Pre-Integrated Architectures for sustainable complex Cyber-Physical Systems

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Abstract: The paradigm of Cyber-Physical Systems is spreading widely across several industrial domains such as Automotive, Construction, Energy, Health, Manufacturing, Smart Cities. But the system architectures, processes and operations related to these Cyber-Physical Systems are reaching a high level of global complexity, which is difficult to sustain by the different stakeholders. In addition, new ambitious constraints are being added to the list of requirements that these Cyber-Physical Systems must comply with.
The purpose of this paper is to propose the concept of pre-integrated architectures as solutions to improve the development and operational processes of these complex Cyber-Physical Systems. An outlook of the practical implementations and impacts in four industrial domains will be provided, in relationship with the developments performed in the CPS4EU project.

Keywords: Cyber-Physical Systems; System Architecture; CPS4EU Project; Computing; Connectivity; Sensors; Industry Automation; Energy Distribution.

1. Introduction

As mentioned in the Multi-Annual Strategic Plan of the ECSEL Joint Undertaking [1], “the potential of the upcoming industrial era 4.0 is based on the combination of two novel technologies, Cyber-Physical Systems (CPS) and the Internet of Things”.

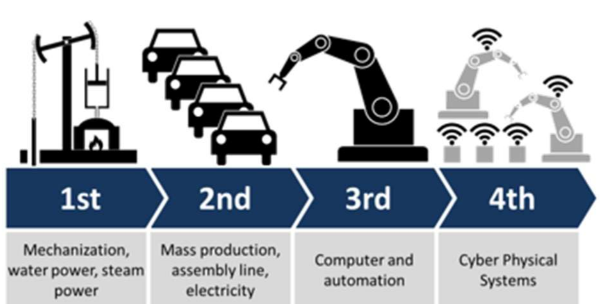

Figure 1: Industry 4^{th} revolution [4]

Beyond the abstract CPS model shown in Figure 2, their applications cover a wide range of industrial domains, as well as covering the complete life cycle, from the early stage or development until product validation, production and decommissioning.

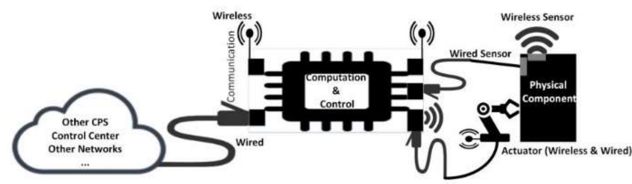

Figure 2: CPS abstract model [2]

Even if the concept of cyber-physical systems is not recent, the emergence and deployment of technologies such as Artificial Intelligence, Wireless Connectivity, Edge Computing, Big Data, Cloud Computing and Robotics are broadening the dimensions of the ecosystem necessary to manage the CPS projects and their related operations [3].

In that sense, CPS are transforming the tasks and responsibilities to develop the new products and perform their manufacturing operations in the most efficient way. The complexity related to the execution of these processes is such that the limits of current business models are reached.

As explained in the paper published by McKinsey [5] about the evolution of software development efforts in the Automotive industry, and illustrated in Figure 3, the gap between the development needs and the capabilities is widening. This situation is not sustainable and will lead to shifts, joint developments or standardized architectures so that sustainable business models can become compatible with the end user expectations.

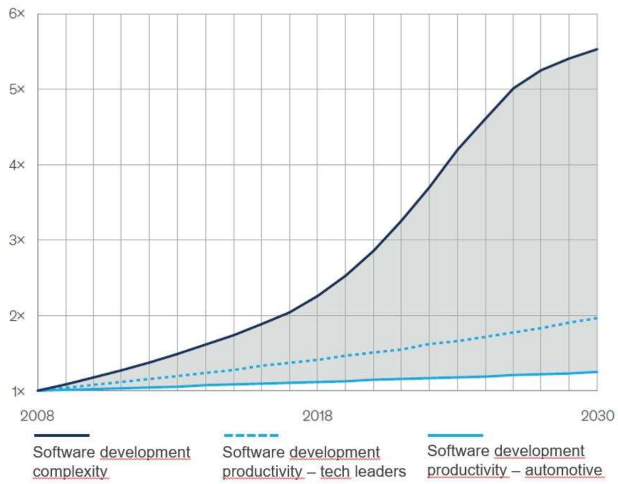

Figure 3: Gap between software complexity and productivity levels (from McKinsey)

Another factor influencing the development of complex CPS is the substantial increase of functional or non-functional constraints coming from industry standards, business reasons or societal expectations. Among these additional constraints, we can mention:

- Functional safety
- Cybersecurity
- Privacy and Ethics
- IP rights, Export rules
- Liability, Traceability
- CO2 neutrality, minimal usage of natural resources

All these new constraints will be gradually embedded in the products and processes involving the CPS towards Trustworthy-oriented Architectures. They will require very specific competences and increase development complexity, widening the complexity to productivity gap shown above if no corrective trend is proposed to the CPS stakeholders.

In line with the previous statements, the main objective of the CPS4EU project is to propose Pre-Integrated Architectures (PIARCH). Our target with the PIARCH concept is to reduce the R&D effort needed to design and produce complex CPS with Trustworthy-oriented Architectures.

Another ambition of the project is to decrease the learning curve for the development of new complex CPS. A global 360° view of the necessary workflows will be provided, as well as pre-validated instances of the PIARCH covering all the CPS layers, ie Physical, Cyber and Internet of CPS.

The generic developments in the project will lead to practical prototypes and demonstrators in four industrial domains: Automotive, Energy, Industry Automation, and applications from SME partners.

Figure 4: CPS4EU visual identity

To provide more details and illustrate the developments planned in the CPS4EU project and its Pre-Integrated Architectures, this paper is organized with the following sections:

- Section 2: Pre-Integrated Architectures
- Section 3: Descriptions of Pre-Integrated Architectures in the CPS4EU Project
- Section 4: Practical Implementations in Cyber-Physical Systems
- Section 5: Conclusions

2. Pre-Integrated Architectures

Related Work

Similar Concepts have been proposed in several collaborative projects. The AXIOM project [19] proposed a computing platform composed of ARM Cores and an FPGA based on the Xilinx Zinq. Sensors and connectivity devices were plugged through Arduino Shields. The SAFECOP project [20] provided a Safety Insurance framework and an architecture to monitor the Safety of cooperative systems. Another approach related to Cybersecurity measures was defined in the SEC4CPS project [21]. A synthesis of potential cyber attacks on all the CPS layers was defined in this project. Machine Learning Algorithms were implemented to supervise potential attacks or abnormal behaviours. And the use of design patterns in CPS has already been presented [11], but our objectives go beyond those mentioned,

PIARCH Formalism

At the beginning of the CPS4EU project, a strong need to share common views and terminologies related to CPS occurred across the project partners. In order to reach this common language without excessive technical hurdles, the formalism from the document published by NIST [6] was adopted, as illustrated in Figure 5:

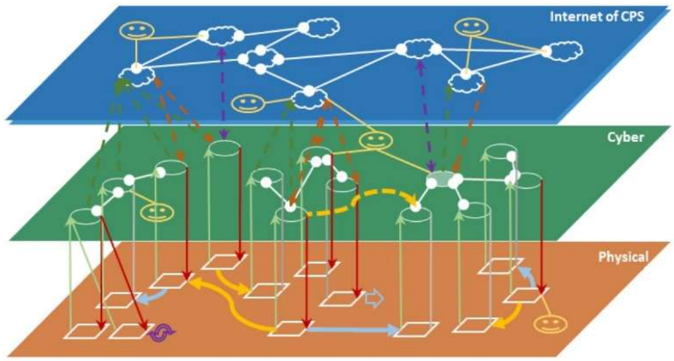

Figure 5: A CPS view, Systems of Systems (from NIST)

Very early in the project, the partners formulated the vision that the hurdles inherent to complex CPS developments could be broken through pre-integration of components in PIARCHs. The structural complexity [9] of CPS using PIARCHs would decrease, and the duration of the development process would also be reduced, as shown below:

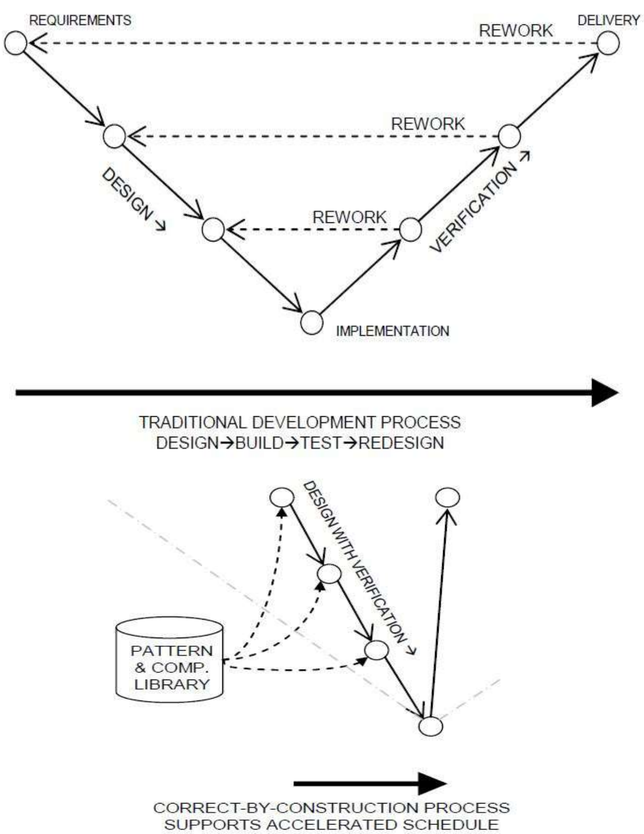

Figure 6: Impact of correct-by-construction development process [10]

Beyond the existing ideas of modularity or product portfolio or platforms [7], the main expectations formulated by the project partners concerning the Pre-Integrated Architectures were the following:

- Address the development and integration issues in the three CPS layers: Physical, Cyber and Internet of CPS
- Provide scalability, efficiency and savings in the development effort vs traditional methodologies
- Remain compatible with legacy components, processes and tools
- Ensure inter-operability with other components or tools thanks to standardized interfaces
- Contain the necessary pre-validated concepts or standard procedures to allow the homologation as Trustworthy-oriented architectures
- Provide the flexibility to be configurable according to the developers needs within the pre-validated perimeter
- Include the possibility to be extended with additional features when new technologies or new expectations arise.

To reach these objectives, the project partners shared the idea of extending the Design Pattern concept [8] to CPS to describe these Pre-Integrated Architectures (PIARCHs).

The PIARCH concept proposed sits between components and systems. A PIARCH integrates components, and allows the exploration of a set of possible instances or products, with components variations and market adaptations. It targets multiple levels of detail, from high-level views to physical boards. As a reuse-oriented concept, it aims at mutualizing work between similar but different products, while being aware of the too general to be useful trap of reusable components. Emergence is one of the approach used: existing practices among the project partners are considered for the definitions of PIARCHs.

PIARCHS are validated in the CPS4EU project, as a focal point between the project components and the use cases from the project partners.

Later in the project, the formalism attached to the PIARCHs will allow to provide better estimations about the total effort needed to develop new projects, manufacture new products or provide new digital services using CPS. To provide these estimations, the authors plan to use the methodologies defined in reference [9] related to the evaluation of the structural complexity of a system described by its architecture.

The construction of the PIARCHs developed in the CPS4EU project through its Components and Tools will be detailed in the next section.

3. Descriptions of Pre-Integrated Architectures in the CPS4EU Project

In order to implement the objectives assigned to the CPS4EU project, the partners are organized in a networked ecosystem, with four main categories of responsibilities:

- Component providers, mainly from SMEs
- Tool providers, mainly from the Academic sector
- Pre-Integrated Architecture assemblers
- Use case developers, mainly from Large Enterprises with operations in the fields of Automotive, Energy, Industry Automation, and from the SME sector.

To cover the the industrial domains involved in the project, five PIARCHs are developped following the needs expressed by the use case developers.
The Heterogeneous Computing PIARCH addresses the integration of different types of computing capabilities into a system, notably Neural Network accelerators with optimized power consumption [12].
The Secure-to-X PIARCH covers the development of the connectivity part of a CPS, with the flexibility of various connectivity options such as Ethernet, NarrowBand-IoT, Bluetooth, WiFi, 4G. System development is pre-defined thanks to simulation models and physical boards (Figure 7). This PIARCH also includes a secure gateway and a trusted execution environment as cybersecurity features.

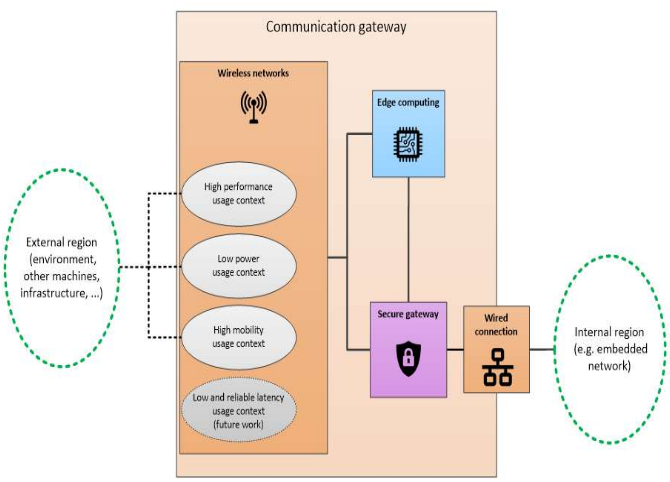

Figure 7: Secure CPS-to-X Connectivity PIARCH [13]

The cooperative system PIARCH pre-integrates the various layers and components necessary for a large scale, connected set of devices [15]. It describes how local and global decisions and data processing can be distributed over a connected system, between the local and global levels.

The industrial edge computing PIARCH covers the definition of a compact, computing capable device at the Edge and its integration in system wide development tools (Figure 8). It includes also the connectivity means necessary for the data transfer with the enterprise IT networks: 4G, Zigbee, Serial communication, Bluetooth, Ethernet, Wi-Fi, RFID, Modbus, and CAN.

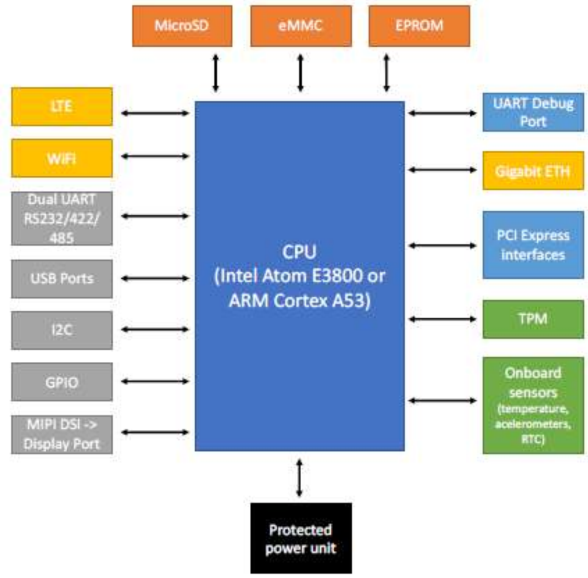

Figure 8: Industrial Edge Computing Gateway PIARCH [16]

Finally, the Sensing PIARCH targets the pre-integration of various sensor types (cameras, LIDARs, GNSS). The software stack involving DNN algorithms and sensor fusion for robust vehicle localization and detection of surrounding objects is also provided with the PIARCH [14].

Several implementations of these Pre-Integrated Architectures will be described in the next section.

4. Practical Implementations of Pre-Integrated Architectures in Cyber-Physical Systems

CPS4EU is a project managed by the ECSEL Joint Undertaking, involving 36 partners from 5 European Countries. The project eco-system includes equal representations of Large Entities, Academics and Small and Medium Enterprises. The project started in July 2019, and its duration is planned for 36 months.

The CPS4EU partners have committed to deliver 16 use cases. The use cases correspond to industrial applications targeted for commercial exploitation in 3 to 5 years from the start of the project. The CPS performing the use case objectives will use a combination of PIARCH instantiations developed during the project, with legacy components or sub-systems provided by the partners, or other commercial products.

These use cases cover new products or applications, with high potential benefits, but with also significant system structural complexity. The use case teams will provide demonstrators up to TRL6-7 in the fields of Automotive, Energy, Industry automation, and for other SME applications.

Illustrations of several use cases are provided below:

Figure 9: Valeo use cases in CPS4EU – Urban Automated Driving

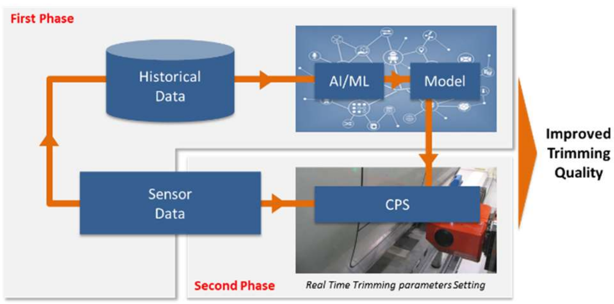

Figure 10: Leonardo use case in CPS4EU - Improved Trimming Quality [17]

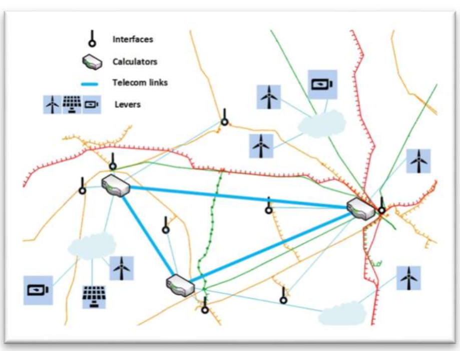

Figure 11: RTE use case in CPS4EU - Distributed controls for Energy transmission network [18]

During the use case implementation phase, it is already clear to the developers that the PIARCHs facilitate the integration of new technologies like Secure Connectivity or Laser Scanners, and new processes related to AI or Machine Learning in their future products or services. This improvement benefits to the use case developers coming from both Large Enterprises and from SMEs.

In a symmetrical manner, this new way of working creates entry points for SMEs and Academics to provide their components and tools to the PIARCH integrators. This aspect provides them with broader perspectives to supply their specialized tools or high-performance components to a wider customer base, beyond their traditional domain of activity.

All the project partners involved in these use case implementations recognize the need to have a better management and a higher interoperability of all the tools needed for the different developments or operation phases. This question has been reviewed and will be discussed in a following publication related to CPS4EU.

Finally, the methodologies, workflows and lessons learned during these practical implementations and their future exploitations will be synthesized in the next public deliverables published by the CPS4EU project.

5. Conclusions

In this paper, we have proposed the introduction of Pre-Integrated Architectures (PIARCHs) for complex Cyber-Physical Systems (CPS) as solutions adapted to the industrial developments and operations in a networked ecosystem. Our proposals are applicable to a wide variety of industrial applications, for Large Enterprises and for SMEs, with the support from Academic and Research Organizations.

With the practical implementations of this new framework, we plan to restore a sustainable way to develop these complex CPS with an ever-increasing level of functional performances and non-functional requirements, expected by the end-users and needed by the societal changes.

The developments illustrated in this paper represent a work in progress and will lead to other publications on topics such as: a classification and usage of the tools to develop CPS, PIARCH composability, and a formalization of a PIARCH solution space. A publication is also being prepared with another European collaborative project on the evaluation of project complexity in the field of Cyber-Physical Systems.

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Glossary

AI: Artificial Intelligence

CPS: Cyber Physical Systems

CPS4EU: European collaborative project supporting this study

DNN: Deep Neural Networks

GNSS: Global Navigation Satellite System

IT: Information Technology

ML: Machine Learning

PIARCH: Pre-Integrated Architecture

R&D: Research and Development

SaaS: Software as a Service

SME: Small and Medium Enterprises

TRL: Technology Readiness Level