Foundations of Cyber-Physical Systems

- a workshop organized by ”Platforms4CPS”

www.platforms4cps.eu/

Summaries of inputs including position papers and previous agendas

Co-arranged with CPSE-labs (www.cpse-labs.eu/) and the ICES competence network (www.ices.kth.se)

Workshop outline

Brief round of presentations!

Introduction – Platforms4CPS and Workshop introduction

First part: Foundational CPS topics

09.15-10.35: Initial set of inspirations talks < 10 min. presentations per speaker

10.55-11.10 – Short summaries of provided workshop inputs (existing roadmaps, positions)

11:10-12:40: First world café session – 4 themes (group work)

- Humans as part of CPS; CPS and systems engineering; Autonomy, AI and self-awareness; Composability

12:40-13.05: Plenary summaries of table discussions

13:05-14:05: Lunch!

Second part: Reconciling topics, how to address them and longer-term discussions

14:05-14.25: Initial inspirational short talks

14:25-15.50: Second world café session - 3 themes (group work)

- Reconciling the topics; How/where to address identified topics; How to stimulate and maintain a longer-term discussion among experts on CPS foundations

15.50-16.15: Plenary summaries of table discussions (25 mins)

16.15-16.40: Overall wrap up and next steps!

First part: Foundational CPS topics - summaries

10.55-11.10 – Short summaries of provided workshop inputs (existing roadmaps, positions)

- Existing roadmaps:
  - Road2CPS (separate slides)
  - CPSoS,
  - CyPhERS agenda
  - CPS Summit inputs
- Position statements
  - Self-aware CPS;
  - Modeling challenges for CPS;
  - A science of software and system design
  - Human centric design of CPS/IoT;

The corresponding documents/position statements are available here:
https://platforum.proj.kth.se/tiki-index.php?page=Foundations+of+CPS+-+Related+Work

CPSoS agenda – summary by Martin T.

Cyber-physical systems of systems (CPSoS) are large complex physical systems that interact with and are controlled by a considerable number of distributed and networked computing elements and human users. Examples are rail systems, electric grids, … and large production facilities.

CPSoS are CPS which exhibit features of SoS including …

- Large, distributed, complex dynamics,
- Partial independence and autonomy constituent systems
- Dynamic reconfiguration of the overall system and continuous evolution
- Possibility of emerging behaviors

Also refers to enabling technologies like Computing/communication, sensing, …

The engineering and operation of SoS must build upon theories, tools and knowledge from a large number of domains!

Strong needs for an interdisciplinary approach for cyber-physical SoS **where the knowledge about the physical side of the systems is indispensable**

CPSoS agenda – key research topics

Challenge 1: Distributed, reliable and efficient management of cyber-physical systems of systems CPS which exhibit features of SoS

- *Decision structures and system architectures (uncertainty, risk management)*
- *Self-organization, structure formation, and emergent behaviour in technical systems of systems*
- *Real-time monitoring, exception handling, fault detection and mitigation of faults and degradation*
- *Adaptation and integration of new components*
- *Humans in the loop and collaborative decision making*
- *Trust in large distributed systems.*

Challenge 2: Engineering support for the design-operation continuum of CPSoS

- *New engineering frameworks*, semantic integration, cross-layer design, …
- *Modelling, simulation, and optimization of CPSoS*; methodologies for model management and integration,
- *Establishing system-wide and key properties* – dynamic requirements management, theory for successive refinements and abstractions of cont. and discrete systems, joint use of assume-guarantee reasoning, simulation based and exhaustive verification techniques

Challenge 3: Cognitive CPSoS

- *Situation awareness … with decentralized management and control*
- *Handling large data in real time to monitor performance, and to detect faults and degradation*
- *Learning good operation patterns from past examples, auto-reconfiguration and adaptation*
- *Analysis of user behaviour and detection of needs and anomalies*

Which of these are foundational aspects?

CPSoS agenda – key research topics

Challenge 1: Distributed, reliable and efficient management of cyber-physical systems of systems CPS which exhibit features of SoS

- *Decision structures*

Attempt to summarize and extract key directions:

Coordination

Self-organization and adaptation

Humans in the loop

Different scales

Cyber-security

Engineering frameworks to realize the above

”MBSE” for CPSoS

Cognitive CPSoS – context awareness

- *Learning good operation patterns from past examples, auto-reconfiguration and adaptation*
- *Analysis of user behaviour and detection of needs and anomalies*

Which of these are foundational aspects?

CyPhERS agenda – summary by Martin T.

Different and sometimes contradicting characteristics and requirements of physical and cyber, as well as local and global processes

Characterization rather than definitions:

- Cross, Live, Self
- Emphasis - different types of CPS
- Perspectives – viewpoints of CPS

CyPhERS agenda - highlights

Broad socio-technical scope of identified challenges and recommendations

A scientific approach integrating multiple paradigms at the required breadth and depth is essential.

- **Multi-Disciplinarity**: the scientific landscape lacks the necessary instruments to facilitate multidisciplinary collaboration
- **Socio-Technical Character**: systematic treatment of the capabilities/limitations as well as the active management of the intensions and expectations of human users by “systems”
- **Foundational Theories**: for physical, technical, organizational, and social processes – are not combined nor adequately linked
- **Multi-Domain Modeling**: lack of established knowledge on how to adequately model all the relevant aspects of CPS, for combinations, level of abstraction; varying level of detail; confidence quality
- **Technological Challenges – Complexity:** Uncertainty, Dependability, Privacy, Autonomy, Interoperability

CPS Summit – summary by Martin T.

grand challenge of constructing of societal-scale CPS that are safe and secure …

Main recommendations: collaborative US and Europe pre-competitive CPS research and development, including

(1) joint research for establishing a new systems science for predicable and trustworthy CPS,

(2) driving open standards and platforms for capitalizing on synergies in building CPS,

(3) creating and coordinating the operation of joint platforms and living labs for testing and experimenting with CPS, and

(4) the exchange of best practice for CPS training and education

CPS Summit - highlights

- Construction of composable and predictable (within quantifiable tolerances) CPS
- Assessment of the resilience of CPS against failures and cyber attacks
- Consideration of humans as elements of CPS in an integrated approach
- Large scale orchestration of CPS, including a taxonomy of architectures, and Design, production, operation, life-cycle management and evolution of CPS
- Breaking domain barriers: Architectures; Integrated Modeling Hubs; Linking Hubs with Tradeoff Analaysis and Design Space Exploration; Requirements Representation and Management

Self-aware CPS – summary by Martin T. (position statement: Axel Jantsch)

Self-awareness proposed as a foundational topic requiring further research

Insight that concepts related to "self-awareness" will be needed to handle

- HW faults
- SW and functional failures
- Malicious attacks (e.g. HW trojans)
- the significant adaptivity needed in autonomous systems and safety critical systems

Modeling challenges for CPS - summary by Martin T. based on paper suggested by Edward Lee

CPS applications operate in an intrinsically nondeterministic world

Position: important role of deterministic models – as ”blueprints”

However - current abstractions fail to cover key cover key elements: A major problem for CPS: combinations of deterministic models are nondeterministic

➔ Timing is not part of software and network semantics

Limitations of deterministic models: Complexity, Uncertainty, • Chaos, Incompleteness

From the paper: Fundamental Limits of Cyber-Physical Systems Modeling

A science of software and system design – summary by Martin T. (position statement: Stavros Tripakis)

Software as a dominating cause of complexity

A ”science of design” exists and is applicable to CPS

Design as (1) trial and error, or ➔ (2) model-based

- Importance of models – abstractions,
- Importance of formal methods
- Key concepts from formal Methods to "modern" system theory: Spec. vs. Impl, correctness, termination, transition systems, reachability, hierachy, compositionality, interfaces, abstraction, refinement
- Need to build bridges and interfaces to close the gaps between various disciplines
- Multi-view modeling, compositional simulation, theories of contracts and interfaces, and semantics preserving techniques to bridge high-level models and their implementation

Human centric design of CPS/IoT – summary by Martin T. (position statement: Kristina Höök)

Current IoT and CPS are built using very limited interaction models – typically drawing from the desktop domain

Moreover, each IoT device comes with its own limited interaction model – making interaction very cumbersome

Strong needs for a new interface paradigm **Smart implicit interaction**

- emphasizing context awareness achieved through
- data analysis of speech; movements; and other contextual data (location, …) – to avoid unnecessarily disturbing us or grabbing our attention
- continous adaptation through data driven machine learning techniques

Beyond state of the art and rule-based behaviors