1, and detailed hereafter:

1. A finite state machine (or symbolic model) is firstly constructed, which is equivalent or approximates the continuous control system.

2. The original control design problem is solved at the discrete abstraction layer on the symbolic model obtained.

3. The symbolic controller synthesized at the discrete layer is appropriately refined so that it can be successfully applied to the original continuous control system.

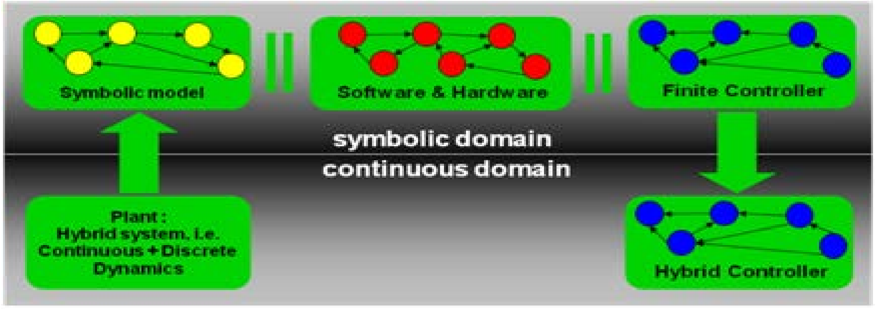


Figure M1.1: Correct-by-Design Embedded Control Software.

The correct-by-design approach guarantees that controllers synthesized at the symbolic layer enforce the desired specification on the continuous layer with guaranteed approximation bounds. Moreover, this approach provides the designer with a systematic method to address a wide spectrum of novel logic specifications that are difficult to enforce by means of conventional control design paradigms. The kernel of this approach resides in the definition and construction of symbolic models that are equivalent or approximate continuous and hybrid systems (Step 1 in the aforementioned methodology).

DEWS researchers have been active in this research topic and their collaboration with researchers from the University of California at Los Angeles (USA) and the Université Joseph Fourier (France) was fruitful.

The first contribution concerned symbolic models for nonlinear control systems. We identified two key ingredients to accomplish this ambitious goal: the notion of approximate bisimulation, introduced by Antoine Girard and George Pappas in 2007 and the notion of incremental stability introduced by David Angeli in 2002. We showed that these two key ingredients can be combined so that for any incrementally input-to-state stable nonlinear control system with compact state space it is possible to construct a symbolic model that approximates the original system in the sense of approximate bisimulation with arbitrarily good accuracy. This result was then generalized to the case of control systems affected by disturbances, time-delay systems and switched systems. The generalization to control systems affected by disturbances required the introduction of a novel notion of approximation that is termed alternating approximate bisimulation; this notion guarantees that control strategies synthesized on symbolic models, based on alternating approximate bisimulations, can be readily transferred to the original model, independently of the particular evolution of the disturbance inputs. The generalization to time-delay systems and switched systems required also the introduction and characterization of novel notions of incremental stability for these classes of systems.

Previous results concerning symbolic models for control systems affected by disturbances were of existential nature: indeed the proposed construction of symbolic models was based on the computation of the set of reachable states which is a hard task in general. For this reason we proposed in [BPDB12b], alternative symbolic models which can be effectively computed; the key idea was to leverage results from spline analysis for approximating the disturbance inputs functional space.

All these results were based on a notion of incremental stability. In [ZPMT12][1] we relaxed this assumption and showed that any incremental forward complete nonlinear control system admits symbolic models that approximate the original system in the sense of alternating approximate simulation. Incremental forward complete assumption is a rather mild assumption which is fulfilled for example by unstable linear control systems.

We also considered the class of discrete-time piecewise affine control systems in [PDB14][2]. We proposed a sequence of symbolic models that can be effectively constructed and that converge, without stability assumptions, to the original control system in the sense of the so-called simulation metric. Symbolic control design was then addressed with specifications expressed in terms of non-deterministic finite automata. A sequence of symbolic control strategies was derived, which converges, in the sense of simulation metric, to the maximal controller solving the given specification on the control system.
We then used symbolic models for control design purposes. In particular, we faced the problem of designing symbolic controllers that enforce a control system to satisfy a specification expressed in terms of automata on infinite strings and so that the interactions between the control system and the symbolic controller is non-blocking. An explicit solution to this problem was explicitly derived, resulting in the non-blocking part of the approximate parallel composition between the specification automaton and the symbolic model of the continuous system. While being powerful, this approach often encounters some limitations in concrete applications, because of the large size of the symbolic models needed to be constructed in the implementation. Inspired by on–the–fly techniques for verification and control of finite state machines, we proposed in [BPDB12a][3] efficient algorithms that integrate the construction of the symbolic model of the continuous system with the design of the symbolic controller.

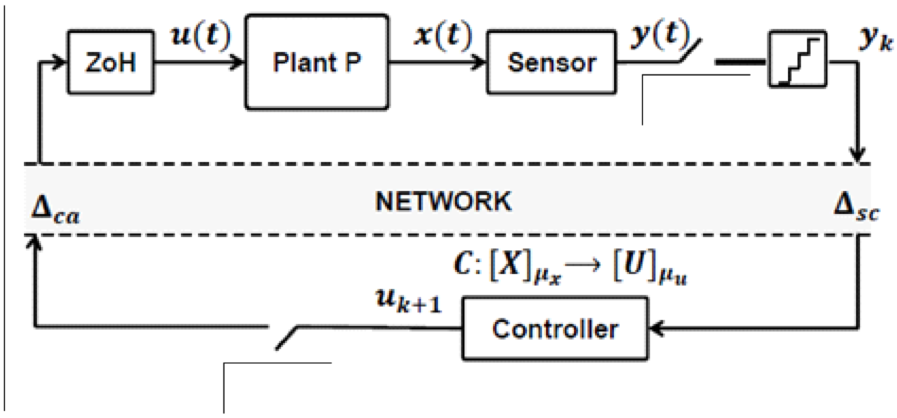


Figure M1.2: Networked control system architecture.

The results above do not consider imperfect communication infrastructures conveying information between the plant and the controller. For this reason, we considered symbolic

[1] [ZPMT12] M. Zamani, G. Pola, M. Mazo and P. Tabuada. Symbolic models for nonlinear control systems without stability assumptions. *IEEE Transactions on Automatic Control*, 57(7):1804-1809, July 2012.
[2] [PDB14] G. Pola and M.D. Di Benedetto. Symbolic Models and Control of Discrete-Time Piecewise Affine Systems: An Approximate Simulation Approach, *IEEE Transactions on Automatic Control*, 59(1):175-180, January, 2014
[3] [PBDB12a] G. Pola, A. Borri and M.D. Di Benedetto. Integrated design of symbolic controllers for nonlinear systems. *IEEE Transactions on Automatic Control*, 57(2):534-539, 2012.

control design of Networked Control Systems (NCSs). In particular, we considered a fairly general framework of NCSs which comprises most relevant non-idealities in the communication channel as quantization errors, saturations in the control action, bounded time-varying network access times, bounded time-varying communication delays induced by the network, bounded time-varying computation time of computing units, limited bandwidth in the communication channel and bounded packet losses. The NCS scheme we considered is depicted in Figure M1.2. In [BPDB12b][4] we showed that NCSs with incrementally input-to-state stable nonlinear control systems admit symbolic models that are an alternating approximate bisimulation of the original NCS. The proposed symbolic models were then used to solve symbolic control design problems for NCS where specifications are expressed in terms of automata on infinite strings. The results of [BPDB12a] were generalized in [BPDB12c][5] to the case where control systems are incrementally forward complete, hence, possibly unstable. On-the-fly type algorithms studied in [PBDB12] were extended to the symbolic control design of nonlinear NCS.

The frameworks above consider only one plant and one controller. In order to tame complexity or realistic large-scale NCS we considered in [PPDB14][6] the case where several plants interact with one another in order to accomplish a given task. More specifically, we considered networks of discrete–time nonlinear control systems and we showed that under some small gain theorem–type conditions, a network of symbolic models can be constructed which approximates a network of incrementally stable control systems in the sense of approximate bisimulation with any desired accuracy. Compositional design of quantization parameters of the symbolic models was also derived and based on the topological properties of the network.

In the reporting period 2015-2018, starting from the results above, we developed them along several directions.

We first extended [BPDB12b, BPDB12c] from networked control architectures with static controllers to networked control architectures with dynamic controllers. This extension is allows using the proposed approach to solve control problems with a wider class of logic specifications than those that can be considered in [BPDB12b, BPDB12c]. This study has led to the publication [BPDB18].

Further studies have been devoted to the construction of symbolic models for networks of discrete-time nonlinear control systems, leading to the publication [PPDB16b]. These results were then instrumental to study in [PPDB18b] techniques of supervisory control for networks of discrete-time nonlinear control systems. Apart from the interest per se in investigating this issue, results reported in [PPDB18b] also offer a key approach to tame computational complexity in deriving controllers. In [PPDB18a, PPDB15] we studied necessary and sufficient conditions characterizing some important stability notions for discrete-time nonlinear control

[4] [BPDB12b] A. Borri, G. Pola and M.D. Di Benedetto. A symbolic approach to the design of nonlinear networked control systems. *Hybrid Systems: Computation and Control* 2012, pp. 255-264, I. Mitchell and T. Dang (Eds.), 2012.

[5] [BPDB12c] A. Borri, G. Pola, M.D. Di Benedetto. Integrated Symbolic Design of Unstable Nonlinear Networked Control Systems. 51st IEEE Conference on Decision and Control, Maui, Hawaii, December 10-13 2012.

[6] [PPDB14] G. Pola, P. Pepe, M.D. Di Benedetto, Symbolic Models for Networks of Discrete–Time Nonlinear Control Systems. 2014 American Control Conference, Portland, Oregon, USA, June 4-6, 2014.

systems with time-varying time-delay in the state; these results will be also instrumental to derive symbolic models.

In many concrete applications, plants are characterized by time-varying delays in the state evolution. Motivated by this, we extended in [PPDB15] our previous results concerning construction of symbolic models for nonlinear systems with constant time-delays to nonlinear systems with time-varying time delays. This extension has required also the introduction of a novel notion that we termed incremental-input-delay to state stability and a characterization of this notion in terms of Lyapunov–Krasovskii functionals as well as functional techniques to approximate the unknown delay signal.

All results above assume knowledge of the state variable of the process which can be limiting in some applications. In [PDB17] we propose symbolic models for nonlinear systems with output variables.

Analysis of observability, diagnosability and predictability of finite-state machines, networks of finite state machines and hybrid systems

Critical observability has been previously introduced for a finite state machine and is the property of deducing the belonging of the current state of the system to a given set, called "critical", from the knowledge of the output evolution. When considering networks of finite state machines, testing critical observability for the resulting monolithic machine can become prohibitive, because of complexity issues. Therefore, in this research line we first studied in [PDSDB17b, PLP+15] critical observability of networks of finite state machines, by showing techniques which allows a simplification of the model and giving conditions for the existence of a decentralized critical observer.

We then proposed novel notions of diagnosability and predictability for finite state machines in [DSDB17, FDS+18]. Diagnosability is the property of detecting the belonging of the state to a critical set, with some delay, while predictability describes the property of estimating in advance the future belonging of the state to a critical set.

The results in [DSDB17, FDS+18] are established in a nominal setting, hence they do not consider measurement errors in sensors. For this reason, we extended the results of the above cited papers in [PDSDB18, PDSDB17c] to a novel notion of diagnosability, termed approximate diagnosability, and in [FDS+18], to a novel notion of predictability, termed approximate predictability. Extensions above not only take into consideration measurement errors but also allow studying notions of diagnosability and of predictability for purely continuous or hybrid systems, by leveraging results on discrete abstractions described in the section above.

In [FDSDB2018] the analyis of diagnosability of hybrid systems has been extended to the more general case where the available information may be corrupted by an external attacker, by introducing the new notion of secure diagnosability.

Finally, a comprehensive analysis of observability of hybrid systems has been published in [DSDB16].

Analysis and control of stochastic linear systems via bisimulation theory

The contribution in this research line was first focused on studying a theory of bisimulation for stochastic linear systems in both discrete-time and continuous-time domains. In this regard, we first proposed a new definition of stochastic bisimulation and a geometric characterization of it; we then developed model reduction techniques preserving stochastic bisimulation equivalence and studied connections with stochastic optimal control and the notion of equivalence of stochastic external behavior, see [PMVdS+18, PMDB16, PMvDS+16, PMvDS+15]. We then studied control via equivalence of stochastic external behavior in [P17], and via equivalence of stochastic bisimulation in [PMDB19].

Industrial applications of hybrid systems theory

In [FBF+17], [FFB+18] and [FBB+18] hybrid systems techniques have been applied to synthesize a hybrid controller for pressure swing adsorption (PSA) processes. Since the process is described by a set of partial differential algebraic equations, first a local reduced-order model for the process is developed and is formalized as a hybrid system. A hybrid controller is designed for purity control of the process in the presence of external disturbances by determining the maximal safe set of the LROM. A hybrid backward reachability analysis is performed for this purpose. Considering a realistic scenario for PSA processes where the states are not available and the number of measurement sensors is very limited, the desired states are estimated by using a hybrid observer. The controller is designed and applied to a two-bed, six-step PSA process whose dynamical behavior is simulated by a full-order principle-based model of the process. An excellent performance of the controller is obtained.

M2: Communication and protocol design for pervasive and cognitive networks

The objective of the research in M2 is the overall development of communication and networking technologies for supporting advanced applications. Since the early stage of DEWS activities in 2001, M2 has pursued theoretical research in close cooperation with M1; recently, it has leveraged embedded SW methodologies and tools that are investigated in M3. In this reporting period the research organization of M2 has been further expanded: while still focusing on major items described in the latest report 2009-2012 (algorithms, techniques and models for signal processing, transmission systems and protocols for secure and efficient networking), the set of activities has been extended according to both specific internal interests and to novel projects also proposed by industrial partners. Moreover, the activities often include experimental validation and are in many cases connected to methodologies addressed in M3 for implementation issues; a close connection with the applications depicted in the Research Line A3 is pursued. Although mainly focused on the wireless domain, our concept of networking has been actually spanning across a set of heterogeneous components that are integrated not only on the traffic side but also in terms of management and control. In the following we provide a short description of recent achievements and work in progress, according to our major topics:

- signal design and physical layer techniques for novel communication paradigms, that include cooperative and cognitive wireless systems, network coding, distributed MIMO and spatial modulations;
- characterization of interference as a prominent and limiting feature of many wireless environments, along with evaluation of achievable performance and development of novel paradigms for radio resource management;
- analysis, modelling and specification of cross-layer protocol stacks that are able to meet specific application requirements in distributed wireless systems;
- network management and traffic modelling in broadband infrastructures for the future Internet;
- distributed algorithms and platforms for localization, sensing and security in networked embedded systems.

Modelling and Design of Satellite Digital Transparent Processors: from Communications Link Performance to Hardware Complexity

The evolution of satellite systems for telecommunications has been driven for decades by the need to overcome the limitations of network configurations relying on pure star topologies that are typical of transparent satellite architectures, and to support instead more advanced mesh topologies that have been later enabled by regenerative satellite architectures. Nevertheless, the implementation complexity and heavy processing power demand of the regenerative approach have posed serious limitations to the achievable performance in terms of capacity and communication bandwidth of current payload developments. The latest developments in satellite communications encompass semi-transparent transponder architectures. Those architectures have potentials i) to operate with enhanced frequency planning flexibility and physical layer specifications of evolving communications standards, and ii) to support dynamic reconfiguration of connectivity plans. Semi-transparent payload solutions resort on a main digital transparent section, which is devoted to the routing of the bulk of traffic data and is named Digital Transparent Processor (DTP), and a regenerative section, that is devoted to handle a much smaller amount of control traffic. This kind of architectures are emerging as a viable alternative to provide broadband connectivity in modern network topologies with larger users' populations and a variety of requirements in terms of bandwidths and QoS, while maintaining the payload complexity affordable. In this frame, significant on-board digital processing is involved, which calls for careful system modelling and accurate digital hardware design to achieve feasible trade-offs between hardware efficiency and overall link-budget performance. The interest in translucent architectures has motivated investigation efforts by both academy and industry on efficient design of flexible on-board multi-rate digital signal processors. First of all, it can be observed that a proper framework for performance analysis of this novel kind of payloads is needed. As a matter of fact, the approach proposed in this work represents a step further in system modelling with respect to the existing literature: it is inherently suited to characterize a whole cascade of blocks in terms of equivalent noise sources and to easily include the overall impact of all sources of degradation in a hybrid analog-digital architecture. Specifically, a detailed description of a general DTP HW architecture is provided: as it does not rely on specific hardware description (e.g. C description, VHDL code or signal graph), it represents the adequate level of abstraction to enable the computation of degradation indexes (noise figures) of all digital blocks to be considered since the early stage of link budget analysis. Nevertheless, the architecture description of each block in the DTP chain is suitable for supporting the computation of hardware complexity and the design approach for the digital hardware. Furthermore, a comprehensive derivation of expressions for noise spectral densities and noise figures is provided, along with their expressions that relate to the more general versions of DTP blocks. Finally, the validation of the design choices in the DTP chain are obtained through an FPGA-based prototype.

A satellite digital transparent payload is composed by analog receiving and transmission chains with a fully digital but non regenerative chain between them. Modeling and performance characterization of the analog sections are well consolidated in the radio communications community, and a remarkable amount of literature also exists for modeling the sources of non idealities in single digital processing blocks. Indeed, many papers are focused on detailed analysis of rounding errors in fixed point arithmetics. Usually, when the effects of fixed point arithmetics are considered other effects (namely, linear distortions) are neglected. Nevertheless, a large body of literature also exists on the specific analysis of distortions effects, wherein the effect of rounding errors induced by fixed point arithmetics is neglected. Methods for the design of filters that guarantees the Perfect Reconstruction (PR) has been analyzed, however, in order to overcome problems encountered in filters' optimization, in particular when large stop-band attenuation and a large number of extrapolated channels are required, approaches based on the Near Perfect Reconstruction (NPR) have also been proposed. When flexible frequency-band reallocation (FBR) networks are concerned, it has been evidenced how practical realizations with zero distortion and aliasing errors can not be approached: indeed, the application of a PR policy for all feasible combinations and reallocation schemes may not be an affordable task. However, this latter limitation may not be considered as a major problem in practical context, since a Filter Bank only represents a block in the communication chain, which of course includes other sources of error: therefore, the problem arises on how to drive the DTP design in order to introduce an overall degradation that needs to be quantified and then kept limited when compared to other sources of degradation within the whole chain.

In these regards, an equivalent noise model for the analog-digital hybrid receiving chain that composes the satellite transparent transponder has been proposed [SGSF16], [SGSF18]. The proposed analytical method is applied to a specific DTP architecture and the validation is discussed by comparing results with those obtained via Monte Carlo simulation. The papers [SGSF17] and [SGSF18] provide a detailed description of the architecture of each block within the DTP chain. The papers [SGSF17] and [SGS+18] include the hardware complexity analysis

of the basic building blocks and of the whole DTP chain. These papers also provide an overview of the general system scenario enabled by advanced transponders. The paper [SGS+18] is then concerned with the definition of the DTP noise model and the different design approaches. The paper [SMS+18] presents numerical examples that illustrate the application of the developed framework and the related design methodology in scenarios of practical interest, with a first validation of the design choices in the DTP chain that are obtained through an FPGA-based prototype benchmark that has been specifically developed in our lab.
On-going work is concerned with optimization problems that rely on the proposed models. Our current work is also focused on further developments and adaptations of the developed framework to several scenarios of interest in satellite communication. Among the prospected scenarios the 5G wireless context deserves particular attention. In this global frame satellite communications can provide a valuable resource to extend and complement terrestrial networks both in terms of throughput and global connectivity. There are also high expectations in the so-called megaconstellations of MEO and LEO satellites. When on-board transponders are considered, transparent satellites are considered an appealing solution to provide backhaul connectivity to the on-ground Relay Nodes. The theoretical framework and the related design methodology proposed then have potentials to approach the design of future transponders, with a first extension to consider the effect of interference and to include beamforming features. In the general 5G arena, it seems that the developed framework might also be useful to address terrestrial network segments, e.g. in non-regenerative relaying and front-haul architectures of cellular systems.

Modelling and Design of Wireless Protocols Towards Energy Neutral IoT

The *energy neutral communication paradigm* has recently emerged as a key concept for the development of next-generation self-sustainable wireless systems, especially within Wireless Sensor Networks (WSNs) and Internet of Things (IoT) ecosystems.
Energy neutrality design enables single and networked devices to operate on a potentially infinite time horizon without the need of always-on power sources, allowing for self-sustainable pervasive connections. This appears to be a critic feature for IoT applications, where heterogeneous and high density connectivity implies strict constraints on energy consumption and management. From a communication viewpoint, energy neutral systems can be intended as a generalization of classic energy constrained systems (e.g., WSN), where the maximum usable energy needs to be properly reduced given limited available energy resources. Instead, in self-sustainable systems, the constraints on maximum usable energy can be relaxed and the limits are on the maximum rate at which the energy can be used.
Instrumental to achieve energy autonomy is the ability of harvesting energy from the surrounding environment and possibly storing the scavenged energy at individual devices. Thus, energy harvesting technology applied to communication systems is gaining a great interest in the research community. Within the broad range of available renewable energy sources, such as solar, body motion and heat, Radio Frequency (RF) harvesting appears as the natural choice for powering next generation ubiquitous networks.
Systems relying on RF energy sources can be classified as *dedicated power systems*, where networked power beacons disseminate the energy needed to power-up the devices, or opportunistic systems, where the devices harvest the energy from ambient radio sources, possibly from multiple frequency bands without the need of on-purpose energy infrastructures. On the one hand, dedicated power systems are more controllable and reliable, but require the deployment of additional resources. On the other hand, opportunistic energy scavenging can reduce deployment cost, but also suffers of decreased reliability due to the lack of guarantee of a sufficient source of energy.
In both cases mentioned above, due to the intermittent nature of the energy available in the environment, energy storage modules are necessary. Among various technologies for energy storage, rechargeable batteries such as lithium-ion batteries are the prominent energy storage

solution thanks to their relatively low cost and ability to hold charge. The main drawback of this technology is the limited battery life time and power density. Batteries cannot be charged and discharged an unlimited number of times due to aging effect. Their State of Health (SoH) not only depends on charge/discharge cycle counts (battery lifetime), but are also depends on charge/discharge rate (power density). As a consequence, the aging effect in batteries is even more dominant when deployed in renewable energy systems. Harnessing energy opportunistically from renewable sources causes a dynamic fluctuation in the charge level which may significantly degrade their SoH. In such systems, if the battery aging effect is not limited, the effective capacity and energy density may rapidly deteriorate. Alternatively, *supercapacitors* can be exploited as energy storage. Differently from rechargeable batteries, supercapacitors do not suffer from aging effects, however their ability of holding charge is extremely low if compared with battery (i.e., leakage effect)

In this context, new challenges arise in the derivation of energy management strategies with the objective of optimally balancing the system performance and the capability of the system to be self-sustainable in terms of energy provision. Energy constraints can be formalized in various ways depending on the application requirements, the considered energy source and the chosen storage technology. For instance, in a battery-powered wireless system, the energy usage has to be controlled in order to mitigate the aging process of the battery, which represents one of the main limitations to the energetic autonomy. On the other hand, when super-capacitors are considered, the energy management policies have to be designed to face fast energy leakages, thus can be typically instantiated as "duty-cycle" control strategies.

A paradigmatic instance of energy neutral communication ecosystem are Radio Frequency IDentification (RFID) systems. The RFID context is intrinsically conceived to be energy autonomous on the tag side and it can be addressed as a relevant example of Simultaneous Information and Power Transfer (SWIPT), where RF signals carry both information content and energy required to power the target devices.

Passive Radio Frequency Identification (RFID) systems represent one of the core technologies for future Internet of Things (IoT) applications due to their capability of collecting information from a large variety of objects in a fast and almost "energy-neutral" way with reduced computational effort. Furthermore, tags equipped with sensors allow the applicability of this pervasive technology to a wider and more intriguing set of applications in domotics and biomedical, environmental and goods monitoring fields.

Typical RFID systems consist of a data collector unit (i.e., the reader) and a tag population to be identified, where the commands that trigger tag's replies and the required energy to power up the tags are carried by the same modulated waveform sent by the reader.

Moreover, passive systems are based on a highly asymmetrical architecture, where the computational and processing burden is demanded to the reader. On the contrary, the tags architecture is taken as simple as possible and due to the absence of a dedicated power supply at the tag side, tag-reader communication is based on backscattering techniques. As a consequence, communication protocols are required to be efficient despite a limited reader commands set and reduced overhead traffic constraints.

The *de facto* standard for passive RFID communications is the EPC (Electronic Product Code) Generation 2 (Gen 2). The EPC Gen2 protocol specifies the Physical (PHY) and Medium Access Control (MAC) layers for passive systems operating in the Ultra High Frequency (UHF) band. Specifically, the standard define a Dynamic Framed Slotted Aloha (DFSA) based channel access scheme driven by an adaptive algorithm known as Q--Algorithm, where the parameters for channel contention are changed dynamically during the tag identification procedure. An EPC Gen 2 inventory session consists on a sequence of broadcast commands issued by the reader carrying information to instruct the tags replies. The tags powering opportunity as well as identification performance and reliability are strictly related to the characteristics of the underlying channel, thus the propagation scenario plays a crucial role in such systems.

Furthermore, given the central role that RFID systems will play in the upcoming diffusion of pervasive wireless systems, recent research trends devote effort for extending RFID systems capabilities and features that enrich the applicability span of such systems. For instance,

passive tags architectures can be designed to allow accurate ranging, localization and tracking of objects by integrating Ultra-Wide Band (UWB) communication modules with classic UHF design. The orchestration of UHF and UWB communication provides a fertile research field and allows the derivation of high efficiency, low cost and low consumption RFID solutions.
In the contexts illustrated above, energy harvesting wireless system were studied with the objective of providing design guideline and transmission policies structure that are tailored for energy neutral operations and prolonged system life-time. The presented modeling and optimization frameworks are *battery-centric* in the sense that the described communication strategies are influenced by the energy trajectories of the storage devices. A great relevance was given to the problem of battery capacity fading, which represents one of the main limitations to the achievement of self-sustainable communication systems. In particular, the first part of the research activity was devoted to derivation of optimal communication control strategies and channel access mechanisms for batteries degradation mitigation in energy harvesting wireless networks. Moreover, as an instance of the energy neutral ecosystem, passive RFID systems were considered. Specifically, cross-layer analysis of existing RFID protocols and different novel techniques for UWB/UHF multi-mode operations orchestration were proposed. Relative to UWB/UHF hybrid RFID systems, novel tags' and readers' architectures were proposed and exploited to design communication solutions able to substantially improve performance and energetic consumption.
The main achievements of the research plan are described below:

- A modeling and optimization framework for the transmission trajectory of battery-equipped wireless nodes was derived. Battery degradation is explicitly included as a constraint. The optimization is based on MDP theory, where the embedded stochastic model captures the energy arrival and channel fading processes. Based on the proposed framework, optimal aging aware transmission strategies were derived and the tension between throughput maximization and degradation rate mitigation was analyzed. Furthermore, aging-delay tradeoff was also analyzed. Finally, a heuristic channel access scheme for networked wireless systems was derived with the objective of maximizing the network performance while keeping bounded the battery degradation rate of the network.
- A framework for the optimization of transmission trajectory and power allocation of battery-equipped wireless nodes relying on RF energy harvesting was presented. The optimization framework was still based on MDP theory, where the embedded stochastic model captures the energy arrival process as a function of channel fading conditions and data generation process. The provided modeling rationale was based on an abstraction of the physical behavior of the target system and provides a more detailed description of the system components with respect to the modeling approach presented in the previous point. Battery degradation was measured exploiting a more refined model based on rainflow counting techniques, where the aging rate is a function of the characteristics of individual charging/discharging cycles within the energy trajectory.
- A cross-layer stochastic framework for performance analysis of the EPC Gen 2 protocol for passive RFID system communications was developed. The proposed model jointly considers the propagation scenario and the dynamics of the MAC layer, allowing for deep understanding of the performance of EPC Gen 2 based inventory sessions. Differently from existing models, the developed framework allows to study performance as a function of different system parameters including the channel characteristics. ''Macro-effects`` induced by the channel on the inventory process, such as failure occurrences, can be quantified based on the proposed approach.

Furthermore, the role of the channel in the tag powering process is accounted in terms of tag powering probability. Based on the developed model, a performance study of the EPC Gen 2 MAC layer was conducted defining different performance metrics and highlighting the peculiarities induced by the channel.

- The orchestration of UWB and UHF technologies for passive RFID system was proposed as a viable solution for tag interrogation efficiency improvement and energy consumption reduction. With the fundamental requirement of maintaining backward compatibility in the RFID domain, a hybrid UWB/UHF architecture to improve passive tags identification both in single-reader and multi-reader scenarios was presented. Furthermore, exploiting the hybrid architecture, two identification algorithm were proposed. The first solution is based on an enhanced version of the adaptive Q-algorithm enforced by the EPC Gen 2 protocol where UWB signaling allows to reduce the occurrence of collisions by means of tag population estimation and ranging. The second solution is based on Compressive Sensing (CS) ans exploits UWB and UHF orchestration to reduce the total amount of time slots spent for tags identification. The effect of timing synchronization error was also accounted in the performance analysis.

Many research opportunities for extending the scope of the described research activity remain. In what follows we list some of these directions.

- The energy availability process in RF harvesting systems strictly depends on the dynamics of the underlying wireless channel. Indeed, the instantaneous power at the input port of the harvesting circuitry undergoes both large and small scale fluctuations induced by shadowing and multi-path fading respectively. We adopted a log-normal model to represent the slow component of channel gain variations and neglected the fast fading component. Although the log-normal model has been shown to properly approximate composite channel statistics, abstraction of channel dynamics via Markov processes theory requires the introduction of multi-time scale Markov chains to consistently represent the superimposition of slow and fast channel variations. Thus, the derivation of more accurate models and optimization strategies for this kind of systems still requires investigations and analysis.
- Co-simulation techniques may be adopted to jointly characterize RF energy sources, propagation scenarios and harvesting circuitry, giving rise to "deep`` cross-layer description of RF harvesting wireless devices. An interesting undergoing research direction aims at stressing co-simulation approaches to include communication protocols dynamics in the simulation framework. In such a scenario, complex physical behavior can be investigated such as battery degradation mechanisms and realistic energy management/performance interactions.
- In the context of cross-layer analysis of passive RFID systems, more accurate channel description that includes fading spatial correlation and time-variant propagation scenarios may be adopted to generalize the proposed framework for RFID performance analysis. Furthermore, Stochastic geometry rationales may be exploited to formally characterize spatial features in the envisioned systems and scenarios.
- Passive pervasive systems relying on backscattering communication has recently received a renewed interest in the context of the IoT. The definition of battery-assisted passive architectures with sensing capabilities and the inclusion of accurate ranging and localization features via UWB appears to be a promising research direction that is

strictly related to the presented research activity presented.

For references, see [VLF15], [DVB+15], [VDLB15], [ADS+15], [ADS+16], [VL16], [VLS16], [VLS18], [ALVL18], [VAS18].

Safe Cooperating Cyber-Physical Systems using Wireless Communication

Modern embedded systems, coupled with advancements in digital communication technologies have been enabling a new generation of systems, tightly interacting with the physical environment via sensing and actuating actions - Cyber Physical Systems (CPS). These systems, characterized by an unprecedented level of pervasiveness and ubiquity, have been increasingly relying upon wireless communication technologies to provide seamless services, via flexible cooperation actions, enabling true systems of systems we refer to as Co-CPS. As these Co-CPS systems start reaching into safety-critical application domains such as automated vehicle platooning in the automotive and maritime domains, or even process control in hazardous industries, safety becomes a crucial topic that must be carefully analysed in such systems, considering failures and errors might lead to hazardous situations causing death, injury or severe environmental damage. All these systems that are required to perform a specific safety function or functions to ensure that the risk of failure of a system is at a minimum or at an accepted level, constitute a case of a safety-critical system.

However, although we have been witnessing a tremendous interest in using such technologies in such application areas, attaining the desired Quality of Service (QoS) levels is still a challenge, especially in what concerns the safety and security interplay with traditional QoS system properties such as timeliness, scalability or energy-efficiency. For a system to properly function, computations and communications must be correct, produced before a given deadline and with the smallest energy consumption. To attain the desired pervasiveness, these systems are expected to be highly heterogeneous and cost-effective, maintainable and scalable. Therefore, achieving an effective and efficient balance of all these QoS properties is quite a complex issue in wireless communications, especially when some might be conflicting. For instance, improving timeliness might decrease energy-efficiency, or improving scalability, might impact timeliness due to the introduction of routing delays in the network. For example, in automotive applications like vehicular platooning and intelligent traffic management, the IEEE 802.11p-based standards are used in a closed-loop control system where exchanged messages between vehicles contributes to maintaining the safety distance between vehicles. In case of message loss or delay, the consequences might be dramatic as it may lead to serious crashes among the vehicles. In this particular case, real-time and reliability are two important aspects for ensuring the safety of operation of the platoon. Mechanisms must be in place to guarantee an adequate network planning (at design time), and network adaptability (at run-time). Furthermore, security is also very important as any possible attack, such as for example false data injection, spoofing or jamming, would lead to disastrous consequences.

In this regard, our research activities mainly concern Cooperative Intelligent Transport Systems (C-ITSs), Road Safety and Traffic Engineering applications, with a specific focus on the following areas of research:

- Communication technologies and integrated data processing: short and long range communications techniques will be required, along with processing and dissemination of traffic information through dynamic maps that are updated on a local or centralized basis. Depending on the applications, several enabling technology families are considered, such as vehicular ad-hoc networks (VANETs), including IEEE 802.11p-based standard families, and cellular networks for infrastructure architectures, including long-term evolution (LTE) and the incoming 5G network paradigms.
- Accurate localization: satellite-based localization is still the main reference for large scale spatial operations. Improved accuracy can be achieved through data fusion from

different terrestrial surveillance and communication technologies, and also from upcoming satellite constellations, e.g. the European Galileo system. Assisted and autonomous driving will require an even tighter and timely precision, to be attained with more advanced techniques and wider data sets, which are still under definition. Location-awareness is an important research field: cooperative networks paradigms can be used to improve the accuracy of the ultimate on-board estimated location data. Relevant research assets have been developed in this frame by our colleagues of Radiolabs Consortium in the rail domain.

- Cybersecurity: vehicles and related architecture elements will establish a network environment, thus exposed to a wide range of cyber-attacks. Requirements such as authenticity and confidentiality of exchanged information must be guaranteed and security of network elements must be ensured against intrusions.

The contextualization of these topics to the vehicular environment is an open field of investigation and development of architectures, procedures, methodologies, and so on. For validation and testing of various technology components in the depicted scenario, a twofold approach can be envisaged: the deployment of a test-bed with real devices in a typically limited extension operating environment, or the abstraction of a larger scale scenario through hi-fidelity simulation tools that support the definition of high density and high mobility scenarios. In this context, an experimental testbed has been developed and is currently available within our research facilities with the aim to provide a valid analysis tool for V2X communications devices based on the IEEE 802.11p standard. Specifically, a Software Defined Radio (SDR) USRP platform and Cohda Wireless devices have been chosen for testbed development. With regard to the first solution, we use Ettus USRP N210 platforms as front end of the SDR system, together with the GNU Radio real-time signal processing framework. An IEEE 802.11p GNU Radio receiver developed has been implemented with the aim of assessing compatibility between the SDR solution and the "Commercial Off-the-Shelf" Cohda devices. C-ITS applications require a massive broadcast dissemination of cooperative awareness messages to provide information about vehicle position and status to one-hop neighbours. To this end, Cooperative Awareness Messages (CAMs) in the ETSI ITS, as well as Basic Safety Messages (BSMs) in the American WAVE standard, are generated with a frequency typically ranging from 1 to 10 messages per second. Due to this massive dissemination of messages, without proper congestion control, the functionality of both safety and traffic-management C-ITS applications cannot be adequately supported. In our ongoing research activities we consider the ETSI Decentralized Congestion Control (DCC) method and proposed a cooperative awareness solution based on the dissemination of global road traffic information to cope with DCC oscillation and unfairness issues. A peculiar feature of our approach is the commitment of experimental validation for vehicular scenarios applying ETSI DCC techniques in a testbed consisting of the above mentioned COTS devices. In this perspective, further effort will involve simulation techniques to implement our proposed strategy in a dense scenario with realistic mobility patterns. A simulation platform is being developed for performance evaluation and design of a vehicular network environment. The goal is to build a more manageable and less time consuming software platform compliant with existing vehicular standards and methods to support both safety and non-safety C-ITS applications.

For references, see [IVD+15], [IVD+17], [CVP17], [CPV+18], [CVP+18b], [CWLP18], [CCP+18].

M3: Design methodologies for embedded systems

Embedded systems are pervasive in today's products and grow at an impressive pace considering instrumented, networked, intelligent, and cyber-physical systems that are at the core of the concept of smart cities and smarter planet. However, their growing complexity (multi/many cores, heterogeneous, distributed, reconfigurable, networked, etc.) could represent soon an unmanageable limit for design. In fact, apart from possible differences on composition and form factors, one consideration is always true: the design methodology, i.e. the set of adopted models, metrics and tools, plays a major role in determining the success of a product. For this reason, in the last few years, design methodologies for embedded systems have been in continuous evolution towards the adoption of model-based approaches at increasingly higher abstraction levels. In such a direction, essential parts of the proposed methodologies represent the foundations of tools for the automatic generation of HW/SW implementations, as well as other development artifacts to support different types of analyses.

The research lines on embedded system design methodologies at DEWS are based on the experience gained during past (i.e. FP5-IST COLUMBUS - http://www.columbus.gr) and current projects: up-to-date research lines and projects are described below in some details while Table 1 explicitly shows their relationships.

		2010-2015 *ERC-SG* *VISION*	*2011-2014* *Artemis-JU ASP* *PRESTO*	*2012-2015* *Artemis-JU ASP* *CRAFTERS*	*2014-2017* *Artemis-JU AIPP* *EMC²*	*2016-2019* *ECSEL-JU RIA* *SAFECOP*	*2017-2020* *ECSEL-JU RIA* *AQUAS*	*2017-2020* *ECSEL-JU RIA* *MegaM@Rt2*
Research Lines	*Embedded Systems Rapid Prototyping*	x		x		x	x	x
	Model-Driven Engineering	x	x	x	x	x	x	x

Table M3.1: Research lines vs. Projects

Embedded Systems Rapid Prototyping

This research line is about scouting and experimenting innovative HW/SW technologies, industrial methodologies and commercial tools for the rapid prototyping of embedded systems. Its goals are mainly to:

1) develop meaningful technology transfer capabilities towards industrial domain;

2) design novel and up-to-date academic and industrial courses;

3) support other research activities with usable design frameworks and platforms.

The activities in this research line are mainly related to the following projects:

VISION (*Video-oriented UWB-based Intelligent Ubiquitous Sensing*)

VISION proposes to develop an innovative infrastructure (Figure M3.2) for strengthening future wireless sensor networks (WSN) with the capability of supporting intelligent services for ubiquitous sensing, with particular emphasis on real-time 3D video sensing. Since the requirements for high-quality video transmission cannot be easily satisfied in a sensor field, the complexity and the cost of sensor devices have up to now discouraged the use of real-time video sensing services. VISION exploits full system adaptability to the context as a ground-breaking approach to overcome these limitations. VISION adopts a dynamic QoS management that relay on a specific ultra-flexible middleware (MW) which links together all HW components of the system.

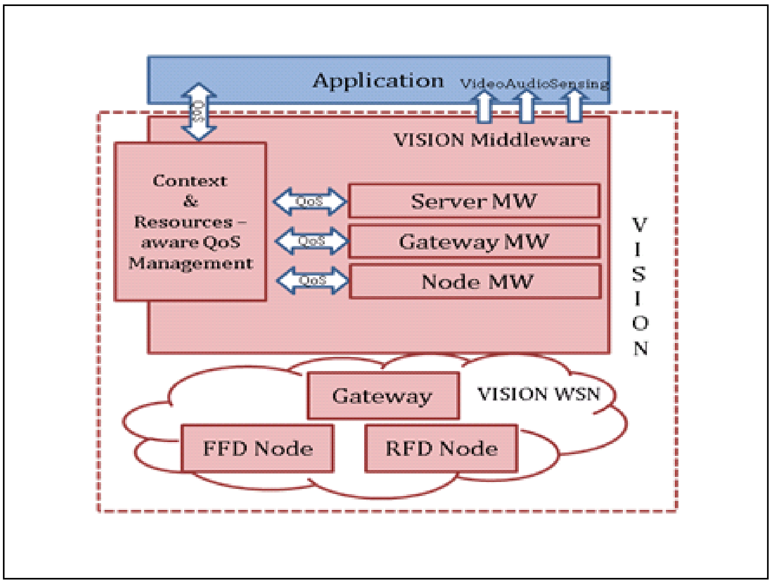


Figure M3.2: VISION Framework

The main contribution of DEWS, in the considered period, is related to such a middleware layer. In fact, the project has led to the development of an innovative mobile-agent based MW. Such a MW is based on an existing one (i.e. Agilla) that has been ported from TinyOS 1.x to TinyOS 2.x and enhanced (Agilla 2.0). Then, the Agilla Instruction Set Architecture (ISA) has been characterized with respect to timing and energy consumption to allow proper UML-based modeling and simulation activities. The proposed approach makes use of both a UML profile and an executable model library for Agilla. Execution times, annotated on Agilla instructions and patterns in the library, are given as additional input parameters during the model execution to carry out a timing analysis of the simulated Agilla applications. Figure M3.3 sketches the proposed approach, where boxes represent artifacts whereas rounded boxes represent operational steps.

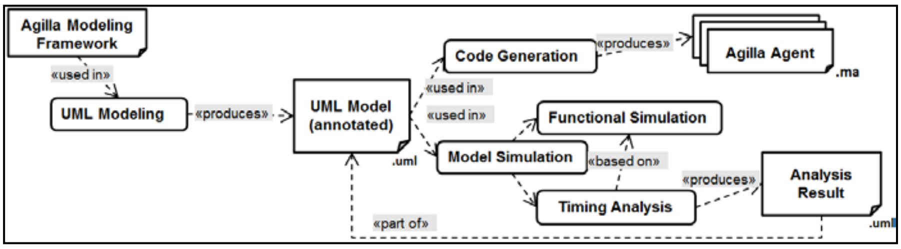


Figure M3.3: Modeling and Timing Simulation of Agilla Agents for WSN applications in Executable UML

Main publications in the reporting period are: [PCD16] [PSM15] [PRG15] [PBD15] [PCD15].

SAFECOP (*Safe Cooperating Cyber-Physical Systems using Wireless Communication*)

SafeCOP is a project that targets the so-called Cooperating Cyber-Physical Systems (CO-CPS), that is systems that rely on wireless communication, have multiple stakeholders, use dynamic system definitions (openness) and operate in unpredictable environments.

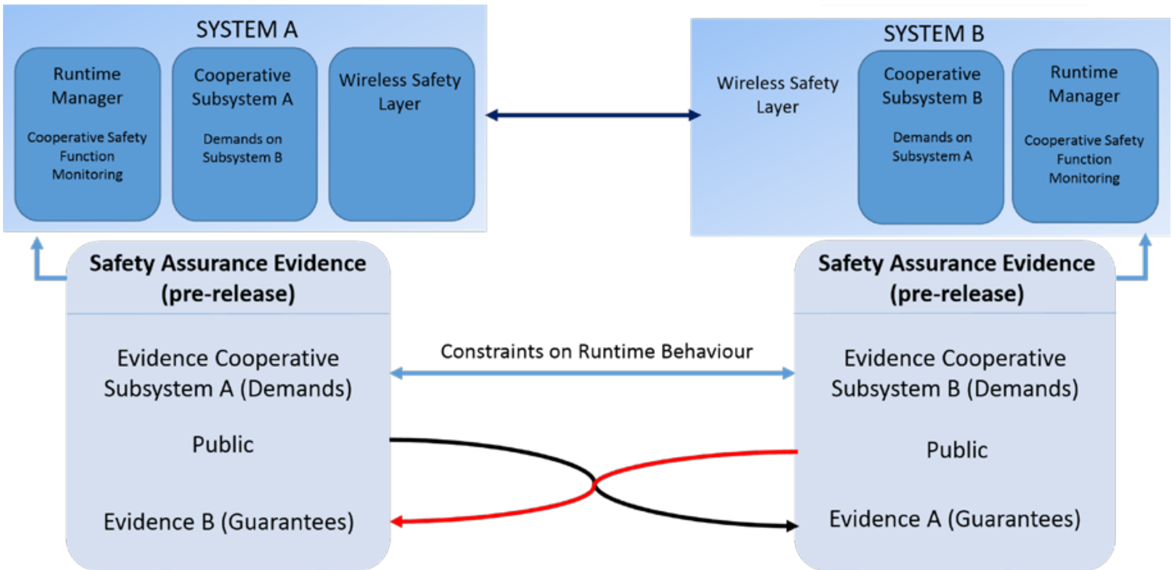


Figure M3.8: Safe Cooperating Cyber-Physical Systems

Problem

No single responsible stakeholder can be identified in these scenarios. This means that safe cooperation relies on wireless communication and security is an important concern.

Solution and expected results

SafeCOP will provide an approach to CO-CPS' safety assurance, thus allowing their certification and development. In particular, the project will define a runtime manager to detect abnormal behaviors at runtime, triggering, if needed, a safe degraded mode.

SafeCOP will also develop methods and tools to certify cooperative functions and offer new standards and regulations to certification authorities and standardization committees.

The advantages include:

- Lower certification costs
- Increased trustworthiness of wireless communication
- Better management of increasing complexity
- Reduced effort for verification and validation
- Lower total system costs
- Shorter time to market

- Increased market share

The results are evident in 5 case studies:

- Cooperative moving of empty hospital beds
- Cooperative bathymetry with boat platoons
- Vehicle control loss warning
- Vehicle and roadside units' interaction
- Vehicle to infrastructure cooperation for traffic management

Main publications in the reporting period are: [PFR15] [PST17] [PCG16] [PS16] [ABB+16] [ABD+16].

Model-Driven Engineering for Embedded Systems

This research line is about customizing classic Model-Driven Engineering approaches to embedded systems development. In particular, DEWS is focusing on automatic models transformation (e.g. from platform-independent to platform-specific models, from development models to analysis models, from development models to C/VHDL code, etc.) while targeting (reconfigurable) HW/SW heterogeneous parallel architectures. Further, DEWS is working on the development of innovative approaches and tools, at the so called Electronic System Level (ESL) of abstraction, to support the designers in activities where they rely heavily on experience. In particular, in the context of HW/SW Co-Design, DEWS is focusing on Design Space Exploration (and related activities, like ESL Estimation and Simulation) that leads to (semi)automatic HW/SW partitioning, architecture definition and mapping of the model on the defined architecture while trying to satisfy system constraints. Finally, DEWS is working on the development of innovative approaches for ESL Verification & Validation, for both functional (e.g., formal verification and model-checking) and non-functional (e.g., dependability and power consumption) properties.

The activities in this research line are mainly related to the following projects:

PRESTO (*Improvements of Industrial Real Time Embedded Systems Development Process*)

The PRESTO project addresses improvements on test-based embedded systems development and validation, while considering the constraints of the industrial development processes. This project is based on the integration of (Figure M3.4): test-traces obtained by test execution in the software integration phase that is carried out in common industrial practice to validate the requirements of the system; application and HW/SW platform models; design space exploration techniques.

In the context of PRESTO project, during the considered period, DEWS (in collaboration with DISIM) has been working on trace-based non-functional analysis of software/hardware systems, with a particular emphasis on properties specification and performance properties.

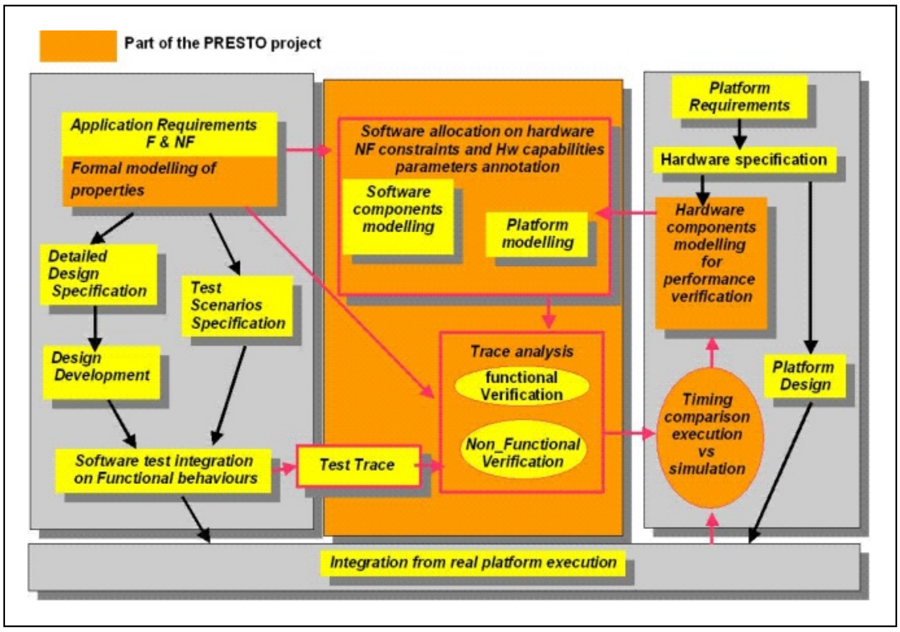


Figure M3.4: PRESTO Framework

Beside this, we have been working in a formal model-driven context in order to investigate how model-driven support can be useful to overcome non-functional limitations of software/hardware systems. So, we have shown how the analysis of certain NFPs can be performed solely based on UML models without translating them into, e.g., queuing networks. Therefore, we leverage the execution semantics of fUML to gain execution traces from UML models and, based on these traces, compute indices, such as response time, taking into account the contention of resources, as well as different resource management configurations, such as balancing and scaling strategies. As sketched in Figure M3.5 here below, we have proposed to: (i) trigger executions of UML models according to specific workloads for obtaining execution traces that reflect the runtime behavior of jobs (i.e., which services are requested in which order), (ii) annotate the arrival time to each of the resulting execution traces, and (iii) compute, based on known service times of consumed services, the temporal relation of concurrently running jobs. Based on the temporal relation of executed jobs, we can step-wise derive their temporal overlaps and compute waiting times in each queue and, in further consequence, the overall response time, throughput, and utilization indices.

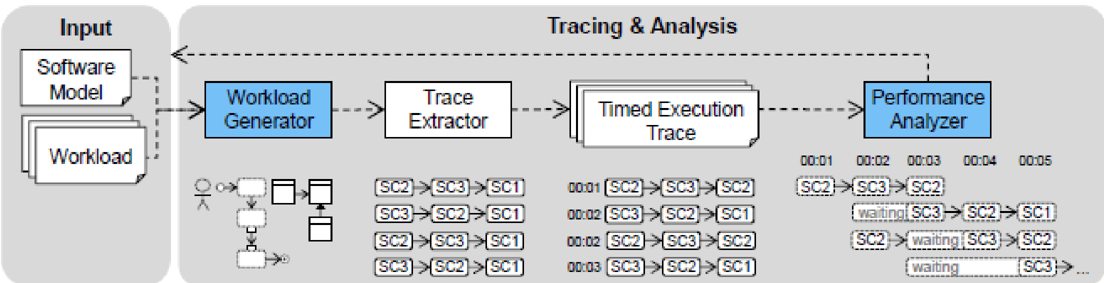


Figure M3.5: Trace-based non-functional analysis of software/hardware systems

CRAFTERS (*Constraint and Application Driven Framework for Tailoring Embedded Real-time Systems*)

The CRAFTERS project faces the problem that ICT-based service and product innovation is curtailed by the growing vertical chain of dependence on poorly interoperable proprietary technologies in Europe. The focus of the project spans the different domains of real-time applications for heterogeneous, networked, embedded many-core systems. These applications suffer from the lack of trusted pathways to system realization and application deployment. Service and product development efforts are high with many uncertainties. Industry is discouraged from engaging in such ventures, leaving the market opportunity unexploited. For this, CRAFTERS proposes a computing environment for many-core systems derived from vertical domains that will enable the evolution to horizontal domains by providing common methods, tools and reference platforms for embedded many-core applications. Final goal of the project is to realize a predictable and flexible many-core platform with a run-time scalable execution environment.

In the context of the CRAFTERS project, during the considered period, DEWS has been working on the design of the architecture of a validation suite for software embedded systems, and on the performance-based selection of system features under uncertainty. In fact, Verification and Validation of the produced artifacts are one of the key issues, as they ensure that the pieces of software meet the functional and non-functional requirements envisioned by the designer. In CRAFTERS, the problem is exacerbated since the overall goal is to provide a multi-core solution, so the proposed approach must alleviate this by design including an adapted V&V layer that collaborates with the rest of the software production tools, runtimes and platforms to be developed in the project. Within this architectural design, we have started to contribute by considering the performance-based selection of software and hardware features under parameter uncertainty. In particular, we have introduced an approach to analyze the correlation between selection of features embedding uncertain parameters and system performance. We provide best and worst case performance bounds on the basis of selected features and, in cases of wide gaps among these bounds, we carry on a sensitivity analysis process aimed at taming the uncertainty of parameters.

Another ongoing activity is related to the exploitation of an existing framework (i.e. DUALLy) to create interoperability among different modeling notations (as well as UML profiles) used in CRAFTERS. DUALLY allows system engineers to transform concepts of system-level design models into semantically equivalent concepts in other models. Conceptually, DUALLY (http://dually.di.univaq.it) proposes a star architecture for managing all the system-level modelling languages that must interoperate. Figure M3.6 shows the proposed architecture and its main entities.

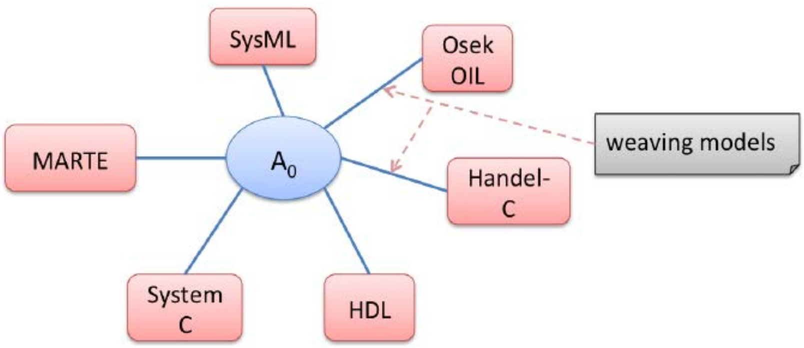


Figure M3.7: DUALLY architecture for managing system-level modelling languages

Finally, since CRAFTERS topics are related also to HW development on FPGA, in this context, DEWS has contributed to two main tasks: the development of HW mechanisms to support off-line and run-time profiling for metrics evaluation, and the development of one of the reference many-core platforms on FPGA (based on ZedBoard - http://www.zedboard.org/product/zedboard) to be used in the development of projects demonstrators.

Main publications in the reporting period are: [PVF17] [PFM17] [PVM16] [PVB16] [PVF16] [PFF16] [PMV16] [PFV15] [PVM15] [VPF15][PMF15].

EMC² (*Embedded multi-core systems for mixed criticality applications in dynamic and changeable real-time environments*)

EMC² project focuses on the industrialization of European research outcomes and builds on the results of several previous ARTEMIS, European and National projects. It provides the paradigm shift to a new and sustainable system architecture which is suitable to handle open dynamic systems. EMC² is part of the European Embedded Systems industry strategy to maintain its leading edge position by providing solutions for: dynamic adaptability in open systems, utilization of expensive system features only as service-on-demand in order to reduce the overall system cost, handling of mixed criticality applications under real-time conditions, scalability and utmost flexibility, full scale deployment and management of integrated tool chains, through the entire lifecycle. The main contributions of DEWS have been related to provide contribution to the development of a MW for service interoperability support, to provide contribution to the definition and the integration of innovative design space exploration approaches and, in collaboration with Thales Alenia Space Italy, to perform the evaluation of different multi-core architectures on FPGA platforms and related development methodologies and tool chains (including RTOS and/or Hypervisor) in order to assess their suitability for space (i.e. satellite) mixed-criticality applications, opening new application domains to the use of multi-cores.

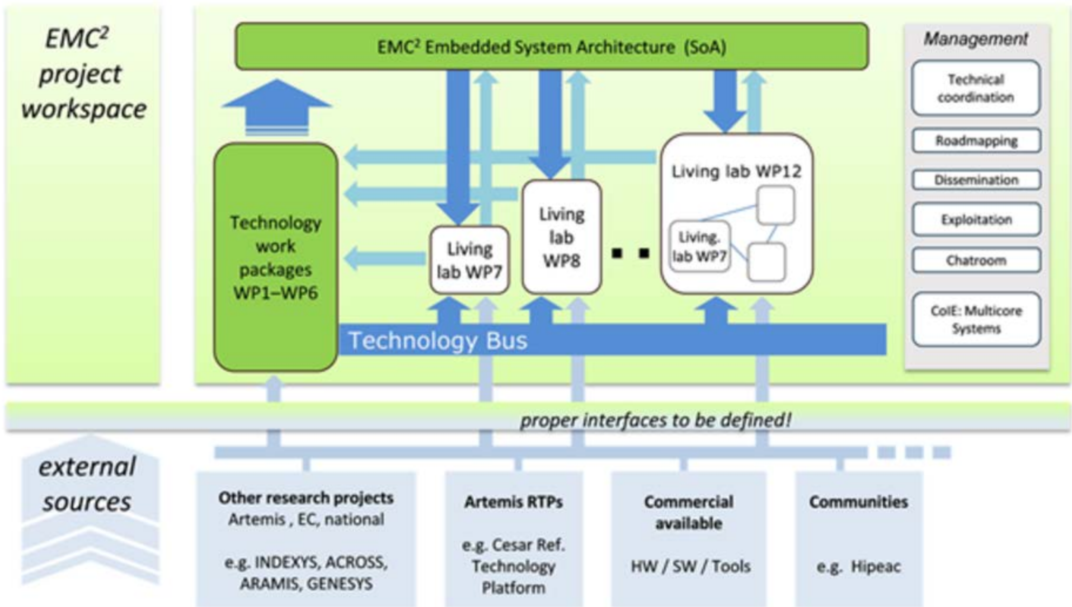


Figure M3.7: EMC² Framework

Main publications in the reporting period are: [PID17] [PAF17] [PMV17] [PAF16] [PVM16] [PFM16] [FMP16] [PCI15] [PDD15a] [PFV15] [PDD15b].

AQUAS (*Aggregated Quality Assurance for Systems*)

The AQUAS project investigates the challenges arising from the inter-dependence of safety, security and performance of systems and aims at efficient solutions for the entire product life-cycle within three essential capabilities of the ECSEL JU MASRIA 2016: Design Technologies (DT), Cyber-Physical Systems (CPS), and European Asset Protection (EAP). The project builds on knowledge of partners gained in current or former EU projects and will demonstrate the newly conceived approaches across use cases spanning:

- Space
- Medicine
- Transport
- Industrial Control

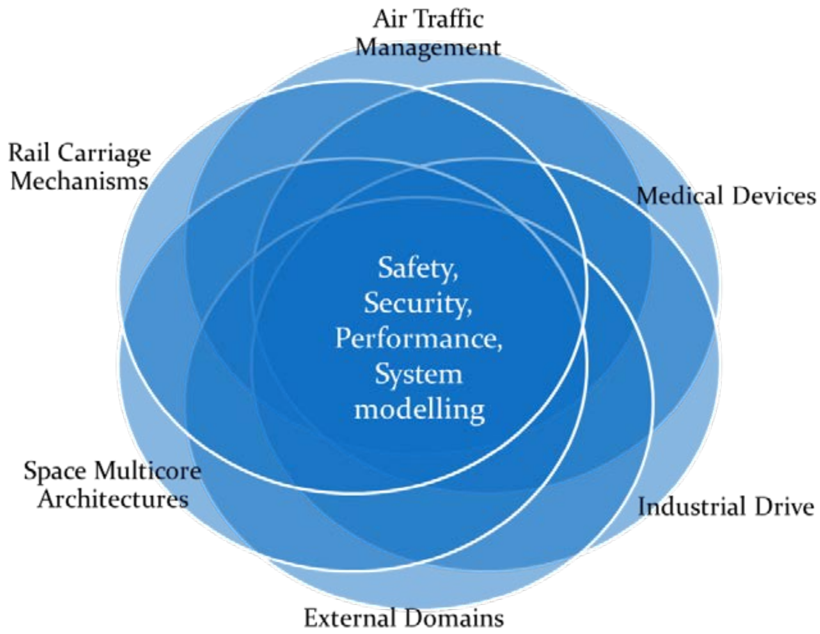


Figure M3.9: AQUAS application domains

AQUAS will aid the technological progress required to provide solutions capable of meeting the challenges of the ever increasing complexity of the systems we engineer in modern society, which includes facing the convergence between embedded world and open world. This complexity creates increasing difficulties, particularly for safety critical systems such as the transportation, space, medical and industrial control domains. Meeting the continuously growing requirements on security and performance, while maintaining safety, requires a coordinated engineering approach. Such a coordinated engineering approach, making available leading edge design for Electronic Components and Systems (ECS) technologies, will increase the competitiveness of key European industrial domains.

AQUAS will support the objectives of the ECSEL JU MASRIA 2016 of keeping Europe at the forefront of the technology development and securing and strengthening the commanding position in design and systems engineering. This will be done by providing solutions for a holistic approach to Safety/Security/Performance Co-Engineering (CE) through a domain-flexible framework, supporting the entire Product Life-cycle (PLC). These solutions need to be pulled into mainstream development, with one supporting factor being our aforementioned wide domain coverage and another key point being our strong contribution to Standards Evolution (SE). These three points, co-engineering, product life-cycle and standards evolution represent the three core goals on which our objectives and work will be founded.

Main publications in the reporting period are: [PVM17] [PID17] [PMV17] [PMVS17].

MegaM@Rt2 (*MegaModelling at Runtime - scalable model-based framework for continuous development and runtime validation of complex systems*)

The MegaM@Rt ECSEL project is aimed at creating a framework that incorporates methods and tools for continuous development and validation, leveraging the advantages in scalable model-based methods to provide benefits in significantly improved productivity, quality and predictability of large and complex industrial systems.

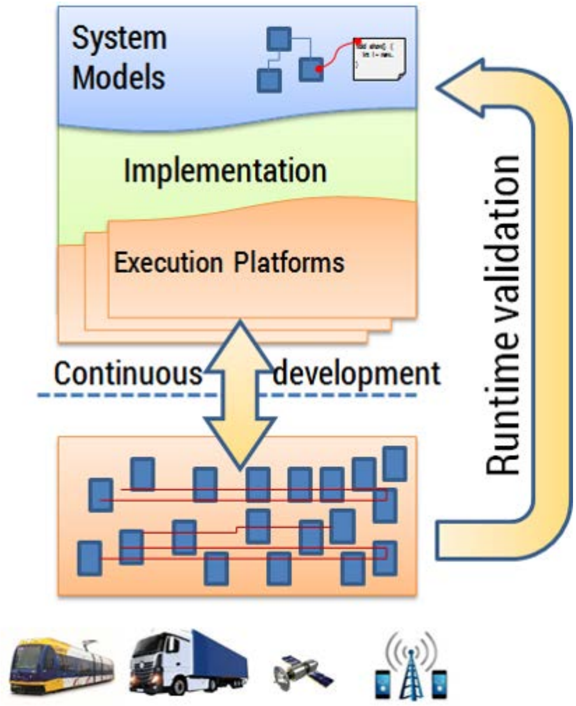


Figure M3.10: MegaM@Rt2 framework

European industry faces stiff competition on the global arena. The electronic systems become more and more complex and call for modern engineering practices to tackle productivity and quality. The model-driven technologies promise significant productivity gains, which have been proven in several studies. However, these technologies need more development to scale for real-life industrial projects and provide advantages in runtime. MegaM@Rt brings the model-driven engineering to the next level in order to help European industry to reduce development and maintenance costs as well as to reinforce productivity and quality.

The specific scientific and technological objectives include the development of:

• scalable methods and tools for modelling of functional and non-functional properties such as performance, consumption, security and safety with mechanisms for representation of results of runtime analysis.

• scalable methods and tools for application validation at runtime including scalable methods for models@runtime, verification and online testing.

• infrastructure for efficient handling and management of numerous, heterogeneous and large models potentially covering several functional and non-functional domains.

• holistic traceability 1) capable to link and manage models and their elements from different tools as well as 2) suitable for large distributed cross-functional working teams.

• specific demonstrators and validate MegaM@Rt technologies through 10 complementary industrial case studies.

Main publications in the reporting period are: [PVM17] [PID17] [PAB17] [PMV17] [PMVS17].

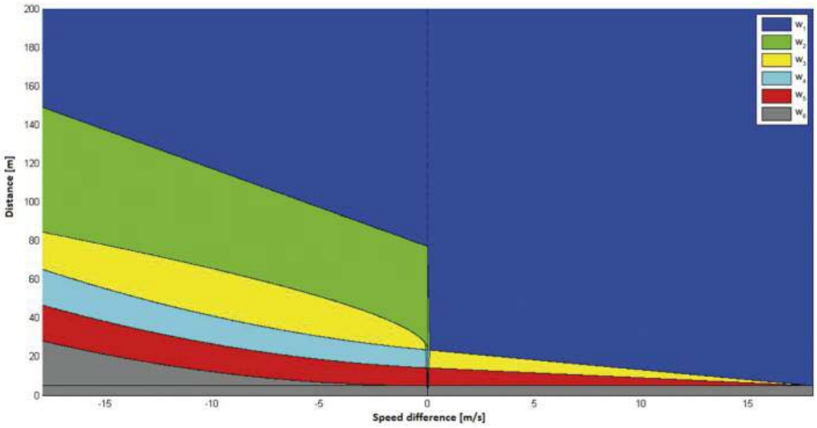
A1: Intelligent transportation systems

Adaptive cruise control

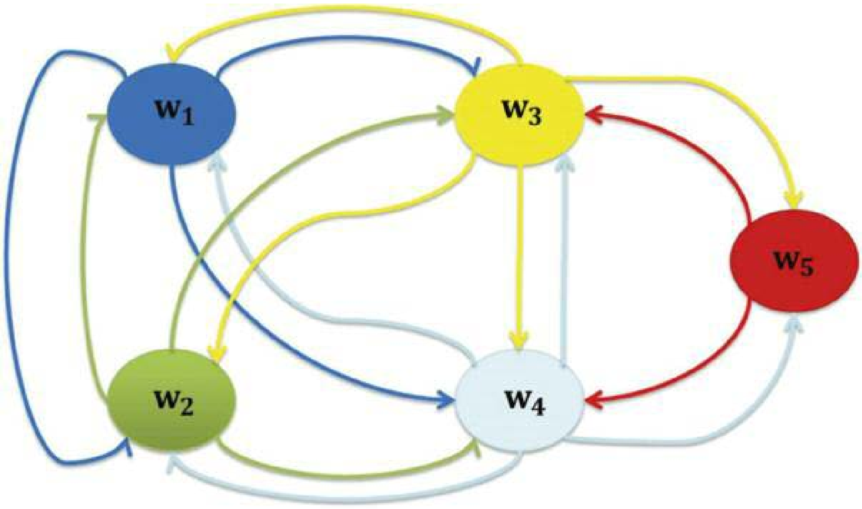
Traffic control is one of the most studied problems in engineering because of its impact on human life: progress in the knowledge and control of traffic systems would improve life quality. The goal of traffic control is to manage the flow of cars in highways so that a number of quantities such as congestion, emissions, travel time reduction and safety are traded-off in an optimal fashion. Driver support systems such as Adaptive Cruise Control (ACC) systems, and Advanced Driver-Assistance Systems (ADAS) provide full or partial driver assistance [2–4] to control traffic. Once ADAS systems are introduced in cars, the behaviour of the cars should follow normal traffic dynamics. To do so, we believe driver support systems should mimic driver behavior.

In [IVD+15], [IVD+17] and [IDDW17] a mesoscopic hybrid model, i.e. a microscopic hybrid model that takes into account macroscopic parameters, is introduced for designing a human-inspired Adaptive Cruise Control. A control law is proposed with the design goal of replacing and imitating the behavior of a human driver in a car-following situation where lane changes are possible.

First, a microscopic hybrid automaton model is presented, based on human psychophysical behavior, for both longitudinal and lateral vehicle control. Then a rule for changing time headway on the basis of macroscopic quantities is used to describe the interaction among next vehicles and their impact on driver performance. Simulation results show the advantages of the mesoscopic model. A feasibility analysis of the needed communication network is also presented.



The interaction zone split in different regions



The possible discrete transitions resulting in the considered hybrid system

Multi Agent Systems

The research effort in multi-agent systems (MASs) relies on the fact that multiple agents have the possibility to perform a mission more efficiently than a single one, may increase tolerance to possible agent fault and provide flexibility during the task execution. During the two last decades, cooperative control of MAS has attracted a great deal of attention due to its broad range of applications in many areas, e.g. flocking, rendezvous, distributed estimation, formation control, consensus, etc. The consensus of MASs means to design control policies that enable a group of agents to reach an agreement regarding a certain quantity of interest (attitude, position, velocity, etc.) by negotiating with their neighbors. A lot of results for consensus problem have been obtained, and a crucial part in the deployment of consensus strategies is the communication and controller execution condition. Although each agent may naturally be described by continuous-time dynamics, the control law is only updated at discrete time instants: these can either be pre-specified, usually separated by a fixed period (time-scheduled control), or be determined by certain events that are triggered depending on the system behavior. In MASs, the small embedded microprocessors form the computational core of the network. They are required to execute a variety of tasks including the relay of information packets, monitoring physical quantities from neighboring nodes and computation of feedback control laws. Since in practice, the embedded microprocessors have limited energy and computation ability, it is very important to increase the functionality of these devices through novel scheduling algorithms. A fixed sampling period is quite inefficient since the worst-case scenario has to be considered. Relaxing the usual fixed sample rate assumption allows scheduling control, where the control value are updated when necessary. Among the various techniques proposed to dynamically adapt the sampling, to reduce the microprocessors and network loads while ensuring the desired control performances, two approaches seem to be promising. Event-triggered control is a methodology where sensors send information to the controller when specific events occur, using a dedicated hardware. It uses a function of the current state to specify when the next sampling time must occur. Sufficient conditions for the existence of stabilizing event-triggered control strategy have been derived for nonlinear systems. The idea it to sample and update the controller when the norm of the measurement error becomes large enough relative to a threshold depending on the norm of the current state. Event-triggering conditions based on the state error or on the input error have been proposed.

Distributed event-triggered controllers have been proposed to solve the first order agreement problem for linear systems under fixed topology where agents require the knowledge of the initial average. Under fixed communication topology and when no disturbance acts on individual agents, an event-based control strategy has been introduced to study the network coordination subject to time delays. Nevertheless, in many applications, the communication topology could change due to communication range limitations, for instance.

Self-triggered control emulates event--triggered control without dedicated hardware. It uses the current sampled state to specify the next sampling time, through a scheduling procedure. At each sampling instant, a lower-bound of the next admissible sampling interval is computed such that the control system maintains some desirable properties, first of all (but not only) the asymptotic stability at the origin or at a neighborhood of the origin.

From a theoretical point of view, the work developed in this line at DEWS [DDD14][7] is a first attempt to study a self-triggered strategy to solve the consensus problem for first order MASs, affected by unknown nonlinear inherent dynamics (considered as uncertainties) under fixed and switching communication topologies. The design of a self-triggered control law for uncertain systems is not an easy task, due to the effect of the sampling, and one has to ensure the stability property also in the inter-sampling. A methodology for the computation of the feedback gains and the next execution times are derived based on multiple quadratic Lyapunov function and Lipschitz condition on the uncertainties. While in the event--triggered control framework there exist methods for the decentralized determination of the sampling instants, such a result was not available in the self-triggered setting. For this reason, the determination of a stabilizing control law has been separated from the determination of the next sampling instant. While the first is computed in a decentralized way, the second is done in a centralized manner. Although this last determination implies the transmission of the state of all the agents for a centralized computation of the next sampling time, the transmission of the input components to each agent is avoided. Only a signal updating the control law, calculated in a decentralized manner, is transmitted. Therefore, even if not completely decentralized, this strategy reduces the use of network resources.

Nonlinear Integrated Control of Vehicles

The attitude control of a ground vehicle is an important issue, aiming at rendering more secure this form of transportation. In automotive the elimination of the mechanical links allows greater flexibility in the control of various subsystems. Examples of subsystems controlled "by-wire" are the steer-by-wire, brake-by-wire, et cetera. More in general this technology, mutatis mutandis, can be applied to vehicle chassis active control systems, developed to enhance vehicle stability and handling performance in critical situations, simplifying at the same time the design of active controllers. Examples include yaw stability control systems, roll stability control systems, and integrated vehicle dynamic control systems. These active devices modify the vehicle dynamics imposing forces or moments to the vehicle. In the next future, the active systems will possibly use more sensors than those actually available onboard, allowing precise and distributed measurements from the environment, especially of the tire-

[7] [DDD14] M. Defoort, S. Di Gennaro, and M. Djemai, Self-Triggered Control for Multi-Agent Systems with Unknown Nonlinear Inherent Dynamics, IET Control Theory & Applications, Vol. 8, No. 18, pp. 2266-2275, 2014. ISSN: 1751-8644.

road friction. All these new sensors will increase the performance of the control action, the vehicle stability, and the safety and comfort of the driver.

In [ACCD15] the activity was focused on the design of an integrated active controller, with Active Front Steering (AFS) and Rear Torque Vectoring (RTV) as controls. Three aspects were taken into account: the integrated design of an AFS/RTV control, the vehicle roll dynamics control, and the reconstruction of unmeasured variables. Works on these aspects can be found in the literature, but no work was available dealing these three issues simultaneously. The interest is a clear advantage of an integrated control design in terms of simplicity, since the interaction of different actuators is an issue for the vehicle stability. A further issue is the limited power available in a vehicle when the controllers for each subsystem are designed as stand-alone, while integrated controls can use a synergy. The perturbative action of the roll dynamics, is usually neglected in the controller design, but it is important for particular types of tall vehicles with no active devices on the suspensions.

In order to obtain a control action with higher performance, in [ACCD16] an active control was considered, with AFS and RTV as actuators. The controller was designed taking into account also the perturbative dynamics due to the roll of the vehicle. The lateral velocity, not measured, was estimated by a robust estimator. The CarSim software was considered for validating the proposed observed-based active control. Also, a challenging double steer maneuver has been used for this validation. The reason of choosing CarSim is due to the performances of this software in predicting the dynamic vehicle behavior, very close to real responses. In fact, CarSim is proven to represent accurately the vehicle dynamics, is extensively validated with experimental tests, and is supported by automotive enterprises, such as the Ford Motor Company, Chrysler, etc.

The works available in the literature on the controller design of the various subsystems are mainly in the continuous-time setting. Their usual implementation is via zero-order reconstructors, so obtaining emulated algorithms. If not appropriately adapted to take into account the digital implementation, these emulated algorithms could lead to poor performance of the resulting controller. This is due to the fact that sampled dynamics of the system are not considered in the control design. A practical solution to this problem is to use high sampling rates, with the disadvantage of increasing the cost of the ECUs. This disadvantage has conducted the researchers to develop tools to synthesize control laws directly in the digital domain. However, the effectiveness of this approach strongly relies on the accuracy of the sampled model. Unfortunately, except for linear systems and a restricted class of nonlinear systems, rarely one can determine the exact sampled model. Therefore, one usually exploits approximated methods, i.e. truncated models of desired approximation. Approximated discrete-time models can be obtained adapting numeric methods, neglecting higher order terms, or more simply considering trivial Euler approximations. These methods do not preserve the variational formulation of the mechanics in the discrete setting. As a result, the performance of digital controllers obtained on the basis of these approximated methods may be not satisfactory as the sampling period increases. The determination of approximated, but accurate, discrete-time models of the vehicle nonlinear dynamics is a crucial issue. This aspect motivated the work [NDRALC16], which aimed at designing a discrete-time controller inherently robust versus changes of the sampling period. The advantage of the so-called symplectic Euler method, used in this work, is that it discretizes the variational principle of the Euler-Lagrange formulation, instead of the final equations of motion. Very effective digital controllers can be determined from the discrete analog of the Euler-Lagrange equations that truly follow from the variational principle. As a matter of fact, this technique showed to be successful also in other fields, such as that of electrical machines, and of under-actuated robotic systems. Hence, in [NDRALC16] a novel discrete-time model of the vehicle dynamics was obtained using a variational integrator, known as symplectic Euler method. It discretizes the variational formulation of mechanics preserving the variational structure in the discrete setting. Using this model, an active controller was designed, relying on the AFS and RTV technology, to track desired references for lateral and yaw velocities.

In [AD17] an adaptive controller was designed for the tracking of desired references, in the presence of uncertainties in the parameters describing the tire-road friction coefficient and the lateral tire stiffness, and in the presence of external perturbations, such as lateral wind. The proposed control schemes allow the identification of these unknown parameters, also in the presence of sudden changes, as for the friction coefficient with wet/iced surfaces. At the same time, they can identify disturbances acting on the vehicle, such as those due to wind gusts. Finally, the implemented controller incorporates some dynamics reconstructing the lateral velocity, which in practical cases is not directly measured.

In [BBDD17], an integrated control scheme of AFS and RTV was proposed. In an integrated control structure, a larger number of degrees of freedom are available for control, thus potentially limiting the saturation occurrences. On top of that, the additional computational effort compared to the use of stand-alone controllers (one per actuator) is rewarded by the increase of performance and by improved comfort and stability conditions. Most of the works on active chassis control do not consider explicitly the issue of actuator saturation, which limits the maximum obtainable performance of mechanical actuators operating under physical constraints. The problem of input saturation has recently received increasing attention in the control research community and in the automotive field. In vehicle control, the basic approaches to deal with input saturations aim either at preventing saturations or at managing the occurrence of saturations. The main contribution of this work is the design of a control law, achieving balancing of the workload on the actuators. Load balancing is a principle that is common to different fields in engineering in order to optimally distribute the workload across multiple resources, balance the utilization, increase reliability, and avoid overload. The balancing problem is hence formulated and solves as an optimization problem, with the goal of guaranteeing that the actuators remain as far away as possible from saturation conditions.

Energy Management Systems for Battery Electric Vehicles

This research line was carried out in collaboration with Pure Power Control (Pisa).

Due to the reduced energy density of electrochemical accumulators with respect to conventional hydrocarbon fuels, vehicle range is perceived as a major drawback for widespread expansion of electric vehicles in the market. Therefore, efficient energy management is a major issue for Battery Electric Vehicles (BEV).

Range anxiety, that is the fear of becoming stranded with an empty battery, can be tackled by advanced energy management systems offering: optimized control of the electric powertrain for efficiency maximization; accurate prediction of vehicle range based on navigation real-time data; maximum range mode control for range critical travels. Above objectives were investigated applying a model-based approach. First, a model of a BEV was developed including longitudinal dynamics and electrical powertrain dynamics. Then, a tool for powertrain specification and analysis of powertrain component losses and overall powertrain efficiency were developed. Hence, algorithms for accurate prediction of vehicle range were developed and optimal control for powertrain management were investigated.

A2: Energy

Data-driven model predictive control for energy saving in energy efficient buildings

Research activities on building automation have been carried on by DEWS researchers in the context of the INnovating City Planning through Information and Communication Technologies (INCIPICT) project of the University of L'Aquila, funded by the Italian Government under Cipe resolution n.135 (Dec. 21, 2012). The importance of this research is motivated by the fact that the building sector consumes around 20% of world energy use, which is 40% in the United States. Therefore, it is economically, socially, and environmentally significant to reduce the energy consumption of buildings. Achieving substantial energy reduction in buildings may require rethinking the whole process of design, construction and operation of a building. Hence, the aim in controlling such a process is to save as much energy as possible while guaranteeing comfort for their occupants. Due to the scale and heterogeneity of control systems for large buildings, the design of the control algorithms and communication networks for these systems becomes very challenging and difficult to be carried out manually. The control design must take into account time-varying user loads, renewable energy availability and weather predictions, while abiding by the comfort constraints for the occupants. Model Predictive Control (MPC) is a natural choice in this scenario as a control methodology that can improve building thermal comfort, decrease peak demand and reduce total energy costs by using all the aforementioned predictions.

However, a main problem that arises in the use of MPC on such systems is related to the heterogeneity and complexity of buildings that make the modeling procedure really hard. Creating a thermal model of such structures can be extremely complex. To tackle this problem DEWS researchers started to investigate the field of data-driven control. This research line goes perfectly with the increasing attention that research on smart cities have received in the last years. The idea is using the huge amount of data collected in smart cities to derive mathematical models and use them to apply optimal control design. New methodologies have been developed, and others are currently under investigation, also in collaboration with the research group of Prof. Rahul Mangharam at the University of Pennsylvania. In particular, data-driven modeling techniques have been developed based on methodologies from Machine Learning, in particular Regression Trees and Random Forests. The learning algorithms have been modified to derive state space models of thermal and power dynamics of buildings only using historical data. Starting from these models, optimal predictive control strategies have been applied to different case studies, both simulative and experimental, to minimize the power consumption of the structure while guaranteeing thermal comfort for the occupants. Alternative approaches, based on Neural Networks, Gaussian Processes and subspace identification techniques, are currently under investigation.

Experimental testing has been conducted in 2 different buildings of the university, i.e. the Human Sciences Department (DSU) and the "Red House", as well as exploiting data from a private off-grid house in L'Aquila. To conduct such experiments a significant work has been done on the buildings. In particular, DEWS researchers have first investigated the characteristics of the buildings, i.e. analyzed the status of the structure and of the Building Management System (BEM), and then created a custom SCADA system via Labview to both monitor and control such systems. The idea is to extend this work to different structures of the

university that are currently under reconstruction, first of all the new Rectorate in Palazzo Camponeschi.
Results obtained until now have been published in top conferences and journals both in control and energy communities [JSBM18], [SJDD+18], [BSM16], [SJMD+18], [JSM17].

A long-term objective is to use the buildings of the university as a living lab, where the collected historical data and the capability to access the systems in real-time will be shared with the academic and industrial communities. A strong point of this environment is represented by the variety and heterogeneity of the structures, which vary from new buildings, such as the DSU, to historical buildings, such as Palazzo Camponeschi, and small buildings, such as the "Red House". In this way, the aim is to promote projects and experimentations related to the concept of smart cities.

Supervision, control and protection systems for novel nuclear plants

The generation of electricity from nuclear energy allows reducing pollutant gases (CO2 and others) and present important advantages (among the others: little amount of fuel and more economic transport, virtual geo–political independency, continuity of electricity production, small amount of waste – although radioactive) over electricity produced from fossil fuels. Among the disadvantages, the critical one is the security of nuclear plants. Human errors (Chernobyl), improper accident management and old plants (Fukushima) require the development of reactors of new generation, where the safety and security issues are central. From a general perspective, control systems design has to satisfy all requirements imposed by process, safety and operational constraints, at the same time. In the case of nuclear plants, safety becomes the most important parameter that must guide the design phase, as underlined by the lessons learned from the Fukushima accident. Control systems are the basic instruments the operator can use to guarantee that all process parameters are kept inside a given safety range, or to ensure that protective actions are actuated to lead them back into the range. The problem, when dealing with nuclear plants, becomes of utmost importance when a failure occurs. In this case, the operator must rely on robust control systems able to guarantee a rapid, effective feedback action to put the system in a safety mode, as prescribed by the regulatory procedures. Then, the problem of a proper controller design reveals crucial and, in fact, has been considered of primary importance in the design of Generation III/III+ Nuclear Power Plants. To this aim, the design phase can be strengthened in terms of reliability by using a simulation environment able to reproduce the behavior of the plant control systems, and to evaluate the controller performances before implementing it in a real device.

The research activities at DEWS, in collaboration with ENEA Casaccia, focused on the design of dynamic controllers for the primary circuit of a PWR, using a simulation environment to test the effectiveness of the control actions [CCD15], [CCDD15], [CCD16]. The model used to derive the control is accurate enough to capture the nonlinear, time–varying, and switching nature of the system. An important feature of these controllers is that they do not use direct measurements of the pressurizer pressure or temperature. In fact, they rely only on pressurizer wall temperature measurements, while the pressurizer temperature and pressure are reconstructed by the controller dynamics. Hence, it can be also used as a simple decision support tool in case of pressure sensors failure. A further advantage of such a dynamic controller is that it can attenuate the classical drawback due to the long response of temperature sensors, which may cause some troubles to pressure control. Moreover, disturbances and parameter variations are compensated by the use of sliding–mode terms, which guarantee further robustness to the control scheme. The designed controllers are then implemented in Simulink, and it is shown that they ensure good performance even in the presence of unmodeled uncertainties and disturbances. The switching nature of the controller, reflecting the switching nature of the pressurizer dynamics, and the nonlinear terms implemented in the controllers, along with classical PI terms, ensure better transient behaviors. Hence, they represent an evolution and an improvement with respect to classical PID controllers, usually implemented in standard control actions. Moreover, the digital implementation of this controller was considered.

Nonlinear control of a DC microgrid

To improve resilience and robustness, the electricity grid is moving from its actual shape of a MacroGrid to an aggregation of MicroGrids, whose main feature is the ability to reduce the physical and electrical distance between generation and loads thanks to the integration of Distributed Generation.

Microgrids can be disconnected from the main grid (islanded mode) and have different characteristics from the existing grid; in particular, an increasing interest has been addressed in moving from the Alternate Current (AC) framework to a Direct Current (DC) one. DC MicroGrids present an increasing interest as they represent an advantageous solution for interconnecting renewable energy sources, storage systems and loads as electric vehicles.

In [ISDDD2016] and [ISDDD2017], a realistic DC MicroGrid composed by a PV array, two storage devices, a load, and their connected devices is modeled. It is controlled in order to correctly provide a desired amount of power for feeding an uncontrolled bounded load while ensuring a desired grid voltage value. Hypotheses on the ad hoc size of the components are done to physically allow the power exchange. Stability analysis is carried out for the complete system, and physical limitations are also considered. Simulations show the robustness of the adopted control action both during the transient and in steady-state operation mode in case of constant or time-varying load. Comparisons with the standard vectorial control are also carried out, illustrating that the nonlinear controller counteracts the quick interconnected disturbances present in such systems, what is not possible for the linear nested PIs composing the vectorial control.

Power Management for a DC MicroGrid

In recent years, great effort has been put into the development of DC microgrids dedicated control methods for the different control levels to the purpose to develop an efficient high level controller dedicated to operate power flow analysis and control. A multilevel management is usually adopted, where economic aspects and energy or power requirements are treated at different time scales (see Meng et al. (2017)). Target of the papers [IDDD2017] and [IDDD2018] is to develop a power management system able to provide power references to the physical devices, taking into account energy considerations coming from an hierarchical higher Energy Management System (EMS).

The power management problem is usually formulated as a nonlinear set of equations describing a permanent steady-state regime, neglecting the transient state; due to computational problems, a static formulation of the problem is often proposed, while a dynamic power management model would result more efficient and able to schedule in real-time according to load and meteo forecast.

In the recent literature, the main target has been to develop high level controllers for MicroGrids where all the sources were supposed to be controllable in power, i.e. a desired power output reference was provided to each device in charge of connecting and control each source and was successfully reached. Unfortunately, not all MicroGrids have direct controllability of each node.

Indeed, most of them can have devices where the power output cannot be selected a priori and imposed, but depends on the ongoing situation. When dealing with different storage devices in an islanded configuration, the different characteristics of each device lead to different targets, and the one in charge of controlling uncertainties and unmodeled problems cannot have its power output imposed a priori. Nevertheless, its power output needs to be monitored and controlled, since it clearly impacts its state of charge. A management controller must then take it into account in a different way. It must to be noticed that to select the right reference for a device means to properly select the needed amount of power such device must provide or absorb.

In [ISDDD2016] and [ISDDD2017], the DC MicroGrid integrating renewables and storages, already studied in [ISDDD2016] and [ISDDD2017], is considered. Target of these papers is the design of an energy management controller able to provide the needed references to the low level controllers that are dedicated to each physical device in such islanded DC MicroGrid, considering the different limitations of each device and the available degrees of freedom. Indeed, since the supercapacitor does not have a power reference to follow, the battery has to be controlled such to indirectly control the state of charge of the supercapacitor never to be neither completely full nor discharged. By considering power losses and converter efficiency, the resulting optimization problem is nonlinear, and has to be solved with a Mixed Integer Quadratic Programming (MIQP) approach or a Mixed Integer Second Order Conic Programming (MISOCP) one by using the Model Predictive Controller (MPC) technique.

Constraints regarding the nature of the devices or the physics of the grid are also considered. Optimization algorithms on a power management model are implemented in order to exactly determine the needed amount of power, while the objective for such algorithm will be a desired operation level of voltage. In this way, the introduced high level controller will deal with an optimization problem on a power management model, while the low level controller will translate a reference on power level into a voltage or current level.

Secure State Estimation for DC Microgrids Control

Thanks to the pervasive introduction of information and communication technologies (ICT), the electric grid is evolving into the so-called Smart Grid. However, the mutual interdependence between physical processes, computational resources and communication networks increases the vulnerability of the whole system to failures or intentional attacks. Traditional security measures protecting only the computational or communication layers are not sufficient for guaranteeing the safe operation of the entire grid against the presence of malicious attackers. Therefore, new strategies that explicitly address the strong interconnection between the physical, the computational and the network layers are needed.

The paper [FIDD2017] focuses on Direct Current (DC) microgrids, which presently represent the best solution for renewable energy diffusion, having a hierarchical control architecture composed by different levels. We take into account the presence of low level controllers (LL controllers) (see [ISDDD2017]) , regulating the operating points of the different devices, and a higher level controller (HL controller) (see [IDDD2018]) sending the optimal reference values to the LL controllers.

To the aim of computing the optimal reference values, the HL controller receives sensor measurements sent by the LL controllers. This information is assumed to be exchanged through a (wireless) communication network, which can be compromised by sparse attacks. We illustrate how known secure state estimation techniques for cyber physical systems under sensor attacks can be efficiently used by the HL controller to correctly estimate the internal state of the system, when the measurement signals sent by the lower level devices can be corrupted by sparse malicious attacks.

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