Project number: 826276

CPS4EU

Cyber Physical Systems for Europe

D10.23 – Road mapping & Benchmarking v3

Reviewer: Philippe Gougeon (Valeo)

Dissemination level: Public

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Version	Date	Author (name – company)	Comments
V1.0	01/09/2022	Etienne Hamelin, CEA	D10.22 Complements and Update

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Table of contents

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Table of Figures

Tables

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

1 INTRODUCTION

1.1 *Purpose*

Task 10.5 “Road mapping and Benchmark of CPS Activities” aims at following the evolution of the market trends and the state of the art innovations in Cyber Physical Systems (CPS) so as to adapt the vision of the project and use cases to these latest developments. Deliverable 10.21 and 10.22 (Roadmapping and Benchmark v1 and v2) provided an overview of developments in CPS, including an evolution of the international landscape through a bibliographic analysis of IEEE journals and conferences as well as NSF projects. Since the release of D10.22, the global situation has continued to change, and this version provides an update on the global economic and strategic situation.

1.2 *Document Structure*

The structure of the current deliverable is as follows:

i) Four market sections (sections 2, 3, 4, & 5) concern the major market verticals relevant to CPS4EU (automotive, industrial automation, smart grids) as well as the defence segment, chosen for the importance it places on interoperable systems and its development of autonomous systems that are a form of CPS. For each one, reference architectures, key market & technology trends and activities relevant to pre-integrated architectures were identified ; the automotive field analysis was completed with new hindsight updated during the last year of CPS4EU.

ii) Section 6 follows a more bottom-up approach looking at the development of pre-integrated systems and ecosystems developing hardware development kits, and integrated development environments, with relevance to three of the PIARCHs: sensing, communications and computation.

iii) Section 7 looks at design automation for CPS and the various design automation challenges and methodologies under development.

iv) Section 8 provides a summary of recent primary research carried out by CEA (outside the specific scope of this project), but for which we have included findings relevant to CPS4EU partners.

v) Section 9 provides an analysis of the new inflexions on the CPS roadmaps and PIARCH-based design approach, which may derive from the global events that occurred during the course of the CPS4EU project.

1.3 *Summary of the external research with relevance to PIARCH development*

The following elements (trends, technologies, etc.) are discussed in more detail in the body of this deliverable, but are grouped here for clarity.

Within the automotive field:

- **A high level of centralization, with zone consolidation**—Gateways and super cores are interconnected via the automotive Ethernet TSN backbone.
- **Versatile and scalable processor devices**—Dedicated automotive microprocessors support all OEM requirements for next generation vehicles (over-the-air software updates, security & safety features).
- **Software from hardware abstraction**—New MCUs support HW virtualization thanks to hypervisors.
- **I/O separation from compute**—Physical connections to peripheral sensors and devices are separated from the computing resources, to improve scalability and reduce physical complexity and wiring.
- **Compute serverization**—Computing resources are allocated dynamically among various software applications, as needed, much like a cloud-computing model.

Within the field of smart grids:

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- **Multi-agent systems architecture**—MAS architectures seem highly relevant for large-scale distributed and decentralized CPS like smart grids.
- **Distributed intelligence**—Control mechanisms are distributed and enable lower communication needs. Individual devices with local computing only pass on critical information to the upper level.

Within the field of industrial IoT:

- **Protocol standardization and middleware**—Increasing I/O standardization (such as IO-Link) and middleware solutions (notably OPC UA) are providing solutions for easing industrial automation.
- **IoT Gateway connectivity**—IoT gateway connectivity solutions are generally in line with PIARCH specifications though interfaces for peripheral support (UART, SPI, and USB) seem more extensive.
- **Micro Clouds**—on premise (Edge) trends toward micro Clouds could change the nature of computing requirements, in particular the balance between computing in the micro Cloud and at the IoT gateway.

Within the defense field:

- **Use of GVA standards**—The Generic Vehicle Architecture promotes open standards for software and hardware interfaces to enable simple and rapid replacements or upgrades of equipment.
- **5 priority pre-integration functions**—Communication and connectivity, sensors, communication equipment and encryption, computing power and autonomy are the five functions that are dealt with transversely between the players, in particular through the construction of standards.
- **Communication and connectivity standards are priority for any defense project**—DDS plays a key role as it is always used as the data-level middleware for any interoperable platform.
- **Pre-integrated sensors are quite common**—New generations of integrated packages exist as well as the Configurable Open System Architecture (COSA) framework. No standard exist for this integration, though working groups are looking into the subject.
- **Autonomy kits are now appearing on the market** –The Rheinmetall A-kit provides a base software architecture that still has to be adapted to the sensor software, but is otherwise vehicle-agnostic and has integrated payload capabilities.

Within the development of technologies and ecosystems relevant to the PIARCHs:

- **HATS and shields**—The original development kits (Raspberry Pi, Arduino) have since become modular platforms thanks to domain-specific daughter-boards that include sensing, connectivity and cluster computing.
- **Pre-integrated sensors**—Multi-sensor pre-integration already exists (for example in motion sensing, gas sensing, air quality) and is developing for standard IoT applications like machine condition monitoring.
- **Pre-integrated connectivity modules**—Multi-connectivity options (for example, Sierra Wireless's range of CF3 modules) are in line with the communication PIARCH. Developments in ecosystems such as Sierra's MangOH and Arm's Mbed OS are important to monitor for their focus on IoT connectivity.
- **Heterogeneous Edge AI**—Edge AI development boards (Grove Studio, Luxonis, Coral/Google, ADLINK) are becoming commonplace; ADLINK's heterogeneous computing platform is worth close monitoring.

1.4 *Link to other documents/tasks*

ID	Description
D2.1	D2.1 – Specification and architecture of the communication modules
D4.1	D4.4 – Specifications of prototypes of the framework
D8.2	D8.2– Use case requirements v2
D8.3	D8.3 – Use case design and modelling v1

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

1.5 *Table of Abbreviations*

Definitions, Acronyms & Abbreviations	Description
ADAS/AS	advanced driver-assistance systems
BLE	Bluetooth Low Energy
C4I	Computerized Command, Control, Communications and Intelligence
CF3	Common Flexible Form Factor
DCU	domain control unit
DDS	Data Distribution Service
DPA	defense procurement agencies
ECU	electronic control unit
E/E	electrical and electronic
FPGA	field-programmable gate arrays
GVA	generic vehicle architecture
HAT	Hardware Attached on Top
HUMS	health and usage monitoring systems
IDE	integrated development environment
IOA	Interoperable open architecture
MAS	multi agent systems
MG	microgrid
OMG	Object Management Group
OPC UA	Open Platform Communications Unified Architecture
PCM	phase change memory
PLC	programmable logic controller
REST	representational state transfer
SOA	service-oriented architecture
SOC	system on chip
SG	smart grid
SDF	Semantic definition format
SOSA	Sensor Open Systems Architecture
TOPS	Tera operations per second
TSN	Time Sensitive Networking
UAV	Unmanned airborne vehicle
UWB	Ultra-Wide Band

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

2 CPS for automotive applications

2.1 *Automotive industry background*

2.1.1 Key market trends and industry needs

The market for software-intensive automotive electronic systems is expected to grow by some 15% annually between 2020 and 2030[1]. Connectivity, autonomous driving, electrification and mobility are key drivers to develop the new automotive E/E architectures:

- Advancements in software, compute and sensors are enabling a wide array of innovations in advanced safety systems on the path to fully autonomous driving.
- Consumers are demanding new features for safety, comfort and convenience with increasing frequency.
- Consumer preferences, tightening regulations and improving battery costs are moving the industry toward electric vehicles.
- 5G and other wireless technologies are creating opportunities to deliver vehicles that are even more connected than they are today.

The shift from conventional mechanical design to future-ready digital automotive experiences is a result of the growing need for sophisticated electronic features in vehicles.

Automotive E/E architecture continues to evolve in the direction of software-oriented design. However, this innovation translates into an increase in the cost and complexity of the vehicle E/E architecture:

- A need for further sensor/actors and high computing power for future vehicles.
- A need to host and transfer a vast amount of data (which is exponentially increasing) that is not only costly, but increases vulnerabilities to hacking.
- The software for automated vehicles will include between 300 and 500 million lines of code.
- Today's ECUs offer the computing equivalent of 20 personal computers and transmit more than 25 gigabytes of data per hour but they are severely limited by the CAN's data transfer rate of 1 Mbps.

2.1.2 Competitor trends and value chain development

In future vehicles, OEMs will consolidate these new features into fewer, more powerful control units. How far this consolidation should go, however, is a point of major debate. Some advocate for a centralized architecture with a few, or a singular, very powerful ECU(s) managing vehicle functions. Others consider a distributed architecture with a greater number of ECUs a better option, primarily to create redundancy in vehicle systems.

But changing the E/E architecture is a difficult task for traditional OEMs, and it appears easier for newcomers as they do not have an established architecture and supply chain.

As OEMs and suppliers look to innovate via the E/E architecture, they will need to evolve their development processes to integrate across domains, automate design tasks, and provide robust data coherency in order to tackle the challenges that come with technological and organizational change.

For instance, Bosch created the Automotive Electronics division to coordinate the production of control units and vehicle computers across all vehicle domains. In this way, the company is also achieving synergy effects in its manufacturing operations. The new manufacturing network will employ some 24,000 associates across 21 plants in 14 countries.

The typical automotive supply chain is growing longer and larger due to the increasing E/E content in vehicles. Longer and larger supplier pipelines can greatly increase the time required to cascade and implement design changes. Ensuring that all teams understand the change being implemented and its effects on their domain is already a key challenge. Contracting with additional suppliers and expanding the supplier ecosystem to provide desirable features only compounds this problem.

1 https://www.greencarcongress.com/2020/07/20200722-bosch.html

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

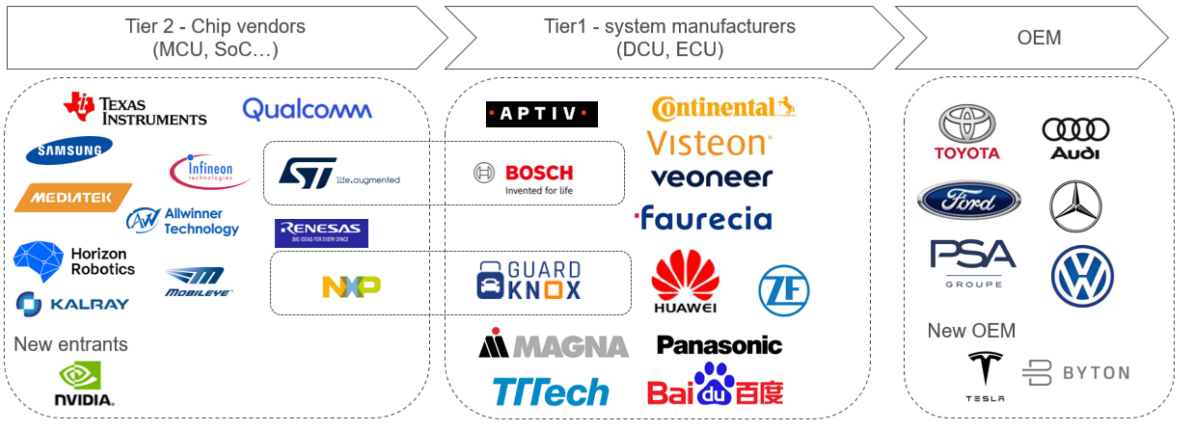


Figure 1 – E/E architecture value chain (non exhaustive)

Non-automotive digital companies explore new opportunities as the ecosystem evolves:

- Visteon, Continental, Bosch and Aptiv dominate the cockpit DCU (Domain Control Unit) market;
- Chinese players like Huawei, Desay SV, Shenzhen Hangsheng Electronics and Neusoft race to unveil their cockpit DCU solutions.
- And when it comes to autonomous driving chip, Nvidia is a clear leader with the Nvidia Drive PX2 and Nvidia Drive Xavier products being widely deployed by vendors.

2.2 *Automotive vehicle architectures systems & their evolution*

The growing need for sophisticated electronic features in vehicles, translates into increased cost and complexity of the vehicle E/E architecture: a move to Service-oriented architectures (SOA), in which applications are broken down into specific functional components or "services" that can be remotely accessed on computers or the web and updated independently[2].

2.2.1 Today E/E architecture: Domain-based architectures

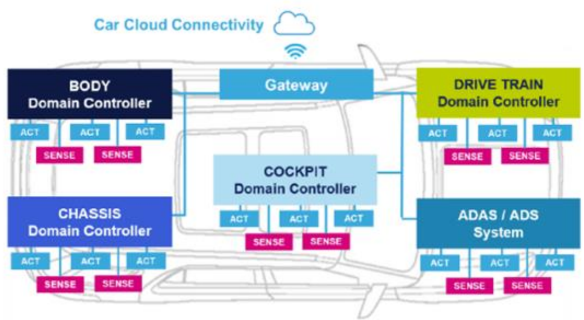


Figure 2 – Today E/E architecture[3]

Currently, OEMs implement domain-based architectures, in which the functions are consolidated, or fused, into specific domains. Generally, five domains are defined: Body, Drive/Powertrain, ADAS/AS, Chassis, and Cockpit, with different security, safety, computing resources and connectivity requirements.

The domain-based architectures implementation needs two main devices:

- The domain controllers (compute devices)
- The central gateway (connect device) that connects the domain controllers to the backbone.

2 https://www.netscribes.com/automotive-industrys-call-to-redesign-vehicle-e-e-architecture/
3 "Smart Automotive Domain Gateways" Khaldoun Albarazi – ST Microelectronics

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Benefits of the domain-based architecture include:

- Supporting incremental functionality through domain centralization.
- Reducing cost, weight and power consumption
- Leveraging silicon and software innovations

2.2.2 Tomorrow and Future E/E architecture: Zonal-based architectures[4]

Tomorrow's E/E architecture (Figure 3, by 2024) will have a high level of centralization, with zone consolidation (instead of function consolidation):

- Sensors and actuators physically located in the same zone will be connected to a Zone Gateway ECU.
- Ethernet TSN (Time Sensitive Networking) will be used as a backbone communication link, with high bandwidth and true real-time communication facilities
- Some domains controllers will be fused (Cross-Domain controllers); in general, three cross-domain controllers (Body, Cockpit, ADAS/AD) are defined.

The two main devices of this type of architecture are:

- The cross-domain controllers (or supercore)
- The zonal gateways that connect the I/O and sensors/actuators to the cross-domain controllers.

Benefits of this zonal-based architecture, also called partial centralized architecture include:

- Reducing complexity through intelligent zone control and management
- Service-Oriented-Architecture (SOA) direct memory access
- Parallel computing offering redundancy and safety
- Open scalable platform for OEM system integration (more or less applications according to car range)

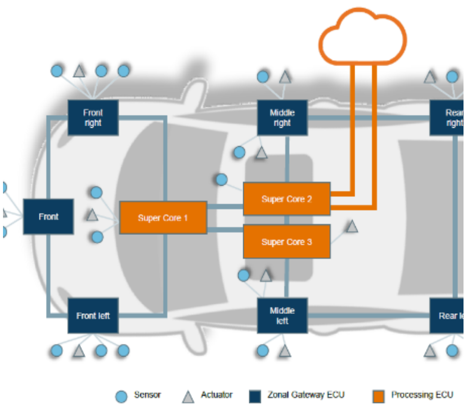


Figure 3 – Tomorrow's E/E architecture

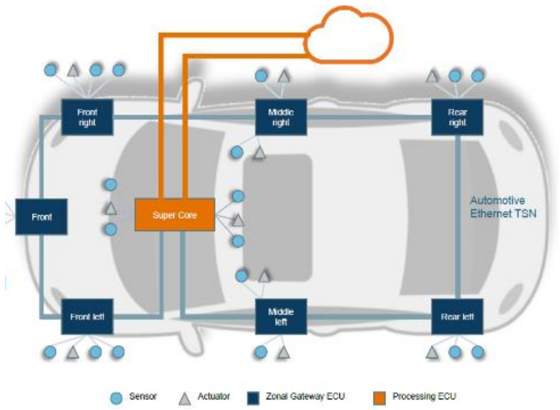


Figure 4 – Future E/E architecture

The future E/E architecture (Figure 4, by 2028+) is expected to be fully centralized and domain-independent, with a central super computing platform consolidating all the processing units, and Zone Gateway ECUs.

With this architecture, two main devices are needed:

- A "super" computing device including redundancy consolidating all the processing units
- Zone Gateway ECUs for the I/O and sensors/actuators connectivity to the Ethernet backbone.

Benefits of fully centralized architecture include:

- Service-Oriented-Architecture (SOA) network access oriented
- Dynamic configuration and seamless redundancy
- Blade upgradeable concept

4 Progressive Innovation and Next-Gen Intelligent Automotive Implementation – Marcku Schupfner - Visteon

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

2.3 *Zonal-based E/E architecture main devices*

2.3.1 ECUs gateway / Zone controllers / Zonal ECUs

Zone controllers/gateways are nodes in a vehicle that serve as hubs for all of the power distribution and data connection requirements for devices – the various sensors, peripherals and actuators – within a physical section of the vehicle. The zonal gateway are domain-independent.

- The number of zone controllers can vary depending on the requirements and complexity of the vehicle.
- They can include customizable models corresponding to progressively higher levels of automation.

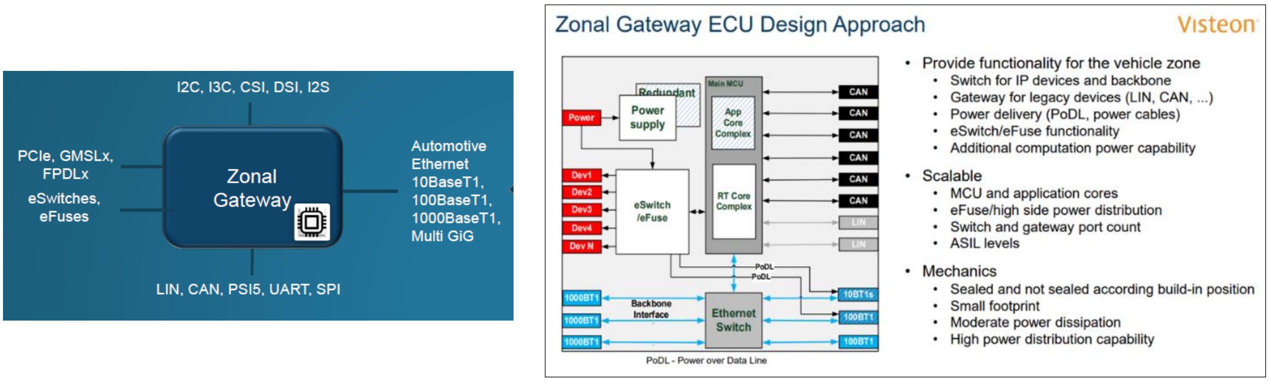


Figure 5 – Visteon Zonal Gateway[5]

The Zonal Gateways are generic devices with different roles/functions:

- Logical concentration points for multiple ECUs.
- Logical location to consolidate input/output (I/O) from the various sensors, peripherals and actuators, as well as to integrate functionality of certain electronic controls. Each sensor and actuator connects to a local zone controller based on its location and there is support for any kind of interface for sensors, actuators, displays.
- Separate I/O from compute: local data transformation aggregates the data and puts it onto a single high-speed cable that connects to the compute.
- Can distribute power and provide protection as well

Benefits of Zonal Gateways include:

- Divides the electrical infrastructure of a vehicle into more manageable segments and makes assembling wiring harnesses easier to automate.
- Reduces the physical complexity of today’s cable harnesses and the large number of individual ECUs and puts the focus on software, as multiple functions are integrated into the zone controllers and other centralized devices.
- Creates I/O abstraction from computation

5 Zonal EE Architecture: Towards a Fully Automotive Ethernet–Based Vehicle Infrastructure – Jochen Klaus-Wagenbrenner - Visteon

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

2.3.2 Cross-Domain Control Unit / central controllers / vehicle server

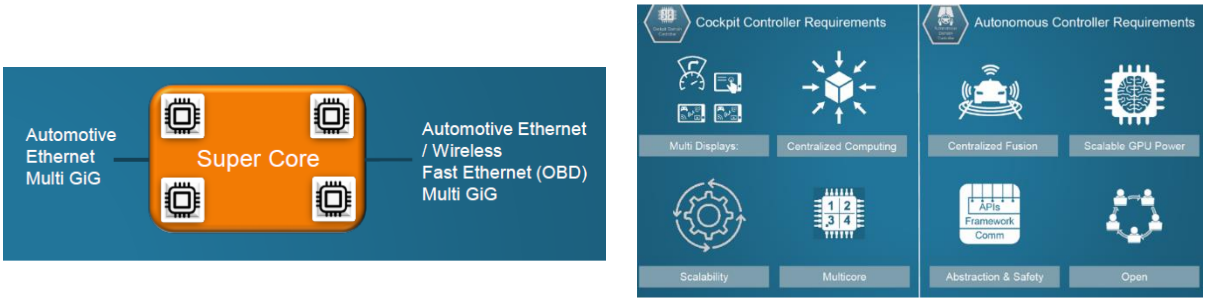


Figure 6 – Visteon SuperCore[6]

The Cross-domain controllers have different roles/functions:

- May act as application servers, supporting Service-Oriented Architecture (SOA)
- May be a multi SoC-based control unit with Multi GiG Ethernet interface. Can include specific SoCs (e.g. for AI)
- Fully scalable and upgradable platform
- Connects to Edge and Cloud back-end
- May act also as zonal gateway

Depending on the domain to control, the **implementation and integration will be different** (i.e. different computing resources, real-time or ultra-real-time, including dedicated SoCs for AI…):

- For compute-intensive applications such as ADAS and user experience (entertainment), the controller may be implemented as an open server platform (cf. Aptiv – SVA open server platform[7]) which dynamically allocates computing resources to both safety-critical and non-critical functions (serverization: the processing is distributed among several compute devices).
- For less compute-intensive applications such as Body control, the domain control can be implemented in a Central Vehicle Controller (CVC), which is also responsible of network management, power control for all of the zone controllers, and communications with the outside world.

2.3.3 Devices: MCU, GPU, SoC…

The device manufacturers provide dedicated processing devices (Network processors, MCU, GPU, SoC…) for automotive E/E architectures. A combination of networking, performance and safety features to meet cross-domain controllers requirements (and zonal gateway) include:

- A heterogeneous multiprocessor architecture, depending on the processing requirements (real time or ultra-real-time). Integration of different ARM-Cortex core types.
- Support of HW virtualization, to allow several ECUs to share the same processor (needed in centralized architectures) and hosting of multiple applications developed with different tooling and on different software schedules.
- Non-volatile Phase-Change Memory (PCM) to support safety by delivering single-bit overwrite capability and very effective Over-the-Air updates with no downtime
- Upgraded safety to ASIL D
- Support different communications ports (CAN, Ethernet, I2C…)

STMicroelectronics STELLAR MCU Family has been developed using Bosch specifications; the MCU integrates several ARM Cortex-M4 and ARM Cortex-R52 core, and supports HW virtualization.

6 Zonal EE Architecture: Towards a Fully Automotive Ethernet–Based Vehicle Infrastructure – Jochen Klaus-Wagenbrenner - Visteon
7 Smart Vehicle Architecture - Aptiv

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

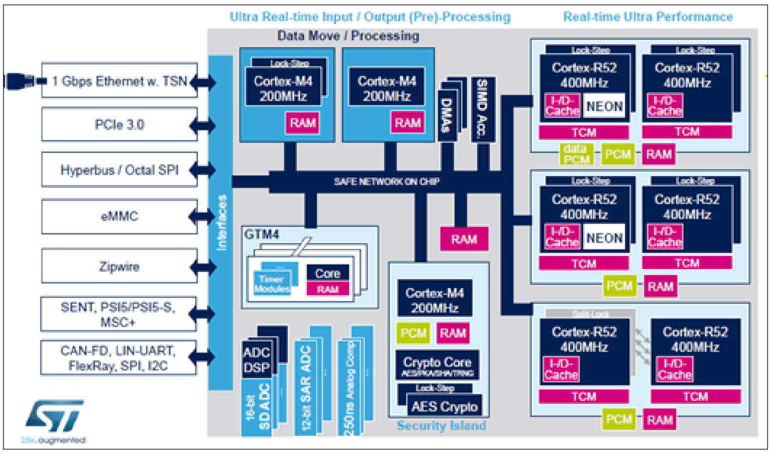


Figure 7 – ST STELLAR MCU FAMILY[8]

On its side, NXP launched the S32G Vehicle Network Processor, a versatile processor that combines ASIL D safety, hardware security, high-performance real-time and application processing, and network acceleration for service-oriented gateways, domain controllers and safety co-processors.

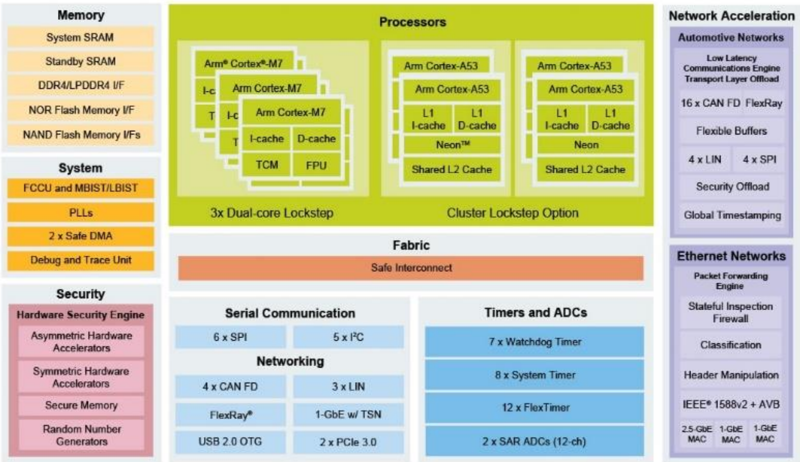
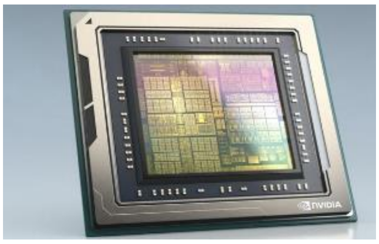


Figure 8 – NXP S32G Vehicle Network Processor[9]

For Autonomous Driving, Nvidia introduced DRIVE AGX Orin[10], a software-defined platform for autonomous vehicles. The System-on-Chip Orin integrates NVIDIA GPU cores, Arm Hercules CPU cores, deep learning, computer vision accelerators etc…



NVIDIA ARM SoC Specification Comparison			
	Orin	Xavier	Parker
CPU Cores	12x Arm "Hercules"	8x NVIDIA Custom ARM "Carmel"	2x NVIDIA Denver + 4x Arm Cortex-A57
GPU Cores	"Next-Generation" NVIDIA iGPU	Xavier Volta iGPU (512 CUDA Cores)	Parker Pascal iGPU (256 CUDA Cores)
INT8 DL TOPS	200 TOPS	30 TOPS	N/A
FP32 TFLOPS	?	1.3 TFLOPs	0.7 TFLOPs
Manufacturing Process	7nm?	TSMC 12nm FFN	TSMC 16nm FinFET
TDP	~65-70W?	30W	15W

Figure 9 – NVIDIA Orin SOC

8 https://www.globenewswire.com/news-release/2020/10/20/2110984/0/en/STMicroelectronics-Unveils-Features-of-Multi-Application-Deterministic-Automotive-Microcontrollers-to-Maximize-Safety-and-Security-in-Next-Generation-Domain-Zone-Architectures.html
9https://www.eetasia.com/auto-network-processor-from-nxp/
10 https://nvidianews.nvidia.com/news/nvidia-introduces-drive-agx-orin-advanced-software-defined-platform-for-autonomous-machines

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

2.4 *Summary and PIARCH impacts*

Processor devices become versatile and scalable

Devices manufacturers (ex: ST and NXP) design dedicated automotive microprocessors combining networking, performance and safety features.

- ➔ They can be used in many different places inside a vehicle — ranging from a gate processor to a domain controller and ADAS safety processors.
- ➔ They support all OEM requirements for next-generation vehicles: over-the-air software updates, security & safety features, connectivity, support of large volumes of data through multiple interfaces

Several players on same ECU[11]

When ECUs become domain-independent, functions are no longer associated with an ECU: a single function is constituted by services, provided by different ECUs interconnected via Automotive Ethernet TSN. This implies that several SW suppliers are delivering services to the same ECU.

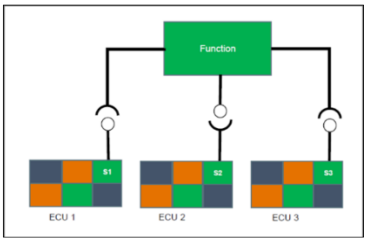


Figure 10 – Services run on different ECUs

Software from Hardware abstraction

The new MCUs support HW virtualization, thanks to a hypervisor:

- This allows several ECUs to share the same processor in centralized architectures
- This allows continuous release cycles for the software; the software in a vehicle should be able to update more frequently than the hardware it runs on.
- This also allows developers to reuse software more easily as they move it to different platforms, rather than port it.
- Finally, this allows the addition of new applications (programmed by SW) without changing the HW.

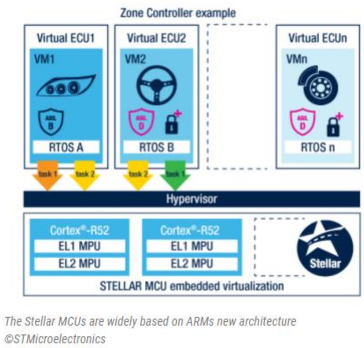


Figure 11 – The Stellar MCUs support HW virtualization

11 Zonal EE Architecture:Towards a Fully Automotive Ethernet–Based Vehicle Infrastructure – Jochen Klaus-Wagenbrenner - Visteon

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

I/O separation from compute

All the physical connections to peripheral sensors and devices are placed into zone controllers that are separate from the computers in the domain controllers. The zone controller delivers power and data connections to the sensors and other devices, with just a backbone connection to the domain controllers.

- This approach improves scalability and reduces physical complexity and wiring.

Compute serverization

The computing resources in a vehicle are allocated among various software applications dynamically, as needed, much like a cloud-computing model.

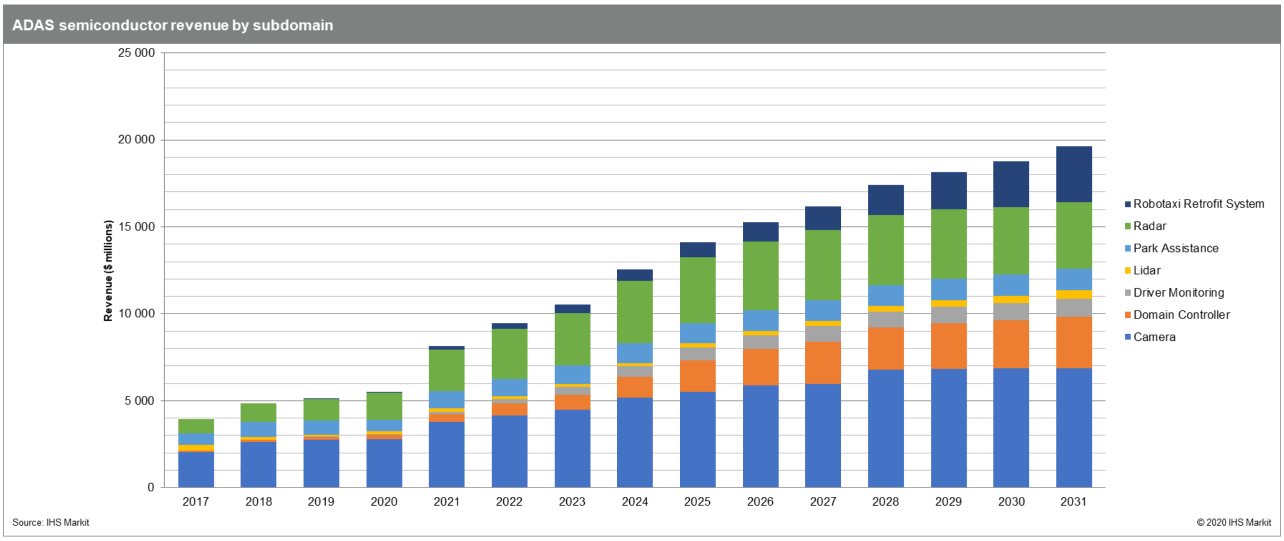
- Allocates the necessary compute power, RAM, graphics processing, and so on, to applications based on priority and need.
- Allows sharing of resources among physically separate domain controllers, so they can operate logically as one.
- Additionally, this approach supports mixed criticality; that is, a critical safety feature that requires more processing power, for example, has priority over less critical functions such as infotainment.

2.5 *Automotive market: year 2022 update*

The following chapters presents a Valeo-oriented perception of the evolution of the Automotive CPS market since preveious version of this deliverable.

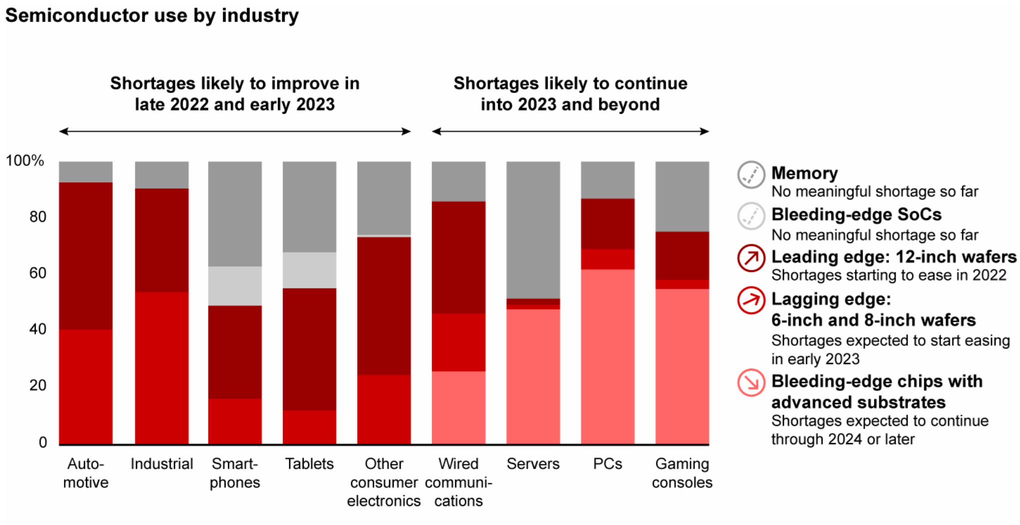
New Trends for Electronics on Automotive market

Valeo view about the growth of the Electronic Automotive market is shown below from a private report produced by IHS Markit and issued in 8/2021. This report shows a sustained growth for this market, with a 16.4% CAGR over the 2018-2025 period, and a 5.7% CAGR for 2025-2030. The cameras and radar represent the largest segments, but domain controllers show the highest growth. The share of robot-taxi retrofit in 2030 seems highly questionable.

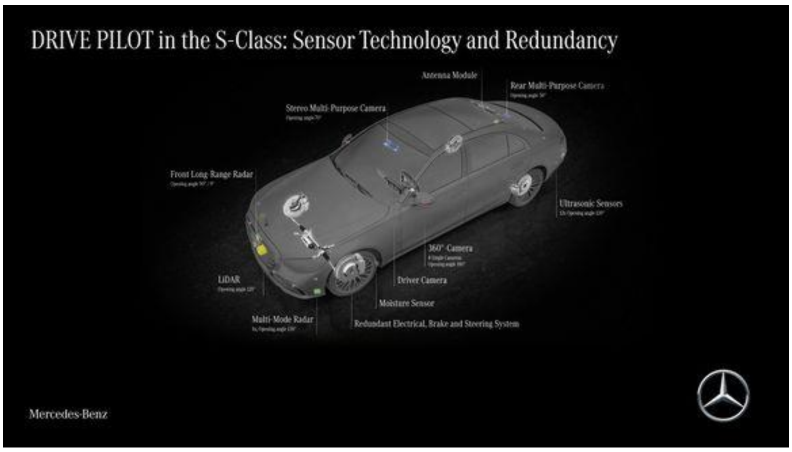


Shortage of components: according to the report from Bain&Company in 9/2022, the situation for the automotive industry starts to improve in the 2nd half of 2022. Other domains like PCs or gaming or servers will remain strongly impacted in 2023, see the picture below from this report.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

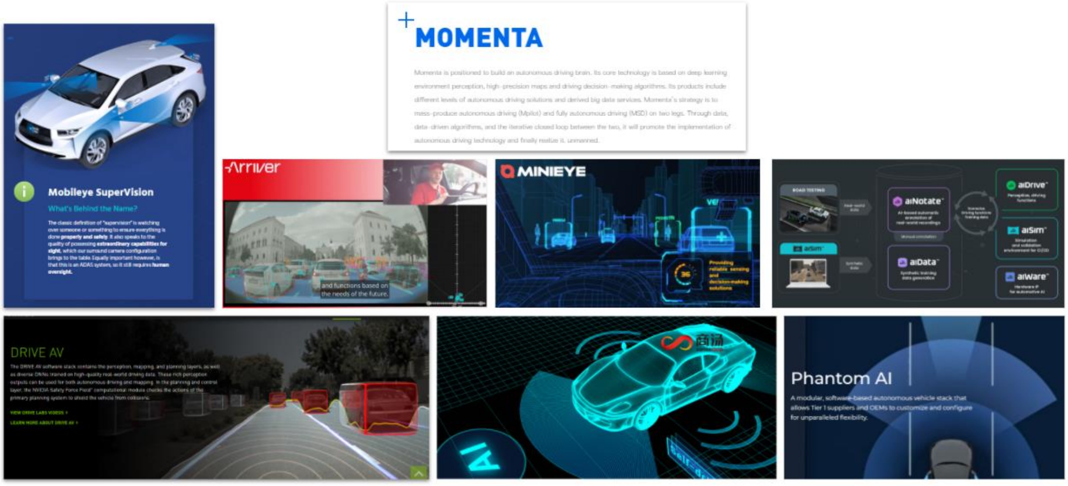


Homologation of Automated vehicles: the Mercedes S-class becomes the first vehicle to obtain the homologation for Conditional Automated Driving Level 3 according to the regulation UNECE-R157. Up to now, this homologation for the Mercedes Drive Pilot function is granted only for automated driving on German motorways, and up to a 60kph vehicle speed. The front Lidar shown of the sensor picture below is a Valeo Scala Gen2 similar to those integrated on the Valeo demo car for CPS4EU Use Case 3. The cost of the Drive Pilot option on the S-class is 5000 Euros.

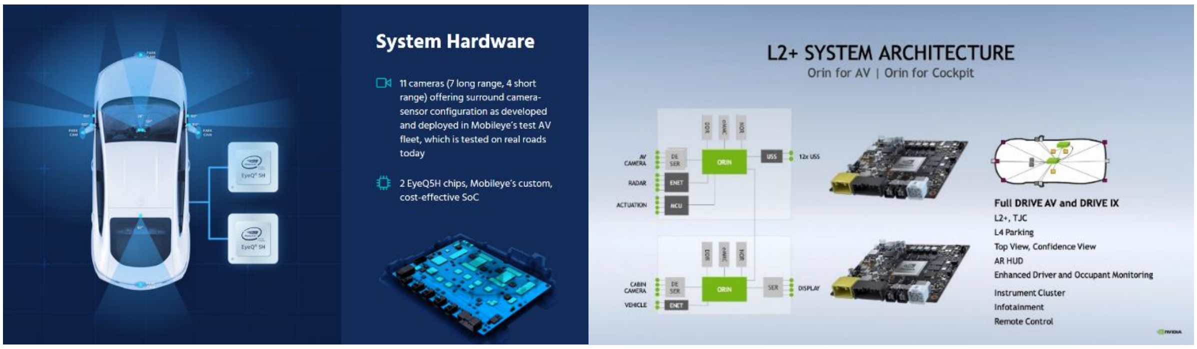


Full Software stacks : multiple SW stacks are built as a product, often lacking the deep sensor insights and knowledge of functions such as low speed sensing and driving.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276



Silicon providers such as Intel, NVidia, Qualcomm are pushing full system implementation towards the carmakers in closed black box architectures:



Silicon independence and in-house software: 50% of Top 10 OEM's are pushing to have their own computing SOCs by 2026 and are investing heavily in bringing SW in-house through partnership models. VW Cariad and Stellantis Software X are two examples of new entities covering all the software developments across all their respective model brands. For the New Mobility Providers, Cruise has announced that they will also design their own SOCs, to be manufactured by an undisclosed Chinese supplier for 2025.

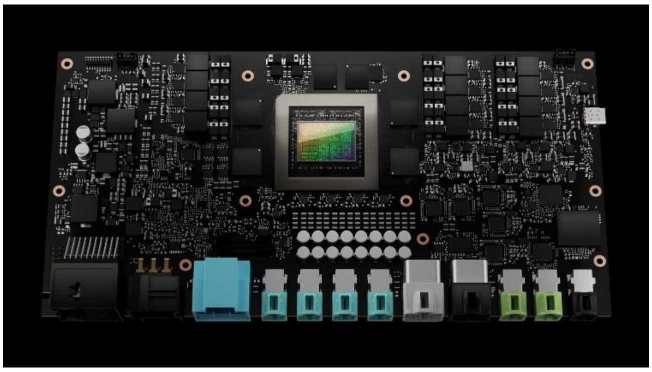
This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

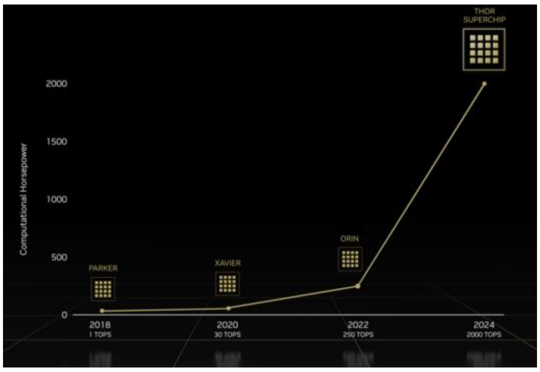
2.6 *SOCs*

NVidia announced in 9/2022 the launch of the Thor SoC with a performance reaching 2000 TFLOPS in FP8. The start of production is planned for 2025, for a Chinese carmaker affiliated to Geely. The previous SoC Orin launched in 2022 has a performance of 250 TFLOPS.

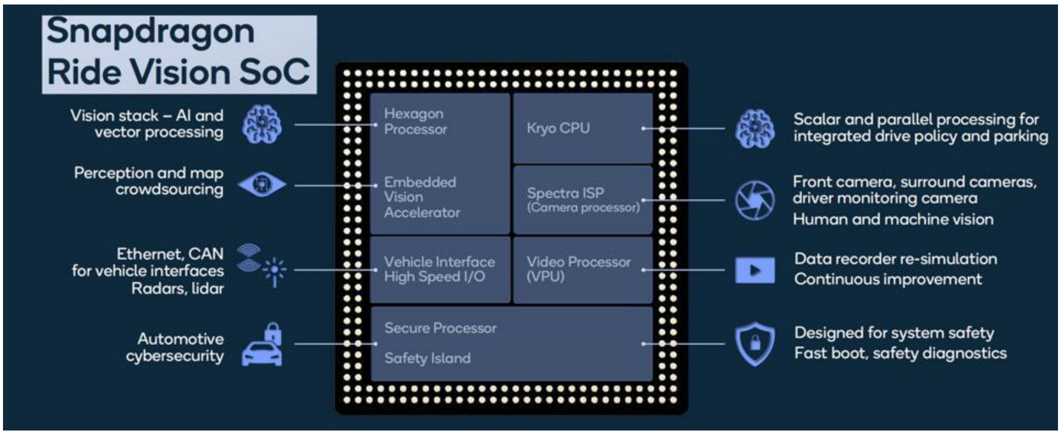
As stated in NVidia press release from 9/2022:

DRIVE Thor is the first AV platform to incorporate an inference transformer engine, a new component of the Tensor Cores within NVIDIA GPUs. With this engine, DRIVE Thor can accelerate inference performance of transformer deep neural networks by up to 9x, which is paramount for supporting the massive and complex AI workloads associated with self driving. Another advantage of DRIVE Thor is its 8-bit floating point (FP8) capability. Typically, developers lose neural-network accuracy when moving from 32-bit FP data to 8-bit integer format. DRIVE Thor features 2,000 teraflops of FP8 precision, allowing the transition to 8-bit without sacrificing accuracy. The new superchip also uses the latest NVLink®-C2C chip interconnect technology, while running multiple operating systems. The advantage of the NVLink-C2C is its ability to share, schedule and distribute work across the link with minimal overhead. This equips automakers with the compute headroom and flexibility to build software-defined vehicles that are continuously upgradeable through secure, over-the-air software updates.





Qualcomm Snapdragon: in 3/2022 Qualcomm Arriver division (ex-Veoneer software division) and BMW announced a partnership for the development of automated driving softwares. These softwares will be ported on Snapdragon Ride Vision SoC, see the picture below.

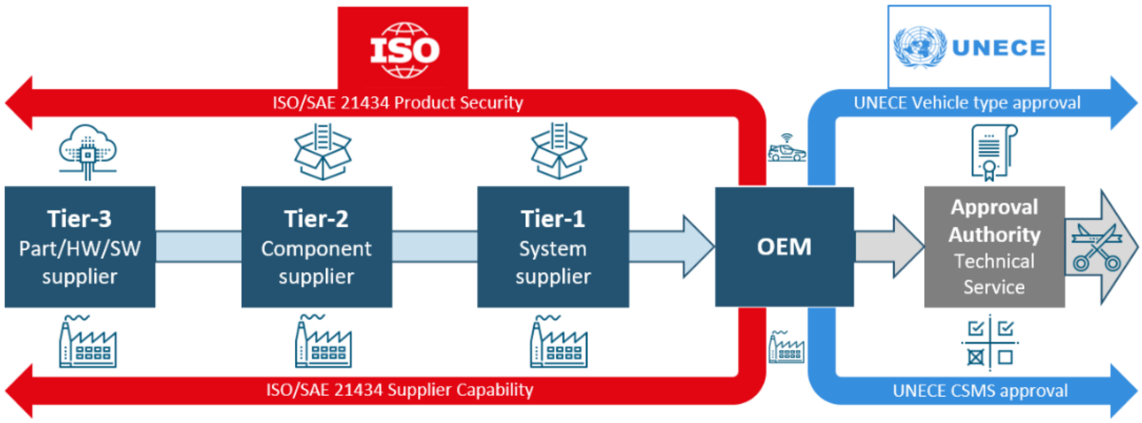


Several carmakers plan to use the Snapdragon for their cockpit or ADAS/AD functions**.** Among them BMW, GM, Hyundai, Mahindra, NIO, Renault, Stellantis, Volvo Cars.

2.7 *Cybersecurity*

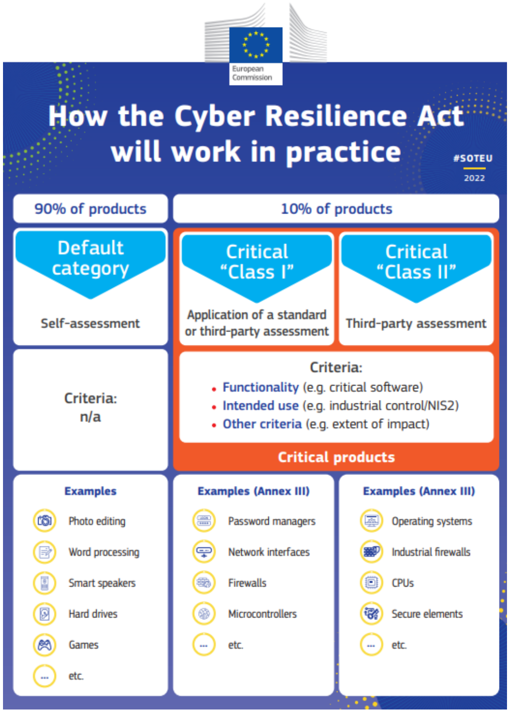
Following the publication of the ISO 21434 and UNECE R155 in 2021, the automotive industry has committed to introduce the 'Cyber Security Management System' aka. 'CSMS' across the whole automotive eco-system, as shown on the picture below. In Europe, the compliance to the UNECE R155 regulation is necessary for the homologation of the new vehicle types since 7/2022.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276



In 9/2022, NHTSA (National Highway Traffic Safety Administration in the USA) published a document called 'Cybersecurity best practices for the safety of modern vehicles'. This document refers widely to the ISO/SAE 21434 principles. Among the exhaustive best practices, this document recommends to the suppliers and vehicle manufacturers to maintain a database of their operational hardware and software components and version updates in each electronic control unit and in each vehicle.

This commitment from the automotive industry towards cybersecurity comes ahead of the Europe Cyber Resilience Act presented in 9/2022, which outlines the cybersecurity regulations in Europe for all the hardware and software products in all industrial domains, as shown below. The entry into force date for the regulation linked to this Cyber Resilience Act is not defined yet by the EU Parliament and Council.



2.8 *Artificial Intelligence*

A must read is the new paper from Y.Le Cun published in 6/2022, 'A path towards autonomous machine intelligence'. This paper proposes a new vision for artificial intelligence based on processes applied by humans and animals to represent the world, predict, act by observation. See the picture below:

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

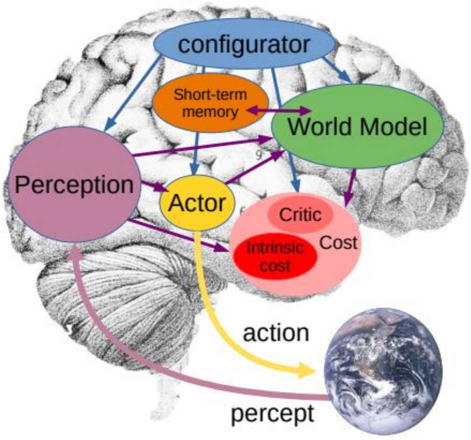
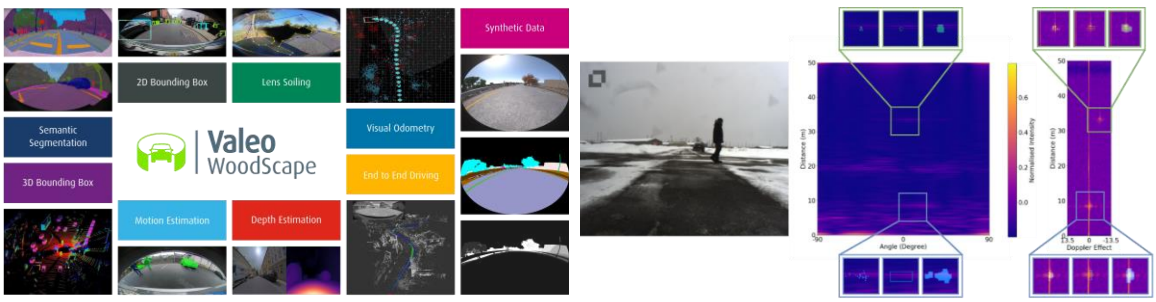


Figure 2: *A system architecture for autonomous intelligence. All modules in this model are assumed to be "differentiable", in that a module feeding into another one (through an arrow connecting them) can get gradient estimates of the cost's scalar output with respect to its own output.*
The configurator module *takes inputs (not represented for clarity) from all other modules and configures them to perform the task at hand.*
The perception module *estimates the current state of the world.*
The world model module *predicts possible future world states as a function of imagined actions sequences proposed by the actor.*
The cost module *computes a single scalar output called "energy" that measures the level of discomfort of the agent. It is composed of two sub-modules, the intrinsic cost, which is immutable (not trainable) and computes the immediate energy of the current state (pain, pleasure, hunger, etc), and the critic, a trainable module that predicts future values of the intrinsic cost.*
The short-term memory module *keeps track of the current and predicted world states and associated intrinsic costs.*
The actor module *computes proposals for action sequences. The world model and the critic compute the possible resulting outcomes. The actor can find an optimal action sequence that minimizes the estimated future cost, and output the first action in the optimal sequence.*
See Section 3 for details.

Concerning AI for the automotive and new mobility domains, Valeo is significantly contributing to the research community with its entity Valeo.ai . A lot of information, publications, challenges, keynotes can be found on the Valeo.ai web site.

Among the main challenges outlined in Valeo.ai recent activities:

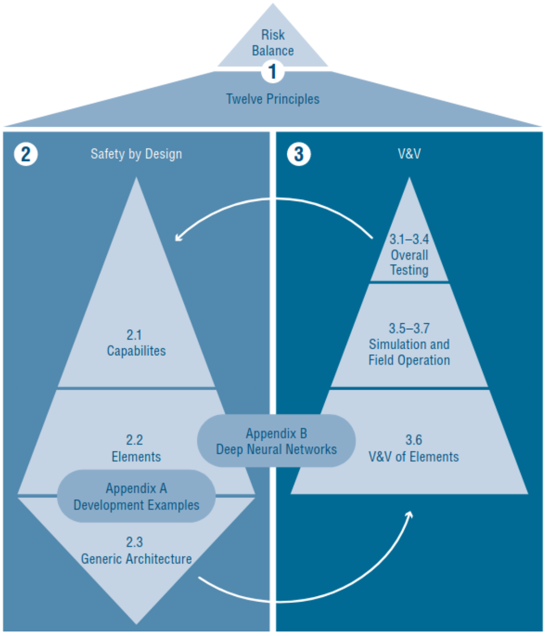
a) Multi-sensing perception, as shown with the management of the Woodscape public database and with the CARRADA dataset (Camera and Automotive Radar with Range-Angle-Doppler Annotations):



b) Uncertainty estimation, mainly in situation where bad ambient lighting and adverse weather conditions occur, as reviewed during the Vision For All Seasons workshop at the CVPR2022. In this context, Valeo.ai is also involved in the challenge organized by the ACDC group 'Adverse Conditions Dataset with Correspondences'.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

c) AI and Safety, mainly as part of the [working group SAIAD](#) 'Safe AI for Automated Driving', involving BMW, Bosch, Daimler, Intel, Stellantis, Valeo, Volkswagen, among the contributors



The SAIAD group is aligned with the recommendations written in the white paper Safety First for Automated Driving (see the picture above). For the specific questions related to AI and safety, SAIAD is still in progress, and is organized in the following manner:

1. Specification

DNN behavior: How to describe the DNN behavior?

Dataset specification: How to specify the training and test data to argue a full coverage of the input space?

2. Data and DNN Architecture Selection

Synthetic data and data augmentation: How can synthetic data and augmentation help make Deep Networks safe?

Special DNN design: How can special DNN design increase the trustworthiness of DNN model output?

DNN redundancy strategies: How to incorporate redundancy in architectural design (e.g. sensor fusion, ensemble concepts)?

3. Training

Transparent DNN training: How do models extract knowledge from training data and use a-priori knowledge in training data?

New loss functions: What new loss functions can help focusing on certain safety aspects?

Methods for meta classification: What is the effectiveness of meta classifiers (e.g. based on uncertainty modeling, heat maps)?

Robustness to anomalies: How to Increase robustness to anomalies in input data and how to defend adversarial attacks?

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Robustness across domains: How to Increase robustness of AI algorithms throughout different domains/datasets?

4. Evaluation / Testing

Novel evaluation schemes: What novel evaluation schemes are meaningful for safe AI in automated driving?

Interpretable?: What diagnostic techniques can provide insight into the function and intermediate feature maps / layers?

Evaluation of diagnostic techniques: How to evaluate and compare techniques for interpreting and explaining DNNs?

5. Monitoring

Uncertainty modeling: How to model uncertainties during inference (e.g. via Monte Carlo dropout)?

Detection of anomalies: How to detect anomalies in the input data (e.g. adversarial attacks, out-of-distribution examples)?

Plausibility check of the output: How to check the DNN output for plausibility (e.g. implausible positions and sizes of objects)?

2.9 *Conclusions for CPS4EU*

The trends observed during the first two years of CPS4EU are continuing with a widespread evolution of the ECS (Electronic Components and Systems) eco-system for the automotive applications.

In the Use Case 1 ‘AI for perception’, the latest Deep Neural Network algorithms are implemented and tested in prototype.

In the Use Case 2 ‘Robustness of CPS in AD level 4’, the principles of functional safety in the context of Automated Driving and AI algorithms are developed and tested.

Finally, in the Use Case 3 ‘Urban automated driving’, the previous results are integrated in the full system architecture of the CPS4EU vehicle to perform the automated driving function in an urban environment.

The three use cases in CPS4EU, lead by Valeo with the contributions of the CPS4EU partners, correspond very well to the adaptations required by these evolutions. Computing power, safety, cybersecurity and AI are the cornerstones required for a wide adoption of the CCAM (Connected and Cooperative Automated Mobility) in the future.

3 CPS for Industrial Automation (Industry 4.0 or Industrial IoT)

3.1 *Industry 4.0 background*

In its 2015 whitepaper[12] entitled “Industry 4.0: How to navigate digitization of the manufacturing sector”, McKinsey describes Industry 4.0 as the digitization of the manufacturing sector. It states that the interest in Industry 4.0 derives from the fact that traditional productivity levers have been largely exhausted: from the lean manufacturing approaches in the 1970s and 1980s, pioneered by Toyota, to the outsourcing and offshoring practices of the 1990s, with low-skill manufacturing moved to low-cost countries. McKinsey contends that during the 2000s, the advantages of offshoring began to shrink as wages rose and transport costs increased.

Today, factors including time to market and customer responsiveness are key success factors, putting a premium on more localized manufacturing with the investment in automation and robotics being a means to address labour cost differentials in lower-cost countries. One might add that the Covid-19 pandemic is forcing organisations to rethink their supply chains and to consider reshoring certain activities in the quest for greater resilience.

Of course, industrial automation is not new: one can point to the automation of production lines at Ford in 1910, distributed control systems and programmable logic controllers (PLCs) in the 1970s, notably by companies such as Honeywell and Schneider Electric and Siemens, to automated manufacturing execution system (MES) software

12https://www.mckinsey.com/business-functions/operations/our-insights/industry-four-point-o-how-to-navigae-the-digitization-of-the-manufacturing-sector

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

in the 1990s. What might therefore ask if anything is new? In reality, data is the real driver of Industry 4.0 and it is the confluence of data collection technologies (sensing), communication (the IoT), and computation (both in the Cloud and at the edge) that organizations such as McKinsey see as the real tipping point. According to McKinsey analysis : "Data is the core driver: leaders across industries are leveraging data and analytics to achieve a step change in value creation."

One of the differences noted by McKinsey for this revolution in industrial automation is that replacement of manufacturing equipment is not the key driver. Of course, industrial robots may be an exception, but by and large, industry 4.0 is about adding sensing, connectivity and intelligence to existing industrial equipment and not simply replacing it. Of course, issues still exist with connecting existing machines: not all equipment easily supports this connectivity and industrial clients may be confronted with a panoply of communications protocols that require further work to enable true integration and data sharing.

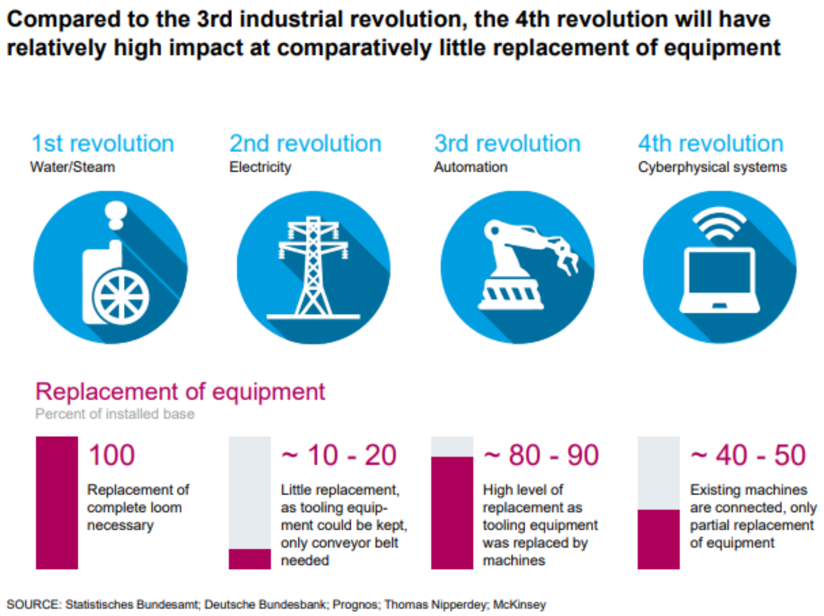
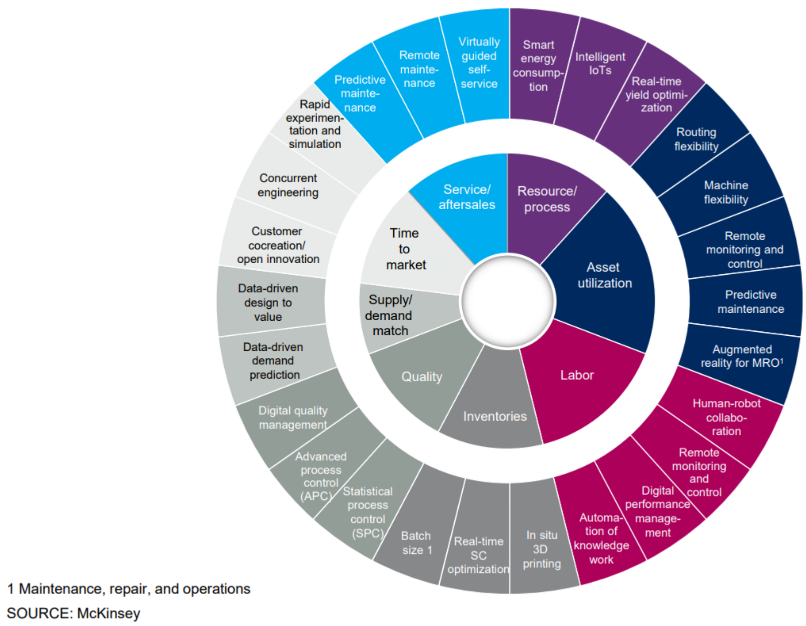


Figure 12 – Industry 4.0: CPS and connecting to existing machines

3.2 *Key industry needs and market/technology trends*

McKinsey defines eight key value drivers for industrial clients from industry 4.0 initiatives and then maps different industry 4.0 product/service offerings (levers) to these value drivers. Many of these levers have already been



This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

described in section 2.4 of deliverable D8.2. This segmentation approach is useful for organizations seeking to focus on particular value drivers, but is also a way of positioning the specific industrial use cases within CPS4EU.

Figure 13 – A typical industrial control system

The following table highlights how CPS4EU industry CPS use cases map to the different industry 4.0 levers and value drivers (it is non-exhaustive):

CPS4EU Use case	**Brief Description**	**Industry 4.0 levers**	**Value drivers**
UC 4 - Automated Vacuum System	Automate drilling activities on such structures that currently are human driven	• Human-robot collaboration • Predictive maintenance	• Asset utilization • Labor • Service/after sales
UC 5 - Trimming quality improvement	Collect data coming from sensors and numerical control machines for defect analysis and corrected action	• Remote monitoring & control • Real-time optimization • SPC	• Asset utilization • Resource/process • Quality
UC 6- Thermoplastic production line monitoring	Monitor and control process parameters to achieve the best possible quality of the final thermoplastic product	• Remote monitoring & control • Real-time optimization • APC	• Asset utilization • Resource/process • Quality
UC 7 - Aircraft Health Management System	Data retrieval for troubleshooting, trend monitoring, maintenance planning and spare parts management.	• Remote monitoring & control • Predictive maintenance	• Asset utilization • Service/after sales
UC 8 - Material flow analytics & simulation	Flexible production through a complete digital model (digital twin) of the shop floor	• Remote monitoring & control • Machine flexibility • Advanced process control • Digital performance management	• Asset utilization • Resource/process • Labor • Inventories
UC 9- Mobile CPS	Addresses “cooperative lifting” challenges with distributed decision making, and collaborative algorithms	• Human-robot collaboration • Predictive maintenance	• Asset utilization • Labor

Table 1 : CPS4EU use cases and mapping to generic IIOT value drivers

Despite the fact that the six CPS4EU industrial use cases have come from individual partners in a bottom-up manner, it can be seen from Table 1 that there is a good overall mapping to the key generic value drivers for industrial users as well as to Industry 4.0 (functional) levers.

To achieve the potential benefits inherent in deploying IoT and CPS solutions, industrial end-users must nevertheless overcome a number of barriers to deployment. Chief among the needs voiced by end users are issues with connectivity and data model standardization at the I/O and OT levels. In-depth findings from CEA primary research are presented in section 8, but trends in connectivity are important to monitor and will have bearing, particularly on the communications PIARCH.

3.2.1 Connectivity

Deliverable D4.4 provides an overview of state-of-the-art concerning Industrial Internet Reference Architectures, the IIOT Connectivity Stack Model as well as relevant core standards. The purposes of this section is not to repeat that work, but rather to focus on some specific trends that could impact the work of CPS4EU partners.

Connectivity for industrial automation and networking is longstanding, but traditionally followed a separate path from traditional IT networking technologies. Communication relied on a variety of protocols at the device (sensor/actuator) level, particularly 4-20 mA wired loops, and at the PLC/SCADA level, with field bus networking architectures such as Modbus or Profibus.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

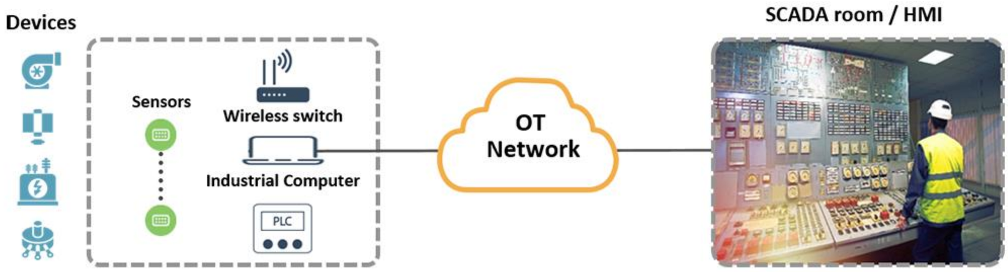


Figure 14 – A typical industrial control system

Today, several new protocols are emerging for industrial connectivity, with implications for PIARCH interfaces destined for industrial applications. Specifically, as noted by analysts at IOT Analytics[13], IO-Link has fast become an important standard for point-to-point sensor/actuator networking. Though IO-Link has limitations in terms of distance (<20m), standardization efforts exist to combine the IO-Link message structure as part of the payload of a standard Ethernet frame, thereby extending the potential of IO-Link.

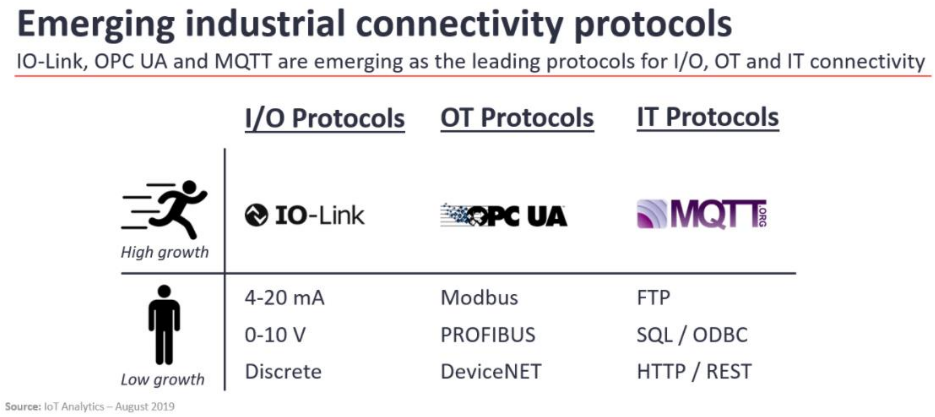


Figure 15 – Emerging industrial connectivity protocols

As described by engineers, including from Pepperl+Fuchs AG, one option in development is IO-Link over SPE (Single Pair Ethernet)[14].

Perhaps of more relevance to the connectivity PIARCH is the potential impact of IO-Link Wireless. As described by Kunbus GmbH, which provides wireless IO-Link modules, the IO-Link wireless specification was first presented in 2018 in Hannover and is an extension of IO-Link at the physical level, defining wireless communication between sensors/actuators and PLC. For users, benefits exist in terms of backwards compatibility existing wired IO-Link systems. With a packet-error-probability of 10^{-9}, IO-Link Wireless is comparable to wired solutions, but better than wireless protocols such as WiFi, Bluetooth or ZigBee that are also addressing wireless sensor node applications. Using the 2.4 GHz frequency band, simultaneous operation of WLAN systems is also possible, as the IO-Link wireless technology hides occupied frequency bands.

Understanding connectivity trends at the PLC/SCADA connectivity level is also important, as connectivity is necessary between IoT gateways and SCADA systems in particular. At this level, there is co-existence between traditional field bus protocols such as Modbus, Profibus or DeviceNET, as well as the industrial Ethernet (for example PROFINET) that has made major inroads into the industrial environment. However, as noted by IoT Analytics, but also from primary research by CEA (section 8), there is a growing importance of OPC UA (for Open Platform Communications Unified Architecture) as a middleware solution.

13 https://iot-analytics.com/5-industrial-connectivity-trends-driving-the-it-ot-convergence/
14 https://profinews.com/2020/09/io-link-vs-ethernet-or-io-link-over-ethernet/

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

OPC UA, released in 2008, is a platform-independent middleware, with a service-oriented architecture that integrates all the functionality of the individual OPC classic specifications into one extensible framework, with the following design specification goals:

- Functional equivalence: all COM OPC Classic specifications are mapped to UA
- Platform independence: from an embedded micro-controller to cloud-based infrastructure
- Secure: encryption, authentication, and auditing
- Extensible: ability to add new features without affecting existing applications
- Comprehensive information modeling: for defining complex information

Finally, at the messaging layer, several new standards have emerged, but the two most important are REST over HTTP and MQTT as described in Deliverable 4.4. REST (for Representational state transfer) was built as an extension to HTTP, operating as a web service, and is commonly used for IoT applications. One potential downside of REST as a client/service protocol is that the client and server need to be on the same network, which can create security issues when devices are behind a firewall. MQTT is a lightweight publish/subscribe messaging format in which both the source and the user communicate with an intermediate broker, meaning it will support devices being behind a firewall.

MQTT is an always connected protocol (versus intermittent REST calls), which can provide advantages if connections are maintained for sending multiple messages as opposed to connections being set up and torn down frequently. Analysis from IoT Analytics but also a developer survey by Benjamin Cabé[15] (Microsoft and the Eclipse foundation) suggest that MQTT is becoming the dominant messaging protocol.

According to IOT Analytics[16], the Global Industrial Connectivity market amounted to around 42 B$ in 2020 and is estimated to grow at 5% a year reaching 51 B$ in 2024. In addition, they estimate that 2020 was the year in which around 50% of the factory assets were connected. Included in industrial connectivity are hardware, software and services, though today industrial connectivity hardware (gateways, PLCs, and remote I/O modules) is by far the largest category though the report sees higher growth of both software, services and complete solutions in the future.

Several reasons for the connectivity trend toward software and services exist, but among them are:

- The ability for IoT edge connectivity devices, with either inbuilt sensors or connecting to legacy sensors and PLCs, to bypass the traditional 5-layer industrial automation stack to provide data directly to dedicated IoT platforms or to the Cloud. These edge devices integrate with standard Ethernet networking (including using power over the Ethernet) or with one of the plethora of newer wireless protocols—cellular (LTE-M, NB-IoT), WLAN, BLE, as well as LPWAN technologies like LoRa—making this transition easier.

- Secondly, trends seen in IT, data-center and telco networking have also migrated to industrial automation, namely the decoupling of hardware and software, with bare metal PLCs and hardware agnostic automation software, notably Linux based. Key examples here are CODESYS an IEC 61131-3 compliant software-based PLC and Node-RED.

15 https://blog.benjamin-cabe.com/2018/04/17/key-trends-iot-developer-survey-2018
16 https://iot-analytics.com/5-industrial-connectivity-trends-driving-the-it-ot-convergence/

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

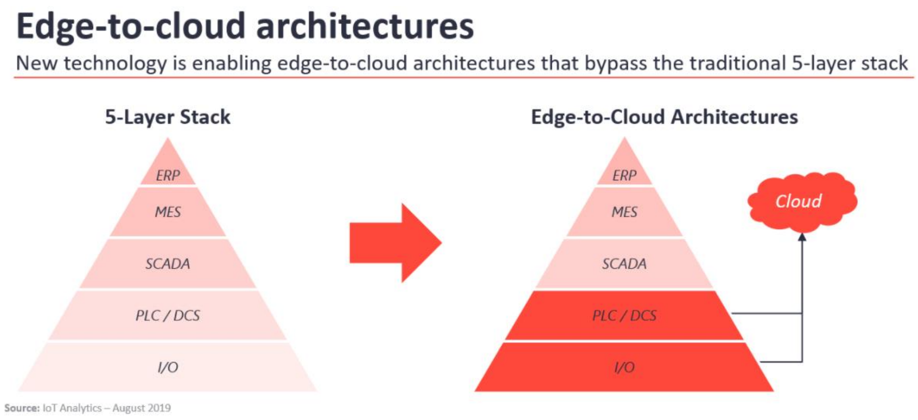


Figure 16 – Bypassing the traditional 5-layer stack

As a result, the traditional 5-layer stack is becoming more blurred and is being replaced by different modules, with different levels of integration that can provide similar overall functionality.

3.2.2 Sensing

The trend toward multi-sensor integration (or sensor fusion) is longstanding and today domain-specific sensor pre-integration is quite widespread. Notable examples with relevance to the field of industry 4.0 are the following:

- In air quality monitoring systems where multiple gas sensors combine with temperature and humidity sensors.
- Condition-based monitoring for machines or as input to digital twins, where the pre-integration of sensors including vibration, tilt, shock, temperature, magnetic field, acceleration and gyros is becoming relatively commonplace.
- Other condition-based monitoring combinations (for example, from Balluff) include vibration, temperature, relative humidity and pressure.

As the notion of creating digital twins increases, the idea that certain combinations of sensors would become standardized is certainly possible.

Alongside this horizontal integration sensor, we can also observe vertical integration as sensor companies make their sensors more easily integratable with IoT platforms and indeed in some cases create their own IoT platforms. Of course, sensor companies have been making wired and wireless transmitter products for many years, but today the integration extends to creating IoT gateways around their sensor products and interfaces for application development.

One example in this respect is the Sensor Integration Machine (SIM) from SICK GmbH. Powered by a dual-core ARM Cortex-A9 CPU with NEON accelerator, the SIM provides sensor / camera processing and IoT gateway functionality in a single device. Ethernet connectivity for cameras and LiDAR sensors combines with an IO-Link Master to connect other sensors. Finally, SICK provides SICK AppStudio, a software tool for developing customer-specific applications on programmable SICK devices. Supported programming technologies include a graphical Flow Editor and Lua script for creating SensorApps.

With the ease of creating Cloud-based IoT platforms and the potential of IoT connectivity, many sensor makers (including smaller companies) have gone further along the value chain by creating monitoring platforms and dashboard analytics services.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

3.3 *Industry 4.0 architectures & their evolution*

Deliverable 4.4 provides an overview of state-of-the-art concerning Industrial Internet Reference Architectures. Nevertheless, it is also worth looking at reference industry 4.0 architectures from the standpoint of physical infrastructure in order to orient the related PIARCH developments. The reference architecture from IBM provides a physical view of the different constituents. In IBM's view, the architecture straddles three potentially distinct locations: the Edge (in reality, the factory floor), the plant and the enterprise. At each point, the IoT platform communicates with three distinct user types: the operator, the plant manager (including integration with plant-specific applications like MES) and the Enterprise manager, and with integration with enterprise-wide application software, including ERP/HR and so on.

Focusing on the edge layer, the reference architecture makes distinct two specific layers with implications for CPS4EU. The first is the discrete device node (a sensor/actuator, machine tool or CPS) and the second is the IoT gateway that acts as a kind of industrial hub or router for connectivity towards the plant. Both of these physical devices require device management (including device security), connectivity, and potentially processing/analytics.

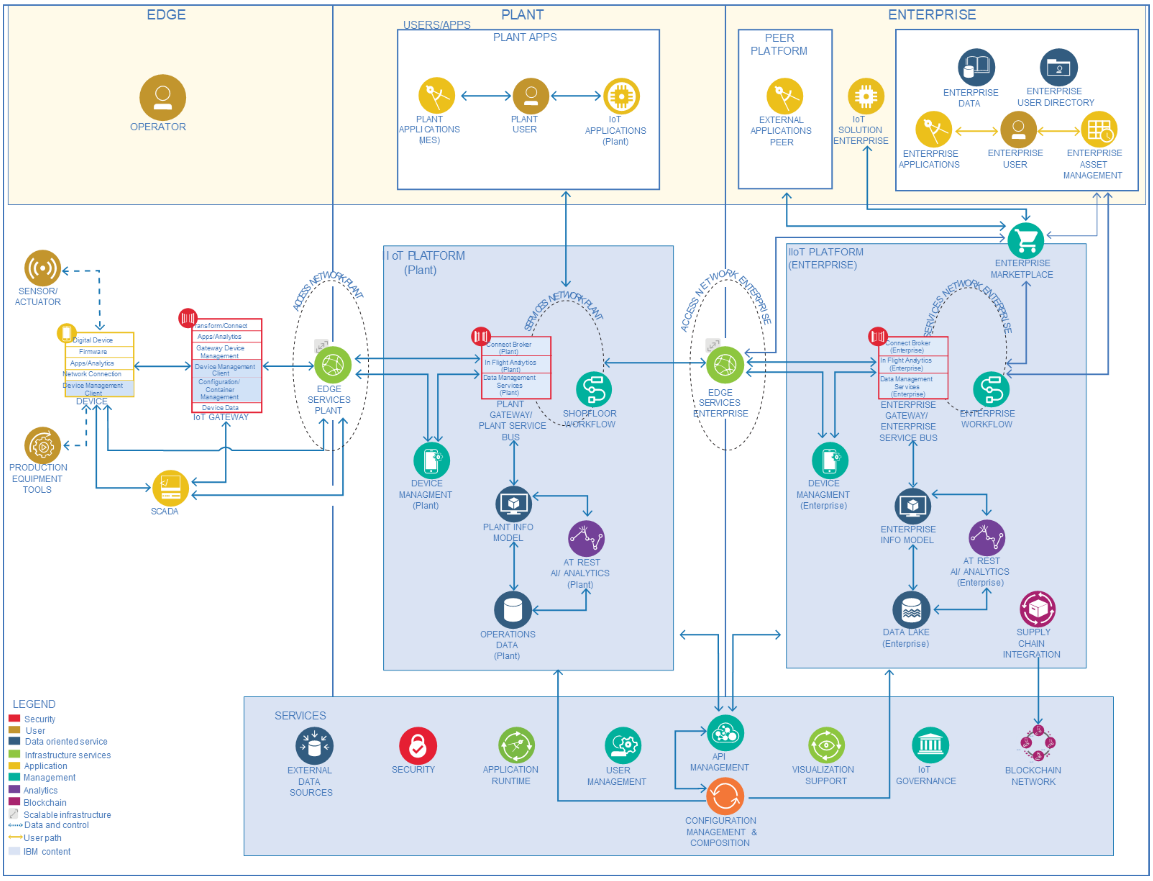


Figure 17 – IBM's three-tier IoT reference architecture for industrial IoT

In effect, the architecture acknowledges that processing requirements may exist all the way down to the sensor node level, or anywhere in between the sensor node and the Cloud. As communications latency becomes more of an issue (for example, for real-time optimization applications), processing requirements will be pushed downward from the plant level to the IoT gateway or even to the device node.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

3.3.1 IoT Gateways

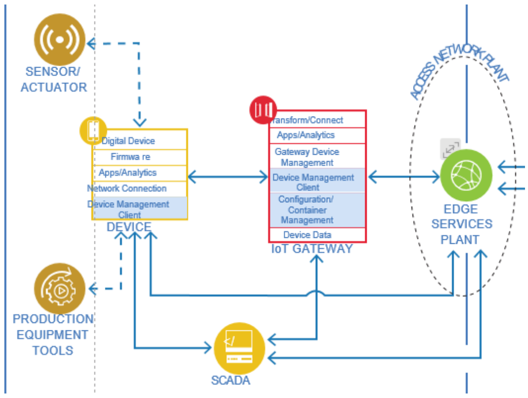


Figure 18 – Expanded view of IoT Gateway

An IoT gateway provides a connectivity hub for sensor device nodes and connected machines as well as northbound connectivity and security to the SCADA (HMI/dashboard) as well as with the rest of the plant. The IoT Gateway may also act as an industrial PC providing PLC functionality and thereby replacing existing PLC hardware.

Other functionalities would include OT and I/O protocol support, protocol conversion for messaging, such as to MQTT, as well as support for device authentication, end-to-end security and protection from cyber-attack.

Connectivity requirements affecting the communication PIARCH will obviously be on a use-case-by-use-case basis as noted in deliverable D2.1, but will also need to take account of the I/O connectivity trends noted earlier. For example, if the connectivity with I/O devices was through an IO Link master transceiver (physical layer), typical interface requirements would include UART at the very least.

Most IoT gateway vendors provide various communication interfaces, with several coming as standard, notably Ethernet, WiFi and/or Bluetooth, with optional 3G/LTE support via PCI expansion cards. Of note is that in industrial settings, as opposed in wider IoT markets, the environments are still primarily wired, and therefore interfacing with wired LAN networks is standard. The table below provides data on some typical industrial IoT gateways from several vendors and their support of different connectivity standards.

Vendor	**Built in connectivity**	**Optional/expansion slots**
Advantech (WISE 3620)	Ethernet, WiFi	3G/LTE
Dell Edge Gateway 5100	Ethernet, USB, WiFi, BLE, 3G or LTE	CANbus card Wireless mesh modules: IEEE 802.15.4 ZigBee/6LoWPAN combo module.
HP Edgeline EL20	Ethernet	WiFi; 3G; WiFi/Bluetooth
Huawei AR510	Ethernet, WiFi, 3G/LTE	
Telit Smart IO	Ethernet, WiFi	Cellular

Table 2 : IoT gateway vendors and their connectivity options

Of course, many such vendors provide different connectivity customization, but it is important to note the focus on wired Ethernet connectivity, as well as WiFi in industrial settings. This focus is already taken into consideration in the configuration of the central board for the connectivity PIARCH. The addition of Bluetooth within the central board also seems correct given what we have seen in recent trends in wireless sensor connectivity, noted both above and in section 7, but also in recent IoT gateway market research.

In Global Market Insights latest IoT gateway market report[17], the company estimates the global market for gateway devices at 9 billion$, with a growth rate of 14% from 2020 to 2026 reaching more than 16 billion $. Of this global IoT market, industrial IoT is the dominant segment representing about 34% of the market, the other two major segments being automotive/transportation and healthcare. The report points to increasing adoption of Bluetooth in industrial IoT gateways as the technology is used for machine-to-machine communication.

The table above is not exhaustive, but of note is that few of these industrial IoT gateways integrate LTE-M or NB-IoT. Of course, such connectivity is available from IoT vendors, but as defined in the connectivity PIARCH it would

17 https://www.gminsights.com/industry-analysis/iot-gateway-devices-market

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

seem to make sense to have this connectivity as a separate module that may or may not be pre-integrated. From an industrial standpoint, the integration of wireless mesh networking may also make sense.

In particular, standards like IEEE 802.15.4 are not only the basis of ZigBee, but also of wirelessHART, an important wireless industrial sensor-networking standard. Support for wireless HART comes from vendors including ABB, Emerson, Endress+Hauser, Honeywell, Pepperl+Fuchs and Siemens and these companies also provide IoT gateway products based on the standard.

From a modular connectivity perspective, worth noting is how connectivity module vendors, but also companies providing embedded wireless modules and design-in services for IoT platforms, segment their offerings. For example in the wireless design-in services from Advantech, connectivity options (mostly in the form of PCI-e boards) show similarities to the PIARCH configuration between the central board and further wireless extension modules.

Figure 19 – Advantech wireless design-in services with embedded connectivity modules

As discussed further in section 7, Sierra Wireless offers a range of communications modules for IoT connectivity in a CF3 (common flexible form factor) format allowing flexibility and scalability[18]. The table below shows modules available as well as additional interfaces.

CF3 module	Wireless connectivity	External I/O
BX3105	WiFi, Bluetooth & BLE	Ethernet, SPI, UART, I2C, GPIO,
HL7702	CAT M1 / NB1 (GPS/Glonass)	UART, USB, GPIO, SPI, I2C, GPIO
WP7607-1	LTE Cat 1 (Optional GPS/Glonass/Galileo)	UART, USB, SPI, I2C, GPIO
WP7607	LTE Cat 4 (Optional GPS/Glonass/Galileo)	UART, USB, SPI, I2C, GPIO

Table 3 : Sierra Wireless CF3 connectivity modules

The interface listing is not exhaustive, but common interfaces for peripheral support are UART, SPI, and USB.

18 https://www.sierrawireless.com/products-and-solutions/embedded-solutions/

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

3.3.2 Edge computing including Edge AI

The mapping of computing tasks for industrial IoT applications will dictate requirements for the compute PIARCH. Industrial PCs have long been used for many of the applications noted in table 1, including predictive maintenance and especially real-time optimization tasks or advanced process control and so the need for edge computing (at some point on-premise) is clear, even if the precise mapping of the computing tasks is not.

Differences with the past may include the way in which the Cloud enables process data to be shared across multiple sites, provides support for enterprise-wide dashboards and allows Cloud computing resources to be used for off-line big data analytics, including performance management. For example, in IoT platforms supporting manufacturing process management, such as GE Predix, it is clear that there is a strong focus on running Cloud-based subscription models, while acknowledging the importance of on-premise computing for real-time data.

Predictive maintenance is one of the most important applications for edge analytics. As noted in documentation for Cap Gemini's predictive asset maintenance solution[19], Gartner predicts that by 2022, spending on IoT-enabled predictive maintenance will increase to $12.9 billion, up from $3.4 billion in 2018.

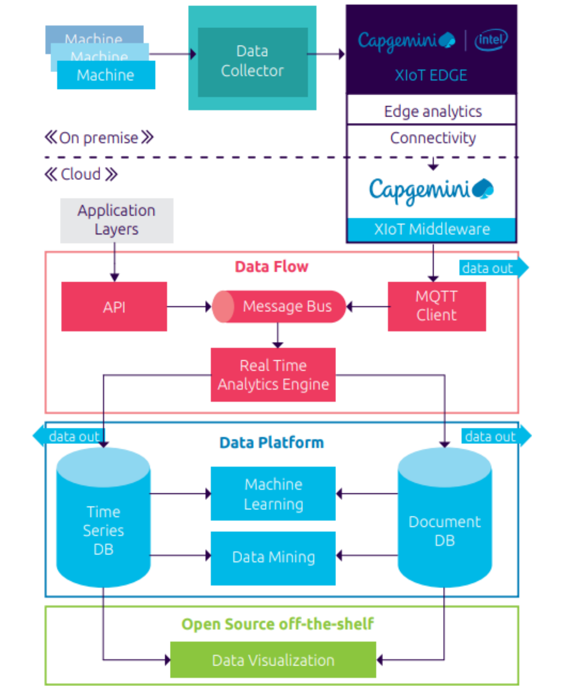
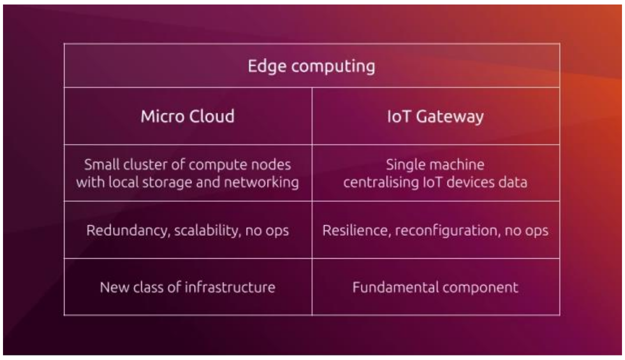


Figure 20 – Cap Gemini predictive asset management

In Cap Gemini's solution, computing is divided across both the edge and Cloud. At the edge, Intel-based processors analyse data in real-time and recommend precise responses and actions, predicting when a machine or device failure might occur or when maintenance is required. Predictive and pre-emptive models are run on a "real-time" analytics engine in the Cloud that interfaces with a data platform running data mining and machine learning on historic datasets

On-premise (edge) computing says relatively little about location in the context of industrial IoT and there are trends toward a further split in edge computing between micro clouds and IoT gateways. In its predictions for 2021 Forester noted that the "Edge is the new Cloud" making reference to the fact that as part of the continuum of computing from edge nodes to the Cloud passing through the "Fog", edge computing is likely split between what are sometimes termed micro clouds and IoT Gateways.



Edge computing	
Micro Cloud	IoT Gateway
Small cluster of compute nodes with local storage and networking	Single machine centralising IoT devices data
Redundancy, scalability, no ops	Resilience, reconfiguration, no ops
New class of infrastructure	Fundamental component

Figure 21 – Evolving Edge computing types[20]

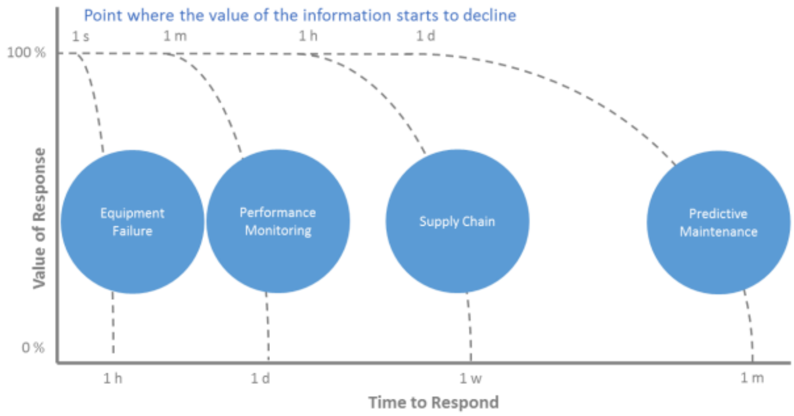
---

19 https://www.capgemini.com/wp-content/uploads/2018/12/Predictive_Asset_Maintenance_with_Edge_Compute-1.pdf
20 https://ubuntu.com/blog/edge-computing-is-dead-long-live-micro-clouds-and-iot-gateways#:~:text=An%20IoT%20Gateway%20is%20a,visualization%2C%20and%20perform%20complex%20analysis.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Advantages for micro clouds include greater redundancy due to having multiple compute nodes. Implications of the development of micro clouds from the perspective of the PIARCH (notably the compute PIARCH) are somewhat difficult to judge. On the one hand, a micro cloud with a more centralized compute architecture, though likely with hardware virtualization, might reduce the number of individual compute nodes: for example, computing embedded in wireless sensors or IoT gateways. On the other hand, a micro Cloud might have a greater need for more heterogeneous computing resources.

As noted by the Industrial Internet Consortium, specific use-cases will define the needs for compute and latency requirements, needs for redundancy and so on that will dictate the need for the physical location of compute resources as well as appropriate communications protocols.



Source: Industrial Internet Consortium

Figure 22 – Impact of latency for different IIOT functionalities [21]

Regarding specific low-latency, high-performance computing initiatives at the Edge, particularly notable is Nvidia, which in 2019 launched Nvidia EGX for Edge AIoT (Artificial Internet of things). At the lower TOPS end of the scale, the EGX range starts with the Nvidia Jetson Nano GPU that targets low-power applications for AI inferencing and image recognition.

Many of the organizations providing edge computing and IoT connectivity (gateway) solutions have incorporated Nvidia EGX into specific smart products with a focus on AI smart cameras and robotics. For example, ADLINK, a company that is discussed further in section 7 for its development of heterogeneous computing platforms and has a range of MXM and PEG format embedded GPU products, has created both edge AI (computing) platforms and a range of forward-integrated AI-integrated smart cameras[22].

Of course, integration of AI inferencing for image recognition has already begun among video surveillance and network-camera industry leaders including Axis Communications, Honeywell, Motorola, Panasonic and Sony, where edge computing (and specifically on-device computing) is seen as necessary given latency requirements, but the technology is clearly starting to democratize for industrial IoT.

3.4 *Robotics 4.0*

Many of the examples of CPS in industrial IoT applications are linked to advanced automation of traditional machine hardware, but robots represent a specific form of dedicated industrial CPS. Robots represent a specific class of CPS, but similar issues of modularity, interoperability, M2M communication standardization, and SDK for application development apply, particularly as robots move toward to more advanced collaborative activities, including human-robotic collaboration, often called Robotics 4.0 as described by Gao et al.[23] with features including Cloud robotics, AIoT and distributed computing, storage and intelligence.

21 https://ubuntu.com/blog/edge-computing-is-dead-long-live-micro-clouds-and-iot-gateways#:~:text=An%20IoT%20Gateway%20is%20a,visualization%2C%20and%20perform%20complex%20analysis.
22 https://www.adlinktech.com/en/adlink-gpu-solutions
23 https://www.sciencedirect.com/science/article/pii/S235197892030963X

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

However, issues of interoperability and collaboration in robotics are acute given that they have been rather closed environments until relatively recently, dominated by proprietary programming languages from the major manufacturers, and certainly much more closed compared to the open-source dominated worlds of machine learning and AI.

In their review of industrial robots from 5 leading vendors (ABB, Fanuc, Kawasaki, Kuka, Yaskawa) , including the extent to which they approximate to the idea of a true CPS platform development, Mikusz et al.[24] describe a number of features common to the industrial robot that are relevant to CPS4EU PIARCH destined for industrial settings.

- A typical set of common internal sensors, including proximity, angle and rotation, temperature, with additional application-specific sensors, such as force and torque.
- Proprietary programming languages are common, with very limited SDKs for add-on development. ABB is one company that provides its RobotStudio, a SDK allowing creation of custom applications, as well Robot Web Services.
- Support for programming robot controllers via 3rd-party automation controller software as well as those using CODESYS.
- Support for interoperable data exchange via the OPC UA protocol
- Specific collaboration features for multi-robot interaction including motion coordination, collision-detection and collision avoidance.
- At the time of the article (2015), only ABB had made steps toward a more modular software architecture.

Though industrial robot interoperability is supported via OPC UA middleware, in the robotics industry in general, OPC UA and DDS (data distribution service) middleware compete. While OPC UA is key for industry 4.0, DDS is in use prominently in defense (as noted in the section below), in professional robotic industries (healthcare, warehouse automation) and in the automotive industry. Calls have existed to unify the two standards and the Object Management Group published OPC UA/DDS Gateway standards in 2020[25]. Both OPC UA and DDS have expanded to encompass Time Sensitive Networking standards and are now able to support real-time communications.

In the face of very limited modular software or the lack of ability to design new applications for robots (robots have largely remained task oriented), the ROS-Industrial program developed the Robot Operating System to provide ROS interfaces to many different kinds of industrial equipment, including PLCs, Robot Controllers, Servos, Human Machine Interfaces and IO Networks.

Section 5 provides an overview of the ROS stack, but it should be noted that robotics vendor support for ROS is relatively limited, with ABB being a notable exception. Supported hardware includes offerings from ABB, Kuka and Fanuc, but software remains at the development stage. In December 2020, at the recent ROS-Industrial Conference, ABB introduced a new ROS driver for ABB robots. The driver, which is now available on GitHub, is designed to ease interaction between ABB robot controllers and ROS-based systems by providing ready-to-run ROS nodes.

3.5 *Summary and PIARCH impacts*

Underlying I/O and connectivity protocol issues remain important for deployment of industrial CPS, particularly with regard to integrating legacy systems, but increasing standardization is underway (I/O Link, OPC UA) as well as the availability of protocol conversion middleware running on IoT gateways. In terms of IoT gateway connectivity, one should remember that wired communications remains very important within industrial automation. Wireless modules defined within the communications PIARCH seem to be in line with industry developments (for example, Sierra Wireless CF3 modules), though interface support in the latter appears wider.

One potential trend from a physical architecture standpoint is the development of micro Clouds. This trend would in effect recreate a Cloud architecture at the edge with potential impacts for IoT gateways. Trade-offs clearly

24 https://aisel.aisnet.org/pacis2015/176/
25 https://www.omg.org/spec/DDS-OPCUA/About-DDS-OPCUA/#document-metadata

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

exist between the two in terms of scalability, flexibility, resilience and redundancy, but there could be implications for the computing PIARCH in terms of the distribution of computing resources.

4 CPS for the Smart Grid

4.1 *Smart grid industry background*

A Smart Grid is a **wide-area cyber-physical system**: it involves many stakeholders, from generator to distributor and prosumer in an interconnected world of social, economic, and technological environments. The increasing complexity and connectivity between components such as smart meters, solar panels etc. requires rethinking of how to analyze and design the CPS aspects of the Smart Grid (SG).

The Smart Grid is an ecosystem, which will heavily rely on (real-time) information acquisition (monitoring), assessment and decision-making as well as management (control). There are peculiar characteristics of power systems, which pose new challenges to CPS: **time-critical**, **highly connected components** to work together in **real time** to achieve system stability, well-regulated voltage and frequency, and **fast response** when new energy needs are demanded.

4.1.1 Current trends

Many traditional parts of the Smart Grid are increasingly CPS dominated [1]:

- In <u>generation</u>, CPS control the connection to the network as well as the operational aspects in the electricity generation side such as solar and wind parks, hydro facilities etc. For instance, **SCADA** are responsible for monitoring and control of power plants.
- In <u>transmission</u> and <u>distribution</u> networks, CPS monitor their conditions and cares for their stability. CPS e.g. **substations, smart meters, concentrators**, **intelligent field devices** etc. are used to manage bidirectional communication.
- On the <u>customer side</u> e.g. in homes, commercial/industrial buildings and infrastructures, CPS manage the energy as well as other automations (e.g. air flow, temperature etc.). For instance, **smart meters** control and measure the flow of electricity. With the emergence of electric mobility and the distributed installation of small-scale generators (e.g. solar panels) the Smart Grid <u>prosumer</u> (producer and consumer) will heavily depend on CPS. Additionally CPS are used to fine-tune the connection as well as the information exchange among the various entities.
- On the <u>operation side,</u> CPS is used increasingly for monitoring, reporting, controlling and supervision.

4.1.2 Future challenges and needs [2]

- Parts of the Smart Grid will be managed by **safety-critical** applications: Automatic tools that do the model checking as well as detect potential safety-critical issues on large-scale multi-dimensional applications will be needed.
- **Multi-domain interactions** and constraints will need to be satisfied at several layers: CPS will have additionally to both support computational as well as physical requirements.
- **Services and applications** will be developed and maintained by **different entities**: Modelling, risk analysis and impact assessment tools for complex systems will be needed.
- **Scalability** and component/layer independent evolution will be necessary: Standardized abstractions among the various layers and open architectures are needed. Additionally it should be possible to use highly configurable components and combine them with guarantees e.g. with respect to performance, safety, dependability etc..
- **Mobility** is a prominent issue in Smart Grids. It is expected that in the future any device that consumes or produces energy will be able to provide this information for others to use: It will be the role of the infrastructure to appropriately support mobility at all layers.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- **Security and Privacy** are potential strong impediments to the CPS Smart Grid since user actions can be monitored or devised from the data. Additionally, the power grid is a critical infrastructure and extra precautions need to be taken to prevent highly sophisticated attacks.
- Assessment of the **huge amounts of data** generated by the Smart Grid will be challenging and require significant processing power, such as multi-core and GPU computing.

4.2 *Smart grid architectures & their evolution*

Service Oriented Architecture (SOA) and Multi Agents (MAS) architecture are promising techniques for realizing smart grid systems. In both cases, smart grid components can be monitored and controlled by an autonomous software component, being either an agent in the MAS sense or a service in the SOA sense [3].

MAS is a popular architecture designed for larger scale distributed, decentralized SCPS (Self-Management CPS). Every subsystem (agent) in MAS is an autonomous system that can make its own decisions based on local context, although these decisions generally are very simple due to the limited resources. Compared to SOA, a MAS-based decentralized solution needs many fewer resources and it has higher robustness and faster response time (even though responses may not be optimal). In generally, MAS is more suitable for large-scale geographically distributed systems, especially those whose subsystems have limited resources [4].

4.2.1 Multi-Agent Systems (MAS)

As mentioned, MAS seem to be a promising approach to provide the **scalability, adaptability and robustness** needed for a reliable Energy Management System, judging by the significant amount of work using this paradigm we see in the literature[5]. In this paradigm, an agent is merely "a software (or hardware) entity that is situated in some environment and is able to autonomously react to changes in that environment." The environment is simply everything external to the agent[6].

An intelligent agent processes several characteristics: **reactivity** (ability to learn the environment and act), **proactiveness** (self-initiative to meet expected goals), and **social ability** (negotiating and cooperating with other agents). Each agent has set goals to perform at a specified **time-period**. Agents are classified into many types based on the type of operation such as **control agent, distributed agents, monitoring agent, centralized control agent, data base agent, etc…[7]**

These agents in a smart grid environment sense, communicate, collaborate and act with each other; they can act autonomously or semi-autonomously, with local or global information[8]. The figure below shows the implementation of an agent consisting of a SEL-735 as a sensor and a Nuvo-1000 as a computation unit [9][8].

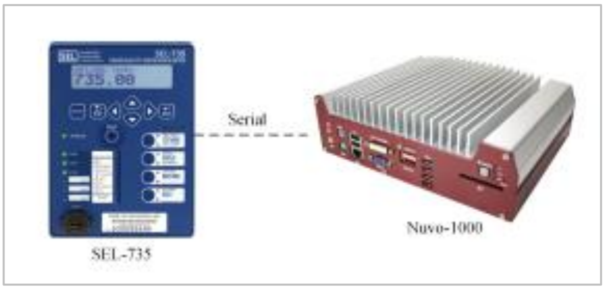


Figure 23 – Agent implementation

4.2.2 Use case: MAS for microgrids

Microgrid (MG) systems aggregate many DER (Distributed Energy Resources) and loads together as an autonomous entity. There has been considerable research into the MAS-based microgrid control systems in the literature. The proposed control scheme [10] is applied to Korea Power Exchange's Intelligent Demand Response Program. It consists of two layers of decision-making procedures:

- In the bottom layer, intelligent agents decide the optimal operation strategies of individual microgrid entities such as Battery energy storage systems (BESSs), backup generators and loads.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- In the upper layer, the central microgrid coordinator (MGCC) coordinates multiple agents so that the overall microgrid can match the load reduction requested by the grid operator.

In the proposed microgrid control system, sufficient intelligence of individual agents is a significant factor for the overall performance of the system. In addition, good coordination of multiple agents is significant as well. The agents use artificial intelligent algorithms such as fuzzy-based expert systems to attain maximum benefits from the task. The MGCC decides the overall operation scheme for a microgrid after receiving the bids from the agents.

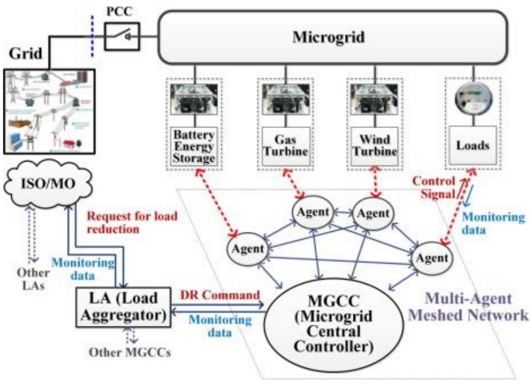


Figure 24 – Configuration of multi-agent based MG energy management

4.2.3 Use case: MAS for Power Distribution Systems Automation

The proposed control scheme [11] has been illustrated by the use of simulation case studies for fault location, isolation and restoration on West Virginia Super Circuit (WVSC) and hardware implementation for fault location and isolation in a laboratory platform.

There are three types of agents in the proposed MAS, i.e., Zone Agent (ZA), Feeder Agent (FA) and Substation Agents (SA). These agents are intelligent units that have problem solving capabilities and can communicate, resolve, coordinate and debate with other agents and make decisions.

- Zone agents are the lowest level agents, which are in contact with their neighbors. The physical switch at the top of each section represents the corresponding ZA.
- Each feeder agent is in charge of a number of zone agents and communicates with the other feeder agents. When FA is provided with the fault location by ZA, it starts negotiation with potential alternate sources and decides whether to solve the optimization problem or use the learning model solution.
- Substation agents just have a communication link to their feeder agents and also neighbor SAs. The role of the SA is to negotiate with other SAs in case there are feeders, which have tie switches to faulty zones and provide the required data for restoring decision-making. They also can operate as a backup FA.

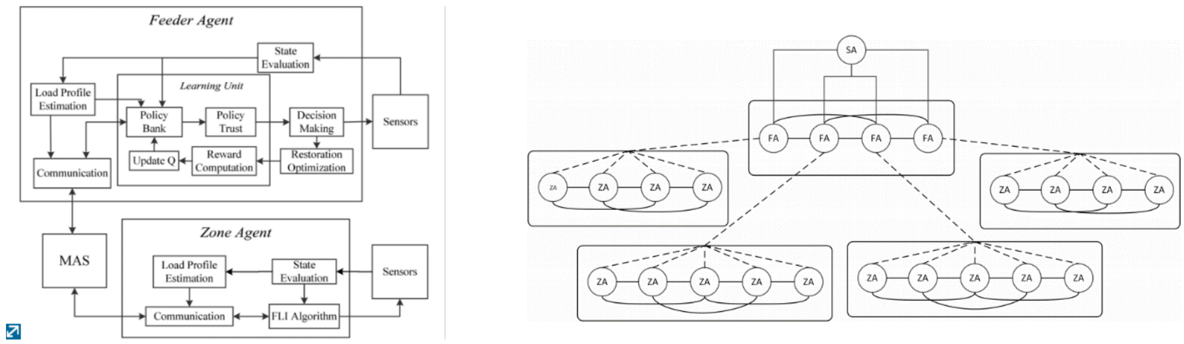


Figure 25 – MAS structure

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

4.3 *Summary and PIARCH impacts*

Multi-agent systems are a promising approach:
MAS architectures seem to be more popular than SOA for large scale distributed, decentralized CPS like smart grid. Such a method has already been adopted in SG applications, for microgrids control or power distribution systems automation, as shown earlier.

Many types of agents exist:
Agents are classified into many types, depending on the type of operation to perform in a dedicated application, with many different requirements (computing resources, communications links, time scales…). Agents can be software (or hardware) entity, implementing sensors and computing units and using artificial intelligent algorithms.

A reliable communication system
In multi-agent systems, synchronized real-time information is a key factor for reliable control of power distribution systems. Hence, it is critical to define the communication requirements and design the reliable, secure and cost-efficient communication system. MAS require a two-way reliable communication with guaranteed quality of service i.e. low latency and sufficient bandwidth.

Different time scales at different layers
Control strategies for SGs can be divided in three layers (economic & planning, cyber, physical & operations), each of which requires different time scales to impose controls, from millisecond response for transient controllers to minute responses for smart meters in the cyber layer.

Autonomy and distributed intelligence
Every subsystem (agent) in MAS is an autonomous system, and distributed decision support is key in making SGs more responsive to user demands. Control mechanisms distributed with local agents enable lower communication needs. Individual devices, with a computer to process information locally, only pass on critical information to the upper level. Grid or local computing can be adopted as future computation platforms, to synthesize and harmonize various subcomputing tasks within local computing facilities.

Several layers of decision-making
Each level can make decisions and the upper levels are responsible for global coordination and overall operation. This approach gives higher robustness and faster response speed.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

5 CPS for defense applications

This chapter is focused on the defense industry, chosen because of the importance it places on developing strategies to implement interoperable subsystems. Indeed, the path to interoperability usually starts with the choice of a high-level architecture standard. The following explains how the standards and the technical information they support allow the industry to propose pre-integrated modules.

As part of this section, and in order to get feedback about the PIARCH approach, we spoke to Milrem Robotics. Milrem Robotics, based in Estonia, is the leader of the project consortium iMUGS (Integrated Modular Unmanned Ground System) composed of several major European defense, communication and cybersecurity companies and high technology SMEs. The European Commission sponsored project aims at developing the European standard unmanned ground system (UGS).

5.1 *Defense industry background*

Interoperability is a growing quest for defense and security equipment. Indeed, many missions now imply the use of multiple command and control systems – it could be for ground control stations managing Remote Operating Vehicles, Land Platforms that need to integrate new functionalities, etc.

5.1.1 Key trends and industry needs

The ultimate goals of the defense agencies are to facilitate technology insertion (upgrade, update, replace, repair, remove and addition) and reduce cost of ownership. Agility is sought, for example in order for vehicles to be quickly re-configured for different roles: new sensors to install on vehicles to counter the development of threats. This installation can be done quickly if the sensors are plug and play for instance.

Historically, the approach of defense procurement agencies (DPA) was relatively basic. First, a major program was defined, around the need for a specific system (vehicle, aircraft, ship, etc.). A prime systems integrator (SI) was selected to deliver the system through a call for tender. The prime SI was responsible for systems integration and timely delivery. Contracts were usually tied to throughout-life maintenance and management.

With system lifecycles often extended across multiple decades, such contracts were becoming an issue and both DPAs and SIs struggled to sustain the supply chain for multiple proprietary vehicle designs.[26] In addition, there is limited commonality in subsystem supply or opportunities for economies of scale for the DPAs across their multiple vehicle procurements, factors that drive up costs, as each vehicle is essentially a one off.

In recent years, the proliferation of flexible unmanned systems (ground, underwater, aerial) and the control systems that accompany them (placed within a single command & control system), raised issues concerning interoperability. For end users, it is essential to develop the ability to command and control multiple unmanned vehicles as well as other sensors and to deliver complex services (such as automatic asset tasking, mission planning and re-planning or 3D representation of threats to name a few) using the same systems and environments to rationalize costs and improve efficiency. This ability enables future upgrades to be carried out in a cost effective manner, with the reuse of selected command & control components that can come from multiple vendors.[27]

One of the first players to embrace this issue was the UK MoD (Ministry of Defence). Around 2010, it imagined the Generic Vehicle Architecture (GVA) approach based on established systems engineering principles, in which the GVA defines a generic architecture that requires open implementation standards to support cost-effective integration of sub-systems on land platforms (electronically, electrically and physically). With this approach, the MoD raised the bar for systems of systems integration management by initiating a shift in perspective regarding collaboration between DPAs and SIs.

This collaborative approach was followed by other defense agencies and now in the defense sector, there is a high flow of collaborative projects aiming to develop modular and scalable architectures for hybrid systems.

---

26 https://www.army-technology.com/
27 www.camelot-project.eu

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

The following paragraphs present the major independent functions considered as a “PIARCH” – a subsystem independent and interoperable – and the approach used by the defense sector players.

The different functions usually found in defense system architecture				
Communication and connectivity	Sensors	Communication equipment / encryption	Computing power	Autonomy

Table 4 : Typical defense system architecture functions

An additional paragraph is also focused on robotic applications – although it is not specific to the defense ecosystem, many military projects involve such applications.

5.1.2 Technologies trends relevant to CPS

The term CPS (cyber physical system) does not appear in the defense or security sectors. Yet, as mentioned before, autonomous systems are a key trend for defense and security sector. Consequently, technology development is focused not only on autonomy, but also on the interoperability of the systems. If we refer to the GVA, then this approach has led to an integration by function. The communication and connectivity function has thus been the first function to be addressed.

5.1.2.1 Communication and connectivity:

To have an interface to communicate between the different equipment, payloads, etc. is a key issue from the perspective of defense players as was communicated in an interview with Milrem Robotics[28].

For this example, the **Interoperable Open Architecture (IOA) Def Stan 23.09** open standard is described – the standard results from the MoD GVA project. The MoD, QinetiQ and IBM, in conjunction with a range of collaborative partners including Selex , IVECO, Supacat; Raytheon, RTI, L3 Communications, Paradigm, MaxOrd Ballistics, Aeroflex, Hypertac, Polar Com, Smiths Detection, Allen Vanguard, Britannia 2000 , GE Aviation and many others published the standard in August 2010, with an agreed 18 month revision cycle.

- DefStan 23-09 defines physical and communications interfaces on a vehicle to allow interchange of equipment and provides definitions of the Human Machine Interface.
- The purpose of this Def Stan 23-09 is to enable the MoD to realize the benefits of an open architecture approach to land platform design and integration. This is achieved by mandating and applying the appropriate interface standards.
- Def Stan 23-09 addresses integration for the entire electrical system, everything from the automotive control systems to power management, sensors, human machine interfaces, health and usage monitoring systems, weapons and C4I. In short, anything with a processor, software and communication paradigms between subsystems is included in the GVA.

To reach this IOA, the principle lays on the consumption and production of data. Indeed, the MoD has assumed full responsibility for defining and maintaining a system data dictionary (SDD) of the complete vehicle defined on a subsystem-type basis (sensors, C4I, HUMSs, etc.), a dictionary and vocabulary for communication between subsystems. This SDD is completely open.

The MoD uses the Data Distribution Service (DDS) standard for the open-standard middleware for all data communication within the vehicle. The DDS is a middleware protocol and API standard for (see D4.4 §2.2.5 - Middleware support for self-adaptive CPS) from the Object Management Group (OMG). It integrates the components of a system together, providing low-latency data connectivity, extreme reliability, and a scalable architecture that business and mission-critical IoT applications need.[29]

The industry collaborators recommended DDS for the communication of data in a real-time environment as it ensures interoperability between independent subsystems when used in conjunction with the land data model.

28 Interview with Milrem Robotics (11/02/2021) – Markku Rautio & Silver Lätt
29 DDS foundation

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

According to Army-Technology, the decision to implement the IOA through the specification of a data model leads directly to a data-centric development approach. DDS middleware is the bus that all software systems must use for communication and control and DDS delivers the software data distribution function. DDS is now always used as the middleware for the data level as shown in the example below.

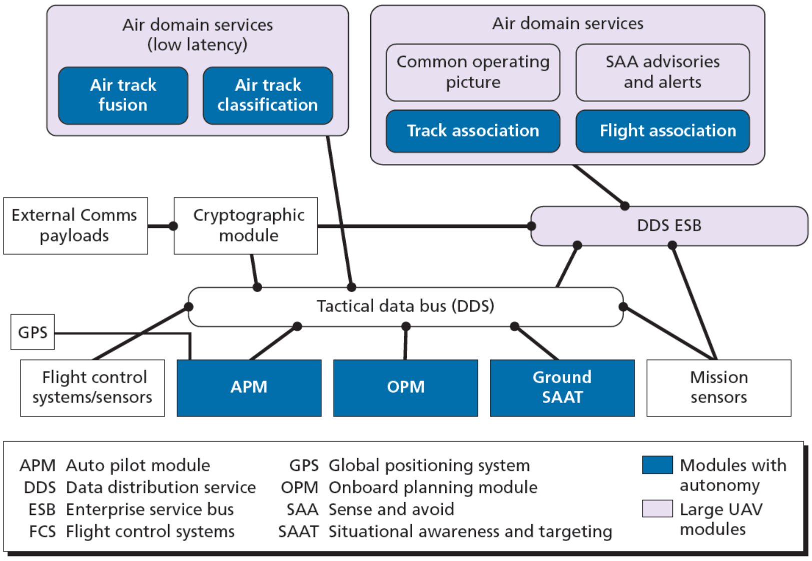


Figure 26 – Example of UAS Modular Technical Reference Model with DDS middleware[30]

GVA also defines the connectors and pin allocations for Power, Ethernet (both copper and fibre), USB and CANbus[31].

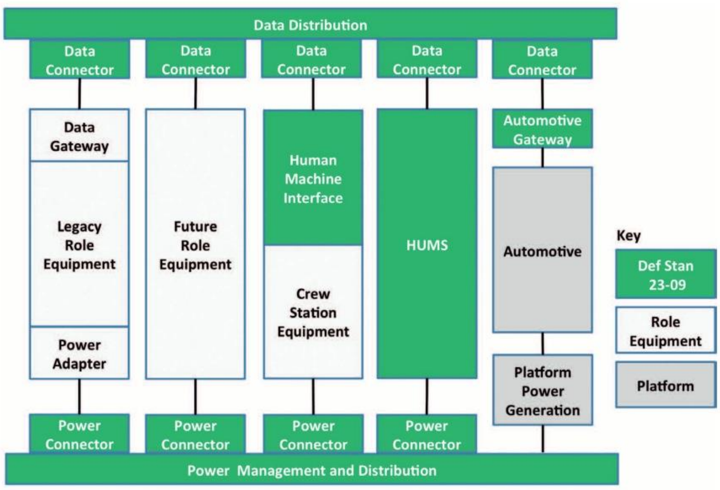


Figure 27 – GVA interfaces

30 Designing Unmanned System with a greater autonomy using a partially open system architecture approach. RAND CORPORATION, 2014
31 Ground vehicle systems engineering and technology symposium vehicle electronics and architecture (vea)- 2014

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

5.1.2.2 Sensors

There is no specific standard middleware existing for sensor interoperability. According to discussions with Milrem Robotics, this is because the sensor technologies evolved too fast in the past few years and there was no time for the sector players to set-up a standard. Yet, such a sensor standard is now in development with one of the most importance projects being the Sensor Open Systems Architecture (SOSA), which seeks to address issues such as affordability, versatility, and capabilities, as sensor systems increase in number, applications, cost, and complexity. SOSA seeks to make sensor systems rapidly reconfigurable and reusable by as many systems designers as possible.

> ***SOSA** administered by The Open Group in San Francisco focuses on single-board computers and how they can be integrated into sensor platforms. It involves a standardized approach on how embedded systems interrogate sensor data.*

Yet, even without standards, many inter-industry initiatives are increasing. The growing ease of blending a wide variety of sensors is giving rise to new generations of integrated packages with small size, weight, and power consumption; unprecedented computer and signal-processing power; and the flexibility to add new sensors to the mix with a minimum of additional integration work.[32]

ABACO chose for example to develop a compliant single-board computer to the SOSA profile (Figure 29). The SBC3511 3U OpenVPX rugged single-board computer is for high-performance command, control, communications, computers, intelligence, surveillance, and reconnaissance, (C4SR), where interoperability is necessary. It features a 40 Gigabit Ethernet data plane, delivering alignment with the SOSA profile for maximum multi-vendor interoperability[33].

Figure 28 – GVC1001 graphics, vision, and AI evaluation embedded computer (Abaco Systems).

Figure 29 – The SBC3511 3U OpenVPX rugged single-board computer from (Abaco Systems)

North Atlantic Industries in Bohemia, N.Y., have come up with a framework, called the **Configurable Open System Architecture (COSA)**, for blending off-the-shelf hardware and software in sensor and signal processing applications. COSA represents a modular portfolio of rugged embedded smart modules, I/O boards, single-board computers, power supplies, and ruggedized systems, all pre-engineered to work together and be easily changed or reused in the future. The architecture uses field-programmable gate arrays (FPGAs), and system on chip to help engineers create smart modules for configurable mission systems rapidly while reducing or eliminating embedded computing overhead.

Figure 30 – SIU36 configurable rugged embedded computing system

COSA enables systems designers to select components, and customize them in modular fashion by selecting from more than 70 high-density I/O, communications, measurement and simulation, and smart-function modules.

32 https://www.militaryaerospace.com/sensors/article/14068659/system-interoperability-for-sensors-and-sensor-processing
33https://www.automationworld.com/supplier-news/news/21205222/abaco-systems-abaco-wins-major-order-to-equip-next-generation-sosa-aligned-multifunction-processor-for-military-aircraft

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Designers can place OpenVPX, VME, CompactPCI, and PCI Express boards into rugged systems ranging in size one module to high-density systems supporting as many as 10 motherboards and 60 smart modules. Designers can build multiple payloads on the same platform without re-designing the box with interfaces to those payloads**Erreur ! Signet non défini.**.

5.1.2.3 Communication equipment / encryption

According to Milrem Robotics, software/hardware pre-integration for security/encryption functionality is something that is covered in the iMUGS defense projects with the approach of using a software-defined networking architecture, though no information has been found. This is perhaps that such functions are classified from the early stages.

5.1.2.4 Computing power

From discussion with Milrem Robotics, computing power is viewed as a priority for pre-integrated architectures to address defense challenges. Although, there is no existing interoperable open architecture, increased awareness of this topic is highly likely in the near future within the defense sector. In particular, modular integrated computing capabilities will be needed close to the sensors.

5.1.2.5 Autonomy

Various types of autonomous systems have been developed in aeronautics and space domains, involving various forms of automated reasoning. Autonomous architectures were defined by automatic planning, scheduling and diagnosis, while execution was managed by a smart executive. The **Boss architecture** for example, demonstrated by CMU (Carnegie Mellon University), combines perception, planning and behavioral executive functions in a modular and scalable software environment[34].

New collaborative projects aim at improving autonomous functions by developing fully tested Autonomy Kits (for example, the iMUGS project).

Private companies also develop autonomy kits: Rheinmetall Canada has recently released a proven autonomous kit (**A-kit**) called **PATH**, that allows military vehicles to operate unmanned even across complex terrains in hostile weather conditions[35]. PATH can be controlled by a tablet, smart watch, soldier system, or a single-hand controller and features multi-layers of protection against cyber attacks.

This autonomous driving vehicle capability currently integrated into Rheinmetall's Mission Master vehicle – it is considered to have reached **TRL8**. The A-kit provides a base software architecture. It has to be adapted to the sensor software[36], but is otherwise vehicle-agnostic and has integrated payload capabilities.

---

34 Christopher R. Baker, David I. Ferguson, John M. Dolan (2008). Robust mission execution for Autonomous Urban Driving, Intelligent Autonomous Systems 10, 2008
35 https://www.edrmagazine.eu/
36 https://www.qut.edu.au/institute-for-future-environments/about/news?id=169476

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

5.1.2.6 *Specific case of robotic applications*

For some systems requiring robotic functions, the Robot Operating System (ROS 1 & ROS2) is used. It is an open source set of software libraries and tools for building robot applications. The ROS framework simplifies the creation of robotics research applications; it includes a rich ecosystem of visualization tools and functional packages, and has support for many types of robotics components[37]. ROS 2 was designed from the start to use the best available technology for the system interconnectivity. ROS2 is based on the open-standard Data Distribution Service (DDS) framework (Figure 31).

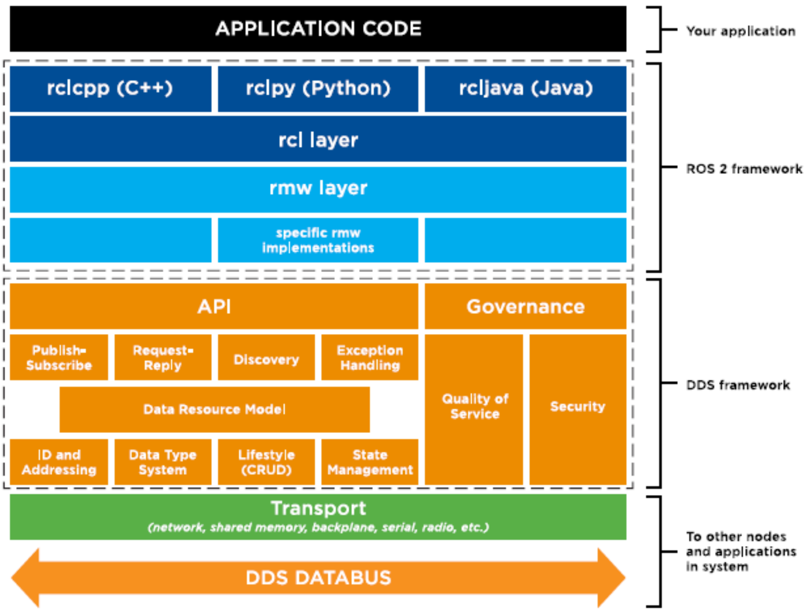


Figure 31 – DDS/ROS2 technology stack

5.2 *Summary and PIARCH impacts*

From MILREM robotic, a UAV company involved in European collaborative projects on interoperable systems, the PIARCH approach is legitimate. Search on the defense area shows already that some such embedded sub-systems do exist or are developed for some functions, notably autonomy, and sensor layers.

However, the interoperability of systems or subsystems in the military sector is tightly bound to standard architectures. Initiated by the UK MoD, the GVA approach helps fast subsystems development and integration. Now, the NATO GENERIC VEHICLE ARCHITECTURE (NGVA) is becoming the reference. NGVA is a NATO Standardisation Agreement (STANAG 4754) based on open standards and designed to integrate multiple electronic sub-systems onto military vehicles, which are controllable from a multifunction crew display and control unit.

37 RTI whitepaper ROS2 - 2017

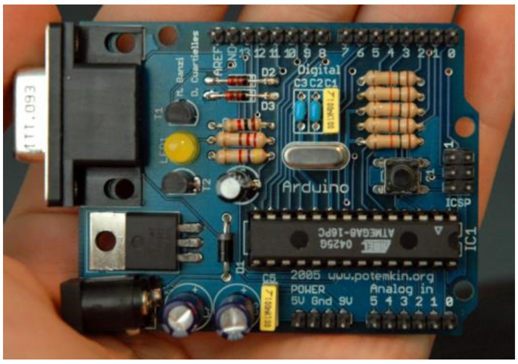
This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

6 Historic developments in modular electronics & pre-integration

6.1 *Modular design kits relevant to CPS4EU*

Key value propositions of the PIARCH approach developed within CPS4EU are the ability to promote rapid product development, modularity, interoperability with PIARCH reuse and as a result allow final developers to focus on application development, rather than needing to assemble their hardware products from underlying discrete modules. From the perspective of competitive benchmarking and understanding future industry directions, we should consider other historical examples of modular electronics design and their evolution in order to position current and future CPS4EU developments.

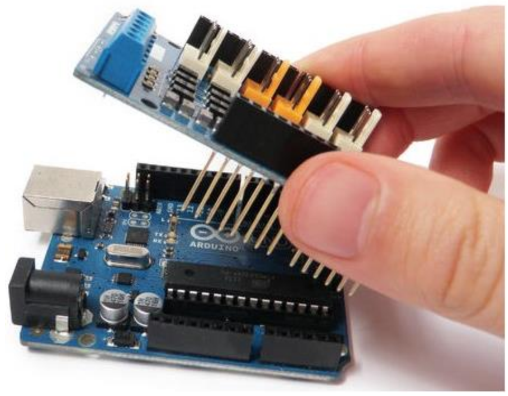
Firstly, we can point to two classic hardware kits, Arduino (2007) & Raspberry PI (2012), which started as open-source electronics/computing platforms targeting hobbyists and students. The initial boards, already a form of pre-integrated architecture, combined processing (Atmel's AVR microcontroller for Arduino, or a Broadcom SoC with ARM microprocessor, GPU & RAM in the case of Raspberry PI) together with I/O interfaces allowing connection of additional components such as an external display and keyboard. Both platforms are based on open-source software with an integrated development environment (IDE), using either C++ (Arduino) or Python (Raspberry PI), and access to libraries allowing for easier and faster application programming.



Source: Wikipedia

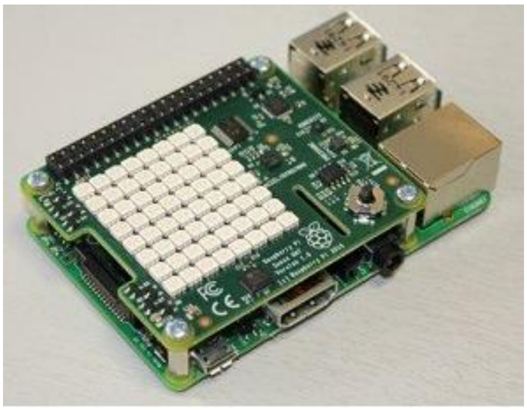
Figure 32 – An early Arduino board, with RS232 interface and digital/analog I/O

If we now look at the early evolution of both platforms, both underwent the same broad transition, namely the ability to integrate other basic or domain-specific functionality. In much the same way that PCI buses allow the connection of other peripherals and expansion cards to standard computers so both Arduino (in 2009) and Raspberry PI (in 2014) created standard interfaces allowing stacking of other modules/boards. For Arduino these daughter boards are known as Shields and for Raspberry PI, as HATs, for Hardware Attached on Top.



Source: Développez.com

Figure 33 – Arduino main board, with a motion control Shield



Source: Antratek

Figure 34 – The Raspberry Pi Sense HAT, combining multiple sensors stacked on Raspberry Pi

In this way, both platforms allow the modular integration of different types of functionality: for example, connectivity modules (ZigBee for home automation, BLE, cellular) beyond basic built-in Ethernet connectivity, or domain-specific functionality (such as motor control or sensors).

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Though Arduino and Raspberry PI boards are the most well known, similar hardware development kits, most often built around ARM microcontrollers combined with software development tools, exist from a number of vendors, including ST Microelectronics (Discovery kits and Discovery Shields) and Texas Instruments (LaunchPad and functional plug-in modules, Boosterpacks).

For ST and TI, as leaders in the microcontroller IC market, the objective is clear: Provide easy access to microcontroller hardware, an integrated development environment with debugging tools, as well as the ability for modular component integration to drive microcontroller sales.

6.2 *Pre-integrated sensor modules with connectivity*

The addition of modular functionality to the hardware development environments above proceeded, in general, at the board or shield level, a WiFi or GSM board for example, but these functionalities may themselves be pre-integrated. For these development kits, the clearest example of this pre-integration is not surprisingly at the sensor level as the example of the multi-sensor Raspberry PI Sense HAT shows.

The trend toward multi-sensor integration (or sensor fusion) is longstanding, as is the notion of smart sensing (adding intelligence to basic sensor functionality), and domain-specific sensor integration is commonplace across many industries:

- In the automotive industry, with the integration of multi-axis inertial measurement units comprising accelerometers, gyros, magnetometers, pressure sensors.
- In cellphones, where similar multiaxis sensors are used for motion capture, with GPS, magnetometers and pressure sensors for advanced position sensing.
- In air quality monitoring and for HVAC systems where multiple gas sensors combine with temperature and humidity sensors.
- In industrial settings, where historically temperature, pressure and humidity sensors were often integrated for process monitoring and where today, the level of sensor integration is often much wider, combining other sensors for condition-based monitoring.

Numerous examples of such sensor pre-integration exist today to the extent that many final product/application developers would never consider the idea of starting at the individual sensor level. However, for such sensor manufacturers (and module integrators), the question of further levels of functional pre-integration is clearly relevant, notably the integration of connectivity. Connectivity integration responds to the demand for IoT-ready sensors that can communicate with gateways or directly with the Cloud.

Developers in the area of combined sensor-connectivity pre-integration come from the large sensor manufacturers themselves like Bosch, Siemens or ST and from those companies also looking to integrate sensing with connectivity and microcontrollers. Again, notable developers of the latter are microcontroller suppliers like TI, ST Microelectronics and Cypress Semiconductor (now part of Infineon).

6.2.1 Bosch

Bosch is a major sensor provider and the company provides a number of pre-integrated sensor solutions combining intelligence and connectivity. For example, Bosch Sensortec provides a range of package-integrated inertial measurement units, with integrated microcontrollers, for use for dead-reckoning systems for wearable applications. The company also provides prototyping development boards and reference designs in combination with Arduino (Bosch Sensortec Shield), NXP, Nordic Wireless, Telit and TI.

In industrial sensing, Bosch provides a range of board-level integrated wireless sensor products[38]. Multi-sensor combinations are oriented toward specific applications, most commonly with BLE :

- A Sense-Connect-Detect device has built-in sensors for vibration, tilt, shock, temperature, magnetic fields and ambient light intensity, and is aimed at machine monitoring applications. The device includes BLE connectivity.

38 https://www.bosch-connectivity.com/products/industry-4-0/

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- The Connected Industrial Sensor Solution[39] (CISS) provides an integration of eight physical sensors for harsh industrial environments to support applications such as condition-based monitoring, inputs to digital twins and predictive maintenance. Bosch integrates a Bluetooth Low Energy module for connectivity and partners with a 3rd party providing a Cloud-based condition-based monitoring system to offer a complete service.

Figure 35 – Bosch BLE-enabled Connected Industrial Sensor Solution

- The XDK (Cross Domain Development kit) is Bosch's multisensor development kit and somewhat similar to other offerings from companies like ST and TI. The XDK integrates the same sensors as the CISS, with an ARM Cortex M3 microcontroller, and BLE/WiFi connectivity. LoRa connectivity is provided with an expansion board. A software development kit and API is provided and runs on the Amazon FreeRTOS 10 OS. Embedded development is supported through Eclipse Mita.

6.2.2 ST Microelectronics

IC / sensor chipmakers such as ST Microelectronics extend basic hardware development kits by integrating further sensors and BLE connectivity providing a kit for prototyping, evaluation and development of IoT solutions. ST's STEVAL-STLKT01V1 is a development kit that expands the capabilities of the company's SensorTile and comes with a set of cradle boards enabling hardware scalability. Complementing the board with software, firmware libraries and tools, including a dedicated mobile App.

The SensorTile is a tiny, square-shaped IoT module that packs powerful processing capabilities leveraging an 80 MHz STM32L476JGY microcontroller and Bluetooth low energy connectivity based on BlueNRG-MS network processor as well as a wide spectrum of motion and environmental MEMS sensors, including a digital microphone.

Figure 36 – ST SensorTile

6.3 *Pre-integrated connectivity modules*

For sensor makers, a pre-integration architecture roadmap would naturally start with the pre-integration of sensors, depending on the application, and then add on connectivity and processing (microcontrollers). For makers of wireless modules, the starting point is the integration of different types of connectivity, if such pre-integration responded to needs for redundancy, interoperability and a variety of use cases.

39 https://www.bosch-connectivity.com/products/industry-4-0/connected-industrial-sensor-solution/

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

6.3.1 AGILE IoT

Pre-integrated connectivity modules, together with integration to open-source hardware development kits has been a theme of some prior EU projects, notably the AGILE project, for **A**daptive **G**ateways for d**I**verse mu**L**tiple **E**nvironments, part of the European Platforms Initiative.

The aims of the AGILE project were to address technical and syntactic interoperability at hardware and software levels. On the hardware side, the project designed hardware components that extended the current state-of-the-art of available IoT gateway platforms with a twofold objective: to develop a so called "Maker's Gateway" by extending the capabilities of the Raspberry Pi platform and to develop a modular hardware gateway design for industrial purposes. In so doing, the project aimed to allow fast prototyping of IoT solutions for various domains such as home automation, environment monitoring, wearables, etc.).

For the Maker's Gateway, the project contributed a shield following the Raspberry HAT specification, extending the capabilities of the platform by two additional sockets for radio modules, with several sensors including a GPS, and with further wired sensor connectivity options. Hardware modularity provides support for various wireless and wired IoT networking technologies such as KNX, ZWave, ZigBee, Bluetooth Low Energy, etc.)

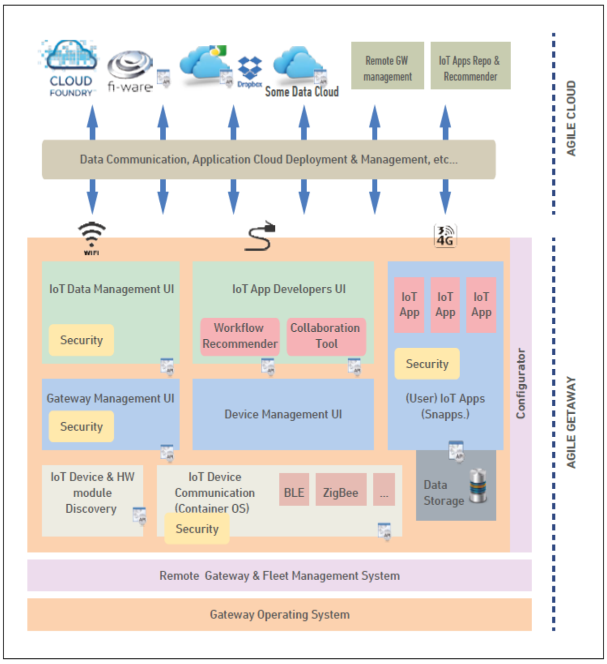


Figure 37 – AGILE Project Architecture

From a software perspective, the AGILE project released open source code through the Eclipse Foundation to IoT software developers / makers, making it easier for them to configure their devices or gateways according to the relevant platform environment in which they will be integrated. The code was designed with gateway platform interoperability in mind, minimizing dependencies and thus supporting not just the two gateways hardware platform variants developed inside the project but also other platforms available on the market.

6.3.2 Sierra Wireless and the MangOH open-source hardware environment

One company with a long history in the pre-integration of wireless modules to support rapid solution deployment, particularly regarding M2M solutions, is Sierra Wireless. Building on what was, at the time of their 2013 whitepaper[40] already an established trend in the mobile phone business to integrate microprocessor and multiple wireless modules on a system on chip, Sierra Wireless sought to apply the pre-integration approach to M2M applications.

Motivation for the pre-integrated M2M modules was similar to the PIARCH within CPS4EU, namely to avoid OEMs needing to select all of the discrete components, integrate, test and certify them as part of an M2M solution.

Sierra Wireless developed a multicore architecture with ARM processors and a variety of wireless connectivity options (notably cellular) together with an Open Application Framework (with a software library and development tools) designed to make it easier for application developers to develop their solutions. The advantages highlighted by Sierra may resonate with those for CPS4EU including:

- **Increased efficiency**. OEMs begin with a pre-integrated M2M ecosystem on a module and development cycles are devoted to M2M application development

40 Simplifying Deployments of an Entire M2M Ecosystem on a Module (2013) , https://www.sierrawireless.com/~/media/pdf/whitepapers/whitepaper_simplifying%20deployments%20with%20an%20entire%20m2m%20ecosystem%20on%20a%20module.ashx

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- **Reduced size and power consumption**. A pre-integrated module typically has a smaller footprint and better power efficiency than a normal system architecture.
- **Increased security**. More integrated approaches reduce the potential for attacks that target buses or other connectivity between discrete components.

From today's standpoint, MCM integration that integrates processing with multiple connectivity options seems an obvious level of pre-integration from the standpoint of a maker of cellular modems. However, promoting easy integration of multiple cellular modems among developers of integrated sensor and IoT solutions requires a more open and modular architecture.

In June 2018, Sierra Wireless launched MangOH[41], a family of open-source hardware platforms designed "to address common IoT pain points and deliver 90% of your prototype out-of-the-box" allowing application developers to bring products to market sooner.

More specifically, MangOH is designed with both sensor pre-integration and expansion connectors based on the IoT Expansion Card open standard in mind. Compatibility is provided with the hardware development kits Arduino and Raspberry PI, and MangOH is integrated with the open-source software development environment Legato. The Legato Development Environment results from the assembly of two components: Developer Studio, the Eclipse-based integrated development environment, and Legato, Sierra's application framework for M2M development.

In MangOH, replacing a fully integrated MCM is a CF3 (Common Flexible Form Factor) connector, with CF3 modules providing application processing (ARM Cortex A), wireless connectivity, and GNSS tracking and positioning. Wireless cellular CF3 options, with different Sierra modules built around Qualcomm chipsets include 2G, 3G, 4G, LTE-M and NB-IoT as well as built in WiFi/Bluetooth.

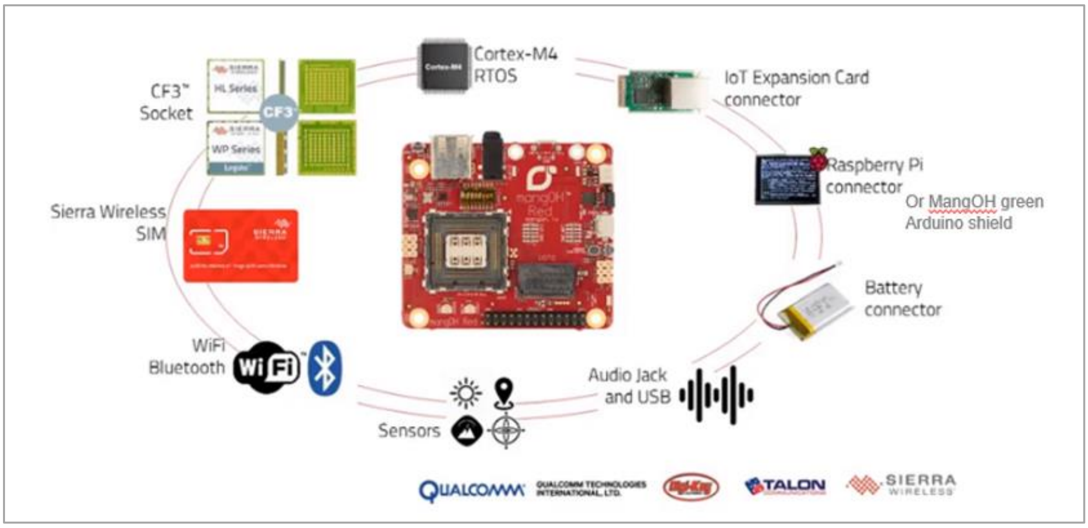


Figure 38 – MangOH modular ecosystem

In addition to CF3 cellular modularity, the different MangOH flavours provide pre-integrated sensor options as well as built-in connectivity:

- **MangOH green**.
  - Built-in serial/Ethernet connectivity
  - A built-in accelerometer & gyroscope and an Arduino Shield connector
- **MangOH red**.
  - Built-in Wi-Fi b/g/n and Bluetooth 4.2 BLE with a Cortex M4 to provide real-time access to I/O;
  - Built-in accelerometer/gyroscope, pressure and light sensors and a 26-pin Raspberry Pi-compatible connector.

41 https://mangoh.io/overview

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- **MangOH yellow**.
    - Built-in Wi-Fi b/g/n and Bluetooth 5.0 BLE , Bluetooth Mesh, NFC tag
    - Built-in accelerometer, gyroscope, magnetometer, pressure, humidity, acoustic mic, air Index quality, temperature, and light sensors

From an application standpoint, MangOH open hardware platform is more directly aligned with industrial IoT than either the automobile or energy segments under study within CPS4EU, though Sierra Wireless' historic M2M solutions target smart metering and other smart grid solutions.

Nevertheless, the MangOH platform is getting much closer to a modular architecture that ultimately targets the greater pre-integration of sensors and connectivity, combined with different processor possibilities (based on ARM Cortex processors). In addition to built-in connectivity and sensing at the board level, support of IoT Expansion cards, provides developers with the possibility to add application-specific sensors with protocol-specific interfaces including wired UART, SPI, GPIO and I2C interfaces, industrial fieldbus (such as Modbus, Profibus, MPI, PPI), as well as more recently LPWAN interfaces like LoRa and Sigfox.

6.3.3 Arm Mbed OS

Notwithstanding the specific examples of Raspberry Pi and Arduino, much of the development of pre-integration (for example, the combination of sensing and communication) is from companies looking to create development boards that make this integration easy, whilst obviously trying to drive sales of their underlying hardware, whether that be communications modules or microcontrollers.

Figure 39 – ARM IP market shares and Total Addressable Markets

Given the share of products based on Arm IP in general (34% of all chips with processors; 90% of the market for controllers in IoT devices), the ecosystem around Arm and new developments therein are important to monitor for CPS4EU partners.

One key longstanding development is Mbed OS, a free, open-source embedded operating system designed specifically for the Internet of Things, which Arm launched in 2013.

The Arm platform integrates the various elements required to develop a connected product based on an Arm Cortex-M microcontroller, including security, connectivity, an RTOS, and drivers for sensors and I/O devices.

Mbed's focus on adding embedded connectivity to Arm microcontrollers is obvious given the companies historic focus in the mobile market and Mbed OS supports cellular, including LTE-M, NB-IoT, Bluetooth Low Energy (BLE), NFC/RFID, LoRa, WiFi, and 6LoWPAN, a sub-GHz mesh-networking standard.

In the first 3 years after launch, third-party IoT platforms based on Mbed OS went from four to 60. Today, Mbed counts 80 development partners across the IoT value chain from component makers to Cloud providers and hundreds of platforms.

As well as an IDE with access to component libraries, Mbed provides a hardware development kit (HDK) with a collection of hardware design resources, including:

- Eagle schematic and board files.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- PDF schematic and board copies.
- CAM Job GERBERS for manufacture (including pick/place and drill).
- Bill of Materials (BOM).
- An online BOM for easy purchasing (eBOM).

Hardware provided by Mbed OS partners falls into three categories:

- **Modules** provide a core Mbed OS platform that *pre-integrate* the MCU, connectivity, front-end, software and services. They can be used for prototyping through to mass production, and are end-to-end system tested with Mbed OS.
- **Hardware components** extend the capabilities of a module or MCU. The component database hosts reusable libraries for different hardware, middleware and IoT services for use with Arm microcontrollers.
- **Boards** provide the development or production platforms that integrate MCUs or modules with components to make a system that Mbed OS runs on. Those featured here are most often designed for evaluation and rapid prototyping and include debug and peripheral connection options used ahead of custom board designs.

At present, the Mbed OS site lists 167 development boards (the largest three vendors being ST, NXP and Nordic Semiconductor), 553 components (from 17 vendors) ranging from sensors to communications to expansion boards and nine modules. This latter figure for modules is interesting in that it includes only a limited number of what are, in effect, pre-integrated modules, combining communications with an Arm microcontroller. The level of pre-integration in available modules seems relatively limited, normally with only one communications standard, but examples also include BLE together with WiFi.

Of course, individual vendors may sell final modules with greater levels of integration and further integration within the Mbed ecosystem is available in the form of development boards for IoT prototyping. For example, board vendor Avnet provides a development board based on ST's SensorTile module with BLE connectivity. Additional sensors come in the form of temperature and humidity sensors, proximity and ambient light sensors and a GNSS module supporting GPS/Galileo/Glonass/BeiDou/QZSS location. In addition to BLE, sub-GHz 6LoWPAN connectivity is provided for long-range communications.

Two other recent developments at Arm are interesting:

- **TrustZone security for IoT**. More recently, Arm has focused on providing end-to-end security for IoT by incorporating its Trustzone technology within Cortex-M based systems (including Mbed OS). In May 2019, Arm and Samsung Foundry collaborated to create what it described as the industry's 1st PSA Certified Arm-based Smart IoT Device demonstrator called Musca-S1, an eMRAM-enabled IoT device with secure PSA Root-of-Trust (RoT).

- **Nvidia acquisition**. Relevant to future CPS4EU PIARCH development could be Nvidia's recent acquisition of Arm, which still needs to pass the regulatory approvals process. Though most of the discussion around the acquisition has surrounded around mainstream computing and the fact that Nvidia might jeopardize Arm's open-licensing model on which many of Nvidia's competitors (like Intel, Samsung, Apple) depend, there could be some impact on the IoT business. Specifically, Arm's strength in the market for low-power wireless sensor nodes based on Arm Cortex microcontrollers could have some synergy with the use of Nvidia GPUs, specifically its Jetson range for edge AI applications. For example, Nvidia's Jetson Nano developer kit targets embedded IoT applications including robotics and intelligent gateways using an Nvidia Maxwell GPU and a quad-core Arm Cortex A57 processor. Ethernet connectivity is built-in, though WiFi requires an external chip. In short, the Nvidia acquisition could have implications for future heterogeneous computing PIARCH.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

6.4 *Cluster and heterogeneous computing*

One common theme of the development kits described previously, and including MangOH and Arm Mbed, is that the processing module (on the host motherboard) is fixed, even though developers can preselect the type of processor they want though typically limited to an ARM Cortex A or M. In other words, processor-level flexibility is more constrained than either sensing or connectivity that have been available for customization through expansion slots, Shields & HATs.

Greater computing flexibility at the edge includes cluster computing, as well as heterogeneous computing, which uses two or more types of computing cores, such as:

- Central processing unit (CPU)
- Graphics processing unit (GPU)
- Field programmable gate array (FPGA)
- Application-specific integrated circuit (ASIC)

The driver for heterogeneous computing is not simply that workloads have begun more varied, but that improving the power density (power consumed per operation) of traditional CPU architectures has become more difficult. As GPUs have replaced CPUs for applications involving pictures, videos and gaming, and more generally for matrix computation, so new architectures and combinations of processing units will be required for other specific tasks, but notably for AI.

6.4.1 ClusterHAT

As originally configured, a Raspberry Pi and HATs are similar to a thin client-server model where most, if not all, of the computation takes place within the host processor and the HAT is essentially providing additional functionality such as HMI, motor control or sensing. But Raspberry Pi introduced the idea of cluster computing in 2017 with the notion of a ClusterHAT that effectively moves computing off the main host board and onto peripheral cards.

Figure 40 – ClusterHAT

The original ClusterHAT consisted of four Pi zero computers mounted on the HAT and attached to a Raspberry Pi 2/3 with a USB connection for powering. The idea of the original Cluster HAT was to make cluster computing accessible to students and developers rather than to make a faster Raspberry Pi. Initial benchmarking showed that the cluster of four Pi Zero boards ran at roughly half the speed of a single Raspberry Pi 3 board, partly due to the slower individual cores but also due to lower node-to-node connectivity rates, with Ethernet over USB than within Pi 3 SoC.

However, the notion of HAT-based computing sitting on top of a Raspberry Pi opens up the possibility in terms of adding additional compute HATS, notably AI based compute modules, thereby bringing AI computing to the edge in the form of a development kit. Examples of the integration of different compute modules for the Raspberry Pi platform include the following, though we note that similar compute extensions exist for Arduino.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- **Seeed Studio[42] Grove AI**. Seeed Studio (Shenzhen, China) is the pre-eminent developer and producer of open-source hardware in China. Its own Grove ecosystem is based around a Grove Shield for Arduino, but it also provides HATs for Raspberry PI. Seeed's Grove AI HAT is built around the Sipeed (Shenzhen, China) AIoT opensource hardware platform, with a RISC-V 600MHz AI module with a dual core 64-bit cpu and a 230GMULps 16-bit KPU (Neural Network Processor).
- **Luxonis**. Startup Luxonis (Colorado, US) develops embedded machine learning and computer vision and its DepthAI platform brings vision and object detection to the Raspberry Pi. The platform is built around Intel's Myriad Vision processing unit.
- **Lattice Semiconductor / Bugblat**. The Bugblat FPGA HAT integrates an FPGA from Lattice Semiconductor, the well-known fabless provider of FPGA ICs, development kits, evaluation boards, and IP cores.

6.4.2 Coral / Google.

Coral is not a HAT or a Shield, but is a platform for accelerating neural network inferencing on embedded devices. At the heart of the platform is Google's Edge tensor flow processing ASIC, which will integrate with Rapsberry Pi or indeed any Windows, Linux or Mac computer though either USB or a PCI

The chip is optimized to run lightweight machine learning algorithms similar to those that Google runs for its cloud services. The TPU is offered as an accelerator and a development board meant for prototyping new ideas, as well as modules that are destined for production devices like smart cameras and sensors.

Google's Coral development board[43] targets clients wanting to do rapid prototyping of machine learning solutions at the edge and provides a pathway to production either in the form PCI-compatible boards or a pluggable system-on-module that can be combined with other client PCB hardware. The development board combines an NXP i.MX 8M CPU with the TPU, provides Bluetooth and WiFi connectivity and comes with two sensor interfaces, one for machine vision using a 5MP Omnivision camera and an environmental sensor board (with temperature, humidity and light sensors) for IoT applications.

Figure 41 – Coral prototyping and production compatible boards and modules

The Coral prototyping boards support the Tensorflow Lite framework, a free and open-source software library to support machine learning initially developed by Google. In addition, Coral supports AutoML Vision Edge, a cloud-based Google service for training machine-learning models based on uploaded labeled images, with the Edge version allowing exporting and deployment of the models on edge devices.

42 https://www.seeedstudio.com/blog/forum-2/about-us/
43 https://coral.ai/products/dev-board/

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

6.4.3 ADLINK’s IoT platforms with Edge AI including heterogeneous computing

From this research, we have found limited examples of pre-integrated heterogeneous computing platforms at the edge, similar to that envisaged by CPS4EU compute PIARCH, but one notable one comes from ADLINK, the Taiwan-based provider of embedded computing solutions. ADLINK employs 1800 people and has design and technology centres in the U.S., Germany and the Pacific Rim. With a vision to deliver “leading EDGE, robust and reliable hardware and software solutions that directly address mission-critical business and technology challenges”, ADLINK is firmly in the territory of solutions that CPS4EU is developing through its project partners.

As the name suggests, ADLINK’s I-Pi (Industrial Pi) development kit, launched in February 2020, is designed for rapid prototyping and is in the spirit of Raspberry Pi. More specifically, ADLINK advertises I-Pi SMARC (for ‘Smart Mobility ARChitecture’) as an industrial IoT prototyping platform that combines the Raspberry Pi-like flexibility of a development kit with production-grade components, software portability, and expansion in a COM (computer on module) form factor. Interestingly, given the foregoing discussion, “the development kit is an industrial-ready substitute for Arduino and Raspberry Pi platforms that are commonly used for prototyping but cannot typically be ‘dropped’ into an industrial solution as-is.”[44]

The ADLINK I-Pi uses an Arm Cortex-A53-based NXP i.MX8M Plus quad core system on chip with optional in-SoC Neural Processing Unit. The I-Pi can also support SMARC modules with Intel processors and uses the MRAA hardware abstraction layer from Intel, an open-source C/C++ library with Java, JavaScript, and Python integrations that allows software to be ported from one platform to another. ADLINK claims that MRAA drivers and APIs allow engineers to substitute modules, sensor HATs, and even port code written in Arduino or Raspberry Pi environments to the I-Pi without any rework.

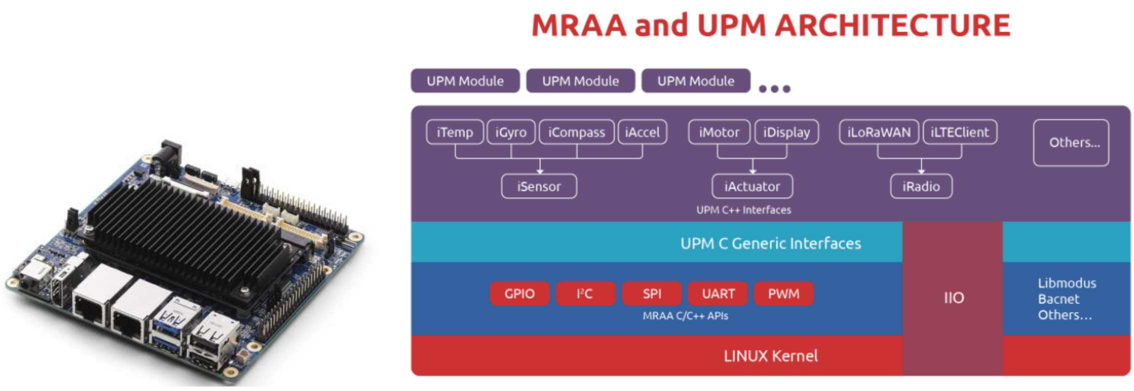


Figure 42 – ADLINK Industrial Pi (I-Pi)

The I-Pi is designed to integrate with various wireless interfaces and support for off-the-shelf sensors comes from UPM[45] (Useful Products & Modules), a sensor library with high-level APIs designed to make it easy to connect and use sensors and actuators in IoT solutions. UPM is open-source (licensed from MIT) and allows added communications protocols such as Wi-Fi, ZigBee, LoRa, Bluetooth. Sensor support for UPM is currently limited though includes sensors from Seeed and Bosch.

A strong focus of ADLINK is edge AI for industry 4.0, and similar to the Coral above, ADLINK has developed its own development kit. In April 2020, it launch Vizi-AI[46] based on Intel’s Movidius VPU, with a software suite for rapid application development. Vizi-AI includes a range of pre-built Intel Distribution of OpenVINO compatible machine learning models. Among Industrial IoT applications targeted by the company’s edge AI platform are:

- Smart pallet : automated packaging and palletization for warehouse logistics
- Machine health : Condition monitoring and predictive maintenance for manufacturing
- Arc welding defect detection
- Machine vision AI

44 https://www.adlinktech.com/en/ADLINK-I-Pi-raspberry-PI-computer-on-modules-rapid-industrial-prototyping
45 https://upm.mraa.io/
46 https://cdn.adlinktech.com/webupd/Vizi-AI-data-sheet.pdf

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

ADLINK has developed what it calls a heterogeneous computing platform optimized for AI, consisting of GPU- and VPU-accelerated board-, system-, and server-level products, enabling system architects to construct and optimize system architecture for both AI inferencing and training applications. Among the specific embedded heterogeneous computing systems developed at ADLINK are the following:

- In September 2019, ADLINK released an Extreme Rugged, SWaP[47]-optimized VITA 75 COTS computing platform, the HPERC-KBL, designed for mission-critical applications such as C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance). The HPERC-KBL contains a quad-core Intel Xeon processor combined with 16GB of ECC DDR4 memory, which can be enhanced with an optional NVIDIA Quadro module for GPGPU-accelerated applications. "The addition of the HPERC-KBL delivers an advanced heterogeneous computing solution with real-time graphics and video processing capabilities, enabling a wide range of next-generation mission-critical applications including intelligence, surveillance and reconnaissance, radar, software-defined radio, sonar, and forward looking infrared radiometry".
- On February 2, 2021, ADLINK launched a compact CPU/GPU deep-learning acceleration platform, the DLAP X86 series. The value proposition of the DLAP is the flexibility it provides for deep learning architects who can choose the optimal combination of CPU and GPU processors based on the demands of an application's neural networks and AI inferencing speed.

ADLINK appears to have strong capabilities around edge, AI and heterogeneous computing. Trying to create an industrial-ready IoT rapid-prototyping ecosystem in the mold of Raspberry Pi and Arduino is further evidence of the importance of the need for easy integration, if not pre-integration. Whereas microcontroller makers, sensor makers or M2M module companies are attacking the issue of forward pre-integration from their respective standpoints, ADLINK's focus on a heterogeneous compute platform for IoT makes it a company worthwhile for benchmarking and future monitoring.

6.5 *Summary and PIARCH impacts*

This section has taken an historical look at the development of approaches that aim to provide developers with similar functionality as that intended by CPS4EU PIARCH. Namely a certain level of hardware pre-integration, with extensions, as well as access to hardware and software development kits and component design libraries that make it easier for users to develop applications. As such, this section shows broad support for the PIARCH approach. One aspect of particular note is the strong use of, and support for, open source software.

Of course, some of the development kits noted have a strong hobbyist flavor, but we see similar approaches from much more industrial-ready ecosystems and today rapid industrial design and production of Raspberry PI or Arduino prototypes is possible—Seeed Studio is a notable CEM.

From the standpoint of the individual PIARCH that this section addresses (namely sensing, connectivity and heterogeneous computing), there have clearly been different developmental timelines, with sensor pre-integration being the most long-established and heterogeneous computing the most immature.

- A more exhaustive examination of sensor pre-integration was beyond the scope of this deliverable, but domain-specific pre-integration has existed for some time, notably around inertial measurement units (once the domain of defense, then in automotive and now in every smartphone), sensing for HVAC systems and more recently strong trends in machine condition monitoring. Outside of wired/wireless industrial automation protocols, the common integration of BLE and WiFi connectivity to sensors is notable.
- Connectivity integration (modular or hardwire pre-integration) has developed rapidly in the last 5-10 years and three wireless module types appear key in addition to Ethernet: Bluetooth/WiFi, traditional cellular evolutions 3G/4G/5G (e.g. LTE1-4) as well as 5G narrow-band (LTE-M, NB IoT). To this grouping, we note considerable support for long-range extensions, particularly LoRa, and to a lesser extent low-power mesh networking.
- In the area of computing/microcontrollers, the importance of ARM cannot be overstated, particularly for mobile and IoT applications. Integration of heterogeneous computing (beyond simple GPUs for

47 SWaP: low size, weight, and power (SWaP) artificial intelligence solutions.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

display support) is much less mature, but we have noted the same trends in support for developmental kits in the last 5 years, with the focus unsurprisingly on AI. In addition to NVIDIA, Google and Intel, notable actors to monitor from the standpoint of CPS4EU are those with a focus on providing Edge AI products and developments kits. ADLINK has been particularly noted from this research, but others probably exist.

7 Design Automation for CPS

7.1 *The CPS design challenges*

Sanjit A. and al. [12] define the unique design challenges for CPS as the combination of following characteristics:

- **Hybrid**: intersection of the computational and physical worlds.
- **Heterogeneous**: The components of a CPS are of various types, requiring interfacing and interoperability across multiple platforms and different models of computation.
- **Distributed**: In today's CPSs, components are typically networked, and can be separated physically and/or temporally.
- **Large-Scale**: The size of CPSs, measured in terms of the number of primitive components a system is made up of, is growing rapidly, leading to a "swarm" of sensors, actuators, computation, and communication devices interconnected and generating vast amount of data.
- **Dynamic**: The environment of the CPS evolves continually. Moreover, the environment can behave adversarially, actively trying to violate desired system properties.
- **Adaptive**: Given a dynamic environment, the CPS must adapt to it, possibly online. The system may employ machine learning to adapt to a changing environment. The distinction between "design-time" and "run-time" is thus blurred.
- **Human-in-the-Loop**: Several CPS operate in concert with humans: they involve human operators or interact with humans and human-controlled systems in their environment. (Examples: semiautonomous vehicles, robotic surgical devices...).

To address these challenges, the design automation community is working on the development of design automation methodologies with the following blend of features:

- **Cross-Domain**: Co-simulating different components of a CPS, such as the mechanical aspects of a robot's motion with the electronic and software processes that control its actions.
- **Component-Based**: Design in a modular fashion, with a need for establishing libraries of reusable, verified components with clearly specified interface contracts. Tools for enabling such component-based, contract-based design are essential.
- **Learning-Based**: Design based on data-driven learning. Must be coupled with principled model-based design (MBD) and formal methods that can give guarantees on correct operation.
- **Time-Aware**: Abstraction of time that accurately captures the joint dynamics of the cyber and physical components of a CPS. Encapsulates suitable abstractions in order to ease the design process.
- **Trust-Aware**: Models threats, design for them, and analyze systems for vulnerabilities.
- **Human-Centric**: Both address the human aspect of design and of the systems being designed.

7.2 *CPS design automation methodologies*

Several CPS design automations directions already exist, and can address the different CPS types and needs. In addition, these directions are not orthogonal to each other and can be combined. The most documented are:

- **Model-Based Design with data driven design**: A model-based approach facilitates the use of formal methods—computational proof techniques—to improve dependability. A data-driven approach facilitates adaptation by learning from the data. Both approaches are essentials for **CPSs that operate in safety-critical or mission-critical settings and dynamic, uncertain environments** (ex: autonomous vehicles).

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- **Human-in-the-Loop Systems:** use of data-driven human modeling; inclusion of relevant aspects of the human–machine interface; presence of the advisory controller. For **interactive CPS** (ex: automobile with ADAS features).
- **Component-Based Design With Contracts:** Based on RTL design flow for digital circuits, with complement of formal contracts to ensure that composition of components maintains desired properties.
- **Design for Security and Privacy:** Use security and privacy as design criteria. For **CPS with high security needs** (ex: Smart Grids).

7.3 *Focus on Component-based design with contract methodology*

From our understanding of the PIARCH, this methodology seems to be of interest as it combines the benefits of component-based design (reuse, clean interfaces, separation of concerns, use of modules and libraries) and the benefits of contract methodology (components desired properties insurance).

One trend studied by A. Sangiovanni-Vincentelli and al. [13] is to combine Platform-based design with contracts.

Different from model-based development, platform-based design (PBD) consists of a meet-in-the-middle approach where successive top-down refinements of high-level specifications across design layers are mapped onto bottom-up abstractions and characterizations of potential implementations. Each layer is defined by a design platform (library of components, models, representing functionality and performance of the components, and composition rules)[14].

Contract-based design [15] complements the PBD methodology by adding a rigorous notion of formal contracts to ensure that composition of components maintains desired properties.

The essence of contracts is, therefore, a compositional approach, where design and verification complexity is reduced by decomposing system-level tasks into more manageable subproblems at the component level, under a set of assumptions.

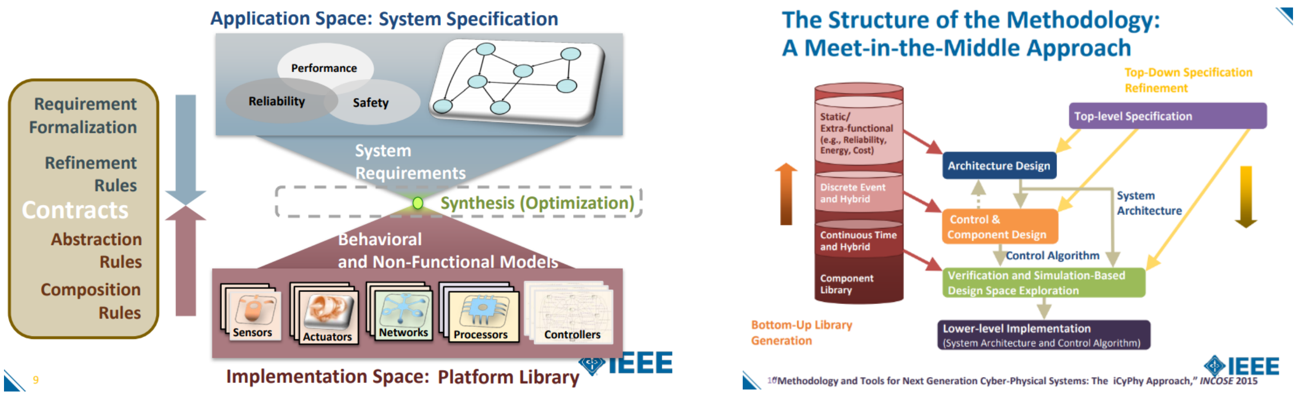


Figure 43 – Combine Platform-Based Design with Contracts[48]

7.3.1 Example of contract definition for a water flow control system design

In [15], one can find an example of system design using the contract based design methodology.

A cylindrical water container is equipped with an inlet pipe at the top, and an outlet pipe at the bottom.

The component specifications are:

- Diameter D = 5m and a height H = 9m.
- Inlet and outlet cross sections are Sin = 0.5m2 and Sout = 0.16m2 , respectively.

48 CPS Design: a Limiting Factor or an Enabling Technology? Alberto Sangiovanni Vincentelli Department of EECS, University of California, Berkeley

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

To proceed with the system specification, a contract including the assumptions and guarantees to be satisfied by the implementation is defined.

Assumptions of the contract:

- The designer can assume a constant inlet pressure pressure $P \geq 5,000$pa, and a maximum evaporation rate $\epsilon = 0.25$m3/hour.

Guarantees of the contract:

- The system guarantees a continuous outlet flow Fout of $1.0 \leq Fout \leq 2.0$m3/sec, after 10 seconds since startup.
- In addition, the system must guarantee that the container will not overflow, and that the energy consumption is lower than a limit El.

7.3.2 Use case: Platform-Based Flow for Electric Power System Design Using Contracts

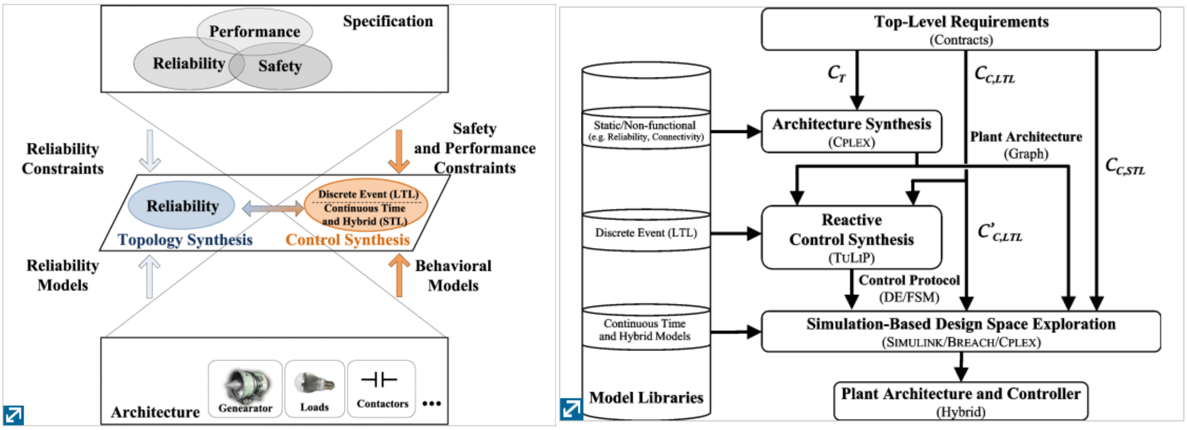


Figure 44 – Pictorial representation of the main steps in the electric power system design flow

The design flow consists of two main steps, topology design and control design:

- The topology (interconnection among the various components) design step instantiates electric power system components and connections among them to generate an optimal topology while guaranteeing the desired reliability level.
- Given this topology, the Bus Power Control Units (BPCU) state machine is synthesized in the control design phase to actuate contactors while guaranteeing that loads are correctly powered.

The above two steps are, however, connected. To achieve independent implementation of architecture and controller, we address the synthesis problem in a compositional way, by using contracts to incorporate the information on the environment conditions under which each entity is expected to operate.

The design process (for topology and control design respectively) includes a top-down and a bottom-up phase:

- In the top-down phase, the requirements are associated to the different entities in the system and top-down vertical contracts are formulated.
- In the bottom-up phase, the library of architecture components is populated (generators, buses, power converters, contactors…). Each component is characterized by its attributes, including multiple models or views (behavioral or reliability views), and finite state machine or continuous-time models. These component models can be used by different, domain-specific analysis, synthesis and verification frameworks. Horizontal contracts specify legal compositions between components. Bottom-up vertical contracts define under which conditions a model is a faithful representation of a physical element in the system.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

8 Primary research for CPS development and deployment

8.1 *Introduction*

In 2020, CEA carried out around 20 interviews with mostly French, but also several multi-national industrial organizations (SMEs, intermediate-size as well as large groups) that cover the entire CPS value chain. The value chain investigated is shown below and covers the production of data (from discrete sensor modules and their integration into machines), connectivity (taking in communication systems, integration and network operation) through to a variety of Cloud and additional IT services including analytics. IT security and cybersecurity were considered as a domain that is transverse across the value chain.

The interviews were carried out as part of an internal programme of research, but non-confidential findings are included in this benchmarking and roadmapping report as CEA believes there is relevance to PIARCH development and to CPS4EU partners.

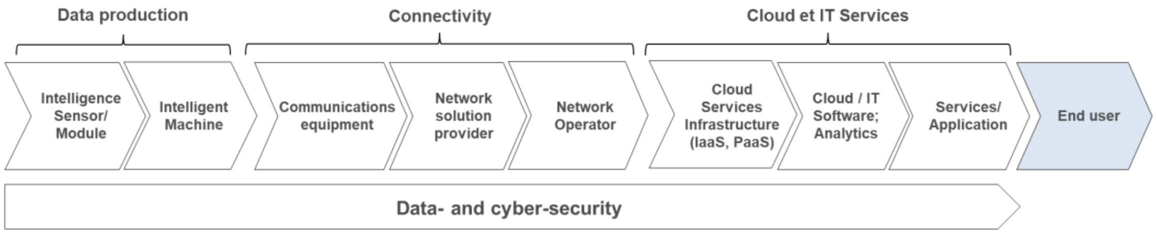


Figure 45 – CPS Value Chain

The aim of the interviews were several fold:

- Understand the barriers to the deployment of secure IoT and CPS solutions in Europe, from both vendor and user standpoints, including the importance of solutions that could be mutualized across different sectors.
- Garner viewpoints concerning the adequacy of the European ecosystem in IoT/CPS across the value chain.
- Understand the views of users regarding issues of Cloud sovereignty, solution interoperability, as well as data sharing.

8.2 *Key findings*

The following high-level findings of the interviewing are provided:

- ***Sensors and intelligent machines: a general adequacy of solutions at the European level.*** For the most part, interviewees do not reason at the national level, but at the European one. Different strengths and weaknesses in certain segments of the national supply chains, around sensing and intelligent machines, are generally smoothed out at the European level and Europe retains a strong base in sensing and embedded ICs. This view is aligned with market research data[49] showing the still considerable presence of European companies in embedded electronics, in comparison to standalone electronics, as well as numerous sensor companies including Bosch, Kistler, SICK, Siemens and ST Microelectronics.

At the level of machine automation (PLCs/SCADA), Europe is also well represented with the likes of ABB, Schneider, & Siemens, though interviewees noted the importance of US companies GE, Honeywell and Rockwell. It should be stated that with the exception of smaller companies, large industrial users and integrators interviewed do not reason at a national or even European level, but at a global one.

49 For example, Decision Etudes & Conseil, November 2018

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- ***Despite the adequate supply, sensing and machines are the weak link in industrial automation and CPS for reasons of legacy systems, the variety of protocols and different data models.*** Industrial users (owners of factories) interviewed are confronted with a variety of issues as they try to upgrade their plants and integrate the benefits of the industrial internet. Three main issues were outlined:
  - **Industrial infrastructure that is of a variety of different ages**. The problem is not with new equipment being installed for which connectivity is built-in natively, but with legacy systems. Legacy equipment some of which is unable to upload machine data and machines that support a variety of protocols and data models.
  - **Equipment from different vendors**. Despite industrial communications standards, different protocols and also particularly data different models, prevent machines from easily talking to one another. As one large industrial automation vendor put it: "it usually takes us far longer to harmonize data structures and models than for data extraction itself".
  - **A history of integrations by different solution providers**. In the the case of large industrial companies with factories of different ages over different sites, system integration has often been carried out piecemeal by different systems integrators. Particularly looking back 10-15 years, not all such integrators had the same experience or looked to standardize data structures company-wide. The result is a variety of systems and data models that make it hard to share the same data (for machine optimization) with the same organization.

- ***75% of interviews cited data interoperability at the OT level as a major weak link in the deployment of digital solutions.*** Two main causes for such interoperability were identified: different OT networking protocols and, in particular, different data models. For the latter, interviewees cited a battle between large suppliers and their customers as to who has the upperhand in imposing a data model standard. Many noted progress in certain sectors that now show a greater degree of standardization; for example, the development of OPC UA and MTConnect data model standards for factory networking and the ZigBee standard for home automation that includes data model standardization. Interviewees in construction and utilities highlighted the greater difficulties encountered in fields that cut across different ecosystem types: the complexity of smart cities for example.

This finding concerning data models is consistent with the results of earlier survey work by the ZigBee alliance and others in 2018. At that time, the alliance hosted a summit of IoT leaders and other IoT standards organizations, which concluded that the most frequently cited challenge was the inconsistency and lack of interoperability across the field of IoT data models. That work led to the formation of the One Data Model (OneDM) alliance of standards development organizations and IoT platform vendors.

- **The need for middleware solutions to drive interoperability.**

In the case of the OneDM, the proposed solution to facilitate interoperability between different ecosystems is a semantic definition format (SDF), a common format for describing data models and defining the mechanisms needed for the translation. This process is illustrated below (source Ericsson) in which source and target ecosystems only need to translate model data to and from SDF, but source and target ecosystems do not need to understand the internals of each other.

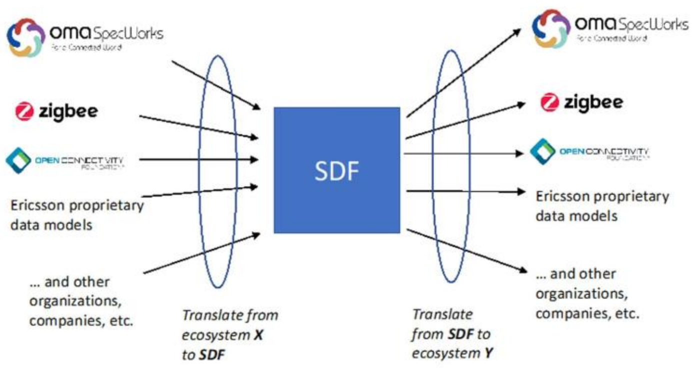


Figure 46 – Semantic definition format

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

While our interviews did not specifically refer to the SDF, their responses echoed the need for data model coexistence. The notion that standards heterogeneity will always be with us and that the answer is not simply a new standard, even if such a thing were possible. Rather, they cited the need and deployment of middleware solutions to create bridges between different solutions and data models. This finding is entirely consistent with the SDF approach, even if a patchwork of solutions is the current reality.

Importantly, this strongly expressed need should be born in mind when looking at investments in IoT component technologies. Deliverable D10.21 noted the relative investments in the different constituents of the IoT and CPS component stack within ARTEMIS and ECSEL initiatives clearly reflecting the importance of IoT middleware as a clear category, together with frameworks and platforms.

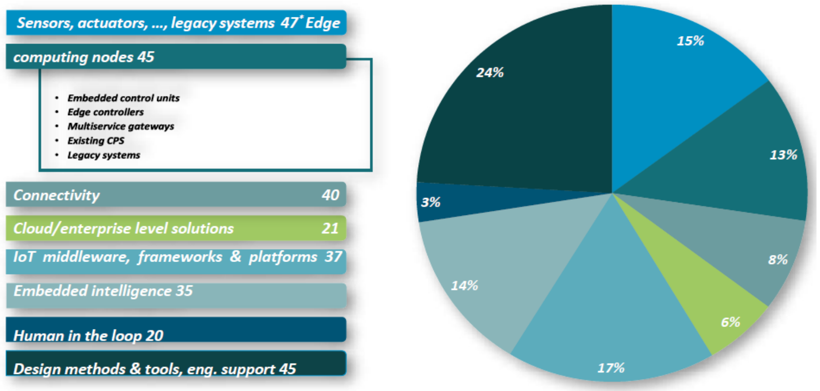


Figure 47 – Percentages of investments by IoT stack macro-components

- **A complex Cloud and IT services value chain segment, with Europe largely seeking to provide complementary solutions relative to US leaders**

The relative weakness of Europe's Cloud services industry was highlighted by many interviewees, with the dominance of US players AWS (Amazon), Azure (Microsoft) and Google. Except in certain sectors, defense and some utilities (notably energy), a majority of interviewees used US Cloud service providers for some if not all of their Cloud services, and despite the US Cloud Act, which in practice could make client requirements for storage localization somewhat less meaningful. In large part, current practices reflect a pragmatic, but hybrid approach to storage and compute requirements, as noted below.

However, interviewees pointed that today Cloud services go well the original notion of Cloud storage and that these additional services of Cloud computing and analytics are increasingly the key points of service-provider differentiation. The result is that smaller Cloud providers have to search for elements of complementarity, without direct or full-frontal competition with the major providers. From an IoT/CPS application standpoint, this means focusing nearer the OT/IT interface, or on the specific needs of market verticals, rather than, for example, in Enterprise-level Cloud services, such as ERP.

- **A pragmatic, hybrid approach to storage/compute that often allows circumventing Cloud sovereignty issues**

The fact that Cloud sovereignty issues seem less acute than might have been expected can be put down to industrials developing a hybrid approach to data storage, in which operational needs dictate storage and compute locations. Industrials point out that real-time operational data needs to be stored in onsite servers (often in the form of on-premise private Cloud infrastructure) for several reasons. Firstly, because of data sensitivity and the fact that operations management cannot depend on the reliability of data services with distant Cloud storage infrastructure. Secondly, as real-time treatment of data is becoming more common to pilot operations, the latency of operations to and from Cloud storage and compute is too long. And finally, the increasing amount of data generated by sensors and intelligent machines, will quickly saturate networks, if the response is simply to upload that data to the Cloud. One important result is the fact that all industrials see the need for computing as close as possible to the generation and reuse of the data, whether that is at intelligent sensor nodes or at OT/IT Edge gateways.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Even when it comes to off-premise storage, users will often use a mix of hybrid private and public Cloud storage. For the public Cloud this would typically be for less sensitive organizational data. Again, reasons for using public Cloud providers, aside from the benefits of lower cost and outsourcing, are to tap into computing and analytics resources. Industrials may consider services in data anonymization of more sensitive data (for example, offline process data) as a way to enable the use of Cloud computing and analytics resources in support of needs for process optimization or predictive maintenance. Again, some sectors are much more restrictive in their use of the Cloud, notably defense, energy and some transportation segments.

- **The need for greater interoperability between Cloud providers to provide greater complementarity as much as increased competitiveness.**

While the Franco-German Gaia-X initiative might be seen as a coordinated response to create European champions in Cloud service provision, the industry members interviewed (some of them Gaia-X founding members) point out that the initiative is focused on transparency and interoperability of Cloud services. Specifically, Gaia-X aims to create a secure, federated system that meets the highest standards of digital sovereignty while promoting innovation. To do so means providing minimum technical requirements for secure federated identity and trust mechanisms, interoperability and portability across infrastructure, applications and data, providing a compliance framework and certification and accreditation services. Moreover, Gaia-X supports modular compilation of open source software and standards.

Users point out that a key need is the ability to easily change Cloud services providers with minimal effort, that otherwise would create a form of lock-in. Secondly, interoperability would allow them to more easily use a variety of Cloud service providers for different tasks. One obvious example is in the field of analytics, where users want the ability to share selected data with would-be service providers. At present, large industrial IoT platforms often provide this mediation between customers and service providers, but a more federated system would aim to put the data owners more in control.

Nevertheless, to the extent that improving interoperability should create a more level playing field, Cloud providers interviewed suggest that Gaia-X should better enable them to provide IT services that are complementary to those of the main Cloud providers.

- **Data security**

If industrials interviewed were more pragmatic in the face of dominant US Cloud service providers, they were united in the importance of end-to-end data security. For many the implementation of data security/cybersecurity solutions is of more importance than the choice of where Cloud data is stored. And this concern for data security applies at all parts of the value chain, including for locally stored data. Robust data security solutions are seen as key for allowing the exchange of data between different players in the value chain. The area is seen as a vital one for innovation and several industrials mentioned the importance of technologies such as homomorphic encryption. Homomorphic encryption is a form of encryption that allows calculations on the encrypted data to be performed without first decrypting it.

While Europe does not have the same strength as the United States in certain areas, (a lack of virus security software was noted for example), industrials viewed European data-security expertise as good, with ATOS, Idemia, Orange and Thales (including Gemalto) cited in the case of France.

- **Data integration, analytics and applications development: the segment attracting most activity and new entrants in search of viable business models.**

From our secondary research and interviews, the area of analytics and application development (for example, decision support solutions), including complete IoT platforms, is the one that is seeing the most active development. Perhaps surprising is the level of engagement with platform and service development that we found from smaller companies whose main expertise is in hardware development. In segments including logistics/tracking, services relating to energy consumption and transport/mobility, numerous small and medium-size enterprises are providing Cloud-based data aggregation and dashboard solutions for operations management.

In the footsteps of leaders including GE, Hitachi and Siemens, medium-size players are adding data aggregation and analytics to their equipment offerings for condition monitoring and predictive maintenance. Owners of the major industrial IoT platforms like ABB, Siemens and Schneider Electric have become the creators of open market

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

places that integrate 3rd-party hardware and data service solutions for their industrial clients. In addition to the historic business of these companies in providing industrial automation equipment such programmable logic controllers and SCADA systems, developers of these IoT platforms are now competing to attract other companies to the ecosystem.

As one large industrial IoT platform provider put it, in the face of a plethora of (for example) predictive maintenance solutions, their role is migrating toward providing advisory services to end-user industrial clients and ensuring a secure environment for data sharing between data owners and would-be data service providers.

9 Roadmap 2021-2022 inflexion

Since previous version of this document (D10.22 Road mapping & Benchmarking v2 delivered in March 2021), the general trends identified in previous chapters regarding the evolution of the CPS market, and modular design approaches have mostly confirmed, except a few details e.g. the merger ARM takeover by NVidia which was abandoned in February 2022.

What had not yet been anticipated however at the start of the CPS4EU project, is that during the approximately 3 year course of the project, the global industry ecosystem was struck by a few significant events which shine a new light on the brittleness of global industrial value chains that are at play especially in the CPS and other high technology fields:

- the COVID pandemic and its indirect consequences on industrial value chains,
- a raising awareness about climate change, energy usage, and sovereignty concerns.

This chapter is devoted to analyzing the impact of these new challenges on the CPS market trends, and design methodologies.

9.1 *COVID pandemic*

After COVID-19 outbreak in Wuhan, China, and failed attempts at containing the virus, a large part of the modern world was hit by the pandemic. Many countries thus attempted to mitigate the health risk by restricting social interactions, travel, border crossing and cross-border shipments. Various events caused by the pandemics, combined into a snowball effect, and caused a major supply-chain crisis, which impacted particularly the electronics and CPS industry, which used to be a fast-growing sector before the pandemics.

In response to the health risk, most industrial countries resorted to partial or full lockdown throughout year 2020 and 2021. This implied simultaneously a massive switch to remote work and remote learning, causing a major surge in demand for computer and peripherals, and at the same time, many factories (especially in China) had to remain closed for several months. Although several countries like China and the US identified the semiconductor industry as an essential critical infrastructure, allowing them to continue their operation despite lockdown, several foundries, packaging or component industries had to shut down. Many vendors depleted their inventories, while some others resorted to panic buying, further increasing the stress on the logistic chains.

When the global economy started to ramp up again by end of 2020 and 2021, the semiconductor providers struggled to replenish their stocks. J.P.Morgan Research estimates[50] however that by end of 2022 the shortage would be nearing the end.

Several industries were more or less directly impacted by the chip shortage, especially the PC and game console industry. In the field of CPS, the car industry is particularly impacted during its transition towards electric vehicles. With 1500 to 3000 chips per single car, the automotive industry is more and more dependent on the IC industry. Some estimate that the global chip shortage could cost the automotive industry US$210 billion in 2021 alone[51]: as a consequence of large shipping delays (sometimes more than a year), several factories were forced to idle production lines or to pile up stocks of unequipped cars for months, and some carmakers even resorted to shipping cars with downgraded equipment.

[50] https://www.jpmorgan.com/insights/research/supply-chain-chip-shortage
[51] https://mitsloan.mit.edu/ideas-made-to-matter/how-auto-companies-are-adapting-to-global-chip-shortage

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Following Russia's invasion of Ukraine in February 2022, tension increased and prices went volatile on several fossil fuel energy sources as well as and gasses, especially krypton and neon. Krypton and neon are mostly sourced from Russia and Ukraine, and are necessary in IC production chains. This new consequence is expected to slow down a return to normal situation.

9.2 *Energy, environment and sovereignty*

Since IPCC's 6th assessment report[52], published in parts between 2021 and 2022, especially the WG2 report on "impacts, adaptation and vulnerability", both populations and political representatives are more aware of the practical impact of global climate change, and of the required mitigations. European policies start to include systematically an evaluation of the environmental impact (e.g. French 4th Investment Plan for the Future[53] in 2021 introduces a new selection criterion, based on environmental footprint). In particular, energy policies are heavily debated. The German 2010 "Energiewende" strategy, originally an ambitious move to phase out of fossil and nuclear energy in favor or renewables, is now considered a failure by many analysists after it was deemed necessary in to re-open 10GW coal production plants to mitigate Russia's gas cuts.

In response to both the increased awareness of climate change, and volatility of oil and gas markets following Russia's attack on Ukraine, European governments are accelerating eco-design plans and even enforcing sobriety plans. Many raw materials are already considered critical because they are heavily demanded in electrical transports, wind and solar farms[54] (especially copper, nickel, lithium, rare earths), so that their sparsity poses severe risks to the feasibility of many energy transition plans. For this, and other reasons, a growing population considers sustainable growth plans as an illusion[55], and speculate a major sobriety or de-growth would happen *volens nolens*, either through a massive political and economic shift, or as a consequence of the collapse of current economic and geopolitical equilibrium caused by the ever increasing impacts of climate change.

In next decades anyway, critical materials as well as all energy-intensive processes will have to be considered as sparse resources, and therefore budgeted with care. Some CPS systems will become necessary to manage, monitor, and actuate precisely all energy distribution, power consuming or actuator devices. This is the case of smart grid, smart city lighting, smart home energy management, and even smart/autonomous emission-less collective transport systems. In the other hand, some trending CPS fields of today might progressively become considered as useless gadgets not worth their energy and environmental footprint. This kind of argument is often raised for instance against the deployment of 5G networks, or disposable battery-operated electronic devices.

This situation change implies that only those CPS systems that prove a high ratio of societal value over environmental impact could be produced at scale. As a consequence, actually fewer CPS systems could be produced, however the ones that go to production would need considerably more effort to optimize down the environmental footprint of their whole lifecycle including fabrication processes, energy usage, reparability, reusability, recyclability, etc.

As a response to their dependency on both global logistic chains and sovereignty issues, both the US and Europe are pushing new their incentives to relocate their IC industries. In the US, the CHIPS (Creating Helpful Incentives to Produce Semiconductors) and Science Act[56] is effective since August 2022, with US$280 Billion new funding into US semiconductor research & manufacturing; and an additional strategic focus against China and Russia (beneficiaries are not allowed to produce advanced ICs in China or Russia for 10 years). In a parallel move, in Europe, the Chips Act[57] proposes to dedicate a budget of more than €41Billion to the European semiconductor manufacturing industry, through IPCEI and MegaFABS projects.

---

[52] https://www.ipcc.ch/report/sixth-assessment-report-cycle/

[53] https://www.gouvernement.fr/sites/default/files/contenu/piece-jointe/2021/12/cma_fiche_verdissement_du_numeriquev2.pdf

[54] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary

[55] https://jancovici.com/publications-et-co/articles-de-presse/vive-la-croissance-verte/

[56] https://en.wikipedia.org/wiki/CHIPS_and_Science_Act

[57] https://ec.europa.eu/commission/presscorner/detail/en/STATEMENT_22_891

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

9.3 *Consequences on the PIARCH-based design process*

The global events and trends presented above might have a deep, long-term impact on the CPS value chain in Europe, and the way CPS systems are designed. In particular, the technical and political response to these events is often to add more technical constraints, and non-technical stakes, on top of the technical challenges of building CPS products.

Besides technical functionality, the physical building blocks used in designing a CPS product will have to meet an increasing diversity of non-technical requirements, concerning for instance:

- minimize the environmental footprint of the whole CPS lifecycle,
- provide traceable information about usage of raw (and critical) materials, instructions on how to re-use, repair, recycle parts, and the energy/CO_2/environmental footprint of its fabrication, etc.
- ethics and geopolitical stakes such as the geographic origin of raw materials as well as preprocessed goods, certificates of ethical quality.

All these non-functional meta-data should be sourced together with any part or component to be integrated into a CPS sub-system or product; so that the whole technical value chain required for building CPS products will be associated with a chain of traceable data: every mechanical part, electronic computing unit, module, down to every single electronic component, shall be traced to some meta-data package that allow to answer these non-technical requirements. For a complex CPS product, assembling and tracing such a data package for the whole system will be extremely time-consuming, unless large parts of that data package are already pre-packaged at subsystem-level. This is why the notion of pre-integrated architecture building blocks will certainly help cope with the complexity of this meta-data chain: every off-the-shelf PIARCH will be pre-optimized against the expected societal values, documented with traceable data regarding these non-technical stakes, and could be completed with reference documentation (tutorials) about how to ascertain compliance with known non-technical requirements or regulation.

Moreover, for CPS production to be more resilient to brittle global logistics chains, CPS makers already attempt to diversify their components sourcing chains. Although pin-compatible interchangeable ICs are not very common, at higher levels of abstraction many hardware components can be interchanged. In many embedded Linux projects for instance, a single-board computer could be replaced with another SBC of similar performance, with only minor additional software validation cost. It is assumed that diversified implementations of the same PIARCH design pattern could coexist, and therefore be replaced with one another in case of a random change in non-technical requirements or logistics supply chain. The Heterogeneous embedded AI Computing PIARCH might be an illustration of such hardware-level interchangeability, since at software-level a similar toolchain is often used to transform the same high-level AI payload (modeled in de factor standard tools like PyTorch, CAFFE, Tensorflow) into hardware-specific implementation optimized for e.g. Kalray's MPPA, CEA's PNeuro, of GreenWaves' GAP9 processors.

In general however, achieving an optimal ratio of societal value against environmental footprint will require cross-boundary optimization, which implies that designing a CPS based on a pre-optimized PIARCH might lead to a local optimum, not necessarily approaching the global optimum.

10 Conclusions

This deliverable has provided an overview of trends in the major market verticals relevant to CPS4EU (automotive, industrial automation, smart grids) as well as the defense segment, with a view to drawing out some high-level inferences for the development of CPS4EU PIARCHs. In addition, a section looking at a number of ecosystems and individual actors developing modular embedded electronics with both hardware and software development kits (often open source and with a view to interoperability) provides some competitive context for PIARCH development.

At a broad level, we find support for the PIARCH concept of the pre-integration of functional-specific modules in support of rapid application development, even if the level of pre-integration is variable across the different functional domains and specific examples by industry vertical are not always available.

- In the sensor industry, the notion of pre-integration is long-standing and domain specific: for example, in gas sensing, in HVAC systems and in motion control. Recent years have seen further extensions of this integration trend in applications like machine-based condition monitoring.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

- Strongly aligned with industrial automation, cellular-based M2M connectivity suppliers have been providing pre-integrated SoCs for some time and are now focused on wider opportunities in IoT, providing a larger portfolio of connectivity options to include not only Bluetooth (BLE)/Wifi, a range of cellular options including narrowband LTE- CAT M1 & NB1, as well LoRa. Modules defined with the connectivity PIARCH seem well aligned with external developments though wider peripheral interface support (beyond UART) seems common.
- In the defense industry, the notion of interoperability is well entrenched, with standardization a key element. The functional segmentation of the CPS4EU PIARCH seems well aligned with defense architectures and from discussions, there is a trend toward PIARCH integration. The development of pre-integrated computing modules, in particular, appears a key need going forward.
- The automotive sector encompasses one of the most advanced forms of CPS and electrical/electronic architecture trends are important to monitor. We note the trend away from domain specific controllers toward zonal and in the longer-term highly centralized architectures, with a focus on the separation of I/O from computing and Ethernet as a high-performance interconnect backbone. Existing vehicle processors are already heterogeneous in nature (in particular multiple types of ARM processors to cope with real-time and ultra-real time applications) and support for hardware virtualization is now built-in. The trend toward compute centralisation will only increase this need for HW virtualisation of resources, for example allowing several ECUs to share the same processor, and *could* increase the needs for heterogeneous computing at the board level: for example, by combining CPU- and GPU-like functionality.
- In industrial automation, connecting legacy infrastructure or very different industrial assets can still present issues, but a combination of increasing I/O standardization and middleware solutions (notably OPC UA) are providing solutions. IoT gateways provide the key interface between sensors (OT) and IT networks, and gateway connectivity solutions noted above are generally in line with PIARCH specifications. A clear trend exists in enhanced computing resources at the edge, in particular to support AI inferencing, with some examples of heterogeneous computing being developed, notably by ADLINK. With the clear need for computing decentralization (from Cloud to edge) in industrial automation to support real-time, low-latency applications (as well as data security), we note potential trends toward micro Clouds that could change the nature of computing requirements, in particular the balance between computing in the micro Cloud and the gateway.
- Smart grid CPS developments are less mature and this research has focused on a review of the literature. A key feature of SG CPS is strong decentralization of resources to support scalability, adaptability and robustness and we note that multi-agent architectures seem more popular than more traditional SOA.
- In addition, CPS have unique design challenges, and several CPS design automations directions already exist. Component-based design with contract methodology can be of interest for PIARCH development, but it may not be the best choice for safety-critical or mission critical CPS (Smart Grid or autonomous vehicle).

The scope of the current deliverable is large and the analysis provides a high-level view of market and technology trends with relevance to PIARCH development, including in view of the recent evolution of global situation during the course of the CPS4EU project.

11 Bibliography

[1] S. Karnouskos, “Cyber-physical systems in the SmartGrid,” *IEEE International Conference on Industrial Informatics* (INDIN), pp. 20–23, 2011.

[2] Xinghuo Yu and Yusheng Xue “Smart Grids: A Cyber–Physical Systems Perspective” *Proceedings of the IEEE* | Vol. 104, No. 5, May 2016

[3] Ananthavijayan, R., Karthikeyan Shanmugam, P., Padmanaban, S., Holm-Nielsen, J., Blaabjerg, F., & Fedak, V. (2019). Software Architectures for Smart Grid System—*A Bibliographical Survey. Energies*, 12(6), 1183.

[4] P. Zhou et al., “A Comprehensive Technological Survey on the Dependable Self-Management CPS: From Self-Adaptive Architecture to Self-Management Strategies,” *Sensors* (Basel, Switzerland), vol. 19, no. 5, 2019.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

[5] A bottom-up approach to energy management in a Smart Grid : adaptive and reactive model using a decentralized architecture for a generic user-centered system enabling large scale deployments , Ph.D. Thesis , Victor Lequay

[6] Jawad Ghorbani, “A Multi-Agent Design for Power Distribution Systems Automation”, Ph.D. Thesis, West Virginia University, 2014.

[7] G.S. Satheesh Kumar and S. Tamil Selvi “Applications of Multi-Agent System in Power System Engineering” 2020

[8] Arun Sukumaran Nair, Tareq Hossen, Mitch Campion, Daisy Flora Selvaraj, Neena Goveas, Naima Kaabouch & Prakash Ranganathan, “Multi-Agent Systems for Resource Allocation and Scheduling in a Smart Grid”. *Smart Grids and Sustainable*, 2018

[9] M. Jawad Ghorbani, F. Doost Mohammadi, M. A. Choudhry, A. Feliachi “Hardware Design for Distributed MAS-Based Fault Location in Power Distribution Systems” *IEEE* 2014

[10] C.-H. Yoo, I.-Y. Chung, H.-J. Lee, S.-S. Hong “Intelligent control of battery energy storage for multi-agent based microgrid energy management” *Energies*, 6 (10) (2013)

[11] Mohammad Jawad Ghorbani, Muhammad Akram Choudhry, Ali Feliachi “A Multiagent Design for Power Distribution Systems Automation”, *IEEE Transactions on Smart Grid* - 2016

[12] Sanjit A. Seshia, Shiyan Hu, Wenchao Li, Qi Zhu “Design Automation of Cyber-Physical Systems: Challenges, Advances, and Opportunities” IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (Volume: 36, Issue: 9, Sept. 2017)

[13] P. Nuzzo, A. L. Sangiovanni-Vincentelli, D. Bresolin, L. Geretti and T. Villa, "A platform-based design methodology with contracts and related tools for the design of cyber-physical systems", Proc. IEEE, vol. 103, no. 11, pp. 2104-2132, Nov. 2015.

[14] Nuzzo, P., Xu, H., Ozay, N., Finn, J. B., Sangiovanni-Vincentelli, A. L., Murray, R. M., … Seshia, S. A. (2014). A contract-based methodology for aircraft electric power system design. IEEE Access, 2, 1–25.

[15] A. Sangiovanni-Vincentelli, W. Damm and R. Passerone, "Taming Dr. Frankenstein: Contract-based design for cyber-physical systems", Eur. J. Control, vol. 18, no. 3, pp. 217-238, 2012.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276