Cyber-physical Systems of Systems

Importance and Characteristics

Outline

- Scope
- Importance
- Characteristics
- Enabling technologies

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

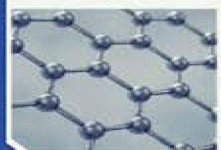
of many distributed, real-time computing systems and physical systems

Examples

- Airplanes
- Cars
- Ships
- Buildings with advanced HVAC controls
- Manufacturing plants
- Power plants
- ...

Systems of Systems (SoS)

Many interacting components



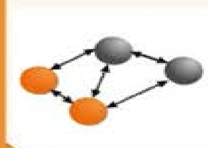
Examples

- Large industrial sites with many production units
- Large networks of systems (electric grid, traffic systems, water distribution)

Physical connections

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

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)

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

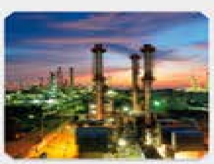
The overall SoS shows behaviours that do not result from simple interactions of subsystems

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

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

Importance of Cyber-physical Systems of Systems

- Key elements of the socio-technical infrastructure
- Providing essential services to the citizens
- Backbone of the industrial infrastructure
- Vulnerable
- Difficult to engineer and to operate
- Good engineering and efficient management is crucial for
  - Energy and resource efficiency
  - Economic competitiveness of the industries
  - Quality of life
- Main potential is on the system level

Characteristics: Physical System Elements

- *Significant* number of *interacting* components that are (partially) physically coupled and together fulfill a certain function, provide a service, or generate products.
- The components can provide services independently but the performance of the overall system depends on the "orchestration" of the components.
- After a removal of some components, the overall system can still fulfill its function, with reduced performance.
- The physical size or geographic distribution of the system is not essential but its complexity and the partial autonomy of the components.

Characteristics: Control and Management

- Not performed in a completely centralized or top-down manner with one “authority” providing all the necessary control signals but with distributed decision power
- Structures vary from a (multi-layered) hierarchy to a fully decentralized structure where only technical constraints, economic incentives and human interactions connect the subsystems.
- Partial autonomy of the control and management systems of the components
  - Disturbances can be handled (to some extent) locally
  - Subsystems can exhibit “selfish” behaviour with local goals, and preferences.
  - Autonomy can result from human users or supervisors taking or influencing the local decisions.
- The “managerial element” of the components goes beyond classical decentralized control.
- Drivers are economic, social and ecologic.

Dynamic Reconfiguration and Evolution

- Addition, modification, replacement or removal of components on different time scales
- Changes of the connectivity and the mode of operation
  - Components may come and go (like in air traffic control)
  - Reaction to faults
  - Changes of system structures and management strategies following changes of demands, supplies or regulations.
- Systems operate and are continuously improved and modified over long periods of time.
  - The infrastructure "lives" for 30 or more years, and new functionalities or improved performance have to be realized with only limited changes.
  - Management and control software has long periods of service, while the computing hardware base and the communication infrastructure change much more rapidly.
- Engineering is re-engineering and takes place at run time.

Characteristics: Emerging Behaviour

- Occurrence of pattern formation, self-organization, oscillations and instabilities on the system level
- Not always anticipated in the design
- Many emerging phenomena are not intended in technical systems
- Simple feedback phenomena and design flaws should not be mixed up with emerging behaviour.

Enabling Technologies

- Systems and control theory and technology
- Communication technologies and communication engineering
  - Where is co-design of communications and control needed?
- Computing technologies, high-performance, distributed and dependable computing
- Human-machine interfaces
- Security of distributed and "open" systems

Transdisciplinary Approach Needed

- **Cyber-physical systems of systems require a multi-disciplinary approach!**
- The behaviour of the physical part of the system must be modelled, simulated and analysed using methods from **continuous systems theory**, e.g. large-scale simulation, stability analysis, design of stabilizing controls
- Methods and tools from **computer science** for the modelling of distributed discrete systems, for verification and testing, assume-guarantee methods, contract-based assertions etc. are indispensable to capture both the behaviour on the low level (discrete control logic, communication, effects of distributed computing) and global effects, in the latter case based on abstract models of complete subsystems.
- **Logistic models** as well as models and **tools for performance analysis** of discrete systems are needed for system-wide performance analysis.
- **Theories from physics**, e.g. structure formation in large systems, and from **economics and social science** (market mechanisms, evolution of beliefs and activity in large groups) may also prove to be useful.