Core Technology: Cyber Physical Systems

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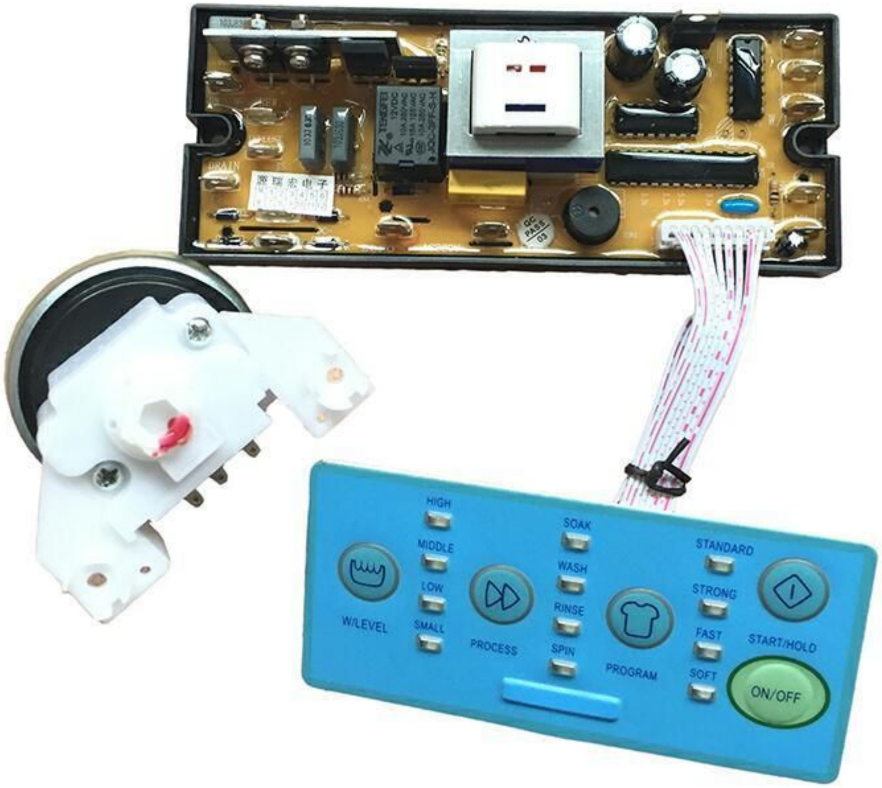
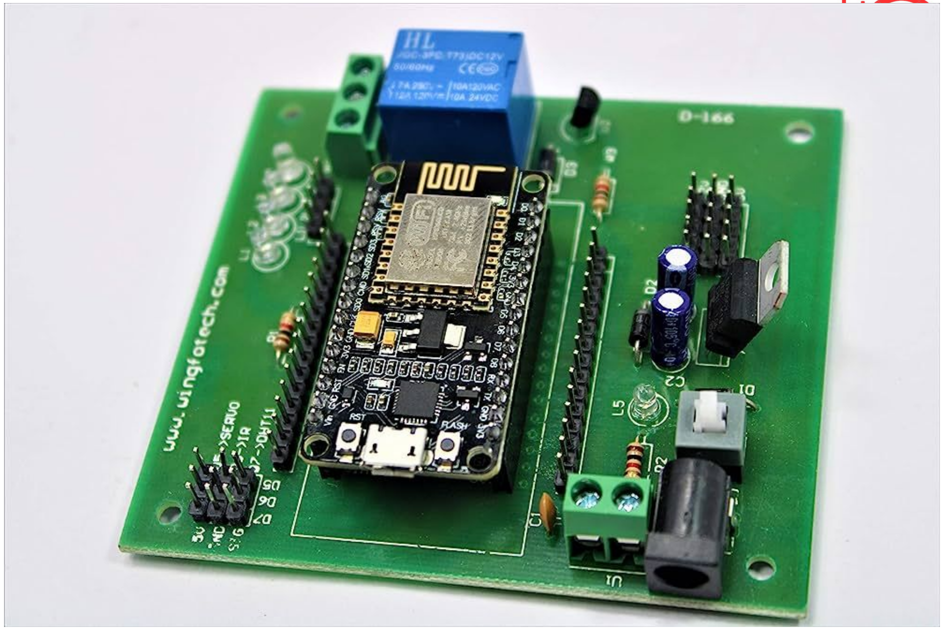
Embedded Systems

- Information systems, which are embedded into physical devices, are called“embedded systems”.
- These embedded systems are found in telecommunication, automation, and transport systems, among many others.
- Lately, a new term has surfaced, the cyber-physical systems (CPS).
- This distinguishes between microprocessor based embedded systems and more complex information processing systems that actually integrate with their environment.
- A precise definition of cyber-physical systems (CPS) is that they are integrations of computation, networking, and physical processes.
- Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa.





Some embedded systems

A Cyber-Physical System (CPS)

- A Cyber-Physical System (CPS) is a system that integrates physical and computational components to monitor and control the physical processes seamlessly.
- In other words, A cyber-physical system is a collection of computing devices communicating with one another and interacting with the physical world via sensors and actuators in a feedback loop.
- These systems combine the sensing, actuation, computation, and communication capabilities, and leverage these to improve the physical systems' overall performance, safety, and reliability.

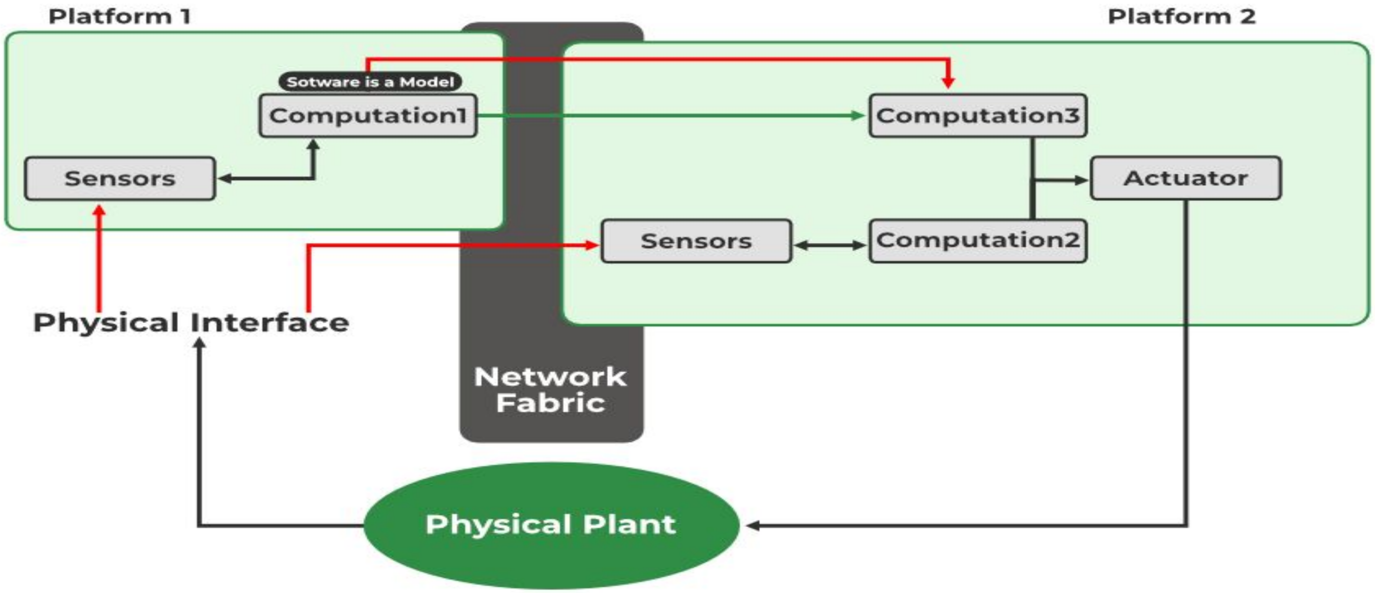
Characteristics

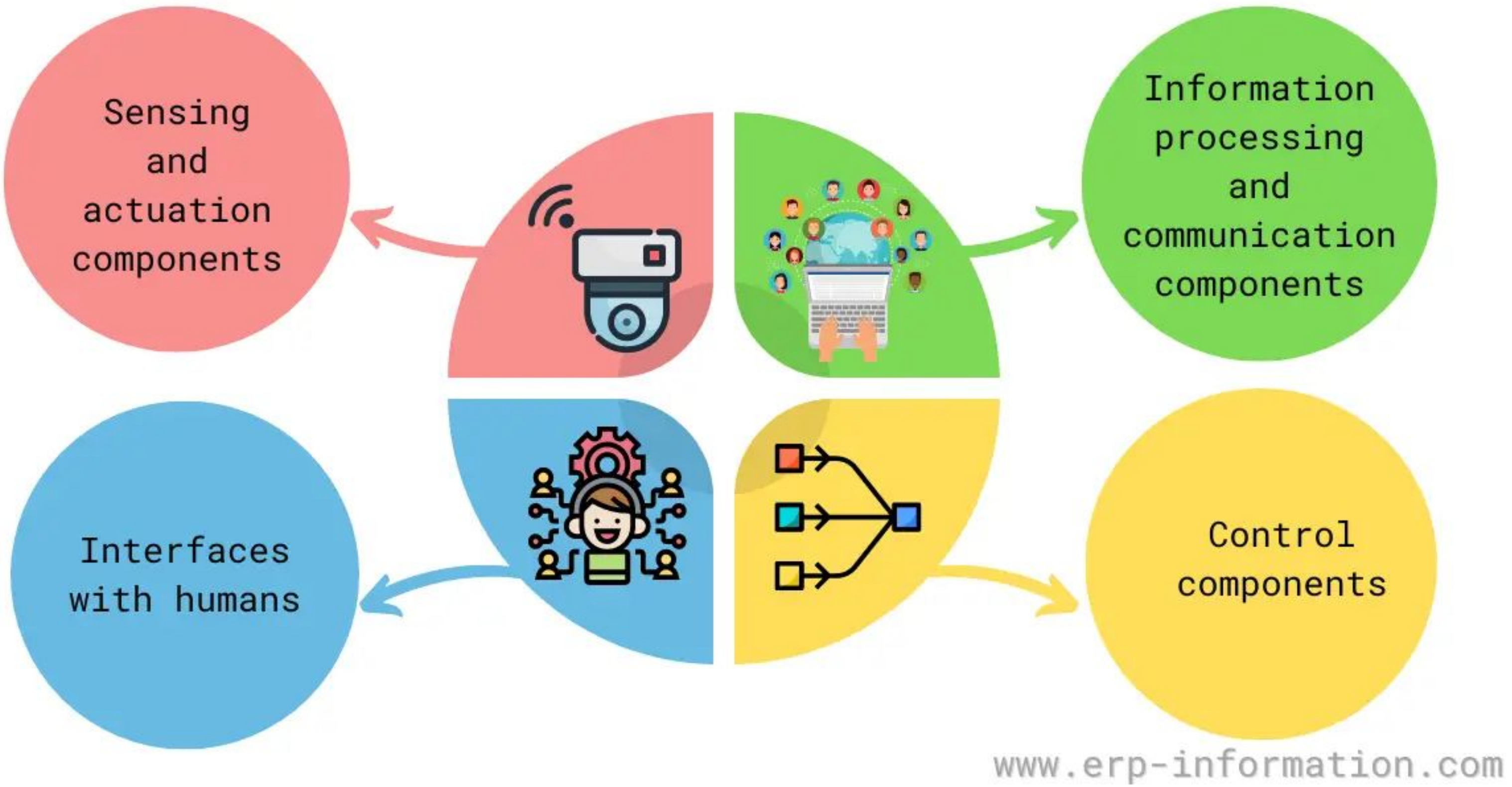
- It is a combination of Physics with cyber Components networked which is interconnected.
- CPS systems are to monitor and control physical processes in a seamless manner.
- In CPS systems sensors and Actuators work in the feedback loop.
- In CPS systems devices are designed to interact with physical processes and control them.
- The CPS systems are more complex compared then IoT devices.

Features of Cyber-Physical System

- in terms of the cyber-physical system, there are some features that are classified.
- **Reactive Computation:** Reactive systems, on the other hand, continuously interact with the environment through inputs and outputs. As a classic example of reactive computation, consider a car cruise control program.
- **Network Connectivity:** CPS systems must utilize the network connectivity basis of communication between the cyber and physical world.
- **Robustness & Reliability:** In order to ensure safe and effective operation in dynamic environments, CPS must need efficient reliability.
- **Concurrency:** In cyber-physical systems refers to the simultaneous execution of multiple tasks or processes in a coordinated manner.
- **Real-Time Computation:** CPS systems have real-time computation capabilities that allow for dynamic decision-making based on physical real-world data.
- **Safety-Critical Application:** In terms of the CPS applications where the safety of our systems higher priority over the performance and development of the system.

Block diagram of CPS



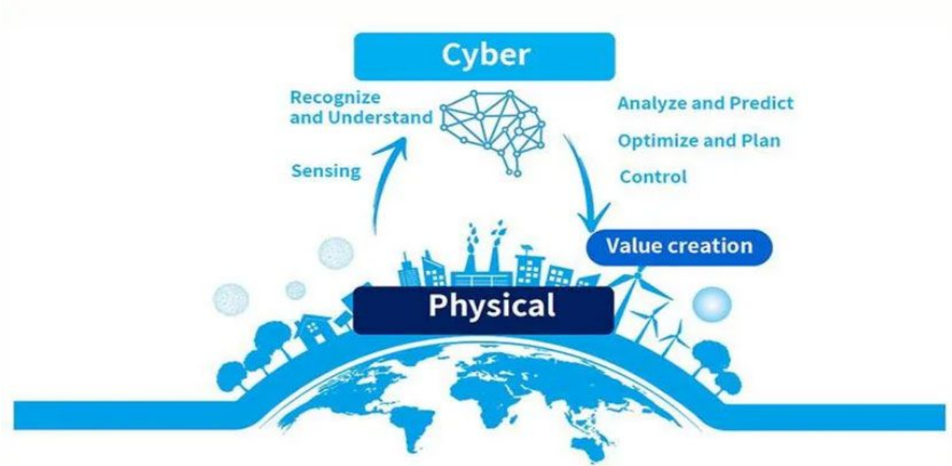


Cyber Physical Systems

Cyber Physical Systems (CPS)

A cyber-physical system can be just about anything that has integrated computation, networking, and physical processes. A human operator is a cyber-physical system and so is a smart factory.

- https://www.youtube.com/watch?v=VhtFv6TtWBo



Source: Toshiba

CPS

- Cyber-physical systems enable the virtual digital world of computers and software to merge through interaction—process management and feedback control—with the physical analogue world, thus leading to an Internet of Things, data, and services.
- One example of CPS is an intelligent manufacturing line, where the machine can perform many work processes by communicating with the components and sometimes even the products they are in the process of making.
- An embedded system is a computational system embedded within a physical system; the emphasis is on the computational component. Therefore, we can think of all CPS as containing embedded systems, but the CPS's emphasis is on the communications and physical as well as the computational domains.

CPS

- Cyber Physical Systems (CPS) are automated systems that enable connection of the operations of the physical reality with computing and communication infrastructures.
- Unlike traditional embedded systems, which are designed as stand-alone devices, the focus in CPS is on networking several devices .
- CPS goes with the trend of having information and services everywhere at hand, and it is inevitable in the highly networked world of today.
- A CPS consists of a control unit, usually one or more microcontroller(s), which control(s) the sensors and actuators that are necessary to interact with the real world, and processes the data obtained.

- These embedded systems also require a communication interface to exchange data with other embedded systems or a cloud.
- The data exchange is the most important feature of a CPS, since the data can be linked and evaluated centrally, for instance. In other words, a CPS is an embedded system that is able to send and receive data over a network.
- The CPS connected to the Internet is often referred to as the "Internet of things".

Critical CPS with embedded processes for Industry 4.0

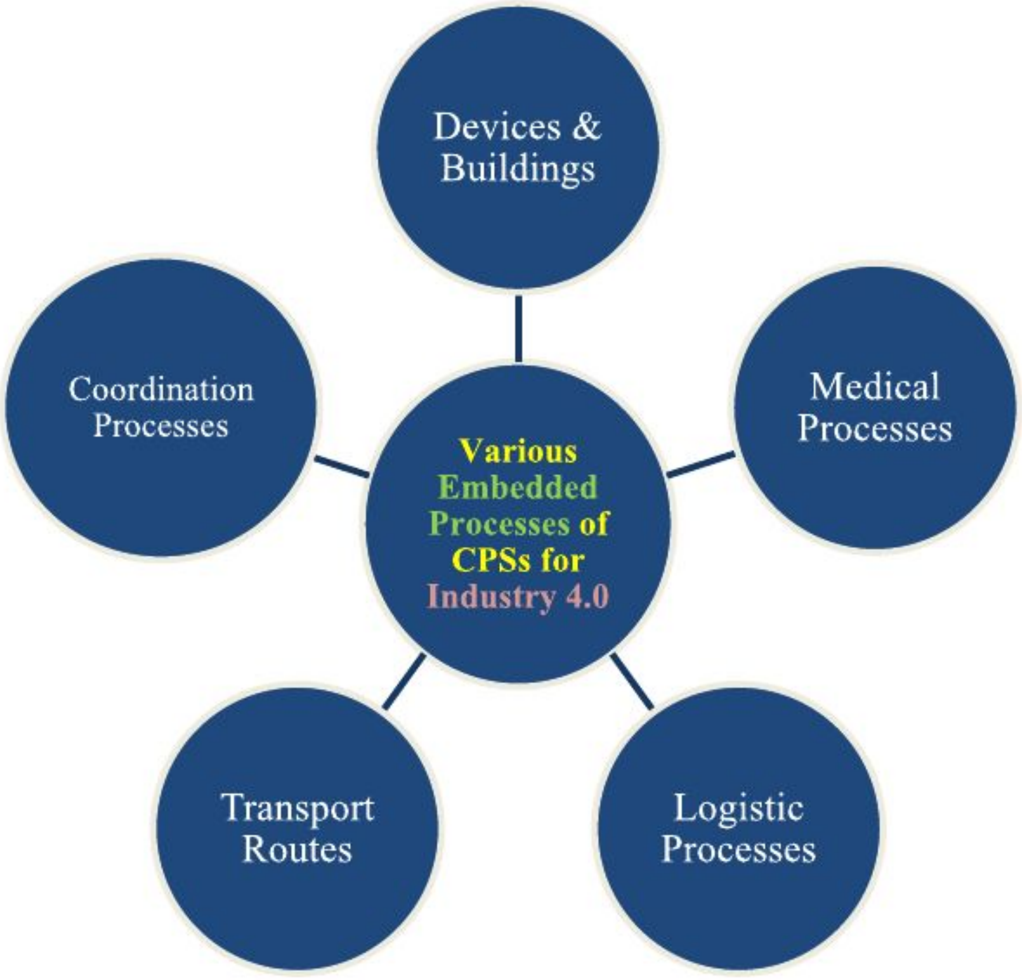


Fig. 1. Typical CPS with Embedded Processes for Industry 4.0.

IMPLEMENTATION OF CPS WITH INDUSTRY 4.0

- An interface to the Internet or a similar network is necessary to extend an embedded system, which is usually made of control units, sensors and actuators, to a CPS.
- In order to achieve this, there are various approaches that have been investigated in the context of this development and will be briefly presented below:

- **Direct system extension**
- **System expansion by microcontroller board**
- **Extension by smart actuators and sensors**

Direct system extension

- In this individualized solution variant, the embedded system, if not available yet, is extended by a communication interface to access the Internet and the software is changed accordingly to enable communication over the internet, e.g. with the cloud.
- To this end, all the sensor signals of the system must be transmitted by the control unit to the cloud.
- Methods should be implemented to control the actuators via Internet.
- Figure 1 shows the arrangement of this solution variant.

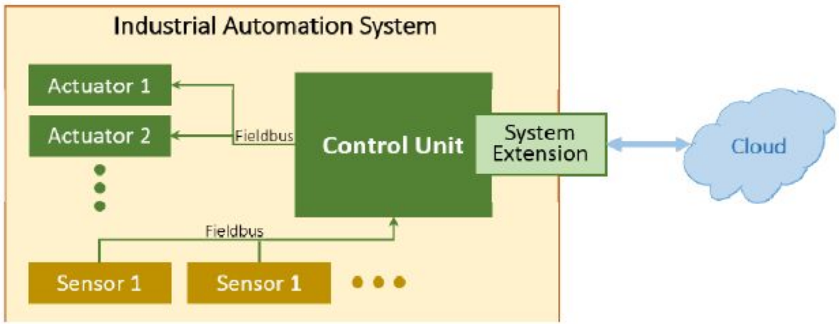


Fig. 1. Direct system control

System expansion by microcontroller board:

- In this solution variant, a microcontroller board that has the various communication interfaces such as CAN, UART, WLAN, Ethernet, etc. is developed.
- This is connected to the embedded system and takes over the communication to the Internet or a cloud. However, this requires uniform interfaces, over which the board can be connected to the embedded system.
- The software of the board must be adjusted separately to each system.
- However, the entire code need not to be rewritten every time, but only the mapping is to be reworked accordingly so that it is relatively easy to transfer this variant to other systems.
- This arrangement is demonstrated by the following figure:

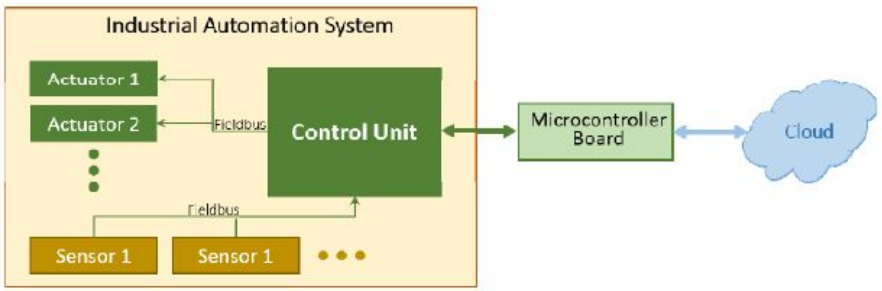


Fig. 2. System extension by microcontroller board

Extension by smart actuators and sensors:

- Traditional embedded systems usually consist of a control unit, several sensors and actuators, which are connected to the control unit via field buses.
- The control unit assumes the signal processing function in such systems.
- Should smart sensors and actuators be used now, the sensors take over even the processing of the signal and the actuators independently check their current status, and correct it, if necessary.
- These sensors transmit their data to a central control unit, e.g. via field buses.
- In order to extend such a system to a CPS, it would be conceivable to also send data from the sensors and actuators, which are sent via the fieldbus, to a cloud, and process it there.
- However, a high data volume is the result here and the cost of smart sensors and actuators must not be underestimated. Figure 3 shows the extension.

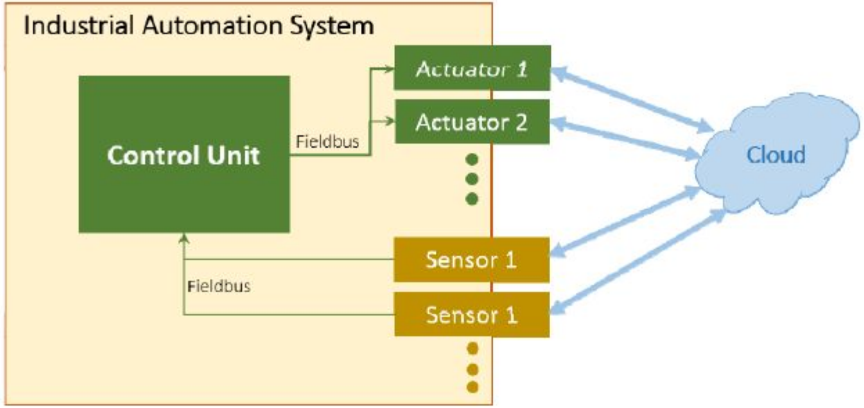


Fig. 3. Usage of intelligent actuators and sensors

CPS reference architecture models

- Notable initiatives include Platform Industry 4.0, promoting digital transformation in German manufacturing, and the Industrial Internet Consortium (IIC), aimed at accelerating the growth of the industrial internet through collaboration with industry executives.
- Here we discuss three main CPS reference architecture models:
    - 5C Architecture,
    - RAMI 4.0
    - IIRA.

Overview of 5C

- The 5C Architecture is a proposal based on automation processes models, centered on data acquisition for industrial devices, with 5 levels for system operation.
- The 5C Architecture provides an implementation guide for CPS ecosystems, but some basic characteristics were not considered for its application in the I4.0 scenario.
- It is necessary to consider information flow both vertically and horizontally between products and machines, processing them according to client specifications.
- Connectivity among clients and service providers in the industry (distinct industries) is essential for I4.0 services to be connected to the Internet along with controllers, machines, products, and other objects.

5C Architecture

- Services like stock management, load transport requests, and purchases can be automated through factory virtualization, leading to the Internet of Services (IoS), a key pillar of I4.0.
- Other reference models like RAMI 4.0 and IIRA were created to meet the needs of the current scenario and provide I4.0 standardization.

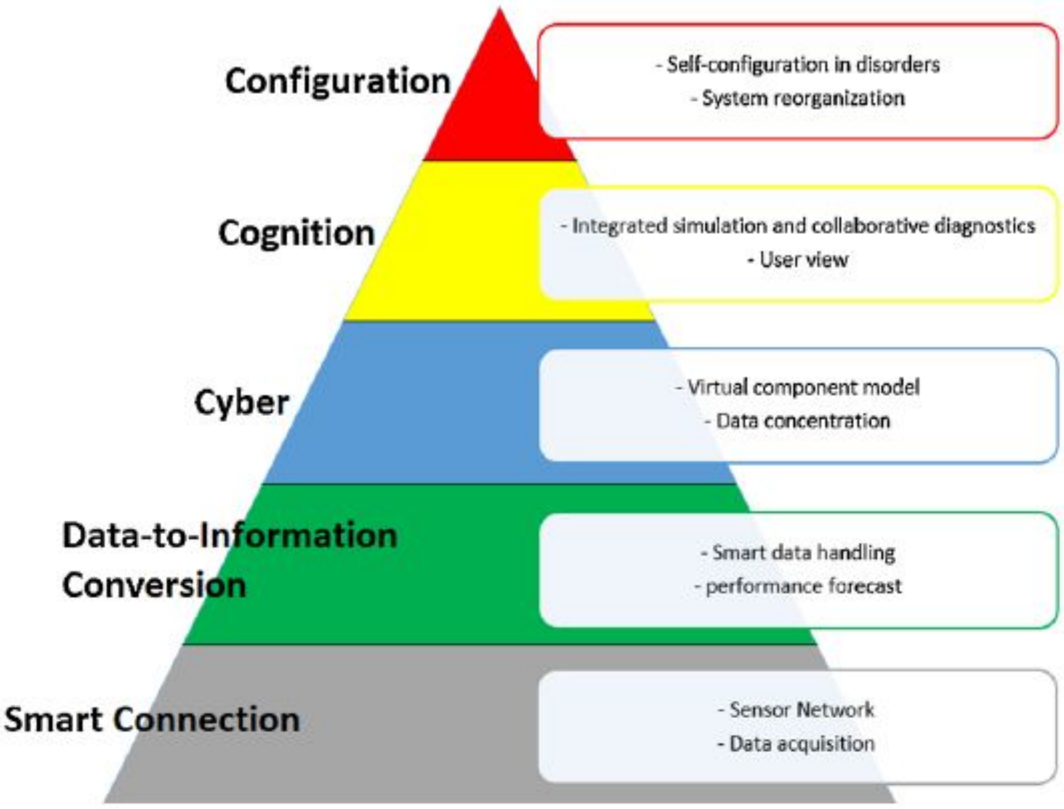


Fig. 2. 5C Architecture of CPS. Adapted from [83].

Overview of the 5C architecture levels.

5C level	Description
Smart Connection	Integration of the physical devices connected in a communication network.
Data-to-Information Conversion	Conversion from monitored device data to information, in order to understand them and apply to the physical world.
Cybernetic	Use of information for the device virtualization. It is also the level responsible for the communication among assets.
Cognition	Functions of monitoring and prognostics for failure prediction and maintenance optimization.
Configuration	Transmission from the virtual to the physical world, making the machines self-adjusting and self-adaptive.

Overview of RAMI 4.0

- RAMI 4.0, Reference Architecture Model Industry 4.0 (Industry 4.0), was developed by the German Electrical and Electronic Manufacturers' Association (ZVEI) to support Industry 4.0 initiatives
- RAMI 4.0 is an Architecture Reference Model for Industry 4.0, created by Platform Industrie 4.0, to define communication structures and a common language within the factory, enabling integration of IoT and services in the I4.0 context.
- It breaks down complex processes into packages, making them easily understandable and including, by design, data privacy & IT security. It addresses and answers all the problems about semantics, identification, functions, communication standards, internationalization, and partnering for the smart factory. RAMI 4.0, is a three-dimensional map showing how to approach the issue of an Industry 4.0 in a systematic and structured way.
- RAMI 4.0 is a Service Oriented Architecture (SOA) that combines IT components to promote horizontal and vertical integration within a factory, connecting products and the Cloud.
- RAMI 4.0 is represented by a three-dimensional map with three axes: Hierarchy Levels, Product Life-cycle, and Architecture Layers.

- I4.0C includes an asset and an Administration Shell (AS) containing relevant information for asset management, representing the physical and digital aspects of a machine, equipment, or product.
- AS serves as a standardized interface for communication networks, connecting physical entities to Industry 4.0.
- All Administration Shells (digital twins) are managed by a Superior System Administration Shell (SAS), facilitating intercommunication between them.

RAMI 4.0

- Axis 1 (Hierarchy Levels) focuses on flexible machines and systems, distributed functions, and improved communication among all involved participants, treating products as part of the architecture. This layer contains below sub-layers like Product, Field, device, Control device, Station, Work centres, Enterprise and Connected world.
- Axis 2 (Product Life-cycle) describes assets from idea to production, usage, and maintenance, representing objects with value for an organization, such as devices or equipment.This layer enables the development of Industry 4.0 software solutions in a consistent way so that different and mutually dependent manufacturing operations are interconnected taking into account the physical and the digital world.
- Axis 3 (CPS Proposal) encompasses the Architecture Layers and focuses on Industry 4.0 Components (I4.0C), globally and uniquely identifiable objects with communication capacity. This layer contains below sub-layer like Product, Field, device, Control device, Station, Work centres, Enterprise and Connected world.

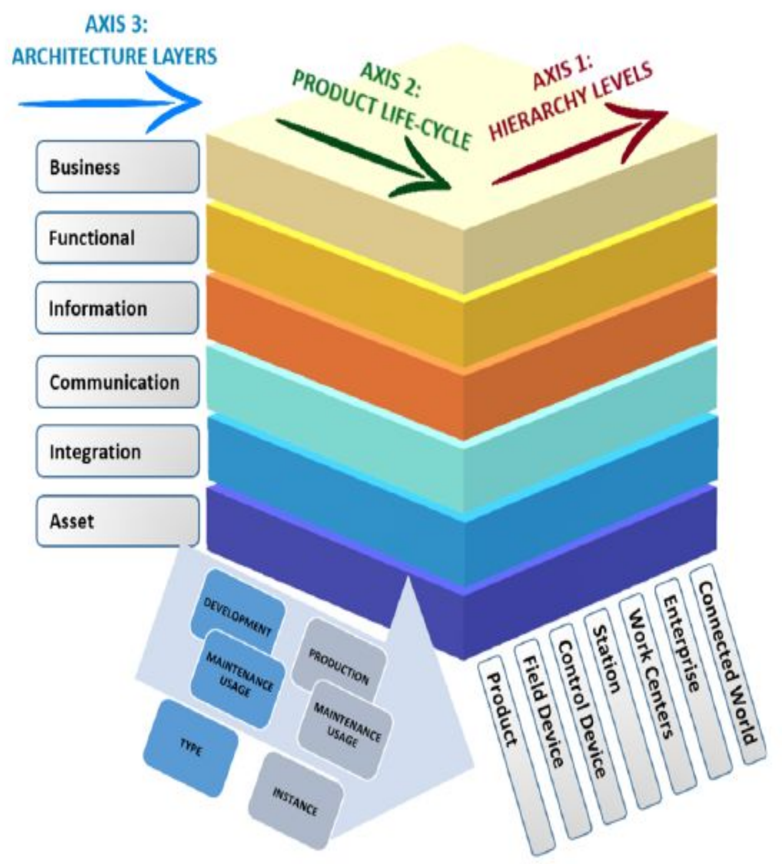


Fig. 3. Three-dimensional model of the RAMI 4.0. Adapted from [89].

Overview of the Architecture Layer of the RAMI 4.0.

Architecture Layers	Description
Asset	Representation of physical things in the real world. These things can be components, hardware, documents and human workers.
Integration	Transition from the physical to the virtual world. It represents the visible assets and their digital capacities, consequently providing control via computers, making it possible to generate events for themselves.
Communication	Standardized communication from services and events or data to the Information Layer, and from services and control commands to the Integration Layer. It focuses on transmission mechanisms, networks discovery and the connection among them.
Information	Description of services and data that can be offered, used, generated or modified by the technical functionality of the asset.
Functional	Description of the logical functions of an asset, such as its technical functionality, in the context of I4.0.
Business	Organization of the services to create business processes and links among different ones, supporting business models under legal and regulatory constraints.

Overview of IIRA

- IIRA (Industrial Internet Reference Architecture) is an open architecture developed by IIC (Industrial Internet Consortium) based on IIoT standards, emphasizing interoperability among industries.
- IIRA is organized into four Viewpoints: Business Viewpoint, Usage Viewpoint, Implementation Viewpoint, and Functional Viewpoint.
- The Business Viewpoint identifies participants and their business views, values, and objectives in IIoT systems.
- The Usage Viewpoint describes the IIoT system's expectations to provide the intended business objectives.
- The Implementation Viewpoint identifies the technologies required to implement the functional components, their communication schemes, and life-cycle procedures.

Overview of IIRA

- The Functional Viewpoint focuses on the functional components, their inter-relation, interaction with external elements, and is divided into five domains: control, operation, information, application, and business.
- The Functional Viewpoint also includes Crosscutting Functions that enable the main system functions and System Characteristics, which are properties or emergent behaviors of the IIRA system.
- Among the Crosscutting Functions, the Connectivity function is responsible for connecting the system functions and ensuring their interaction for complete functionality

IIRA

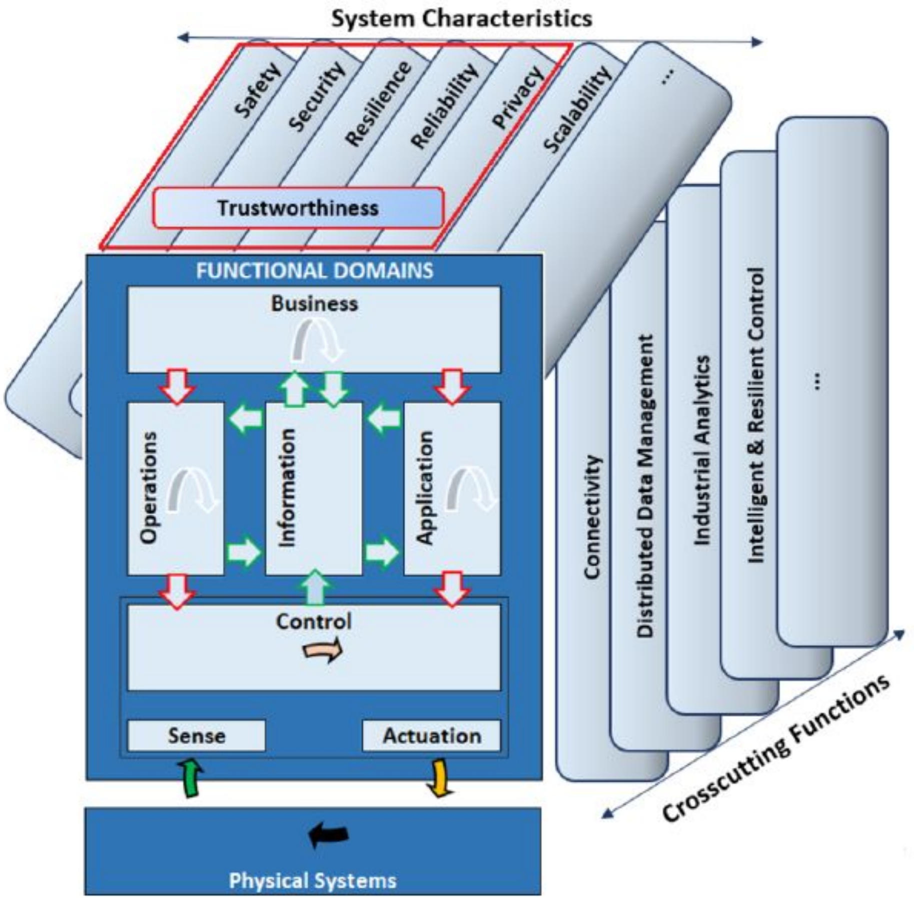


Fig. 4. IIRA functional domains, crosscutting functions and system characteristics. Adapted from [82].

Overview of the domains of the IIRA.

IIRA domains	Description
Control	Functions for industrial control systems, such as: the sensor data reading and writing; communication among sensors, actuators, controllers, gateways and other devices; abstraction of the devices through the representation of a virtual entity; interpretation of data collected by sensors and other devices; operation management of control systems, such as configuration and firmware/software updates; and the execution of control logic for the understanding of the states, conditions and system's behavior.
Operation	Functions for prognostics, management, optimization and monitoring of the systems in the Control Domain, such as: configuring, recording and tracking assets; management commands transmission; detection and prediction of problem occurrences through real-time monitoring of assets; predictive analysis of IIoT systems based on historical data operating and performance; reduction of the energy consumption for the system optimization.
Information	Functions for domain's data collection, and then the data transformation, modeling and analyzing to acquire high-level system-awareness. It includes a set of functions responsible for data collection of operation and sensor states in all domains; and a set of functions for data modeling and analytics.
Application	Functions capable of implementing application logic while performing specific business functionalities. This domain applies: a set of rules with specific functionalities required in considered use cases; and a set of functions whose application can expose their functionalities to other applications that consume them; or user interfaces for human interactions.
Business	End-to-end operation of IIoT systems, integrating them with specific business functions of traditional or new system types.

Correlation among 5C Architecture, RAMI 4.0 and IIRA

- The mentioned architecture reference models (5C Architecture, RAMI 4.0, and IIRA) have CPS concepts but target different goals.
- The 5C Architecture focuses on assets data acquisition and processing, commonly used in embedded systems and small industrial environments.
- RAMI 4.0, based on *The Smart Grid Architecture Model* (SGAM), adapts CPS architecture for the I4.0 scenario, emphasizing manufacturing plant operation and integrating the value chain of the company.
- IIRA, based on ISO/IEC/IEEE 42010, is centered on IIoT systems concerns in all sectors, emphasizing interoperability among industries.

- There are similarities and functional mappings among the architectures, and there is correlation and interoperability among the reference models.
- RAMI 4.0 and IIRA are more discussed in the industrial community, focused on I4.0 proposals, application, services, and business ideas for integration among industries and the manufacturing sector.
- To ensure interoperability between RAMI 4.0 and IIRA, concepts like standardized functions, semantics, and unique identifiers are required.
- Identification, networking, semantics, and functional mapping are fundamental concepts for interoperability between IIoT and Industry 4.0 systems.
- Standardization of parameters allows the recognition of the same product and its respective data in both RAMI 4.0 and IIRA architectures, enabling correct interoperability.

Case Study

PROTOTYPICAL IMPLEMENTATION OF AN INDUSTRY 4.0 APPLICATION FOR AN INDUSTRIAL COFFEE MACHINE

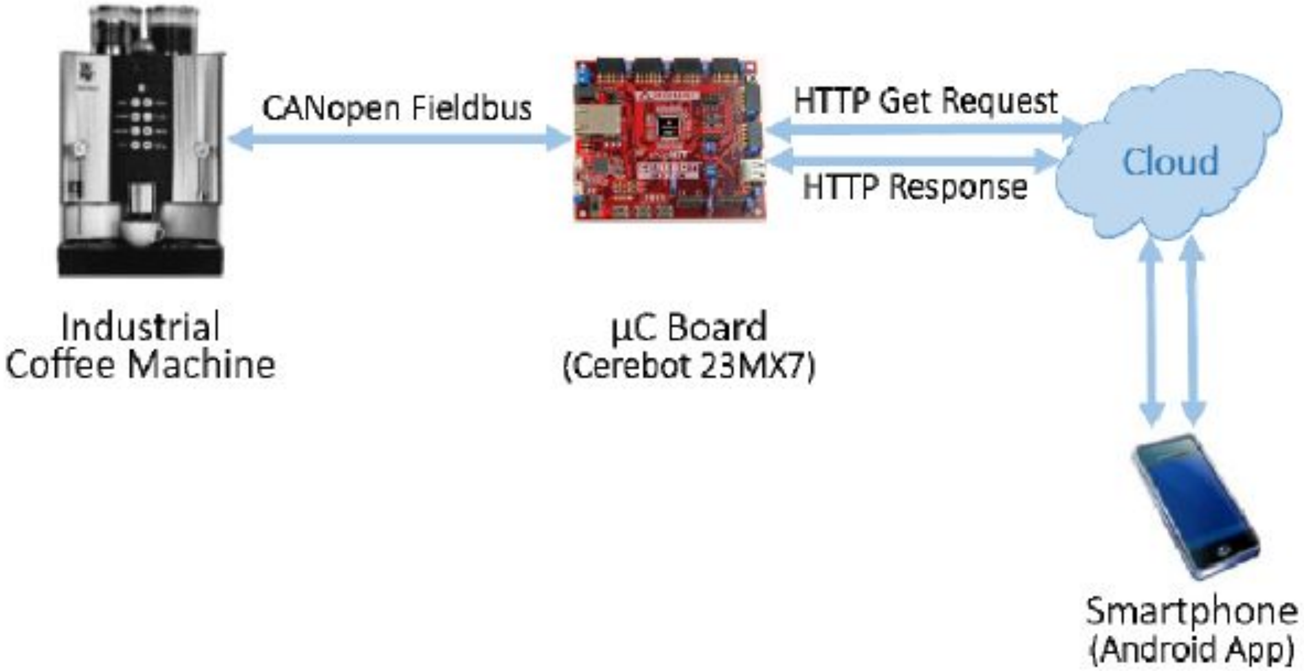


Fig. 4. System architecture


75
Energy
89
Performance

Summary

- We discussed Cyber-Physical Systems (CPS) and their integration of computation, networking, and physical processes.
- The text introduces the concept of Cyber-Physical Systems (CPS), which integrate computation, networking, and physical processes.
- CPS involves embedded systems that interact with the physical world through sensors, actuators, and communication components.
- It enables the Internet of Things (IoT) and offers benefits such as remote diagnostics and customization.
- The case study of an industrial coffee machine transformed into a CPS using a microcontroller board as a cloud gateway is discussed, highlighting cloud-based services and remote maintenance.

Important Points

- Cyber-Physical Systems (CPS) integrate computation, networking, and physical processes.
- CPS involves embedded systems that interact with the physical world through sensors, actuators, and communication components.
- CPS enables the Internet of Things (IoT) and offers benefits such as remote diagnostics and customization.
- A case study involves the transformation of an industrial coffee machine into a CPS using a microcontroller board as a cloud gateway.

- The microcontroller board enables cloud-based services and allows remote maintenance of the coffee machine.
- CPS is a key element in Industry 4.0, merging industrial and digital technologies to revolutionize production and realize the vision of Industry 4.0.
- Effective communication between hardware and software components is crucial for successful CPS implementation.
- The successful implementation of CPS relies on a hub for data interchange and collection, enhancing production processes with automation and knowledge integration.
- There are various approaches to extend an embedded system to a CPS, such as direct system extension, system expansion by a microcontroller board, and extension by smart actuators and sensors.

Application of cyber physical system

- Cyber-Physical systems have the widest application in the real world with technology, cps is mostly applied in many fields as you can see-
- **Agriculture:** Through the cps systems we can develop such kinds of sensors and tractors or harvesters that provide information on soil type and condition.
- **Aeronautics:** Aeronautics is one area that can benefit from CPS integration. In Aeronautics, CPS can be used to improve aircraft control and safety and improve performance and efficiency.
- **Healthcare and Personalized Medicine:** CPS systems have the technology which involves the use of connected medical devices and wearables to monitor patients' health data.
- **Civil Infrastructure:** Cyber-physical systems are using infrastructure improvement with some new efficiency technology. Advanced digital technology like IoT and sensors etc.
- **Manufacturing:** In manufacturing CPS can monitor and control the production process in real-time, improving quality and reducing scrap.
- **Transportation:** In transportation, CPS can improve safety and efficiency through intelligent traffic management systems, vehicle-to-vehicle communications, and self-driving vehicles.

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