Introduction on Cyber Physical Systems

Francesca Palumbo
University of Sassari

CPS Summer School – From concepts to implementation
Porto Conte Ricerche, Alghero (IT)
25–29 September 2017
Let’s go straight to the point!

https://www.youtube.com/watch?v=U7y1wiYqHDc
Numbers: opportunity or issue?

> 7 billion

20 MWh/year

1,800 kg oil

> 1 billion smartphones

8.4 billion connected things in 2017 (+31% wrt 2016)

20.4 billion by 2020

http://www.gartner.com/newsroom/id/3598917

Francesca Palumbo, UNISS
Computing Evolution

UBIQUITOUS COMPUTING & INFORMATION
PERVERSIVE COMPUTING    DISAPPEARING COMPUTERS
EMBEDDED EVERYWHERE

POST PC ERA
+

PHYSICAL ENTANGLEMENT

CPS ERA
CPS are **smart systems** that include *engineered interacting networks of physical and computational components*. National Institute of Standard and Technology (NIST), US. CPS Public Working Group

A cyber–physical system (CPS) is an *orchestration of computers and physical systems*. Embedded computers monitor and control physical processes, usually with feedback loops, where *physical processes affect computations and vice versa*. Edward A. Lee

University of Berkeley
Key Ingredients

- Physical plant/process, users
- Communication view: component to component/human/environment
- Cyber view: software, algorithm, computation

Francesca Palumbo, UNISS
Key Ingredients

- **MODELLING & PREDICTING**
- **DATA FUSION**
- **SENSING**

CONTROL

ACTUATING

Francesca Palumbo, UNISS
CPS are **engineered systems** that are built from, and depend upon, the seamless integration of computational algorithms and physical components.

Advances in CPS will enable **capability, adaptability, scalability, resiliency** ... that will far exceed the simple embedded systems of today.

CPS technology will **transform the way people interact with engineered systems** -- just as the Internet has transformed the way people interact with information.

**National Science Foundation (NSF), Cyber–Physical Systems Group**
**Embedded Systems**: dedicated computing elements, everyday more complex, that brought the integration of information into products.
CPS Concept Map

Francesca Palumbo, UNISS
Characteristics of CPS

**DEDICATED**: towards a certain application. Knowledge of behaviours may
- improve resource minimization and robustness
- require optimized user interfaces
Characteristics of CPS

HYBRID: composed of different
• views (cyber, physical and communication),
• components (hardware and software, analog/digital devices),
• interfaces (e.g. humans, networks).
Characteristics of CPS

**REACTIVE:**
by definition reactive systems are characterized by continuous interactions with the environment where they operate, and execute at a pace that may be determined by the environment.
**Characteristics of CPS**

**DYNAMIC:** CPS are supposed to adapt to
- changes in the environment;
- runtime variation of the requirements;
- fluctuations in the amount of exchanged and sensed data.
Fields of Application

Real-time situation awareness, dynamic and reactive behaviours have application in...

**Smart–Health:**
distributed healthcare assistance to improve quality of life and active and healthy ageing.

**Smart–Society:**
increased building efficiency and comfort (i.e. lightning/air quality management).

**Smart–Transportation:**
autonomous vehicle, improved driver assistance and care.
## Fields of Application

<table>
<thead>
<tr>
<th></th>
<th>Safety</th>
<th>Security</th>
<th>Certif.</th>
<th>Distrib.</th>
<th>HMI</th>
<th>Seamless</th>
<th>MPSoC</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Automotive</strong></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td><strong>Aerospace</strong></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td><strong>Healthcare</strong></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td><strong>Consumer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Francesca Palumbo, UNISS
# Fields of Application

<table>
<thead>
<tr>
<th>Cognitive CPS</th>
<th>TALKING ABOUT TRENDS and APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michael Masin (IBM, IL) and Paolo Meloni (University of Cagliari, IT)</td>
<td></td>
</tr>
</tbody>
</table>

## The (Smart) Cyber–Physical Revolution: From Theory to Practice

Danilo Pau (ST Microelectronics, IT)

<table>
<thead>
<tr>
<th></th>
<th>Safety</th>
<th>Security</th>
<th>Certif.</th>
<th>Distrib.</th>
<th>HMI</th>
<th>Seamless</th>
<th>MPSoC</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Aerospace</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Healthcare</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Consumer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Francesca Palumbo, UNISSL
# Fields of Application

## Cognitive CPS
Michael Masin (IBM, IL) and Paolo Meloni (University of Cagliari, IT)

How CPS applications in biomedicine came to reality
Ugo della Croce (University of Sassari, IT)

CPS Industrial applications in the CPSwarm Project
Alessandra Bagnato (Softeam, FR)

The (Smart) Cyber–Physical Revolution: From Theory to Practice
Danilo Pau (ST Microelectronics, IT)

### Fields of Application

<table>
<thead>
<tr>
<th></th>
<th>Safety</th>
<th>Security</th>
<th>Certif.</th>
<th>Distrib.</th>
<th>HMI</th>
<th>Seamless</th>
<th>MPSoC</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Aerospace</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Healthcare</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Consumer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Francesca Palumbo, UNISS
Fields of Application

Cognitive CPS
Michael Masin (IBM, IL) and Paolo Meloni (University of Cagliari, IT)
How CPS applications in biomedicine came to reality
Ugo della Croce (University of Sassari, IT)
CPS on Smart–Travelling: the CERBERO use–case
Joost Andriaanse (TNO, NL)
The (Smart) Cyber–Physical Revolution: From Theory to Practice
Danilo Pau (ST Microelectronics, IT)

<table>
<thead>
<tr>
<th></th>
<th>Safety</th>
<th>Security</th>
<th>Certif.</th>
<th>Distrib.</th>
<th>HMI</th>
<th>Seamles</th>
<th>MPSoC</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Aerospace</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Healthcare</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Consumer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Francesca Palumbo, UNISS
ISSUE # 1
Modelling CPS

Separation of concerns, normally adopted to simplify complexity and heterogeneity, leads to miss important cross-domain interactions.

We need to find proper way of modelling CPS.
The Kopetz Principle

Many (predictive) properties that we assert about systems (determinism, timeliness, reliability, safety) are in fact not properties of an implemented system, but rather properties of a model of the system.

We can make definitive statements about models, from which we can infer properties of system realizations. The validity of this inference depends on model fidelity, which is always approximate.

Edward Lee, "Cyber–Physical Systems A Rehash or A New Intellectual Challenge?", DAC 2013
The Synchronous Digital Logic Example
The model has exactly one behavior.

Unambiguously definition of the “correct” behavior of the thing being modeled.
Models are EXTREMELY POWERFUL engineering abstractions
The real problem is that NON DETERMINISM arises as soon as you cross the border.
Why does NON–DETERMINISM arise?

- Lack of temporal semantics;
- The real world is full of uncertainties.
The REAL BEHAVIOUR comes out when you put together the model with the physical realization of the system.

You need to guarantee ROBUSTNESS!
Modelling the dynamics and the interaction among the heterogeneous and diverse view of a CPS is certainly an OPEN ISSUE.

- Dynamic and reactive behaviours have to be guaranteed.

TALKING ABOUT MODELLING AND PROPERTIES

Let’s get Physical: Adding Physical Dimensions to Cyber Systems
Alberto Sangiovanni–Vincentelli (University of Berkeley, US)
Modelling the dynamics and the interaction among the heterogenous and divers view of a CPS is certainly an OPEN ISSUE.

Dynamic and reactive behaviours have to be guaranteed.

Let’s get Physical: Adding Physical Dimensions to Cyber Systems
Alberto Sangiovanni-Vincentelli (University of Berkeley, US)
HW/SW Cyber–System Co–Design and Modelling
Karol Desnos (INSA–Rennes, FR) and Julio De Oliveira Filho (TNO, NL)
Modelling the dynamics and the interaction among the heterogeneous and divers view of a CPS is certainly an OPEN ISSUE.

Dynamic and reactive behaviours have to be guaranteed.

Let’s get Physical: Adding Physical Dimensions to Cyber Systems
Alberto Sangiovanni–Vincentelli (University of Berkeley, US)
HW/SW Cyber–System Co–Design and Modelling
Karol Desnos (INSA–Rennes, FR) and Julio De Oliveira Filho (TNO, NL)
Functional & NF Requirements Analysis
Armando Tacchella (University of Genoa, IT)
ISSUE # 2
Heterogeneity and Flexibility in CPS

CPS are requested to be *reactive* and *dynamic* to adapt, prospectively autonomously,
- to rapid changes in the environment and in the system itself;
- to satisfy multiple concurring and, potentially, competing requirements.
The intrinsic dynamic and reactive nature of CPS requires flexibility.

**GOAL:** multi-layer self-adaptation engine, mastering computing infrastructure reconfigurability.
Self-reconfiguration and adaptation have been acknowledged as key features for CPS operators:

- in mixed-critical environments;
- to handle faults.

Adaptivity Issue

- EFFICIENT SCHEDULING
- TASK MIGRATION
- ADAPTIVE PROCESSING
- COARSE-GRAINED RECONFIGURATION
- FINE-GRAINED RECONFIGURATION

Francesca Palumbo, UNISS
Self-reconfiguration and adaptation have been acknowledged as key features for CPS operators:
- in mixed-critical environments;
- to handle faults.

Robust Heterogeneous Computing for CPS
Muhammad Shafique (TU Wien, AU)
Self-reconfiguration and adaptation have been acknowledged as key features for CPS operators
  ◦ in mixed-critical environments;
  ◦ to handle faults.

Robust Heterogeneous Computing for CPS
Muhammad Shafique (TU Wien, AU)
Self-adaptation of CPS: Flexible HW–SW computing
Eduardo De La Torre (UPM, ES)
Self-reconfiguration and adaptation have been acknowledged as key features for CPS operators

- in mixed-critical environments;
- to handle faults.

Robust Heterogeneous Computing for CPS
Muhammad Shafique (TU Wien, AU)

Self-adaptation of CPS: Flexible HW-SW computing
Eduardo De La Torre (UPM, ES)

Low-Power Computing and Emerging Trends
Muhammad Shafique (TU Wien, AU)

Software and Hardware for High Performance and Low Power
Homogeneous and Heterogeneous Multicore Systems
Hironori Kasahara (Waseda University, JP)
Adaptivity Issue

- Self-reconfiguration and adaptation have been acknowledged as key features for CPS operators
  - in mixed-critical environments;
  - to handle faults.

TALKING ABOUT HETEROGENEITY AND ADAPTIVITY

Robust Heterogeneous Computing for CPS
Muhammad Shafique (TU Wien, AU)

Self-adaptation of CPS: Flexible HW–SW computing
Eduardo De La Torre (UPM, ES)

Low-Power Computing and Emerging Trends
Muhammad Shafique (TU Wien, AU)

Software and Hardware for High Performance and Low Power Homogeneous and Heterogeneous Multicore Systems
Hironori Kasahara (Waseda University, JP)

Securing CPSs, new challenge or solved problem?
Francesco Regazzoni (ALaRI, CH)
ISSUE # 3

Model–based Engineering and Design Tools

Despite their big promise, model–based frameworks are not as popular as it could be expected.

Modeling, maintenance, and interoperability overhead are not addressed in a satisfactory way.
Separate design, implementation and validation phases
  ◦ long time to market
  ◦ complex HW/SW tuning phase

Collection of partially integrated toolchains
# State-of-the-Art Tools

<table>
<thead>
<tr>
<th>Tool</th>
<th>M</th>
<th>O</th>
<th>D</th>
<th>G</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulink/Stateflow</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(<a href="http://www.mathworks.nl/products/simulink">www.mathworks.nl/products/simulink</a>)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modelica/Dymola</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>(<a href="http://www.3ds.com">www.3ds.com</a>)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SysML (<a href="http://www.sysml.org">www.sysml.org</a>)</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARTE (<a href="http://www.omgmarute.org">www.omgmarute.org</a>)</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCADE (<a href="http://www.esterel-technologies.com/products/scade-suite/">www.esterel-technologies.com/products/scade-suite/</a>)</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>gPROMS (<a href="http://www.psenterprise.com/gproms.html">www.psenterprise.com/gproms.html</a>)</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

M=Modelling, O=Optimization, D=Design, G=code Generation, S=Simulation
Go for semantic integration rather than for tools combination!
Do not put tools together! Combine the modelling paradigms.

TALKING ABOUT TOOLS

A Contract-Based Design Methodology for Cyber Physical Systems
Alberto Sangiovanni-Vincentelli (University of Berkley, US)

HW/SW Cyber-System modelling tools
Karol Desnos (INSA-Rennes, FR) and Julio De Oliveira Filho (TNO, NL)

High Level Synthesis methods
Jocelyn Serot (Institut Pascal, FR)

From high-level specification down to hardware
Francesca Palumbo (University of Sassari, IT) and Christian Pilato (ALaRI, CH)

HANDS ON DAY
The CERBERO Project tools
THE RECEPY OF SUCCESS

... be open minded!
Humans tend to project their partial experiences as the whole truth, ignoring other people's partial experiences.
Huge mistake in CPS design
- heterogeneity;
- multi-vendor, multi-physics and multi-modelling;
- wide variety of requirements and constraints.

You need to be willing
- to change your point of view;
- to play with new tools and experimentations;
- to combine several different components and domains together.
Integral Approach ... Funding Programmes!

CPS Summer School
www.cpsschool.eu

CERBERO
www.cerbero-h2020.eu

Francesca Palumbo, UNISS
USEFUL READS

Framework for cyber–physical systems, release 1.0

Metronomy: A function–architecture co–simulation framework for timing verification of cyber–physical systems,
CODES+ISSS 2014

Design tool chain for cyber–physical systems: lessons learned,
J. Sztipanovits, T. Bapty, S. Neema, X. D. Koutsoukos, and E. K. Jackson
DAC, 2015

Modeling Cyber–Physical Systems,
P. Derler, E. A. Lee, and A. L. Sangiovanni–Vincentelli
Proceedings of the IEEE, 2011

Is a Unified Methodology for System–Level Design Possible?,
A. L. Sangiovanni–Vincentelli
IEEE Design & Test of Computers, 2008