Workshop summary - Foundations of Cyber-Physical Systems

- by Martin Törngren[1]

On June 2nd, a workshop on the Foundations of CPS took place at KTH in Stockholm, organized by the Platforms4CPS[2] H2020 project and supported by the CPSE-labs[3] H2020 innovation action and ICES[4], the Swedish ICES competence network in embedded and cyber-physical systems. This document provides a summary of the workshop. The summary is authored by summary by Martin Törngren with contributions from and inputs from all workshop participants (see section 3)

The workshop had a two-fold purpose:

- to provide perspectives and reflections on what is currently perceived as "Foundations for CPS", reflecting state of the art, with suggestions for what might be missing (gaps) and how such topics should be addressed, and
- to elicit ideas and discuss how a longer-term discussion among experts to evolve our understanding of CPS foundations can be stimulated and maintained.

The motivation for the workshop was to (1) bring existing viewpoints and investigations on foundations of CPS together, (2) incorporate complementary perspectives such as humans as part of CPS, and (3) dealing with the fragmentation into topical but still related areas such as CPS, IoT/IIoT, systems of systems and data analytics.

22 persons gathered physically to participate in the workshop. The background and competence of the participants covered the following domains and disciplines:

- Domains: Smart cities/Urban systems, Automotive, Aerospace, Rail, Manufacturing, Maritime, Health, Standardization (NIST), Telecommunication, and Electronics
- Disciplines: Industrial engineering, Mechatronics, Systems engineering, Dependability, Computer science/formal methods, Human centered design/HMI, Embedded systems, SoS, modeling languages and MBSE for CPS, Software engineering, Control engineering, Communication networks, Security, Safety, and Computer engineering,

Given that many experts are busy, the approach of the workshop was to create an engagement both prior to, and after the workshop. As part of the invitations to the workshop, there was also a call for position papers, elicitation of relevant roadmaps/agendas, and other references as inputs to the workshop. Several agendas/roadmaps were gathered and several experts responded to the invite by providing direct inputs and/or by stating their interest in taking part of the subsequent discussions.

[1] Important contributions from the workshop are due to all workshop participants (see Section 3) and to summaries from the world-café sessions by chairpersons including Vladimir Cvetkovic, Claire Ingram, Haydn Thomson and Vincent Aravantinos.
[2] https://www.platforms4cps.eu/
[3] http://www.cpse-labs.eu/
[4] http://www.ices.kth.se

A month before the workshop, a wiki was launched for gathering related information and to serve as a platform for continued discussion. This platform, referred to as the *PlatForum,* will also be used for other activities as part of the Platforms4CPS project. The PlatForum, apart from wiki functionality, also among other things supports blogs, forums, file storage and surveys. Activities on the PlatForum related to Foundations of CPS are available here: https://platforum.proj.kth.se/tiki-index.php?page=Foundations+of+CPS+Working+Group

In the following we provide a summary of the findings from the workshop. We then briefly outline further work in order to follow up on the findings and to maintain and grow a community that can continue the dialogue on the topic of CPS foundations.

1. Workshop findings

The approach of the workshop was to provide a rich forum for discussions, giving priority to discussions (organized in the form of world café's[5]). Overall the workshop was structured in two parts;

- **Foundational CPS topics** divided into initial talks (invited inspirational talks, an overview of relevant agendas/roadmaps, and a short summary of the received position papers) and a world-café at which the following themes were included with chairs in parenthesis. For each discussion the participants were encouraged to raise other topics they thought should also be addressed. The 4 selected topics where chosen based on discussions in the Platforms4CPS project and based on submitted position papers.
    - Humans as part of CPS (Vladimir Cvetkovic, KTH)
    - CPS and systems engineering – facets of complexity (Claire Ingram, Univ. of Newcastle)
    - Autonomy, AI and self-awareness (Haydn Thomson, Haydn Consulting)
    - Composability for CPS (Vincent Aravantinos, FORTISS)
- **Topic reflections, how to address them, and how to achieve a longer-term discussion**
    - Reflections on the topics – synthesis (Vincent Aravantinos)
    - How to best address identified and missing topics? EU vs. national level? Which topics should be treated under the CPS umbrella (vs. IoT, big data, 5G, …) (Haydn Thomson)
    - Eliciting ideas on how a longer-term discussion among experts can be achieved (Martin Törngren, KTH)

Overall, the workshop organization and discussion emphasis was perceived as successful by the participants, and involved very engaged discussions.

In the following, we briefly summarize the discussions and findings from each world café theme. The reader is referred to the remainder of the on-line presentations for the inputs to the workshop.

Humans as part of CPS (chaired by Vladimir Cvetkovic) – summary

Inspiration and initial questions for this theme were provided by Vladimir Cvetkovic, see the presentation here.

[5] In a world café setup, the participants are divided into thematic groups, and then rotate among those groups. Each theme has a chair, and in this case the chair prepared initial questions and summarized the discussions from all sessions (involving several rotating groups). See further here: http://www.theworldcafe.com/key-concepts-resources/world-cafe-method/

- There is considerable emphasis in the CPS community on communication in CPS, however mainly referring to communication between technical CPS entities (hereafter referred to as agents). This should be extended to include the communication between CPS and human-social agents, which leads to the notion of cyber-physical-human (CPH) systems. We note that most of the recent CPS agendas/roadmaps that we are aware of (see the PlatForum for representative such agendas) emphasize the importance of humans as part of CPS. However, it is our understanding that rather few projects and efforts are actually addressing this gap. CPS that directly involve humans, constitute a special class of CPS, see Figure 1.
- The key notion for the communication between CPS's as well as CPS and human-social agents is intent, i.e. the understanding of what drives the actions or inactions of an agent. There is a clear need to develop methods for intent identification and specification, as well as to develop intent communication protocols.
- There is a need to broaden the education and training with respect to human – non-human agent interaction and communication. Regardless of type of systems and e.g. levels of automation, humans as developers, operations, users, maintainers etc. will increasingly have to deal with CPS. As such interaction and communication is foreseen to become increasingly dominant in the future, educational content should be developed for all levels.
- There is a need to identify deviations from normal behaviour of human-social agents, in particular behaviour that leads to decisions/actions of significance for the functioning of CPS.

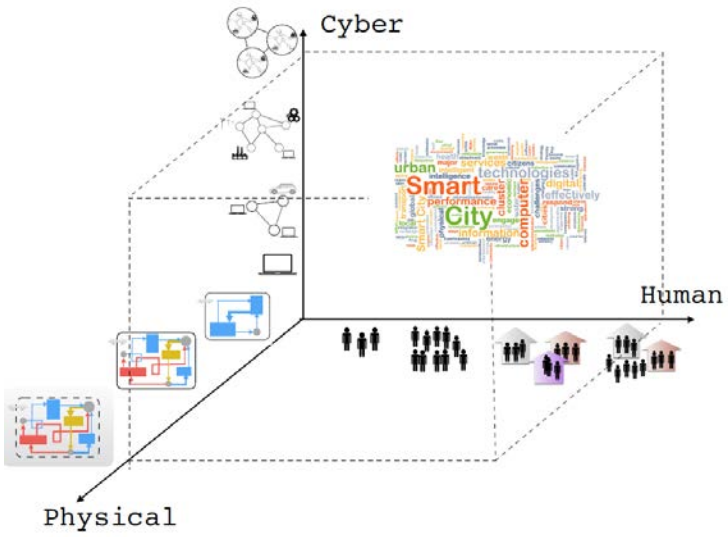

Figure 1: CPS as consisting of engineered cyber and physical components as well as of humans

CPS and systems engineering – facets of complexity (chaired by Claire Ingram) – Summary

Inspiration and initial questions for this theme were touched upon by several speakers, see the initial inspiration talks here.

The discussions centered on complexity management and what/how systems engineering (SE) can contribute to deal with complexity. A short summary of the main points is provided here, see further here for an extended set of notes:

- The essence of complexity is important to investigate and understand to be able to deal with CPS: is it about heterogeneity, humans, abstractions, number of components, or something else?
- Systems engineering is a collection of best practices to address many of the concerns of complex engineered systems. Which of these practices are valid for CPS?
    - Systems engineering provides a lot of advice for decomposition, but re-composing is not the direct inverse of this – putting them back together results in problems. Is there something missing from SE to help us cope with this?
    - While decomposition into components and views is needed to manage complexity, it is unclear which set of best practices would need to be integrated, and moreover if such best practice even can be combined to form a "complete practice", i.e. can we just merge lots of best practices to get a new "global" best practice? This is unlikely as there is too much friction to combine things – e.g. conflicting requirements, uncertainty, etc.
    - Do we commit too early to designs? Should we explore tradeoffs more? We need to get the architecture in as good a shape as early as possible. Hardware is rigid and safety requirements mean it's difficult to change. Also there's an increasing focus on cyber-security and quick response to threats. This directly conflicts with functional safety, which is typically a key focus for CPS. There are no fixed processes for how to solve these issues – resolving security with safety (for example). The more we go into automation the problem gets bigger – demand for more and more function, but conflicts with important cross-cutting performance such as safety.
    - SE emerged to deal with complexity. Are existing SE frameworks ready/capable to deal with the next generation CPSoS? What is needed to adapt existing SE frameworks to CPS?
- Communication is a key aspect in dealing with CPS and complexity. There are lots of disciplines which communicate too little: functional safety, systems, cybersecurity etc. How to resolve this in effective ways (e.g. establishing common views of systems and applications, contextual understanding)? The concept of an "intelligent middleman" was discussed as one potential piece in the puzzle - Is this a person who has expertise in everything, e.g., in computer science, physics, electronics, safety etc. or should we concentrate on middleman as a human operator who has the power to override automated CPS when necessary?
- How to tailor or adapt generic frameworks to CPS? It needs to be feasible to add something to the framework from time to time, so that cross-cutting concerns (e.g., safety) can be added to a framework. Frameworks are needed but must be extensible.
- Concerns with dependability grow as complexity increases. The issues are socio-technical, from assumptions made in design to actual behavior of operators and actual state of systems. The automation paradox – relying on people/or automation is still a challenge. One direction is that of human and CPS collaboration, using the strengths of each. Designing such collaborative systems represent an opportunity and challenge.
- Evolution & long lifecycles. Agile practice can stifle innovation – agile teams tend to focus on getting things done, not innovating. Are we equipped to handle DevOps style updates? CPS's are rarely "clean-sheet" developments, updates are deployed to live systems. Our design practices need to be adapted for change, but current safety standards and process standards make this

difficult. Understanding the impact of changes, and having an architecture where changes do not propagate "too much" is important.

- Dealing with legacy systems is a problem – no one knows or understands the old system, models are rare. Companies do not want to share what they have.

Autonomy, AI and self-awareness (chaired by Haydn Thomson) – Summary

Key issues in Autonomous Systems, AI and Self-Awareness were elicited in the group discussions, covering a range of topics such as technology, relation to cross-cutting topics such as security, assurance, liability, legislation, ethics, and end-user trust. These topics are summarized here.

The discussion ended up in identifying the following grand challenges in the area of autonomous systems and AI:

- Definition of classification for general levels of autonomy
- Definition of an ethical basis for AI considering key rules that need to be adopted
- Guaranteeing safety and certification approaches for machine learning algorithms when it is not possible to understand all potential failure modes

Composability for CPS (chaired by Vincent Aravantinos) – Summary

Composability is well-studied in a number of disciplines, notably in computer science; this needs to be extended to CPS. The following topics were discussed:

- Notion of interface: The notion of interface provides a common language between components, allowing to understand and expose information without revealing all the content, for example with respect to what a component offers but also about limitations of the component. How to extend this notion to CPS – integrating physical aspects and time?
  - How to combine computer science and physical aspects in one common notion of interface?
  - There will probably not be just one notion of composition but several, depending on our objectives for the composed object: There is (probably) no absolute notion of composability. Would this mean that interfaces should be multidimensional?
  - What language(s) should be adopted for different aspects of such interfaces?
  - It is noted that composability is also studied in automatic control but there mainly limited to the composition of transfer functions of continuous systems, with an emphasis on nominal behavior and with little consideration of extra-functional properties.
- In the context of CPS, we have to deal with an immense heterogeneity of components. Chances that there is no common interface maybe needs to be embraced and therefore other mechanisms may need to be investigated: Use sensors/actuators to establish live a common language? Ability to connect to the cloud to discover new languages?

Reflections on the topics – synthesis (chaired by Vincent Aravantinos) – Summary

In this theme, the participants reflected on all previously discussed themes, resulting in the following suggestions:

- Learning across the Cyber vs Physical domains. Stakeholders from one side should learn more about the other, for example: How the "other side" does verification, simulation and organizes their development?
- Try to marry both sides (possibly on a "per topic" basis): Is there a possibility to integrate the way mechanical engineers do verification with the way SW engineers do verification (and similar for the topics mentioned in the previous bullet)?
- Characterization of CPS: It was agreed that there is need for a deepened characterization of CPS. Some topics taken alone are not CPS specific, but considering them in the context of CPS opens up new problems, such as for Security, AI, Simulation and HMI. Further, some topics taken alone are not CPS specific, but considering them in the context of CPS opens new opportunities such as for example design space exploration. It was generally agreed that a characterization is preferable to definitions. Such a characterization should help to deal with questions like, does a CPS (or IoT system) have to include sensing, or actuation … - i.e. by way of characterization to define what makes a CPS and that there are several different types of CPS. Several suggestions for starting points for characterizations were provided here including from the CyPhERS agenda, drawing upon characterizations from systems engineering[6], and considering the NIST workshop on Game Changing and Controversial Topics in Cyber-Physical Systems.
- Identifying open challenges for CPS. As a complement to the characterization, it was suggested to identify, describe and publish open challenges for CPS.
- The following challenges were also discussed:
    - Define a science (or engineering?) of CPS
    - Ethical issues of AI: is there bias? Is it acting in my best interest?
    - Define a "CPS level" similar to autonomous driving levels
    - Machine learning to control a machine: how to ensure safety?

How to best address identified and missing topics? (chaired by Haydn Thomson) – Summary

The scoping of this theme was first delimited to focus on Autonomy, AI and self-awareness and the sub-topics that had been identified under these headings. The most appropriate means of addressing the issues identified were first discussed. The issues that could be addressed at global, European, national and regional level were then identified.

There was some call for definition of a general classification for autonomous systems (aka the classification by the SAE already adopted for autonomous cars) at a global level. There is also a need to encourage public acceptance and trust for autonomous systems. For autonomous cars this is needed at the national and European levels to address different national driving styles and traits. Supporting this there is a need to establish an approach to liability at a European level. European effort is required to develop and specify a common set of models (sandbox) for comparison of autonomous systems. At the global level there is a need for harmonization to ensure interoperability between systems components. There is also a need to define safety boundaries at a global level. This needs to be supported by work on security at a European level. At a national level powers are needed in order to remove misbehaving

[6] A Journey Through the Systems Landscape, a book by Harold Lawson.

entities. Care must be taken to ensure privacy and here national efforts are required to meet local needs. Likewise in the area of robotics for health there is a need for national and also regional engagement.

With respect to AI more generally there is a need to address ethical issues and it was felt that there was a need to do this at a European and a global level. This needs to be supported with clear regulation to ensure that AI systems are acting in the best interests of people. One of the key problems is transparency of what is encoded in the AI systems and here again there is a need for European and global regulation. With respect to guaranteeing safety and certifying future systems, where all the scenarios cannot be predicted and the system is constantly evolving, there is a need for a European and global effort to define an approach to validation and certification/re-certification as changes are made. In many systems there is a need to be able to ensure the completeness of the training set to ensure inclusivity (e.g. handicapped people). Here there is a need for both European and global standardisation. Finally, there is a need to consider security issues and this will need to be addressed at both national and European level.

Further information is available at https://platforum.proj.kth.se/tiki-download_file.php?fileId=22

Eliciting ideas on how a longer-term discussion among experts can be achieved (chaired by Martin Törngren) - Summary

This theme focused on how a community could be best created and maintained, including considering suitable mechanisms and best practices. The following suggestions and discussion points were made.

- Aim internationally and liase/collaborate with relevant other existing organizations such as ARTEMIS-IA and INCOSE. A concrete suggestion here was to organize a roadshow, consisting of a series of consecutive workshops (a number of consecutive days and taking place in different European cities), with workshop hosting supported by local/regional organizations and in with collaborative organization of a number of keynote speakers. (this setup draws upon the INCOSE roadshow experiences)
- Important considerations for establishing a community include the following:
    - What are the pain points for the CPS community and where do we want to be? Example needs that were mentioned included brokerage – facilitating stakeholder contacts; providing overviews of existing efforts/research projects; and the potential to build upon the momentum and contacts of projects beyond their life-time.
    - Who are the stakeholders and what's in it for them? Strategy is key – relating to the previous bullet. Some participants reported on the use of very capable tools to build communities, but also that nothing will happen unless stakeholders are naturally attracted to contribute. The participants agreed that industry to meet academia, and cross-disciplinarity were two important aspects in engaging stakeholders.
    - A clear identify, scope and goals are needed. The arena needs to be non-competitive, promote collaboration and sharing of experiences
    - It is important to communicate what CPS are and their implications are
    - There is a place for a European CPS-VO (referring to the US CPS virtual organization: https://cps-vo.org/).

- An On-line forum will need knowledgeable moderators for the discussion, and frequent activity, with “at least weekly updates”. There should be an approval process for an on-line forum.
    - Perhaps something like the ”Stack overflow” community but for CPS?
- Connecting to other relevant events (such as Dagstuhl workshops), or magazines such as IEEE Spectrum or the MIT Tech review

See here for a slightly extended set of notes.

2. Next steps

We believe that there is strong motivation for continuing the discussion on the Foundations of CPS, leveraging the momentum from the workshop. Follow up work after the workshop will strive to create and evolve a community that continues the work on Foundations of CPS. Use of the PlatForum and follow-up workshops are foreseen.

One aim of the CPS foundations effort is to provide recommendations to the European Commission in order to influence the next framework program. In the longer term, we hope to build up a long-living community (something like a network of excellence in this area). Those that engage in the community will be able to provide inputs, feedback and discuss the recommendations, and will be acknowledged for their contributions.

Short term efforts will request and stimulate stakeholders to engage on the PlatForum by

- Providing feedback on the workshop summary
- Providing further position statements,
- Responding to one of the topics on the Forum or by creating a new one

Further interactions on the PlatForum should be able to make use of Surveys and Voting functionalities.

Mid-term efforts may include the following:

- Elaborating aspects that the workshop did not find time to address fully – “Which topics to treat where” was only treated partially. This could be addressed as part of a follow-up workshop.
- Developing a deepened characterization of CPS
- Synthesizing open challenges for CPS
- Follow-up workshops, tentatively along the lines of the INCOSE experience

3. Participants

Name	Affiliation
Martin Törngren	KTH
Stefan Norrwing	Prevas
Bud Lawson	Private business
Claire Ingram	Univ. Of Newcastle
Cyrille Artho	KTH
David Broman	KTH and UC Berkeley
Edward Griffor	NIST
Eilert Johansson	SICS/RISE (research institute)
Elena Fersman	Ericsson Research
Erik Herzog	SAAB
Finian Rogers	INFINEON
Hans Vangheluwe	Univ. Of Amsterdam
Haydn Thompson	Think
James Gross	KTH
Jana Tumova	KTH
Panagiotis Papadimitratos	KTH
Pernilla Ulfvengren	KTH
Sofia Cassel	KTH
Vincent Aravantinos	FORTISS
Vladimir Cvetkovic	KTH

In addition, a number of persons contributed inputs to the workshop (but were not able to participate in person). See Individual position statements in the workshop program.

Finally, an additional group of people expressed interest in being part of the follow-up dialogue.