Deliverable 4.3

Collaboration on the foundations of CPS engineering

DISSEMINATION LEVEL		
PU	Public	X
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Project Acronym:	Platforms4CPS
Project Full Name:	Creating the CPS Vision, Strategy, Technology Building Blocks and Supporting Ecosystem for Future CPS Platforms
Grant Agreement No.:	731599
Programme	ICT-1: Cyber-Physical-Systems
Instrument:	Coordination & Support action
Start date of project:	01.11.2016
Duration:	24 months
Deliverable No.:	D4.3
Document name:	D4.3 - Collaboration on the foundations of CPS engineering
Work Package	WP4
Associated Task	Task(s) 4.3
Nature [1]	R
Dissemination Level [2]	PU
Version:	1.0
Actual Submission Date:	1st Oct. 2017
Contractual Submission Date	End of Sept. 2017
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The Platforms4CPS project is co-funded by the European Community's Horizon 2020 Programme under grant agreement n° 731599.

[1] **R**=Report, **DEC**= Websites, patents filling, etc., **O**=Other

[2] **PU**=Public, **CO**=Confidential, only for members of the consortium (including the Commission Services)

Change Control

Document History

Version	Date	Change History	Author(s)	Organisation(s)
(0.8)	06-20-2017	Workshop summary (as an appendix to this deliverable) – sent to consortium for feedback	M. Törngren (supported by workshop participants)	KTH
(1.0)	07-04-2017	Workshop summary finalized	M. Törngren	KTH
0.1	09-11-2017	Draft report outline sent to consortium for feedback	M. Törngren	KTH
0.8	09-28-2017	First full report draft	M. Törngren	KTH
1.0	10-01-2017	Update after project level review	M. Törngren	KTH

Distribution List

Date	Issue	Group
10-01-2017	1	Consortium

Consortium contributions

The following consortium partners have contributed in the following ways to this report:

KTH: Main author of the document, organizer of the Foundations workshop and setup of the PlatForum (Martin Törngren, Fredrik Asplund, and Xinhai Zhang).

Fortis: Contributed to workshop implementation and summary (see workshop report) (Vincent Aravantinos)

THHINK: Contributed to workshop implementation and summary (see workshop report) (Haydn Thompson)

Steinbeis: Providing advice on workshop program (Meike Reimann)

Thales: Reviewer of this report and providing advice on workshop program (Charles Robinson).

Additional contributions to the workshop report are described in the workshop summary.

Table of Contents

1 Executive summary

One of the overall goals of the Platforms4CPS project is to build an ecosystem within CPS, establishing collaboration on the range of topics covered by Platforms4CPS. One of these topics is that of the *foundations of CPS engineering*. The rationale for this topic is given on the one hand by the increasing use and societal scale deployment of CPS, and on the other by the increasing complexity of such CPS. In addressing the foundations of CPS engineering, there is a need to link the expertise of the academic community with the needs and experience of the industrial community in order to identify and make recommendations for pivotal research to address concerns that are fundamental across several domains.

This report describes activities and contributions by the Platforms4CPS project in this direction encompassing,

- community building in the area foundations of CPS engineering. Activities during the first year of the project has included the organization of a constituency building workshop on the 'foundations of CPS engineering' in Stockholm (June 2017), and launching the PlatForum - an on-line interactive forum for stimulating debate on CPS. The PlatForum provides features like wiki, blogs, questionnaires, and discussion forums. One dedicated part of the PlatForum concerns Foundations of CPS, including gathering of relevant roadmaps/agendas. A blog on CPS has also been initiated.
- gathering of existing investigations and an ongoing analysis of foundational aspects of CPS engineering. Initial findings include the following:
    - definitions of CPS are very general. Because of this, and since there are many types of CPS, there is a need to develop a characterization that can be used to describe and reason about CPS.
    - addressing the foundations of CPS faces the challenge of disciplinary and theoretical fragmentation (e.g. control, safety, embedded, various software disciplines, and AI) that needs to be overcome, at least "bridges" are needed.
    - key challenges related to the foundations of CPS include developing a better understanding on the facets of CPS complexity, composability of CPS (principles for achieving desired behaviors and properties), handling AI as a novel ingredient in CPS (deserving special attention e.g. w.r.t. robustness, and safety), and human-centered design of CPS.

Further work will be pursued along the lines of community building and investigating the various mentioned facets of CPS.

2 Goals, scope and outline of the work on "foundations"

One of the overall goals of the Platforms4CPS project is to build an ecosystem within CPS, establishing collaboration on the range of topics covered by Platforms4CPS. One of these topics is that of the *foundations of CPS engineering*. The rationale for this topic is given on the one hand by the increasing use and societal scale deployment of CPS, and on the other by the increasing complexity of such CPS.

The description of action for the Platforms4CPS project, in describing the multitude of challenges facing future CPS, states the following: *"Underlying all of these challenges is a need to develop a foundational background to create a "science of system integration".*

This report describes initial work[3], activities and contributions by the Platforms4CPS project in this direction. The work involves all partners in the project and is led by KTH.

The description of work further describes the goals of the task "Collaboration on the foundations of CPS engineering" as follows:

- In addressing the foundations of CPS engineering, there is a need to link the expertise of the academic community with the needs and experience of the industrial community in order to identify and make recommendations for pivotal research to address concerns that are fundamental across several domains.
- Given the multifaceted nature of CPS, relating to multiple academic disciplines and industrial domains, the need for strengthened "cross-discipline/domain" collaboration has been identified as key for advancing the area.
- This linking of expertise should further aim to gather critical mass and pave the way for a common network of practitioners and researchers to advance the foundations of CPS engineering.

Where appropriate, outputs from the Foundations work will be integrated into the roadmaps of Platforms4CPS. The description of work finally describes an approach for reaching these goals, including the following elements:

- Put in place the necessary communication structures for ensuring joined multi-disciplinary foundational research, practice and development in CPS.
- Organising a constituency building workshop on the 'foundations of CPS engineering', for the purpose of discussing CPS foundations with an emphasis on providing new fresh insights from disciplines with which CPS has interacted with less so far, including topics such as systems engineering and human-centered design.

[3] A final version of this report is due at the end of the project.

- As appropriate, formulate further workshops, set-up task forces and stimulate collaboration in the area.

In the following we first briefly review the given task and its goals. In Section 3 we provide an account of what has been achieved so far and what the plans are for further work. Preliminary findings from the investigations are summarised in Section 4, followed by closing remarks in Section 5. As a complement, the summary report from the Foundations workshop in June in Stockholm is provided as an appendix.

3 What has been achieved to date and what is planned ahead

As described in Section 2, key elements of the approach for this task included to organise a first workshop and to initiate community building. Considering the work on the Platforum as part of the Platforms4CPS project, it became natural to make use of the Platforum for the Foundations work. The PlatForum represents an on-line interactive forum for stimulating debate on CPS, established by the Platforms4CPS[4] project. The PlatForum provides features like wiki, blogs, questionnaires, and discussion forums. One dedicated part of the PlatForum concerns Foundations of CPS.

The approach taken implied that "Foundations" was used as a pilot for the Platforum. This approach turned out to be quite useful in that the work was able to support the work on Foundations – in particular community building (see further below), and also by providing examples for other activities of Platforms4CPS for how to make use of the PlatForum.

A brief account of the work undertaken from Nov. 2016 (project start) until Sept. 2017 is as follows:

- Work on defining, setting up and executing the Stockholm workshop[5]. This work included discussions with the CPS community, including inviting people for the workshop and eliciting inputs to the workshop.
- Using the Platforum to gather existing CPS agendas, roadmaps and position papers (as gathered by Platforms4CPS partners) as well as suggested by project-external CPS experts. This already before the workshop provided a useful overview of industrial and academic concerns and positions regarding the Foundations of CPS.
- Providing results from the workshop including presentations and a summary from the workshop. The summary presents findings from the focused discussions during the workshop including (1) perspectives on what is currently perceived as "Foundations for CPS", with suggestions for what might be missing (gaps) and how such topics should be addressed, and (2) ideas for how a longer-term discussion among CPS experts can be stimulated and maintained.
- Initiating a blog on "Context, Foundations and Impact of Cyber-Physical Systems" as part of the Platforms4CPS blogging effort using the PlatForum.
- Following up with CPS experts on how the most promising ideas elicited during the workshop could be followed up. This in particular including requesting interest in hosting follow-up workshops.

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[4] https://platforum.proj.kth.se/tiki-index.php?page=HomePageExternal

[5] https://platforum.proj.kth.se/tiki-index.php?page=Stockholm+Workshop+June+2017

The status so far is as follows.

The workshop was perceived as very successful by the attendees, with great engagement both by those present and by those that could not make it still engaging (e.g. by contributing inputs off-line). The survey of roadmaps/agendas has also received acknowledgement for providing a useful overview.

As an indicator for the interest in the area, the blog on CPS has received good attention. The CPS blog, initiated late July 2017, as of now has 5 postings (authored by Martin Törngren). So far this has according to the statistics of the TikiWiki resulted in some 10,000 views[6]. Although these statistics are preliminary, interests have been indicated through many other channels (at meetings, LinkedIn, emails etc.). We take this as an indication that there is a strong interest in the area.

For the continued effort it is important to build on and draw continued attention from CPS experts in industry and academia. A main challenge in this regard is that these experts are already very busy persons. Continued dedicated workshops, information gathering and blogs appear to be useful ways forward

Planned work ahead include,

- Pursuing the CPS blog with regular postings.
- Considering further relevant information that can be placed on the PlatForum for dissemination purposes.
- Further exploration of opportunities as elicited during the workshop, in particular regarding interest from European stakeholders to host follow-up workshops in the spirit of the Stockholm workshop.
- Arranging further KTH-led workshops. In particular on the following topics:
    - CPS and human-centered design (a workshop is planned for the spring 2018)
    - CPS and AI
    - CPS and systems engineering
- Regionally in Sweden, a competence group on Systems Engineering (SE) has been initiated[7]. This has involved close collaboration with INCOSE (the Int. council on systems engineering) and with international experts (e.g. from Stevens Institute). We believe this provides a forum that could be leveraged for interactions between the SE and CPS communities.

[66] Note that these statistics are being double checked, so for now the actual numbers should not be considered as final.

[7] http://www.ices.kth.se/en/pages/network-industrial-competence-groups-systems-engineering

- Continued analysis and write up on the Foundations of CPS engineering, including an analysis of facets of complexity of CPS and ways to characterise CPS.

4 Foundations of CPS engineering – preliminary summary

4.1 Terminology, definitions and the need for characterising CPS

The concept of Cyber-Physical Systems (CPS) was introduced 2006 in the US to represent the Integration of computation, networking and physical processes where CPS range from minuscule (pace makers) to large-scale (e.g. national power-grid), (Cyphers, 2013). Many definitions have followed, often emphasising the large scale nature and CPS as networks of physical and computational components, (NIST, 2017). The mainstream interpretation of the term “cyber” refers to the use of computers or computer networks, see e.g. (M-W, 2017). The term originates from Norbert Wiener who coined cybernetics based on the Greek term “kybernetike” which means "governance", referring to feedback systems. Both interpretations are relevant for CPS.

As CPS is centred on interactions and integration among cyber- and physical elements, “cyber” as part of CPS therefore relates to the computer interpretation of the term cyber. However, the second interpretation in terms of “control” is also relevant for many types of CPS, since any CPS will involve some form of sensing and/or control/actuation as means for cyber-physical interactions. As for systems (e.g human vs. nature made), there will be different types of CPS, referring to for example the level of decentralisation, the scale, the level of criticality (referring to safety and security), the level of automation and whether the CPS directly includes humans.

A key finding from the CyPhERS project (CyPhERS, 2014), as well as from the Stockholm workshop, is that it is hard to come up with useful definitions of CPS – they tend to be very general. It is then more important to come up with a way to characterise cyber-physical systems, enabling to describe different facets and types of CPS. Such a characterisation can for example draw upon systems engineering and the CPS architectural framework initiated by NIST. The framework emphasises development of safety-critical CPS with common SE viewpoints (such as functions and interfaces), as well CPS specific aspects such as timing and composition, (NIST, 2017).

To elaborate on the subtle aspects of CPS, consider again possible interactions and integration among cyber- and physical elements. Fig. 1 illustrates two conceptual components part of a CPS (a left hand, and a right hand component, where each component has both physical and cyber parts). This illustration would for example be relevant for vehicles (cars, airplanes) and production machines, where each component (e.g. brake, engine, transmission, etc.) incorporates mechanical parts and computing. As apparent from

Fig. 1, there will be many, more or less direct interactions between the various parts, including between the cyber and physical parts. The direct interfaces between the computer system and the mechanical parts, through sensors and actuators, are of course crucial. However, beyond this, the mechatronic components interact physically, and with the mechanical frame on which they are mounted. Further, the components also interact through information exchange and the energy subsystem. The components will also have exchanges and interactions with the environment, e.g. through heat and electromagnetic radiation.

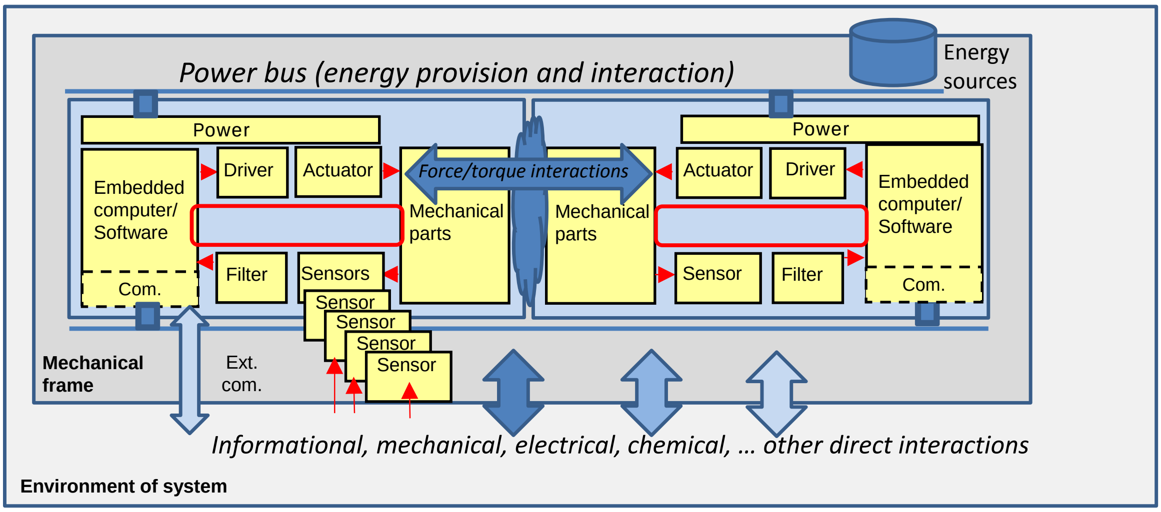

Fig. 1. Typical depiction of CPS components and their various interactions with other components and the environment.

A relevant question would then be as follows: how much of these types of interactions does it take for a system to qualify as a CPS? For now we believe that a characterisation will provide the most constructive way forward.

The increasing connectivity enables direct collaboration among machines, and with external resources such as for computation. Considering a larger scale CPS, its subsystems and components may thus also include machine external computing and communication resources. We note that such computing and communication resources, while normally considered to be part of the cyber-side of a CPS, indeed also constitute cyber-physical systems in their own right since they are composed of software, analogue and digital electronics, power supplies, potentially cooling and mechanical parts. Design of such cyber-CPS will necessarily have to consider interactions and integration among these parts.

4.2 CPS opportunities and relation to concepts such as IoT and Industrie 4.0

A key aspect of CPS is the potential for integrating information technologies and operational technologies in terms of embedded systems and control systems, forming new functionalities. Common trends for CPS further include increasing levels of automation and integration across the design-operation time continuum (so called DevOps).

Moreover, combining advanced in electronics and software together with advances in new materials and technologies such as 3D printing, sensors and augmented/virtual reality, provides unprecedented opportunities for innovation including the adoption of non-traditional business models, within and across existing domains.

Different perspectives to, and/or combinations of, these developments have led to the creation of many terms to represent the new types of systems that can be formed. Such terms, apart from CPS, include the Internet of Things (IoT), Industrie 4.0 (I4.0), the Fog and edge computing, and the Swarm.

The terms have different origin and emphasis in what they intend to describe. CPS emphasises the development of smart systems as co-engineered interacting and collaborating networks of physical and computational components. IoT emphasises sensing of the physical world and uniquely identifiable things with (Internet) connectivity to communicate data with limited or no human interaction. Communication is often considered the key aspect, often in conjunction with business models. CPS differs through a systems perspective, not necessarily requiring Internet connectivity. The Industrial IoT simply refers to industrial usages of IoT. IIoT comes very close to Industrie 4.0 which thus essentially represents the potential for significant advances of CPS and IoT in the manufacturing domain. As an anecdote, it is interesting to note that CPS was proposed as a key term to be used in Germany; politicians and industry then chose to call it Industrie 4.0.

Terms such as fog and edge computing, used in the context of IoT and CPS, represent the growth of internet and telecom networks to also encompass communication between things and machines, a perspective that emphasises computing aspects. Finally, the concept of swarms has been used to describe significant deployment of a large number of sensors into the environment and their interconnection to the cloud.

All the terms share the same paradigm of immersive and distributed sensing and computing, and are typically motivated in terms of their potential to contribute to help to solve societal-scale problems. They also observe the same types of trends, although providing slightly different perspectives to them. As evident from this description there is a lot of overlap between the terms due to the similar technologies and patterns involved. Often they are used as umbrella terms; sometimes they are used in more specific contexts. In practice, many of them are used as synonyms. An even broader concept, often used by decision makers, is that of digitalisation.

The final take away here is that a characterisation would be a useful approach by which different systems can be profiled (regardless of how you want to label them), and facilitating a discussion of what makes the heart of these fields.

4.3 What are the foundations of CPS?

At the Stockholm workshop, apart from gathering existing roadmaps, in-depth discussions took place for the following four topics (see the appendix for summaries of the discussions):

1. Humans as part of CPS
2. CPS and systems engineering – facets of complexity
3. Autonomy, AI and self-awareness
4. Composability for CPS

Further topics were also elicited during the workshop. An additional (yet well-known topic) that was raised and discussed at the workshop is that of how to deal with fragmented disciplines and theories. This topic relates closely to several of the chosen topics.

While CPS provide unprecedented opportunities, future CPS are also likely to be of unprecedented complexity. It is commonly understood that we are already with existing systems stretching the limits with which cost-efficient and trustworthy systems can be developed, see for example the roadmaps collected on our PlatForum.

In dealing with an expanding scope of knowledge, science and engineering has progressed by increasing depth and specialisation of its disciplines. Unfortunately, CPS does not respect these decompositions; end to end system level properties will depend on a multitude of decisions and considerations. The problem is multidimensional since a CPS will be "decomposed" into multiple viewpoints, including

- Theories: Newtonian laws of motion, Maxwells theory of electromagnetism, control theory, hybrid systems theory, computer science theories, instruction set architectures and other computer engineering theories, etc.
- Aspects: referring to for example end system properties such as cost, safety, availability, maintainability, etc.
- Parts and steps: Most engineering methodologies involve ways to divide and conquer a complex problem into separate pieces (parts, or steps part of engineering processes), with guidelines for integration.

The properties of a CPS appear as a result of the component, software and physical system properties and their interactions. Since a CPS typically involves tight integration among components and various technologies, intricate relationships will result which impact system level aspects/properties such as functionality, performance, safety, security, availability and interoperability. Changes in some of the component level properties, or the composition of components, is likely to affect multiple system level properties. This leads to tensions and necessitates trade-offs assuming that these interrelations are understood and can be managed).

The development of CPS, and Cyber-Physical Systems of Systems, will moreover involve huge amounts of people/organisations, tools and standards/regulations. Humans will engage as CPS developers, producers, users, operators, maintainers, or just be affected by the effects of various CPS.

As part of further work, apart from stimulating the community to engage on the CPS foundations, we will continue to analyse the facets of complexity, characteristics and architecting/systems integration aspects of CPS.

5 Closing Remarks

This intermediate drop of Deliverable D4.3 has described the work and achievements so far, including planned work ahead. The final deliverable will be provided for the end of the project.

6 References

CyPhERS (2013): Cengarle MV, Bensalem S, McDermid J, Passerone R, Sangiovanni-Vincentelli A and Törngren M, 2013, Characteristics, capabilities, potential applications of Cyber-Physical Systems: a preliminary analysis, Deliverable D2.1 of the CyPhERS FP7 project, Nov. 2013. http://www.cyphers.eu/sites/default/files/D2.1.pdf

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Merriam-Webster: https://www.merriam-webster.com/dictionary/cyber

NIST (2017): https://www.nist.gov/el/cyber-physical-systems

Appendix: Workshop summary - Foundations of Cyber-Physical Systems (June 2nd, KTH, Stockholm, Sweden)

The summary is available here on the PlatForum: https://platforum.proj.kth.se/tiki-download_file.php?fileId=32

Presentations and the agenda from the workshop are available here: https://platforum.proj.kth.se/tiki-index.php?page=Stockholm+Workshop+June+2017