Roadmap Pitch:
Cyber-Physical Systems of Systems

Platforms4CPS Roadmap Workshop
CPSoS Introduction

- 30 month Support Action
- Provided an exchange platform for Systems of Systems related projects and communities
- Focus on Systems of Systems where large complex physical systems interact with computing and communication systems – Cyber-physical SoS

Goal:
Define a European research and innovation agenda on Cyber-physical Systems of Systems
CPSoS Introduction 2

- Not campaigning for a single community, but
- **Bridging between communities**
  - Systems and control
  - Computer science
  - Software and systems engineering
  - Physics
  - Tool developers (simulation, verification, software engineering)
- **Bottom-up and top-down approach**
  - Analyse the needs in application domains
  - Analyse the state-of-the-art in methods and tools
  - Integrate the two views to define the most important gaps and actions needed
Complexity of Rail System

THE PROMISE

"The timetable is our promise... when we promise a train can run, it will run... safety, punctuality and reliability; and we promise that more trains are able to run next year."

Platforms4CPS
Creating the CPS Vision, Strategy, Technology Building Blocks

Network Rail
ASSET INFORMATION VISION

THE PROMISE

Complexity of Rail System

Platform4CPS - Creating the CPS Vision, Strategy, Technology Building Blocks
Cyber-Physical Systems of Systems

What are Cyber-physical Systems of Systems?

Large, complex, often spatially distributed Cyber-physical Systems that exhibit the features of Systems of Systems.

Cyber-physical Systems (CPS)

- **Tight interaction** of many distributed, real-time computing systems and physical systems
  - **Examples**
    - Airplanes
    - Cars
    - Ships
    - Buildings with advanced HVAC controls
    - Manufacturing plants
    - Power plants
    - ...

- **Physical connections**
  - Material/energy streams
  - Shared resources (e.g., roads, airspace, rails, steam)
  - Communication networks

- **Many interacting components**
  - **Examples**
    - Large industrial sites with many production units
    - Large networks of systems (electric grid, traffic systems, water distribution)

Systems of Systems (SoS)

- **Dynamic reconfiguration**
  - Components may...
    - Be switched on and off (as in living cells)
    - Enter or leave (e.g., in air traffic control)

- **Continuous evolution**
  - Continuous addition, removal, and modification of hardware and software over the complete life cycle (often many years)

Examples of Cyber-physical Systems of Systems

- **Integrated large production complexes**
  - Major source of employment and income in Europe
  - Major consumer of energy and raw materials
  - Many interconnected production plants that are operated mostly autonomously with distributed management structures

- **Transportation networks (road, rail, air, maritime, ...)**
  - Vital to the mobility of EU citizens and the movements of goods
  - Large integrated infrastructures with complex interactions, also across national borders
  - Involve multiple organizational and political structures

Many more examples, e.g., smart (energy, water, gas, ...) networks, supply chains, or manufacturing

Partial autonomy

Local actors with local authority and priorities

- **Autonomous systems ...**
  - ... cannot be fully controlled on the SoS level
  - ... need incentives towards global SoS goals

- **Examples**
  - Local energy generation companies
  - Process units of a large chemical site

Emerging behavior

The overall SoS shows behaviors that do not result from simple interactions of subsystems

- Usually not desired in technical systems, may lead to reduced performance or shut-downs

- **Examples**
  - Power oscillations in the European power grid
  - Oscillations in supply chains
Data Gathering

Platforms4CPS - Creating the CPS Vision, Strategy, Technology Building Blocks

Draft State-of-the-Art Report
Circulation to experts and contributors for feedback

Working Group Meeting Validation + Additional information from open meeting

State-of-the-Art and Research Priorities

- Web Questionnaire
- Questionnaire
- Telephone Interview
- Face-to-Face Interview

Industry
Academia
EU SoS Projects

Working Group Members
World Wide Web
Website
Interviews
CPSoS Research and Innovation Agenda

- Distributed, reliable and efficient management of cyber-physical systems of systems
- Cognitive cyber-physical systems of systems
- Engineering support for the design-operation continuum of cyber-physical systems of systems
Platforms4CPS - Creating the CPS Vision, Strategy, Technology Building Blocks

The Aerospace Sector

In the aerospace sector, air passenger volume is predicted to double air traffic density over the next two decades in an already congested airspace. In key markets and large airports within Europe, there are over 50 million passengers a year, and on the majority of others, there are 10-50 million passengers. Air traffic is increasing, and the number of aircraft is expected to double by 2030. As a global aviation industry, the biggest and most important challenge is to continue to safely accommodate ever-increasing air traffic in support of global economic growth and prosperity whilst protecting the environment. Movement of increasing numbers of passengers requires a complex cyber-physical system of systems across the world that integrates airport operations, baggage handling, and air traffic control to maximize flow. Air traffic control by itself is not enough to achieve this goal. A fully integrated system that encompasses all aspects of air traffic management is necessary. Platforms4CPS is developing the technology and tools to achieve this goal.

1. **Platform 5.4 Publications and participation in fairs and conferences (KTH/M1 – M24)**

2. **Platform 5.5 Final publication / Glossy print of main project results (THHINK/M20 – M24)**

3. **Platform 5.6 Platforms4CPS final conference / EU consultation meeting (THA/M20 – M24)**

4. **Platform 5.8 Strategy to sustain Platforms4CPS after the project end (S2i/M13 – M24)**

Example Aeronautics

The European aerospace industry is a world leader in the production of civil and military aircraft, both engines, propellers, avionics, and equipment, exporting them all over the world. It also provides support services, such as maintenance and training. Aerospace within the EU provides more than 560 000 jobs and generated a turnover of €470 billion in 2013. Employment in the aerospace sector is particularly significant in the United Kingdom, France, Germany, Italy, Spain, Poland, and Sweden. A significant share of value added is spent on research and development (R&D) within Europe.

As ASTRADA [3] is looking at the technological, legislative, and political challenges of how unmanned aerial vehicles can also be integrated with the civilian ATM network, the experience of the sector highlights a number of key issues. Here, it is noted that systems engineers are often stuck in a “requirements first” clean sheet design paradigm and are using a level of detail over the system elements. This is not available in many systems engineering. The key concern is that there is a need for a scientific foundation to handle multi-layer operations and multiple life-cycle management. Supporting this, there is a need for modeling and simulation. The biggest problem in modeling and simulation to ensure that there is a high degree of accuracy in both real-time and off-line simulation. The expectation is that systems of systems approaches will provide a better integrated end-to-end passenger experience experience and reduced emissions. Improved air traffic control will reduce costs and delays, and better integration of systems offers the opportunity to optimize gate-to-gate transistions with on-time or ground delays or existing before approach (with consequent reductions in emissions).

There is a lot of military experience in the operation of aircraft within systems of systems, and it is well known that military capability is enhanced through the synchronization of force elements across time and space. In a civilian context, the same approach can be employed for a more flexible and focused use of information and existing assets to improve capacity. This tends to result in better performance and also monetary savings due to a reduced need for capital equipment and more efficient utilization of assets and resources. Autonomous aircraft operations are not a new concept in the aerospace domain; there are already deployed systems, e.g., for homeland security that indicate that there is a need for a high-level approach. In the military domain, the system of systems approach will provide a better integrated end-to-end passenger experience experience and reduced emissions. Improved air traffic control will reduce costs and delays, and better integration of systems offers the opportunity to optimize gate-to-gate transistions with on-time or ground delays or existing before approach (with consequent reductions in emissions).

Platforms4CPS is looking at the technological, legislative, and political challenges of how unmanned aerial vehicles can also be integrated with the civilian ATM network. As such, it is noted that systems engineers are often stuck in a “requirements first” clean sheet design paradigm and are using a level of detail over the system elements. This is not available in many systems engineering. The key concern is that there is a need for a scientific foundation to handle multi-layer operations and multiple life-cycle management. Supporting this, there is a need for modeling and simulation. The biggest problem in modeling and simulation to ensure that there is a high degree of accuracy in both real-time and off-line simulation. The expectation is that systems of systems approaches will provide a better integrated end-to-end passenger experience experience and reduced emissions. Improved air traffic control will reduce costs and delays, and better integration of systems offers the opportunity to optimize gate-to-gate transistions with on-time or ground delays or existing before approach (with consequent reductions in emissions).

Air traffic control is a prototypical example of a cyber-physical system of systems where elements enter and leave the system all the time. The key challenge is to continue to safely accommodate ever-increasing air traffic in support of global economic growth and prosperity whilst protecting the environment. Movement of increasing numbers of passengers requires a complex system of systems across the world that integrates airport operations, baggage handling, and air traffic control to maximize flow. Tools and methods that automate air traffic control are needed, and modeling, integration, and the handling of emerging effects are key issues. At the same time, the need for unprecedented high levels of aircraft availability is driving the use of sophisticated information and communication technologies for predictive health monitoring, integrated with worldwide maintenance and logistics systems to ensure that aircraft are always fit to fly.
Recommendations for CPS Implementation

Cross-sectorial research and innovation priorities

- System integration and reconfiguration
- Resiliency in large systems
- Distributed robust system-wide optimization
- Data-based System operation
- Predictive maintenance for improved asset management
- Overcoming the modelling bottleneck
- Humans in the loop

Sector-specific priorities

- Integration of control, scheduling, planning, and demand-side response in industrial production systems
- New ICT infrastructures for adaptable, resilient, and reconfigurable manufacturing processes
- Multi-disciplinary, multi-objective optimization of operations in complex dynamic 24/7 systems
- Safe, secure and trusted autonomous operations in transportation and logistics
Recommendations for CPS Research Priorities

1) Distributed Management of Cyber-physical Systems of Systems

- Decision structures and system architectures
- 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
Recommendations for CPS Research Priorities

2) Engineering Support for the Design-operation Continuum of Cyber-physical Systems of Systems

- Support of the design-operation continuum of cyber-physical systems of systems
- Integrated engineering of CPSoS over their full life-cycle
  - New frameworks for integrated cross-layer design, collaborative engineering, (semantic) systems integration, ...
- Establishing system-wide and key properties of CPSoS
  - Automatic analysis and verification, ...
- Modeling, simulation, and optimization of CPSoS
  - Model management, global high-level models, efficient simulation algorithms, legacy systems integration, ...
Recommendations for CPS Research Priorities

3) Cognitive Cyber-physical Systems of Systems

- Situational awareness in large distributed systems with decentralized management and control
- Handling large amounts of data in real time to monitor the system 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
Main Barriers (Enablers) identified

- CPSoS usually already exist -> legacy systems integration essential
- Lack of interdisciplinary heterogeneous, multi-scale CPSoS modeling at different levels of resolution
- Certification of safety-critical CPSoS (parts) is difficult due to CPSoS unpredictability and constant evolution
- Integration, processing, and management of high-quality data across a complete CPSoS is essential
  - Data sources are often not yet accessible to a degree that is needed for CPSoS services and applications
  - CPSoS require continuous monitoring based on high-quality data sets to detect malfunctions and abnormal operation (which are the norm in CPSoS)
- Cyber security is a major concern
Emerging Themes

- Communication technologies, standardized protocols, Internet of Things, Big Data
- Computing technologies
  - High-performance and distributed computing, multicore and mixed-criticality computing, low power processing / energy harvesting for ubiquitous installation
- Sensors, including energy harvesting
- Human-machine interfaces, e.g. head up displays, display glasses, polymer electronics and organic LEDs
- Security of distributed/cloud computing and of communication
- Systems and control theory and technology
Commonality – Strategic Needs

- Similar CPS(oS) challenges arise in many different areas, e.g.
  - Transportation (marine, rail, aerospace, automotive)
  - Logistics
  - Electric power grids
  - Process industries
  - Smart buildings

- Common challenges in these areas
  - Full-life-cycle engineering
  - Coordination and optimization
  - Modeling, simulation, and model management
  - System-wide validation and verification
  - Systems integration
  - Humans in the loop
Contacts

Haydn Thompson (Haydn Consulting Ltd.)
Christian Sonntag (TU Dortmund / euTeXoo GmbH)

haydn.thompson@thhink.com
christian@eutexoo.de

http://www.cpsos.eu