MPM4CPS: Multi-Paradigm Modelling for Cyber-Physical Systems

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Abstract. The last decades have seen the emergence of truly complex, designed systems, known as Cyber-Physical Systems (CPS). Engineering such systems requires integrating physical, software, and network aspects. To date, neither a unifying theory nor systematic design methods, techniques and tools exist to meet this challenge. Individual engineering disciplines, such as mechanical, electrical, network and software engineering offer only partial solutions.

Multi-Paradigm Modelling (MPM) proposes to model every part and aspect of a system, including development processes, explicitly, at the most appropriate level(s) of abstraction, using the most appropriate modelling formalism(s). Modelling language engineering, including model transformation, and the study of their semantics, are used to realize MPM. MPM is seen as an effective answer to the challenges of designing Cyber-Physical Systems.

Research on modelling CPS is typically based on national activities with loose international interaction. To establish an interdisciplinary and inter-institutional platform for scientific information exchange, consensus building, and collaboration, the COST Action MPM4CPS, funded by the EU Framework Programme for Research and Innovation, has been initiated. MPM4CPS aims to develop and share foundations, techniques, and tools related to Multi-Paradigm Modelling for Cyber-Physical Systems (MPM4CPS) and to provide educational resources. In this paper we describe the overall MPM4CPS approach and its current status.

Keywords: Cyber-Physical Systems (CPS), Multi-paradigm Modelling (MPM), Model-Based Systems Engineering (MBSE), Multi-formalism, Multi-abstraction, (Co-)Simulation

1 Basic Project Information

- Name and acronym: **Multi-Paradigm Modelling for Cyber-Physical Systems (MPM4CPS)**
- Project reference: ICT COST Action IC1404, Science Officer: Dr. Mafalda Quintas.
- Budget: Approx. 120,000.00 EUR per year, Duration: 25/11/2014 - 24/11/2018
- Project consortium:
  - ◇ 25 initial participating countries: Austria, Belgium, Bosnia and Herzegovina, Croatia, Czech Republic, Denmark, Estonia, France, fYR Macedonia, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovenia, Spain, Sweden, Switzerland, and United Kingdom.
  - ◇ 3 recently joining countries: Israel, Latvia, and Turkey.
  - ◇ 4 COST International Partners: Victoria University of Wellington (New Zealand), Georgia Tech (USA), MathWorks (USA), and McGill University (Canada).
- Official project web sites: `http://www.mpm4cps.eu` and `http://www.cost.eu/COST_Actions/ict/IC1404`

2 Background

In virtually any area of human activity, truly complex, designed systems, known as Cyber-Physical Systems (CPS) [3], are emerging. These multi-disciplinary systems deeply integrate collaborating physical, software, and network parts.

The foundational infrastructure that is able to unify in a consistent way the plethora of CPS facets is Multi-Paradigm Modelling (MPM) [1, 2, 4]. MPM is a research field focused on breaking the inherent complexity of large-scale and complex systems into different levels of abstraction and views (i.e., rigorous models of some physical or logical reality), each expressed in an appropriate modelling formalism. By appropriate, not only cognitive aspects (which impact learnability and usability of the formalism) are meant, but also technical ones, such as tractability for debugging and analysis.

Modelling language engineering (using model transformations), and the study of their formal semantics, is used to realize MPM, by combining multiple models of computation such as continuous-time, discrete-event, and synchronous data flow. MPM, viewed as the logical continuation of Model-Based Systems Engineering (MBSE), is becoming a successful approach by providing processes as well as software tools that are able to combine, couple, and integrate each of the views that compose a system. The main goals are to analyse (for safety and reliability), to simulate (for optimization purposes) and, where appropriate, synthesize these systems.

Research activities focusing on modelling CPS are typically based on national activities and generally lack a concerted approach at European level. A dedicated interdisciplinary and inter-institutional platform for scientific information exchange, consensus building, and model improvement is thus required. COST provides the best available mechanism for broad European networking and capability-building. A COST Action is the most appropriate framework since only in a non-competitive, interdisciplinary environment it will be possible to identify and verbalize the weaknesses and uncertainties related to CPS modelling approaches, to develop common strategies for improving the

effectiveness of such methods, techniques and tools and to develop and broaden the available research expertise.

The COST Action MPM4CPS aims to involve, support and harmonize the various existing national activities around CPS modelling. One innovative aspect of MPM4CPS is the effort of bringing together scientists and experts in Mechatronics, Smart-Cities, CPS, Software Modelling and Engineering, and Multi-Paradigm Modelling, in order to push the development and implementation of state-of-the-art scientifically justified methodologies of CPS modelling in several application domains, such as automotive and avionics. In order to ensure a direct impact of the scientific output, MPM4CPS is characterized by a high level of specialization and is aiming at a well defined target.

3 Project Objectives

The main **aim** of the MPM4CPS Action is to enhance the quality, visibility and impact of European research and industrial adoption in the trans-disciplinary area of CPS. This goal is pursued by building a network of researchers, educators, industrial practitioners and policy makers in order to establish the foundations and methods of CPS engineering enabled by MPM. This allows coordinating and shaping the efforts on research, education and application in this emerging research field.

The **objectives** of MPM4CPS are the following:

- Develop research-based guidelines for evaluating and characterizing CPS.
- Evaluate current software engineers' practice and system engineers' methods to identify best practices as well as gaps and opportunities for unification.
- Develop hypotheses based on results of national research and development.
- Develop benchmark experiments in representative application domains of MPM4CPS.
- Develop and apply the MPM approach for combinations of different models, modelling languages, simulation and verification tools and assert their applicability in industry.
- Evaluate the interdisciplinary know-how required from a software/system's engineer in order to develop and maintain such kind of systems at the European scale, and if necessary develop new course materials in order to cope with such needs.
- Disseminate information and results within several areas.

4 Project Organization

The MPM4CPS Action is planned to last four years and is operated with a organizational structure in full accordance with COST guidelines.

The activities within the Action are coordinated by the Management Committee (MC) and organized around five Working Groups (see Section 4.1). Each participating country has up to two representatives on the MC. MC members are nominated by the COST National Coordinators (CNCs) of the countries they represent. The MC decides on all budget-related questions, devises the general Action strategy and manages the organisation of the Action's scientific and technological activities. Balance of gender and geographical representation is aimed for in the MC and in all WGs. Participation by Early Stage Researchers (ESR – less than 8 years after PhD) is particularly stimulated.

The Core Group (CG) consists of the chair and the vice-chair of the MC and the leaders of each WG. The CG and ultimately the chair have responsibility for ensuring that the MPM4CPS Action is on schedule and that specified objectives are met.

High priority is given to Short Term Scientific Missions (STSM) to foster personal contacts between researchers, where possible from diverse communities (academia-industry, inter-discipline). Regular calls for STSM proposals are planned. An STSM Evaluation Committee assesses the impact of the scientific visits and their output, and the CG decides on budget allocation.

Training Schools are also key to the Action. In such Training Schools, the challenges, concepts, methods, techniques and tools of MPM4CPS are taught. The intended audience is PhD students and ESRs, including attendees from industry.

4.1 Working Groups

Four main Working Groups (WG1–WG4) make up the MPM4CPS Action and are in charge of carrying out all activities. Participants are encouraged to be aware of and participate in the activities of all WGs, intentionally avoiding a separation and clustering of participants in mutually exclusive groups. In fact, a dedicated Working Group (WG0) bundles cross-WG activities to ensure their cohesion and boost interdisciplinary collaboration.

WG0: Cross-WG Activities, Showcases. WG0 plays a special role within MPM4CPS by bundling cross-WG activities in order to ensure their cohesion, boost interdisciplinary collaborations, while avoiding the natural clustering (e.g., the creation of micro-communities per working group) and minimizing fragmentation and duplication of research and efforts within the large network formed by MPM4CPS. Exchanges between the WGs is promoted, also by financially supporting inter-WG visits.

Furthermore, WG0 oversees tasks related to dissemination towards end users, including the design and development of showcases.

WG1: Foundations - Intra- and Inter-Disciplinary Interaction. The objectives of WG1 are to apply and mostly combine existing modelling techniques (e.g., MPM techniques, Control Engineering techniques, Hybrid Systems) while dealing with the heterogeneity of CPS, and identifying common formalisms and ontologies used in CPS development. WG1 is in charge of characterizing/categorizing existing modelling languages of the different disciplines using typical industrial CPS scenarios, and to compile, evaluate, possibly complete and document existing modelling tools for CPS modelling. Specific tasks of WG1 include:

- Identify existing CPS methodologies and state-of-the-art in CPS modelling and development.
- Identify CPS tools and formalisms/disciplines that are currently under development and favoured for future application.
- Identify the current generic modus-operandi of a typical industrial CPS developer.
- Define a standard terminology (i.e., domain ontology) for CPS.

The deliverables of WG1 are based on previous and ongoing research work, and include a state-of-the-art report on current formalisms used in CPS development, containing: 1) a structured catalogue of modelling languages and tools; and 2) a glossary of terms to be used throughout CPS modelling language evaluation, development, and application.

WG2: Techniques. The objective of WG2 is to conceptualize usable and efficient MPM integrated environments for CPS development, while increasing CPS development productivity (e.g., by means of increased interoperability, and use of visual modelling languages) and reducing the complexity of CPS testing, simulation and certification procedures. A secondary objective of WG2 is to investigate CPS standards that can be used by Europeans regulators in order to increase performance, security and safety of industrial CPS in Europe, and worldwide. Specific goals of WG2 are:

- Investigate which kind of MPM methods and tools are currently under development (e.g., in the domains of software engineering, embedded systems, complex control systems) and favoured for future application/integration in CPS.
- Help develop tools, standards and best practices that can be virtually integrated in a conceptual MPM environment.
- Demonstrate and evaluate the increase of efficiency of such modelling environments on CPS (i.e., not only in what matters to development speed, but also on certification speed).

As a consequence, the deliverables of WG2 include: 1) a report of standards and best practices in MPM modelling of CPS; 2) a report on state-of-the-art in MPM modelling tools used in different disciplines; 3) a report containing considerations for future MPM modelling tools; and 4) an efficiency evaluation of MPM modelling tools on CPS (e.g., versus non-modelling approaches of CPS development and certification, etc.).

WG3: Application Domains. WG3 focuses on the practical constraints in the use of MPM modelling in two representative and distinct CPS application domains: 1) embedded systems, control systems where CPS has emerged from (e.g., automotive, aerospatial); and 2) more networked, unanticipated changes (both structure and behaviour) and less of the traditional plant/controller architecture, which may have emergent behaviour (e.g., smart-cities, complex traffic management). The specific needs of the industry in these domains have to be taken into account in order to successfully implement the scientific improvements gained by the MPM4CPS Action. WG3 works together with industrial partners to ensure a bilateral feedback between the scientific and industrial CPS communities. The main tasks covered in WG3 are the following:

- Define benchmark case studies.
- Assess the current industrial state of CPS and CPS modelling at a national level.
- Collect the requests and requirements of each application domain, and rewrite them from a CPS perspective.
- Assess the suitability of the different application domain models.
- Compile recommendations on the proper use of different models, formalisms and methodologies and the reliable assimilation of current application domain models in the perspective of CPS modelling.

The deliverables of WG3 are: 1) a documentation of recommended procedures for the use of CPS models in the context of several application domains; 2) information on which type of model(s) or approach(es) is/are to be used for which type of scenario; 3) practical guidelines for the optimal use of CPS models or MPM modelling approaches;4) a report on the current state of the art of CPS and CPS modelling at a national level.

WG4: CPS Education and Dissemination. WG4 focuses on the crystallization of MPM4CPS contents into a suitable format for dissemination and educational purposes. The specific tasks covered in WG4 are:

- Identify the adequate profile(s) of CPS experts, i.e., minimum required knowledge such as formalisms and modelling techniques.
- Identify existing courses in the realm of CPS and MPM4CPS in Europe, and the need for new courses on topics relevant to CPS not yet covered by universities.
- Lay the foundations for a European Master/PhD program in MPM4CPS involving several European leading universities and set up the respective discipline roadmap.
- Promote literature on the topic, and define course materials.
- Promote thematic Summer Schools on MPM4CPS for researchers.
- Make young students (future researchers and practitioners) aware of and enthusiastic about the topic of CPS in events such as a "CPS Hacker School".

4.2 Networking Within MPM4CPS

The following instruments are employed by MPM4CPS to pursue its objectives:

- Regular coordination meetings (at least two per year) putting particular emphasis on technical discussions and presentations, and inviting representatives from EU projects and external experts to participate in the technical discussions.
- A series of yearly workshops and symposia, inviting keynote speakers, lecturers on software modelling and MPM, as well as CPS experts from both academia and industry. These events will widen the information input and foster the immediate dissemination of results produced by MPM4CPS.
- A series of annual reports surveying the state-of-the-art on MPM for CPS and reporting case studies on the adoption of CPS technology in real-world applications.
- Yearly training school(s) for young researchers.
- Short Term Scientific Missions (STSM) for junior and senior participants.
- A website (`http://www.mpm4cps.eu`) for information exchange between the members of the Action and to disseminate results.
- Internally, a project management portal with a set of thematic discussion forums and mailing lists to foster collaboration between members.

4.3 Participation

COST Actions are by nature inclusive and actively encourage open participation. We welcome new collaborators wishing to participate in the project and contribute to our goals. If you want to get involved in the project or to be informed about future events and new deliverables, please visit `http://mpm4cps.eu/about/take_action`.

5 Project Outcomes

During the first year and a half most efforts have been focused on the exchange of information among members, the identification of the main challenges, and the start of some

initial tasks in every working group. The basic management and project infrastructure are already in place (WG0). WG1 is actively working on a common ontology for CPS. WG2 currently focuses on tools and processes for co-simulation. WG3 collects a set of standard practices in industry and defines target application domains. Finally, WG4 has set up the web portal and is preparing course material on MPM and CPS. Concrete deliverables for all these activities are planned by October 2016.

WG and MC Meetings are being held as planned, trying to collocate either with modeling or with CPS events (such as the CPSweek, for instance). A Young Researcher Workshop (in Twente, The Netherlands) and Training School (in Tallinn, Estonia) have taken place, and new ones are expected soon, together with new calls for STSM. Register at `http://mpm4cps.eu/about/take_action` to receive information about forthcoming events and calls.

Apart from the outcomes of the individual WGs discussed above, in the last year of the action a summarizing report will be finalized, peer-reviewed and published.

6 Exploitation Approach and Expected Impact

The potential impact of MPM4CPS can be characterized as follows:

- Formation of a dedicated trans-disciplinary, cross-national pool for information exchange intended to last far beyond the lifetime of the MPM4CPS Action.
- Increased quality and level of inter-disciplinarity of MPM for CPS research.
- Reducing fragmentation of research through the definition of a common research agenda on MPM for CPS, and by bringing together experts from both research and industry (MPM4CPS community building).
- Promoting MPM and CPS education by defining the MPM4CPS discipline, while identifying the required profile for CPS expertise, and the core of topics, competencies and specialities in MPM4CPS education.
- Synergy between industrial partners from different application domains around CPS (expected economical benefits for the European region and leadership establishment of the European institutions in the MPM4CPS area).
- Enhanced competitiveness of European ICT industry by: 1) fostering the adoption of the MPM4CPS practices and methodologies, capable of boosting the productivity of the development process of existing and new complex application domains, and 2) creating new markets for CPS tooling.

7 Barriers and Obstacles, and Expected Marketing Value

The number, heterogeneity and different backgrounds of the participants can be considered as strong points, but also introduces significant challenges. Coordination and synchronization of efforts and resources are critical tasks for this Action.

The lack of maturity of some of the methods and tools currently used in some of the disciplines covered by the Action may represent a real impediment for the industrial adoption of the MPM4CPS approach. Being an COST Action we can identify what is missing or immature. We expect (EU) projects spinning off from this Action to address the limitations and issues encountered, in order to facilitate the full industrial adoption

of MPM4CPS practices and tools. Moreover, information about state-of-the-art embedded systems, mechatronics for avionics, mechatronics for automotive, etc., are already exchanged among European countries, but mostly via independent application-specific industrial standards. There is a clear need to bring different solutions from different technology and application domains together around CPS.

This action aims at creating the conditions necessary for promoting the sharing of resources, by integrating, under a common umbrella (i.e., in a consistent and systematic way with a common terminology), the knowledge and experiments across several research projects around Europe (and beyond). In addition, it provides a unique opportunity to establish international cooperation, and to exchange materials (data, models, insights) and compare results. Finally, this Action is expected to provide input to European policy with respect to regulations of the methodologies and procedures to develop and certify this kind of systems, combining national and international legislation. Here is a unique opportunity to determine appropriate ways of dealing with CPS in different industrial environments.

8 References to Related Work and Related Projects

The MPM4CPS Action focuses on MPM for CPS, and these aspects combined are not covered by other COST Actions or EU-projects. As the Action necessarily has to include many aspects of CPS (e.g., mechatronics in several application domains), there are links with other research programmes as indicated in the following:

a) Links and complementarity with other COST Actions
   - IC0901 - Rich-Model Toolkit - An Infrastructure for Reliable Computer
   - IC285 - Modelling and Simulation Tools for Research in Emerging Multiservice Telecommunications

b) Links with other EU research programmes
   - Cyber-Physical Systems European Roadmap and Strategy (CyPhERS).
   - CPS Action Line "Cyber Physical Systems" of the EIT ICT KIC.
   - Industrial Framework for Embedded Systems Tools (iFEST).
   - Combined Model-based Analysis and Testing of Embedded Systems (MBAT).
   - Integrated Tool Chain for Model-based Design of CPS (INTO-CPS).
   - Trans-Atlantic Modelling and Simulation for Cyber-Physical Systems (TAMS4CPS).

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