CPS: research and technological challenges

Some remarks on Modeling, Control and Verification

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Scope of the presentation

http://cpsh2020.car.upm-csic.es/

Introduction

Previous initiatives

CPSH2020 workshop results

USA vision

EU vision and on-going initiatives

Modeling, control and verification of CPSs

Soft-computing and computational intelligence in CPS

Conclusions

Who we are

The Centre for Automation and Robotics (CAR): join task force of UPM and CSIC with 13 research groups in the field of Automation and Robotics and more than 100 persons devoted to R+D.

Uniquely to lead an ambitious work program in the areas of Applied Computer Science, Control and Robotics

Cientific-technological areas: Monitoring and Intelligent Control, Perception Artificial Intelligence and Applied Robotics.

Unique Master/PhD Programme in Automation and Robotics.

Now in DEMANES, ACCUS & EMC2 ARTEMIS projects

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Introduction

Cyber-physical systems (CPS) are smart systems that have cyber technologies, both hardware and software, deeply embedded in and interacting with physical components (Jamshidi,2009).

CPS is an integration of computation with physical processes: composition but also conjunction (**not the union of the physical and the cyber**!).

- Not just large-scale and complex but also characterized by **decentralized, distributed, networked compositions of heterogeneous** and (semi)autonomous elements.
- CPS are **heterogeneous** (many technologies and implementation).
- CPS exhibit **emergent** behaviour (behaviours that are not predictable in advance).
- CPS are **large-scale systems** ("Scale" =logical not necessarily a geographical sense—a system of systems can be a local entity with collocated subsystems).

CPS and SoS: beyond overlapping

SoS and CPS: exciting new vistas thus it is not surprising that overlap exists.

CPS and SoS: differences in the semantics of the terms.

1) The connection with physical systems is a defining feature of CPS.

2) The main focus of SoS on distributed, hierarchical, and compositional mega-/meta-systems

3) Cross-domain decomposition is a must for CPS

Example 1: SISO PID controller, in a digital implementation, suggests opportunities for CPS research!

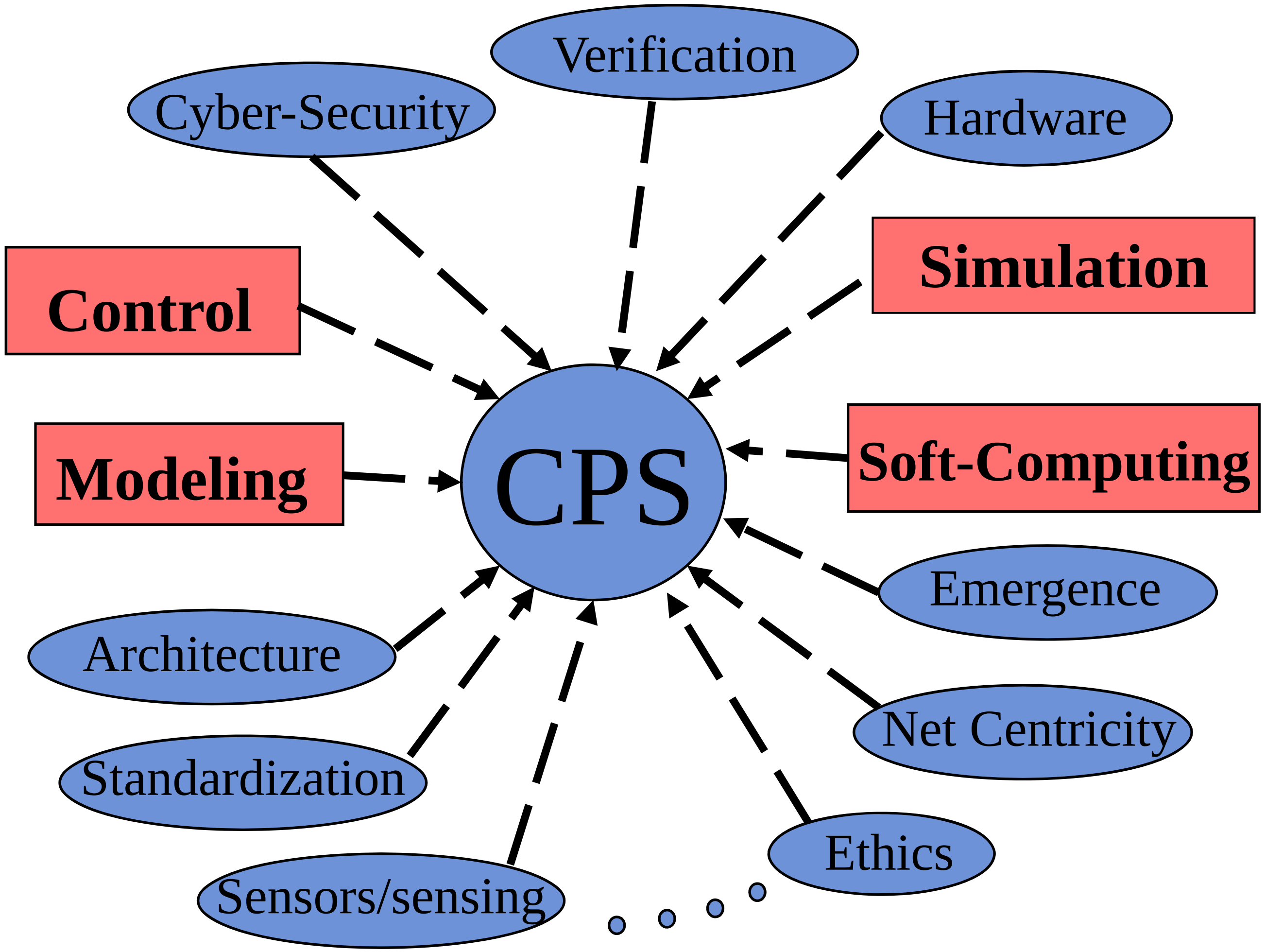
Example 2: The development of reconfigurable multivariable controllers running on sophisticated real-time platforms with adaptive scheduling will lead definitively to a progress in CPS.

Prioritization in topics:

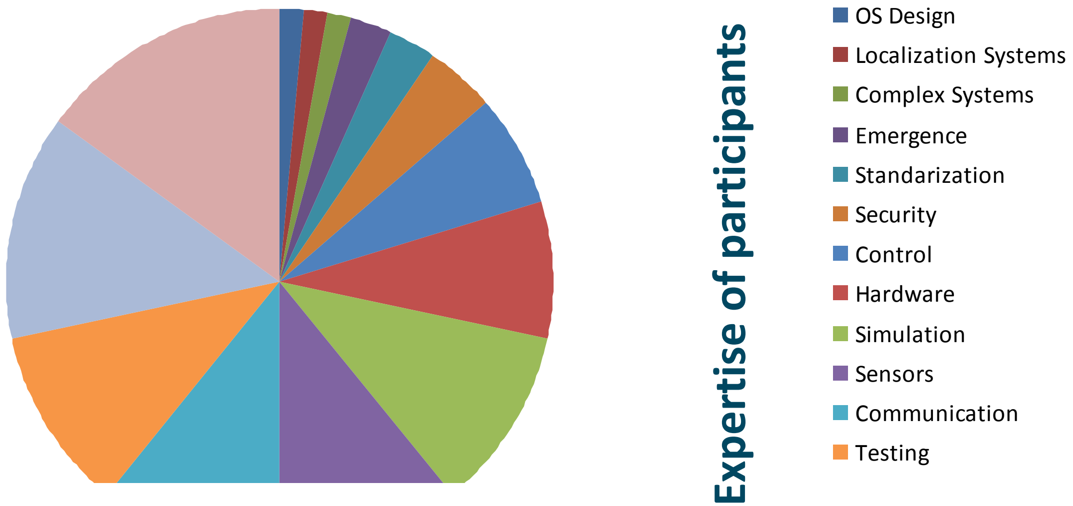
Example 3: verification and validation of RTcontroller implementations over wireless links will likely be more prominent in CPS than in SoS.

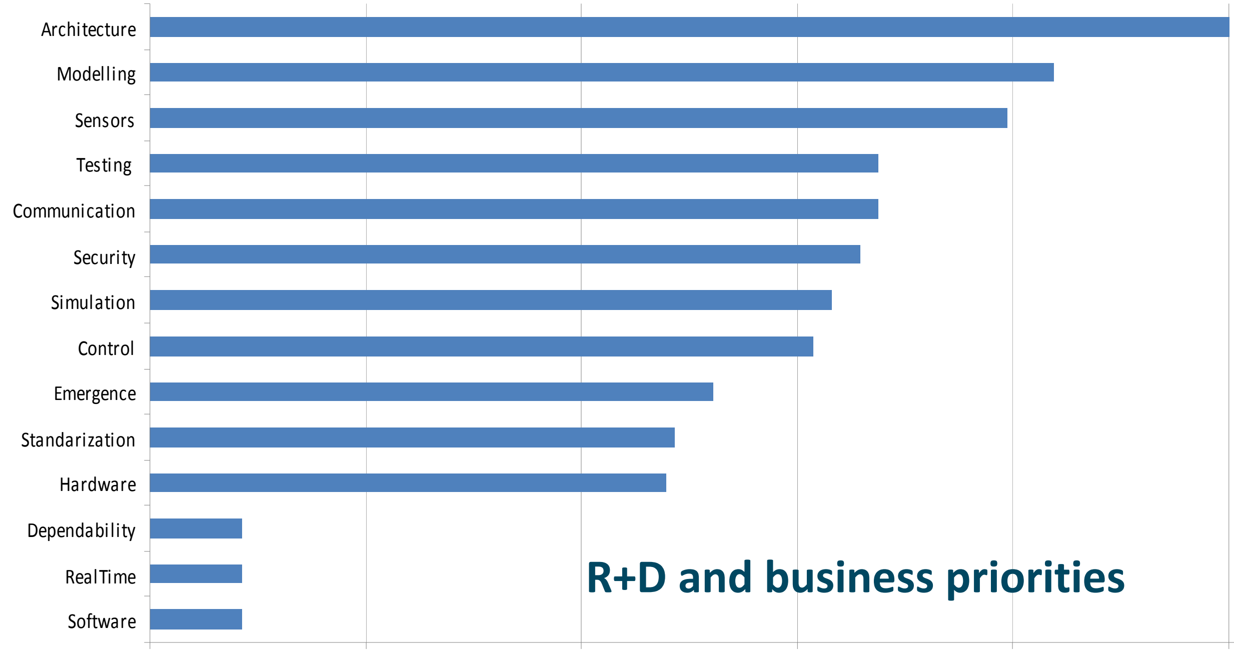
CPS challenges: beyond this talk

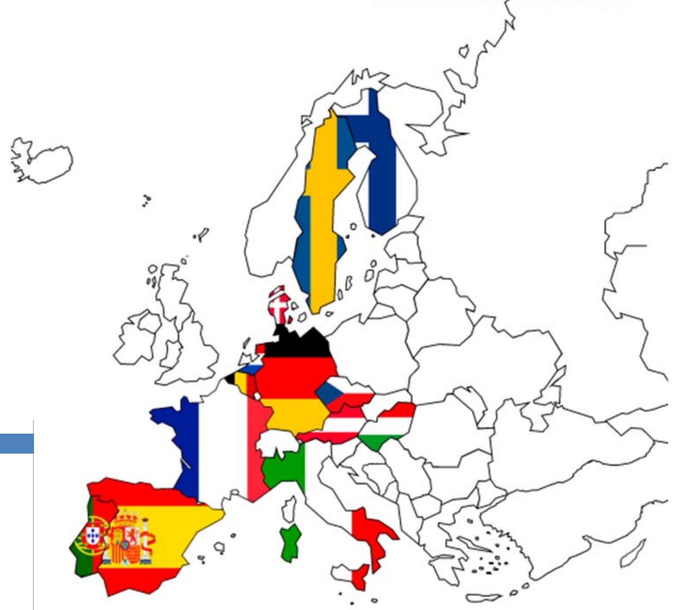
CSA CYPHER and the new ones: Road2CPS, TAMS4CPS, CPS-SUMMIT



Previous Initiatives: CPSH2020 workshop







23 institutions from **12 countries** (NL,GE,IT,FI, FR,PT,AT,EU,DK,HU,CZ,ES)

8 companies: NXP, SAP, Schneider Electric, Thales-Alenia, Indra, Philips, Akhela, Integrasys

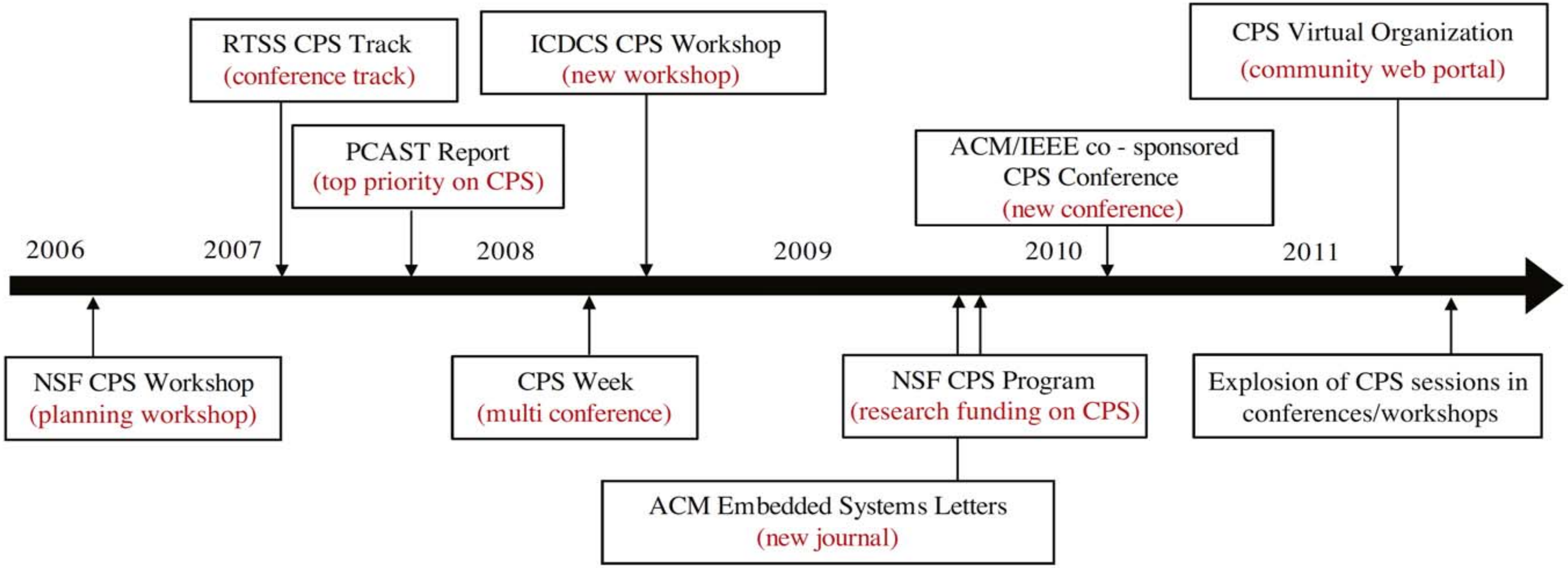
USA vision (I): NIST

Table 1. Sectors Covered in the CPS Situation Analysis	
Smart Manufacturing	Smart, pervasive application of networked information for demand-dynamic economics, integrated computational materials, enterprise and supply chain performance, and broad-based workforce engagement; manufacturing robotics that work safely with people in shared spaces; computer-directed metal-based additive manufacturing.
Smart Grid and Utilities	Systems for more efficient, effective, safe and secure generation, transmission, and distribution of electric power, integrated through the Smart Grid; smart systems applied to water and pipeline systems.
Smart Buildings and Infrastructure	Smart net-zero energy buildings for energy savings while improving indoor air quality; actively monitored, controlled, and optimized buildings, bridges, dams, and other structures.
Smart Transportation and Mobility	Vehicle-to-vehicle communications for enhanced safety and convenience ("zero fatality" highways), drive-by-wire, autonomous vehicles; next generation air transportation system (NextGen); autonomous vehicles for off-road and military mobility applications.
Smart Healthcare	Life-supporting micro-devices, embedded in the human body; wireless connectivity enabling body area sensor nets; mass customization of heterogeneous, configurable personalized medical devices, and natural, wearable sensors and benignly implantable devices.

CPS: Situation analysis of current trends, technologies and challenges, NIST, March 2012.

USA vision (II): 10 years ago!

More than 20 international conferences, journals special issues…



K.-J. Park, Cyber-physical systems: Milestones and research challenges Computer Communications 36 , pp. 1–7,(2012).
M. Jamshidi, Intelligent Control Systems with an Introduction to System of Systems Engineering, CRC Press, 2009.

USA vision (III): *Grand challenges and research*

Specific domains	Research areas
Blackout-free electricity generation and distribution	Real-time system and computational abstraction
Zero net energy buildings and cities	Robustness, safety, and security
Safe and rapid evacuation in response to disasters	Hybrid system modeling and control
Perpetual assistance to busy, elder, and disabled people	Control over networks
Extreme-yield agriculture	Sensor-actuator networks
Location-independent access to world-class health care service	Verification and validation
Near-zero automotive traffic fatalities and significantly reduced traffic congestion	Control and scheduling co-design
Significant reduction of testing and integration time and costs of complex CPS systems (communication and avionics).	Architecture

K.-D. Kim and P. R. Kumar, Cyber-Physical Systems: A Perspective at the Centennial, Proc. of IEEE 100, pp. 1287 – 1308, (2012).

A.Konstantellos, A short overview of control in European R&D programmes(1983–2013): From local loop designs, through networked and coordinated control, to stochastic, large scale and real time optimization systems, European Journal of Control 19, pp. 351-357 (2013).

Europe Vision (I): ICT2014-1?

8 projects on "Science of CPS-Integration":

- Co-simulation/modelling of all of system levels including circuits, communication networks, firmware, operating system, system architecture and software layers.

Vision: entire design will be model-based to build (¿?) cutting-edge cyber-physical systems (CPS)

- **Saving development cost and time**
- **Reducing complexity**
- **Making it easier for innovators to realise new systems**

"***The road to hell is paved with good intentions***"

Fundamental research rather than actual industrial impact

POs and policy-makers want to… but the pool of experts evaluators is what it is, and it is also reflected in the results.

Use-cases	Foundations and fundamental research focus
TAPPS: Health: smart trolley as a hub for monitoring devices from the patient's room or hospital **Automotive: control of electrical motorbike's internals throughout an App**	Platform for open CPS Apps with high security standards. extensibility, pervasive trusted environment
SAFURE: Automotive (low level), Telecommunications **(no web page available)**	Safety and security by construction, for mixed–critical systems. Design and run-time. thermal aware scheduling, safe access to shared resources
UnCoVerCPS: Automotive (self driving cars), smart grids, wind turbines, manufacturing with robots (public in the web only 2) **http://cps-vo.org/group/UnCoVerCPS**	Modeling, verification, conformance testing, code generation, tool chain, integrated runtime control and verification.
U-TEST: Sports: athlete health monitoring, Handling and logistics **http://certus-sfi.no/u-test-a-horizon-2020-funding-recipient/**	Building dependable CPS, testing for uncertainty dealing with uncertainty in CPS.

Use-cases	Foundations and fundamental research focus
AXIOM: Smart video surveillance (coordination of multiple cameras towards a single event), smart living/home (new smart thermostat) http://www.axiom-project.eu/	HW/SW techniques to allow easy programmability of multi-core multi-board systems convergence between HPC (high performance computing) and Embedded computing (EC)
IMMORTAL: Aerospace (satellite control) http://ati.ttu.ee/credes	Reliable design and real time fault management in multi core CPS Minimisation of verification efforts, speeding up fault detection, maintaining system stability with part of the resources failing.
INTOCPS: Automotive, Agricultural, Railway and Building automation http://into-cps.au.dk/	Integrated tool chain for comprehensive model-based design of CPS Support for co-model construction and co-simulation: model, software, hardware in the loop
COSSIM: Smart Grids, Visual search (no web page available).	Open-source framework to simulate the networking and the processing parts of the CPS more accurate, faster and including security and CPS simulation performance and accuracy of the simulation

Modeling topics in CPS (I)

Much of the current work has insufficiently strong semantics to adequately address intrinsic heterogeneity, concurrency and sensitivity to timing of CPSs.

- Models with solver-dependent, non-determinate (Example: Ptolomy II semantics similar to Simulink/Matlab).
- Keeping model components consistent.
- Preventing misconnected model components (e.g., units output and input).
- Modeling interactions of functionality and implementation.
- Modeling distributed behaviors.
- System heterogeneity

Need to bridge an inherently sequential semantics with intrinsically concurrent physical world.

Ptolomy II actor-oriented design approach (i.e. software components) to model components that communicate via ports (also Simulink/Matlab, Modelica, Labview/NI)

Derler et al., 2012, Modeling of Cyber-physical systems, Proceedings of IEEE Vol. 100 (1), pp. 1-28

Modeling issues in CPS (II)

DEMANES project: MARTE (UML extension) + fuzzy inference systems (Del Toro et al., 2013, Macias-Escrivá et al., 2012).

PTIDES project (Eidson et al., 2012): Programming model with formal operational semantics for distributed systems relies on time synchronization. **Coordination language** (not functional details!) for model-based design of distributed real-time embedded systems.

BUNDLE (Vicaire et al., 2012). A group-based programming abstraction for CPSs implemented in Physicalnet (middleware). Logical collection of sensing devices. **Drawbacks**: centralized architecture and slow time response.

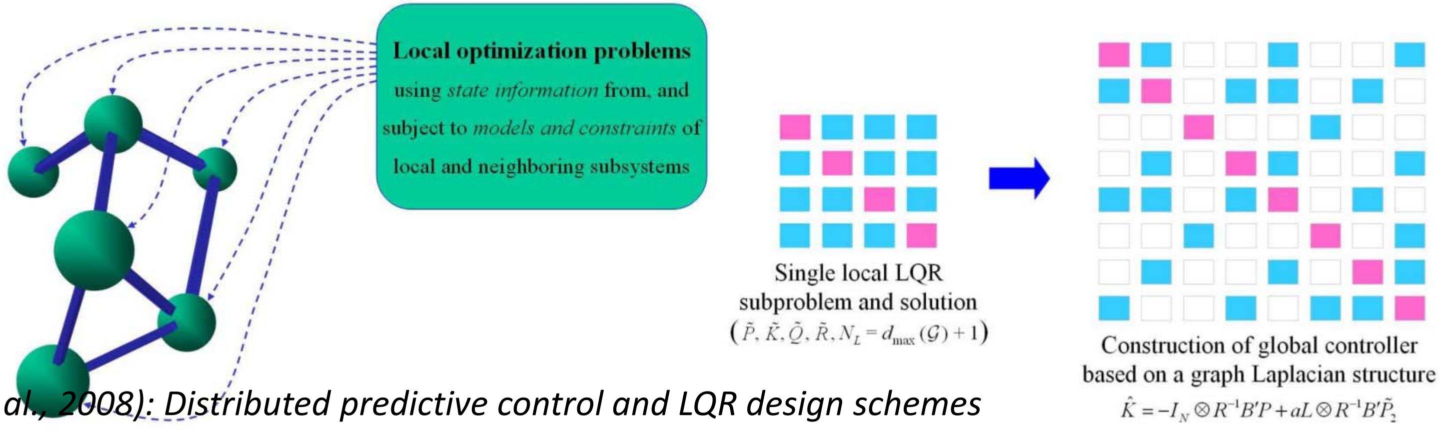
Generic method based on system characteristics and descriptive interface. Computational method that provide static and dynamic description of components and communication links.

Engineering methods for service-oriented architecture.

Control issues in CPS (I)

Wide range of control methods from LQR/LQG up to MPC.

Shared characteristics: Model-based design and qualification of complex systems



(Doyle et al., 2008): Distributed predictive control and LQR design schemes

✓The cost function and constraints couple the dynamical behavior of the subsystems.

✓Each system is a node and the control action at each node is based only on local and neighbouring state information.

✓Requires the solution of a **single local LQR problem**, depending on maximum vertex degree of the interconnection graph (Borrelli &Keviczky,2008).

Drawbacks: Linear mechanisms are considered, but there are important questions remaining about the **behavior in nonlinear regimes**.

Control issues in CPS (II)

MPC: control framework to design of coordinated, distributed control systems: **ability to handle input and state constraints and predict the evolution of a system with time**.
Drawback: Difficulties for explicitly characterizing, a priori, the admissible initial conditions starting from where the MPC is guaranteed to be feasible and stabilizing.

Lyapunov-based design: explicit characterization of the stability region and guarantee controller feasibility and closed-loop stability (Mhaskar et al., 2006).

Decentralized MPC algorithms (Christofides et al., 2013). Mainly for large-scale linear processes subject to input constraints (Alessio, Barcelli, and Bemporad 2011).

Cooperative distributed MPC: the same global cost function is optimized in each node. Each controller optimizes its own set of inputs assuming that the rest of the inputs of its neighbors are fixed to the last agreed value.
Drawback: the interconnections between different subsystems are **weak** and not involved in the controller formulation explicitly.

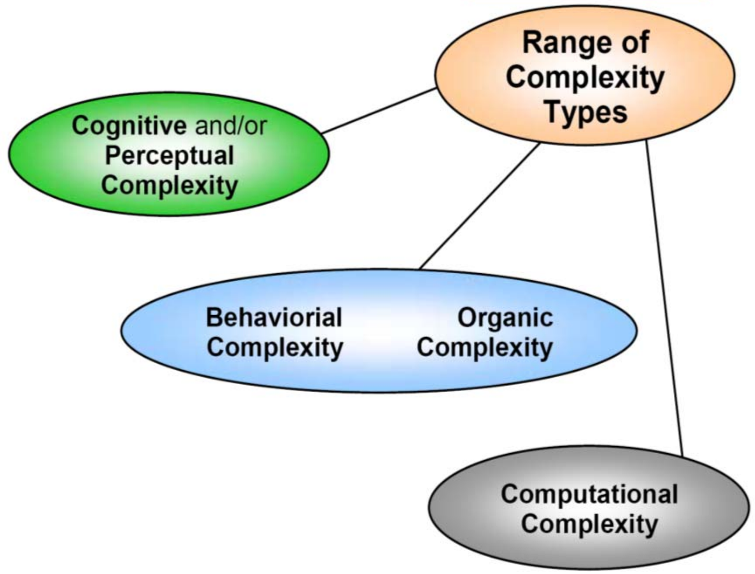
Control issues in CPS (III)

Complexity and computing are not sufficiently addressed to go beyond control of representative approaches.

Passivity and dissipasitivity approach (Antsaklis et al.,2013)

Controller evaluation time, communication network usage and closed-loop stability, performance and robustness are not conjunctively applied.

Current approaches (LQR and MPC): the problem of reconfiguration of the control system is fundamental to cope with changing requirements.



Simpson&Simpson, 2011: Systems Complexity, identification and Control

Verification and validation issues in CPS (I)

Verification of the design process to theoretical Lyapunov stability proofs that take into account uncertainties in the system (Schumann and Liu, 2010).

Formal methods advances include symbolic bounded model checking using mathematical models of the system.

Optimization techniques that can guarantee the behavior of the system given uncertainties (Haber et al., 2010).

Decompositional verification as way to deal with embedded systems with mixed criticalities (Thompson et al., 2010).

Verification based on heuristic techniques. Gradient-free techniques in simulation models for automatically creation of test inputs (Zhao et al., 2003).

Testing is still nowadays, the most widely used technique for evaluating a component-based system in its target environment. Functional online testing: requires minimal functional interference with the running system (Karsai et al., 2010)

Verification and validation issues in CPS (II)

- Development of test models based on soft-computing techniques. Automated test generation as optimization problem.
- Development of strategies for verification of networked complex systems.
  - Verification based on decomposition. Development and application of a formal method. (e.g., symbolic bounded model checking using mathematical models of the system).
  - Verification based on heuristic and machine learning techniques. Simulation-based validation.
- Development of testing techniques for validation of networked complex systems.
  - Functional and non-functional on-line testing procedures by combining AI-based and traditional testing technologies.
  - Automated performance and scalability test by combining AI-based and traditional testing technologies
- Development of a certification strategy based on AI-based techniques for quantification of margins and uncertainties (QMU) and a static analysis approach.

Soft-computing for modeling&control in CPS (I)

Association of **computing methodologies** that includes fuzzy logic (FL), neural computing (NC), evolutionary computing (EC), and probabilistic computing (PC).

Methods to deal with imprecise, uncertain data, and incomplete domain knowledge =>CPS

Hybridization (FL+NC+EC): to integrate knowledge-based and data-driven methodologies to build models for classification, prediction, and control applications.

Munakata,1998

	FLS	ANN	GA	Control Theory	Symbolic AI
Mathematical model	SG	B	B	G	SB
Learning ability	B	G	SG	B	B
Knowledge representation	G	B	SB	SB	G
Expert Knowledge	G	B	B	SB	G
Nonlinearity	G	G	G	B	SB
Optimisation ability	B	SG	G	SB	B
Fault tolerance	G	G	G	B	B
Uncertainty tolerance	G	G	G	B	B
Real-time operation	G	SG	SB	G	B

G: good SG: slightly good SB: slightly bad B: bad

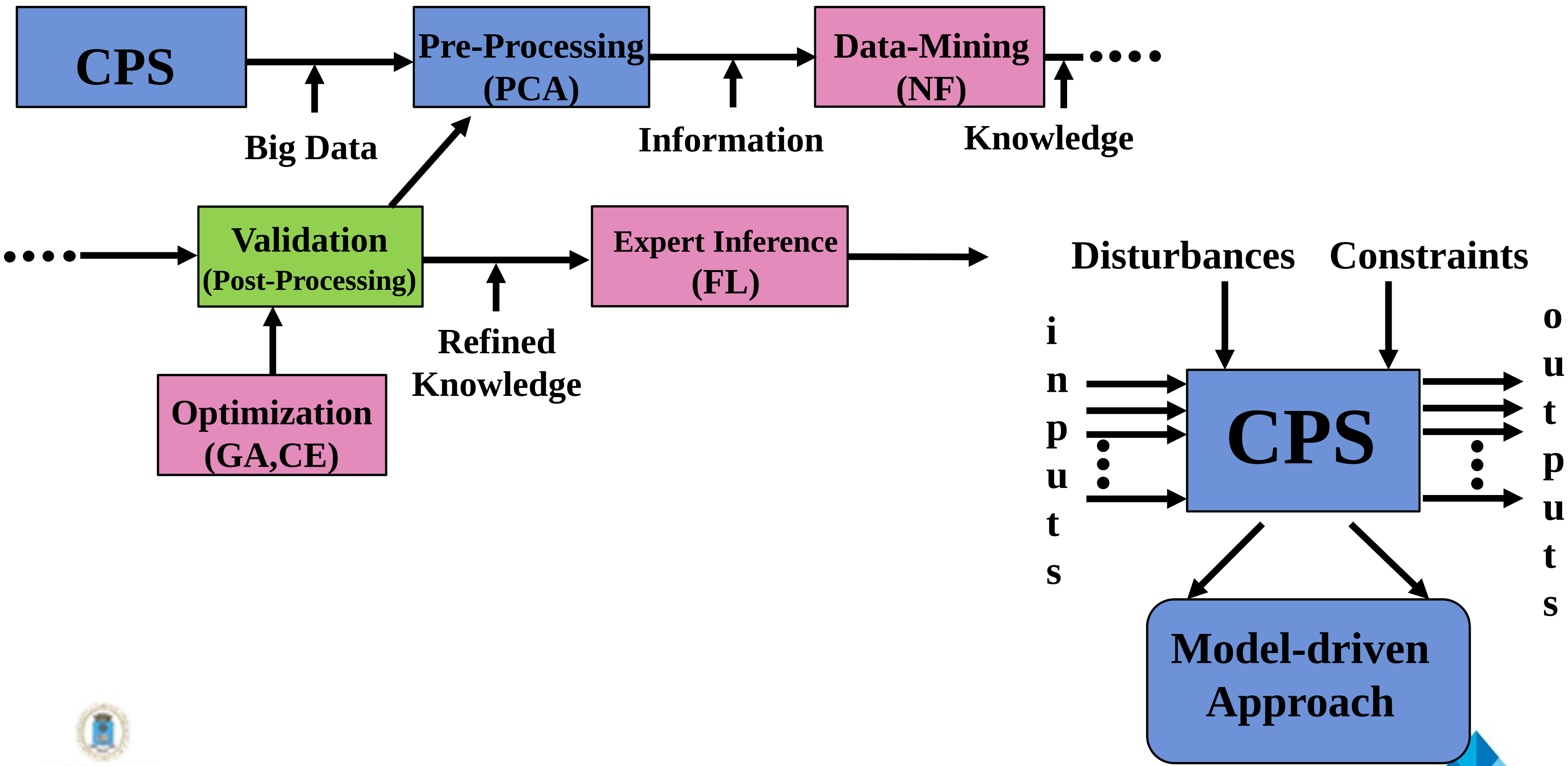
Alternative approaches compatibility with other techniques and approaches.

Soft-computing in CPS:

Fuzzy Control of Storage Unit for Energy Management of Micro-Grids (Jamshidi, IEEE 2012)

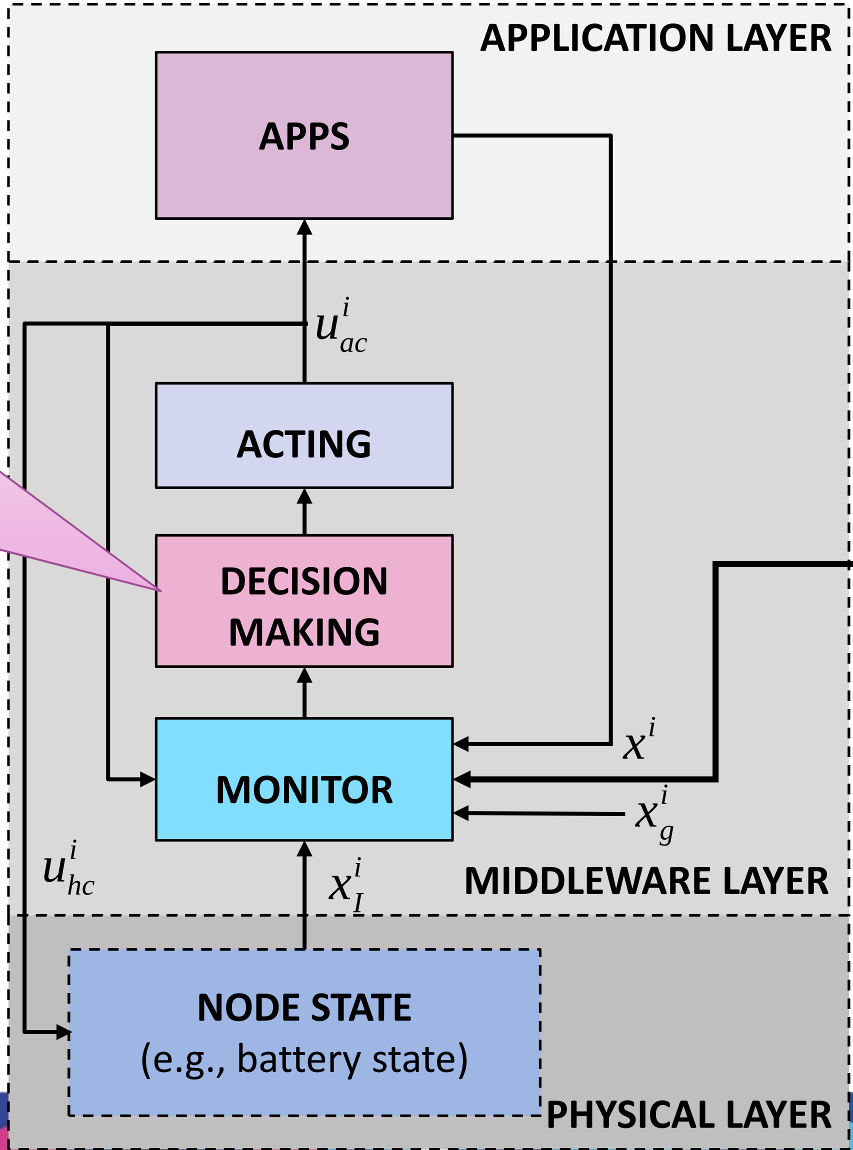
Soft-computing for model&control in CPS (II)

How to conjunctively applied artificial cognition-based methods to deal with complexity in CPS?



Soft-computing for modeling&control in CPS (III)

SOFT-COMPUTING (FL,NN,…).
•Consolidated strategy and widely applied at industrial level in embedded control systems.
•Powerful tool for decision making in situations of uncertainty in models, information, etc.



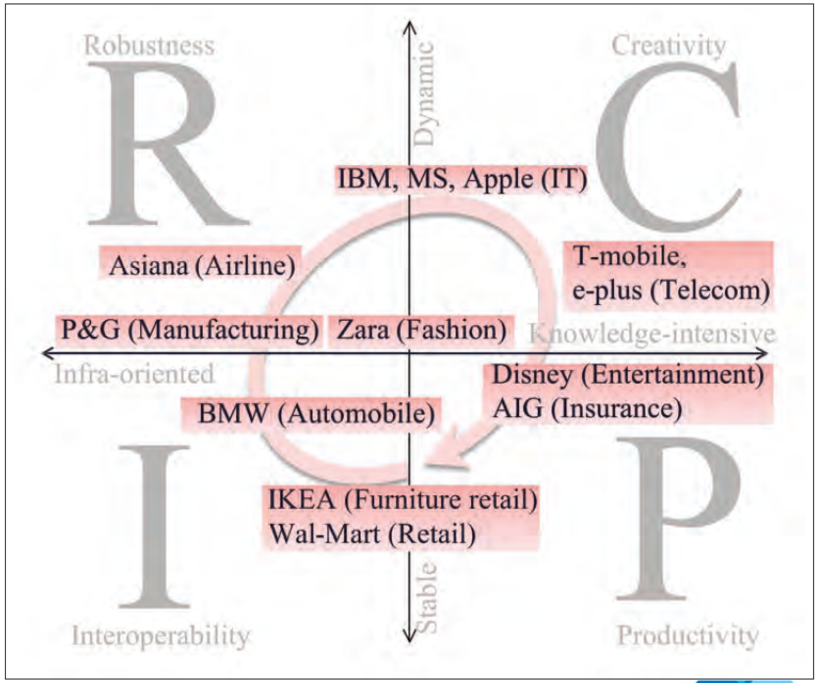
Natural trend?

From CPS to new IoT ecosystems/business ecosystems:

"Economic community involving many companies working together to gain comparative advantages as a result of their symbiotic relationships" (Moore, 1993)

"Symbiotic relationships will benefits consumers and companies
Added-value of new service levels will become key differentiators in ensuring business sustainability (Gossain&Kandiah, 1998)"

Flagship companies (Kim,Lee, Han,2010)



Most cited Software ecosystems (Manikas&Hansen, 2013)

- Eclipse, Eclipse Foundation
- GNOME
- Open Design Alliance
- Anonymized/not named
- Brazilian Public Software (BPS)
- Linux, Linux Kernel
- Android
- GX Software
- Evince
- FOSS
- FreeBSD
- iPhone/iPad App Store
- SAP

Conclusions

New CSAs have been launched to identify new R+D and business opportunities.
ECSEL (as ARTEMIS): achievability/ suitability of the proposed R+D, business and short-term impact of new proposals rather than fundamental research.

The on-going projects (**with information publicly available**) are addressing one or two of the following challenges:

- Complexity of the ecosystems&CPS
- Static and dynamic composition of different spaces/sub-systems
- Dynamic and time-variant operation of the CPS/ecosystems.
- Multi-abstraction-based modeling
- System integrity verification and behavioral validation
- Transformation of the big data generated in CPS&ecosystems
- Prototyping and small-scale pilots
- Robust social compliance of the ecosystems
- Governance
- Security

Therefore, this year is still plenty of R+D opportunities…!!

Thank you for your attention!

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