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Software and Architecture Orchestration for Process Control in Industry 4.0 Enabled by Cyber-Physical Systems Technologies

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Abstract: In the context of Industry 4.0, this paper explores the vital role of advanced technologies, including Cyber–Physical Systems (CPS), Big Data, Internet of Things (IoT), digital twins, and Artificial Intelligence (AI), in enhancing data valorization and management within industries. These technologies are integral to addressing the challenges of producing highly customized products in mass, necessitating the complete digitization and integration of information technology (IT) and operational technology (OT) for flexible and automated manufacturing processes. The paper emphasizes the importance of interoperability through Service-Oriented Architectures (SOA), Manufacturing-as-a-Service (MaaS), and Resource-as-a-Service (RaaS) to achieve seamless integration across systems, which is critical for the Industry 4.0 vision of a fully interconnected, autonomous industry. Furthermore, it discusses the evolution towards Supply Chain 4.0, highlighting the need for Transportation Management Systems (TMS) enhanced by GPS and real-time data for efficient logistics. A guideline for implementing CPS within Industry 4.0 environments is provided, focusing on a case study of real-time data acquisition from logistics vehicles using CPS devices. The study proposes a CPS architecture and a generic platform for asset tracking to address integration challenges efficiently and facilitate the easy incorporation of new components and applications. Preliminary tests indicate the platform's real-time performance is satisfactory, with negligible delay under test conditions, showcasing its potential for logistics applications and beyond.

Keywords: Industry 4.0; CPS; SOA; TMS; Supply Chain 4.0

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1. Introduction

When the concept of Industry 4.0, originating from an initiative within the advanced technology strategy of the German government and intended to foster the digitization of manufacturing processes, was initially introduced, it aimed to propose an innovative paradigm that offers a comprehensive perspective on industrial systems, considering aspects related to organizational structures and their interactions with suppliers, partners, and customers [1]. Other approaches present a compilation of political, social, economic, and technological changes proposed by Industry 4.0 [2].

In a generic manner, and based on the extensive available literature, we can assert that the Industry 4.0 paradigm is grounded in four strategic principles or functionalities: (1) Interconnectivity: related to the capacity of machines, devices, sensors, and human beings to communicate among themselves and each other through the Internet of Things (IoT) and the Internet of People (IoP), concepts that support the latest paradigm designated as the Internet of Everything (IoE); (2) Information Transparency: offering transparency, equipping operators with comprehensive information crucial for decision-making; (3) Technological Assistance: the capability of systems to assist humans in decision-making, problem-solving, and handling challenging or unsafe tasks; and (4) Decentralized Decision-Making: the autonomy of cyber–physical systems to independently make decisions and execute tasks as autonomously as possible [3]. However, more recently, alternative perspectives have emerged, essentially entailing the addition of new dimensions to the core pillars, including concepts like Virtualization, Real-Time Capability, Service Orientation, and Modularity [4–6].

However, human beings play a particularly crucial role in the physical world. Consequently, systems that incorporate humans as integral components of the physical world are referred to as Human-in-the-Loop systems. Essentially, human-in-the-loop systems can be categorized into three groups based on the role assumed by humans: (i) systems where humans have control over the operation, (ii) systems where humans are solely monitored passively, and (iii) hybrid systems combining elements of the previous two. In contrast to the physical world, the remaining components in a CPS are considered to belong to the cyber world or cybernetics [7,8]. Hence, the involvement of humans in the context of Human-in-the-Loop Cyber–Physical Systems (HiLCPS) introduces certain modifications to the traditional CPS paradigm, given the dynamic and distinct nature of human behavior in comparison to technical systems (devices, processes, etc.). The primary areas of human impact on CPS encompass cognition, predictability of behavior, and motivation. This approach necessitates the integration of novel features, including interfaces between human operators and autonomous components traditionally represented by interfaces such as Human–Machine Interface (HMI) and Human–Computer Interface (HCI).

The pursuit of Continuous Improvement remains dedicated to achieving perfection by enhancing products, services, and processes. Two distinct classifications of improvements emerge—one characterized by incremental enhancements through sustained Kaizen activities, and another marked by breakthrough improvements implemented all at once [9].

From the perspective of Industry 4.0, the objective is to promote the digitization of the process. This entails establishing integrated communication systems based on process sensor support and applying the Internet of Things (IoT) concept. These systems generate extensive data with high availability and frequently adhere to real-time requirements. Following their acquisition, the acquired data undergo data analysis techniques and methodologies to ascertain their relationships and generate meta-information. The comprehensive procedures, spanning from acquisition and validation to processing and analysis, are commonly referred to as Big Data.

In essence, the culmination of integrating these concepts results in the creation of a digital replica, known as "digital twins", of the actual process. This facilitates the establishment of an efficient and flexible production system capable of adaptation or alteration in response to variations upstream or downstream of the process.

At the core of this paradigm lies the foundation of Cyber–Physical Systems (CPS). A cyber–physical system integrates computation, encompassing the cyber world, which means embedded systems and power computation, with physical processes through computer networks. Embedded computers and networks play a crucial role in monitoring and controlling physical processes through feedback loops. CPS represents a revolutionary approach to manufacturing by integrating tangible systems with cutting-edge computing, networking, and software advancements. It consists of three key elements: the tangible system, the digital system, and the interface connecting the two. The tangible system encompasses sensors, actuators, robots, and machinery, while the digital system incorporates computing systems, software, and networking technologies.

Furthermore, the deployment of end-to-end services often involves Network Function Virtualization (NFV) functionalities to address technological heterogeneity across various domains. Additionally, it is necessary to accomplish the following: (i) select the domains involved in the service deployment (e.g., where the NFs should be executed); (ii) determine the network parameters to be used for establishing proper data/information traffic routing between the domains; and (iii) create the service subgraphs to be instantiated above the domains. This can be achieved through the digitization of processes and procedures, employing concepts associated with Cyber–Physical Systems (CPS), that is, to produce the softwarization of the system and the orchestration of services.

This means that the objective pursued for optimization through the processing of real-world information is embodied in the cyber–physical system (CPS). CPS seamlessly transfers information from the physical world, immerses it into a virtual space (cyber), subjects it to computational analysis, and subsequently channels the analysis results back to the real world, thereby optimizing real-world operations. Consider the implications when reality becomes programmable, giving rise to the softwarization of reality. Indeed, the softwarization of reality is already unfolding ubiquitously.

Supply Chain Management (SCM) stands out as a critical factor in enhancing the competitive advantage of both small- and medium-sized enterprises (SMEs) and industrial firms. Recent years have witnessed substantial transformations in logistics-related technologies, enabling entities to boost their efficiency through the adoption of systems such as transport management systems (TMS), warehouse management systems (WMS), enterprise resource planning systems (ERP), product lifecycle management solutions, and inventory management software [10]. Beyond organizational measures, improved planning heuristics, flow orientation, process alignment, and product design, automation emerges as a pivotal opportunity for enhancing overall performance and competitiveness in logistics. Notably, automation and robotics within logistics systems are recognized as major megatrends, ranking alongside others like data analytics, artificial intelligence, autonomous and unmanned aerial vehicles, cloud computing, and blockchain technology. The integration of information and communication technologies, compatibility of hardware and software, standardized interfaces, modular system design, consistent information storage, and interoperable hardware and software play crucial roles in automating material flow processes within logistics systems. Furthermore, an intelligent, automatic, and autonomous SCM system is a softwarized SCM.

This article examines the concept of Cyber–Physical Systems (CPS), exploring their applications and significance within emerging industrial frameworks aimed at achieving Industry 4.0 goals. It delves into the integration of new business models, emphasizing software and system architecture orchestration based on the concept of service-oriented architecture (SOA), and the evolving industrial architecture of smart factories, with a specific focus on Supply Chain Management (SCM) environments. This emphasis is due to the unique applications and disruptive potential of CPSs, intending to identify both their impact and challenges.

As a case study, in this paper, a CPS platform is presented that enables real-time data acquisition, from logistics vehicles, using CPS devices, with a special emphasis on the seamless integration of these data into a Transportation Management System. The integration process of data sources and data sinks, in a data acquisition system, can be a very time- and resource-consuming phase. Even if data communication standards and data representation standards are used, in real-life scenarios we will find cases where sensors from different developers use different data formats and communication protocols. This happens even in the case that those sensors provide similar information (e.g., the GPS coordinates of a vehicle). After the data are acquired, the data must be sent to the corresponding sinks, which on the other hand may also require data format adaptation or even transmission using different methods and protocols. A traditional approach for this integration, using ad-hoc integration solutions, may end up with a quadratic number of integration solutions. In the solution that is presented in this paper, that number has a linear growth as the number of data sources and sinks grow.

The rest of this paper is as follows: the second section introduces the concepts involved in Industry 4.0 and describes how CPS can revolutionize the way companies conceive, improve, and disseminate their products. The third section presents the characteristics of CPS and their potential in several applications, with a special focus on Industry 4.0. The next section describes orchestration software and architectures in the context of CPS environments, and related work. Section five presents the case study, which is related to the integration of real-time data for logistics platforms. The last section is the conclusion of this paper.

2. Industry 4.0

Industry 4.0 is characterized by an elevated level of digitalization, organization, and control throughout the entire product lifecycle's value chain. This includes aspects such as traceability, machine-to-machine-to-human connectivity, and personalized customer experiences [11]. The foundations of Industry 4.0 are rooted in emerging paradigms of information and communication technologies, encompassing the Industrial Internet of Things (IIoT), Cyber–Physical Systems (CPS), Service-Oriented Architectures (SOA), edge and cloud computing, and big data implementations. Additionally, innovative strides in cybersecurity, information distribution, and the decentralization of computing capabilities within new industrial-connected ecosystems contribute to the evolution of Industry 4.0 [12,13].

As described before, the Industry 4.0 paradigm is grounded in four strategic principles or functionalities: Interconnectivity, Information Transparency, Technological Assistance, and Decentralized Decision-Making.

Industry 4.0 is constructed upon nine foundational technology pillars. These progressions serve as a nexus between the digital and physical realms, enabling the realization of autonomous and intelligent systems. Supply chains, industrial processes, and businesses are already incorporating several of these innovative technologies. However, the complete realization of Industry 4.0 emerges most prominently when these technologies are seamlessly integrated and utilized in conjunction [9], described as follows. Big Data and Analytics: recently, analytics leveraging extensive datasets have surfaced in the manufacturing sector. This application optimizes production quality, enhances equipment service, and conserves energy. It involves the thorough assessment and compilation of data from diverse sources, providing real-time support for decision-making. Typically, the data reside in CPS and the cloud. Industrial Internet of Things: embedded computing facilitates communication and interaction among field devices, with more centralized controllers incorporating decentralized analytics and decision-making capabilities, enabling prompt real-time responses. The Cloud: high levels of data exchange within the organization, assets, and supply chain, a hallmark of Industry 4.0, serve as the primary catalyst for digital transformation. This forms the basis for cutting-edge technologies, encompassing AI, ML, and IoT, providing a framework for organization, coordination, and communication. Digital Twins' Simulation: a digital twin represents a virtual simulation of real-world products, equipment, devices, or systems, relying on IoT sensor data. It enhances the ability to analyze, understand, and pinpoint specific malfunctioning parts, anticipate potential issues, and enhance the maintenance and performance of products and industrial systems. Autonomous Robots: autonomous robots are intelligent machines proficient in independently executing tasks in the world without direct human control or command. While numerous industries have previously employed robots to handle intricate assignments, there is now a shift towards enhanced utility. These robots are evolving to be more flexible, autonomous, and cooperative, ensuring safety for human operators. Additive Manufacturing: in industrial manufacturing, the adoption of additive manufacturing has commenced; it is classified as a process wherein digital 3D design data are utilized to incrementally build a component through layered material deposits. This technique enables the creation of customized products with construction advantages, such as high-performance and lightweight designs. Augmented Reality: AR-based systems sustain a range of services, including the selection of warehouse components and the transmission of repair and operational instructions across diverse equipment, systems, and mobile devices. Cyber Security: the traditional practice of closed and isolated cyber systems, built on standard communication protocols, is no longer prevalent. The growing interconnectedness of devices underscores the heightened demand for robust cybersecurity protocols. Horizontal and Vertical System Integrations: currently in many industrial applications or solutions, some of the most advanced IT systems remain incompletely integrated.

Presently, there is a requirement for functionalities like cross-organization and universal data integration networks to facilitate and empower truly automated value chains. This encompasses Supply Chain Management (SCM) and the visualization of real-time SCM issues across functional areas, including logistics, quality, R&D, engineering, production, and service.

With the concept of softwarization, supply chain management (SCM) systems are becoming software-driven, and the traditional challenges of unpredictable supply routes may be replaced by intelligent supply routes that optimize transportation lanes and delivery schedules to enhance overall logistical efficiency. Cumbersome manual tracking processes might be substituted with automated systems that provide real-time visibility into inventory levels and shipment status, allowing for proactive decision-making.

Additionally, outdated forecasting methods may be replaced by advanced algorithms that analyze market trends and demand patterns, enabling more accurate demand planning. In this scenario, an SCM system driven by software could lead to a transformative shift, akin to the evolution from conventional city traffic to smart, optimized roads. Autonomous technologies within SCM may streamline processes, ensuring products are delivered precisely when and where they are needed in the supply chain.

The digital aspect of Industry 4.0 introduces fresh opportunities for horizontal integration, involving interactions among industries, suppliers, and customers. This transformation results in a novel approach to conducting business. These innovative business models hinge on the rapid accessibility of extensive data and the complete digitization of the surrounding environment. Industries, manifested as Cyber–Physical Systems (CPSs) linked to an industrial network, offer a range of services to external entities based on a service-oriented architecture, SOA [14]. Within the Industry 4.0 environment, terminology and concepts are leveraged from diverse domains, incorporating elements such as the orchestration of services in a service-oriented environment from the ICT sector.

Furthermore, a vision is presented of the way CPSs can function as a support and technical solution for Industry 4.0 to revolutionize the way companies conceive, improve, and disseminate their products. Manufacturers are incorporating state-of-the-art technology into their production facilities and operations, encompassing various computing paradigms, analytics, the Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML). Referred to as smart manufacturing, Industry 4.0 integrates physical production and operations with intelligent digital technologies, such as big data and ML, to establish a comprehensive and interconnected corporate environment.

3. Characteristics of Cyber–Physical Systems and Their Potential Applications

In the evolution of industry paradigms, one of the most popular models of factory automation adhered to was based on the ISA-95 standard [15]. This standard represents a business model structured around a pyramidal architecture, where information circulates both bottom-up and top-down. The organizational structure includes the following [16]:

- Enterprise Resource Planning (ERP): At the management level, addressing business planning and logistics.
- Manufacturing Execution System (MES): At the planning level, connected to manufacturing and operations management, overseeing production based on decisions and programs formulated at higher levels.
- Supervisory Control and Data Acquisition (SCADA): At the supervisory level, overseeing and supervising data collected from production components.
- Control Level: Managing sensing and data manipulation.

- Devices/Field Level: Engaged in physical production processes.

With the advent of Industry 4.0 and the need to make production processes flexible and customizable, there was a necessary shift in the internal organization of production systems. This concept is based on two premises: conceptualizing relationships within the company and mutually defining interfaces between different IT actors.

The introduction of Cyber–Physical Systems (CPSs) brought about a drastic alteration in this architecture. The transition from the pyramidal profile, with well-defined and separated tasks, shifted towards a proposal based on embedded and distributed systems. CPSs exhibit varying degrees of intelligence and autonomy, actively participating in the value stream of the production process. They now perform tasks previously assigned to ERP and MES systems.

When the physical element of a CPS involves a human, various technical and non-technical aspects need consideration. Industry 4.0 does not exclude human labor but seeks to integrate it through augmented reality (AR), collaborative robots, and the use of diverse human–machine interfaces (HMI).

In this context, Cyber–Physical Systems (CPSs) must possess the capability to autonomously execute specific tasks and engage in communication with the external environment for the fulfillment of diverse functions. According to the RAMI model [17], Reference Architecture Model Industrie 4.0, any component, even software devoid of physical components, can function as a CPS, offering valuable and essential services within an industrial setting. To illustrate, a practical example of a CPS could be a basic sensor providing a shareable measuring function within a network with internet connectivity. Alternatively, a CPS could represent an entire industry involved in the production of specific goods with real-time monitoring and control of every production task across all management levels [18]. RAMI 4.0 embodies a service-oriented architecture that consolidates all elements and IT components within a layered and lifecycle model. It dissects intricate processes into easily comprehensible packages, encompassing considerations for data privacy and IT security. RAMI is grounded on the subsequent principles: adaptability of systems and machines; distribution of functions across the network; interaction among participants across hierarchy levels; communication among all participants; and integration of the product into the network.

The components of Industry 4.0 engage in communication, adhering to the Service-Oriented Architecture (SOA) principle. The self-provided information from an Industry 4.0 component is structured on a Service-Oriented Architecture (SOA) basis, featuring services aligned with a service model (Resource Manager). The technological implementation of these services can be regulated by a corresponding profile of the Industry 4.0 component (e.g., through OPC-UA basic services) [17].

The disruptive technologies of Industry 4.0 promise highly efficient and increasingly integrated smart factories, characterized by a growing exchange of information. Information stands as the primary asset of the fourth industrial revolution. The analysis of the vast amount of data generated by these integrated systems enables a significant shift in the value creation for the entire enterprise. A notable strength of the fourth industrial revolution lies in its high impact, despite the limited equipment replacement, unlike the third revolution. However, to unleash the full potential of Industry 4.0, companies must comprehend the new technologies along with their challenges and opportunities. Therefore, various systems must be seamlessly and fully integrated.

The adoption of cutting-edge technologies, including the Internet of Things (IoT), deep learning, cloud computing, and artificial intelligence (AI), is progressively extending beyond conventional sectors. Continuous advancement of the physical processes can be achieved by implementing measures during the service phase. These measures aim to optimize performance through features such as remote operation, remote programming, and real-time monitoring of controlled equipment and devices, as well as fostering social interaction between equipment and users.

A cyber–physical system (CPS) constitutes an intelligent mechanical environment resulting from the fusion of computation, networking, and physical dimensions. Each CPS comprises a network of devices, often constrained by computing, storage, or bandwidth limitations. Within a CPS, numerous sensors or sensor-based devices gather diverse data types from various access points. This system is characterized by autonomous components engaged in frequent communication [19].

Applications encompass the following domains: manufacturing [6,13]; smart homes [20]; smart cities [21,22]; healthcare [23,24] where an extensive taxonomy has been presented concerning various components and methodologies for the implementation of CPSs; maritime and shipping [25,26]; aerospace [27,28]; smart grids [29,30] to attain high-performance computing, distributed sensing, and control capabilities; supply chains [31,32]; mobile ad-hoc networks (MANETs) [33,34]; and vehicular ad-hoc networks (VANETs) [35,36] in which vehicles primarily rely on individual customization, significant data analysis, and web mining. In the context of shipboard power systems, a cross-layer end-to-end delay analysis framework has been introduced, exemplifying current CPS implementations.

Notably, CPS often incorporates execution nodes in an edge network, utilizing computing resources in these nodes as substitutes for workload execution from resource-constrained devices. Every CPS is composed of a device network, typically constrained in computing, storage, or bandwidth capacities. Additionally, the frequent exchanges of small-scale communications among different components of CPS necessitate the deployment of data and computation in close proximity, facilitating the support of micro-executions. These operational demands give rise to several inherent challenges for CPS, distinguishing them from a conventional computational environment. This approach effectively mitigates resource constraints in CPS execution [37].

The necessity to address, from a vertical standpoint, aspects such as communication, heterogeneity, integration, interoperability, and resource and service coordination often leads to the implementation of dedicated software or the utilization of frameworks and APIs. Therefore, the adoption of concepts like Service-Defined Networks (SDN), Service-Defined Systems (SDS), Message-Oriented Middleware (MOM), and Service-Defined Internet of Things (SDIoT) can be considered facilitators for the process of softwarization.

Paradigms based on Software-Defined principles will play a role in the process of softwarization. By facilitating the division of the process into distinct planes, such as user, data, and control, these paradigms enable centralized orchestration of the entire process. This imparts greater flexibility, scalability, and performance compared to conventional approaches. This includes the creation of execution environments and orchestration for coordinating services and resources in CPS, particularly those associated with communications [37,38].

As the number of companies that develop CPS grows, it becomes clear that its potential application is logistics management. In [39], the role and impact of logistics and transportation services is analyzed, showing how these services are supported by new technologies, including CPS, for creating economic, environmental, and social values, in the context of Industry 4.0. In this framework, this paper proposes an integration framework for the seamless integration of CPS devices and logistics management applications.

4. Software and Architecture Orchestration in CPS Environments

A widely acknowledged description of a cyber–physical system entails the integration of computing and communication capabilities for the reliable, safe, secure, efficient, and real-time monitoring or control of entities in the physical world. The utilization of CPS technologies extends to the formation of situation-aware environments. It frequently involves establishing safety or mission-critical ecosystems and services, showcasing heightened capabilities and performance [40].

CPSs consist of tangible devices governed by cyber components and address diverse networking technologies to establish a robust and adaptable infrastructure for collecting and disseminating information in cyber–physical environments. Additionally, to support and make these environments autonomous, configurable, and flexible, CPSs will address other technologies such as middleware to facilitate cross-layer interactions; information-collecting and receiving devices, in very heterogenous network scenarios for content communication; and a multitude of platforms engaged in processing and storing information, to deal with a large set of applications utilizing information for various purposes.

CPS generally comprises three primary elements: sensors, aggregators, and actuators. Nevertheless, confronted with heightened system complexity, a significant hurdle for CPS involves establishing a balance between flexibility and heterogeneity while upholding Quality of Service (QoS) standards. Similarly, with the onset of Industry 4.0 and the manifold dimensions of IoT and IIoT, the focus revolves around the utilization of Cyber–Physical Systems (CPSs). In essence, these are intricate architectures in which cyber-components exert remote control over physical entities or processes.

From the literature review, it can be concluded that in recent developments, the application of Software-Defined Networking (SDN) to CPS has emerged to attain optimal resource allocation and ensure Quality of Service. This gives rise to a form of CPS known as SDN-assisted CPS [11].

Consequently, Software-Defined Networking (SDN) finds application in CPS, where it oversees the foundational infrastructure and regulates network traffic through controllers or application programming interfaces [41]. SDN facilitates the separation of network control from the data plane, delivering a flexible and time-efficient control capability, or supports centralized SDN controller architecture to allow for the management of network and system resources in real-time, whether in a cloud computing scenario or an edge computing scenario [37].

More recently, research and applications have included security issues, namely blockchain [11] and network function virtualization (NFV) solutions and their functionalities [42], to address the fact that WSNs support smart grid applications, which must be accomplished with new technical challenges such as RT and QoS constraints. Nonetheless, prevailing software-defined approaches for conventional WSNs predominantly address device and communication challenges from the vantage point of sensing and communication layers, lacking alignment with the systematic control demands of a CPS. Two crucial unresolved issues persist. Firstly, a viable systemic architecture is imperative for a software-defined CPS, necessitating global virtualization management and closed-loop control bridging the cyber side and physical side in a CPS. Secondly, the extension of the lifetime of a software-defined CPS remains an open challenge, requiring consideration of virtual resource optimization and the distinctive features introduced by SDN [42,43].

Network Constraints and Features

The rise of software-defined networking (SDN) heralds a prospective network approach, endowing its underlying networks and devices with programmability. Presently, SDN is deployed as the novel networking architecture within conventional Wireless Sensor Networks (WSNs). Such investigations contribute to progressing the networking architecture of Cyber–Physical Systems (CPS) and reshaping the landscape of future networks.

Common configurations of industrial networks primarily rely on managed devices equipped with features like priority queuing and access control protocols. Additionally, it is imperative to incorporate physical redundancy and encompass traditional protocols designed to fulfill general network requirements [41]. The delay prerequisites hinge on the industrial application. Situations where the worst-case delay serves as a targeted metric may find best-effort services inadequate. For hard real-time services, there is a demand for time-sensitive networks, wherein the control and management planes assure a low deterministic latency and minimal jitter.

An intelligently centralized controller, along with network awareness, holds the potential to provide Quality of Service (QoS) support for vital applications. As stated by [41], it can diminish complexity and expenses while enhancing flexibility. In the pursuit of realizing self-reconfigurable Cyber–Physical Systems (CPSs), most studies have underscored the adoption of closed-loop feedback SDN systems.

Hence, in contrast to Wireless Sensor Networks (WSNs), Cyber–Physical Systems (CPS) represent a sophisticated systemic architecture tasked with executing control functions bridging the cyber and physical domains. This involves delivering more intelligent management and feedback capabilities.

However, in industrial contexts that integrate mobility and autonomy features, other attributes are gaining prominence. As a result, the application of the low-energy adaptive clustering hierarchy (LEACH) algorithm was executed to amalgamate sensor data within a Wireless Sensor Network (WSN). The introduction of sophisticated communication technologies, such as ultra-wideband communication, aimed to optimize energy efficiency. Additionally, the integration of inventive approaches like spatial–temporal coverage optimization, cooperative Multiple-Input Multiple-Output (MIMO), Non-orthogonal Multiple Access (NOMA), clustering hierarchy, and cognitive radio networking technologies have been implemented. These forward-thinking measures collectively contribute to the progression of WSNs, elongating their lifespan and enhancing overall energy efficiency [44–47].

Recent computing paradigms within networks, such as Transparent Computing (TC), Fog Computing (Fog), Mobile Edge Computing (MEC), and Cloudlet, have garnered substantial attention in both industry and academia. These models leverage small-scale edge servers with restricted computation resources to promptly serve end-users at the network edge. Fog, MEC, and Cloudlet can be considered as expansions of cloud services to the network edge, given their utilization of comparable computation offloading and storage management approaches. Nevertheless, in the TC perspective, there is a clear separation of computing and storage between end-devices and remote servers, and it promotes the distribution of computing tasks among end-devices and their nearby counterparts, while fetching software and data from remote servers [48].

All these paradigms will exert influence and shape the digitization and softwarization of systems or processes. In other words, their specific characteristics and their associated models and development frameworks must be considered during the implementation of CPS. For a better understanding of this dependency, from the different communications models of IoT, let us briefly enumerate the main characteristics of these paradigms of computing and communication.

TC empowers devices to select services as needed through networks, without delving into the intricacies of service provisioning, encompassing tasks like software upgrades and management. TC operates akin to a client-server model, seamlessly amalgamating the devices distributed across the network and delivering services based on the capabilities of the devices and the prevailing conditions of the networks [49].

MEC has been recognized as a pivotal technology facilitating the transition to the 5G era, allowing cloud computing services for neighborhood mobile users. Implementing MEC servers at macro or micro base stations enhances the user experience by handling user requests at the network edge, thereby reducing latency and improving location awareness. Additionally, MEC helps alleviate the load on the core network and introduces benefits such as network function virtualization and software-defined networking [50].

Initially designed for the Internet of Things (IoTs), fog computing addresses the need for location awareness, timely response, wireless access, and mobility support. Employing an n-tier architecture, it consists of many heterogeneous devices, enhancing service flexibility, allowing all network devices along the data routing path to offer computing and storage services for end devices. While sharing similarities with the concept of MEC, fog computing represents a distinctive network computing architecture, providing capabilities for computing at the network edge [51].

The concept of Cloudlet pertains to micro data centers strategically located near mobile users. The purpose is to enhance the interactive performance of mobile applications, particularly those with stringent demands on end-to-end latency and jitter. Cloudlets empower servers to deliver highly responsive cloud services to mobile users, thereby complementing the three-tier cloud hierarchy, which consists of mobile users, cloudlets, and the cloud [48].

Inspired by the progress of emerging computing paradigms, there is a possibility of witnessing a hierarchical computing architecture that could revolutionize the existing cloud computing structure. This architecture comprises expansive central servers, numerous edge servers strategically positioned at the network edge, and a vast array of distributed end devices. Rather than viewing them as isolated components, most applications necessitate a cohesive orchestration of all these elements to deliver reliable services across various temporal and spatial scales.

All these computing paradigms encompass distinct approaches, contingent upon parameters such as characteristics, stakeholders, access technologies, applications, and key enablers. Therefore, the requirements for the softwarization and orchestration of each module must also consider the system's performance. In a scenario of complete mobility—devices, users, software, and data—the emphasis should be placed on the integration and management of communication and computing resources, beyond the whole system security.

Certainly, contingent on the application and the underlying technologies, particularly the network structures and communication protocols, the implementation of Cyber–Physical Systems (CPSs) can manifest diverse nuances. For example, [16] introduces the 5C architecture of CPS for the Industry 4.0 domain: Connection, Conversion, Cyber Level, Cognition Level, and Configuration Level. This framework, based on five distinct architectural levels, has been identified in the effort to deploy CPS within the Industry 4.0 paradigm. These architectures are designed to establish interconnected and streamlined systems for effective work, convert working datasets into productive outcomes, ensure a secure cyber level for the working environment, comprehend system requirements at the cognition level, and deliver optimal solutions to elicit the best customer responses at the configuration level.

5. Case Study

CPS represents an innovative era of manufacturing systems that facilitate the seamless integration of organizational functions, encompassing entire supply chains and distribution channels.

CPS has a profound impact on the entire manufacturing value chain, spanning from suppliers to customers. Through facilitating instantaneous data exchange, CPS enhances visibility and transparency within the supply chain, empowering manufacturers to swiftly adapt to demand fluctuations, monitor inventory levels, and streamline logistics operations.

Moreover, CPS fosters more efficient collaboration between manufacturers, suppliers, and customers. This collaboration involves the sharing of data and insights, leading to enhanced overall supply chain performance. Real-time data exchange and tracking capabilities enable manufacturers to optimize logistics processes, resulting in reduced transportation costs and improved delivery times. Additionally, CPS empowers manufacturers to tailor their products and services to precisely meet the unique needs of their customers. This means that CPS and its application allow us to obtain and implement computing paradigms related to Manufacturing-as-a-Service (MaaS) and Resource-as-a-Service (RaaS).

Scanning techniques/technologies such as RFiD, QR-Codes, or Bar-Codes can be used to scan and track goods, but complementary information can be collected if vehicle tracking is also used. Scanning products allows us to know where they were at a specific timestamp in the past; however, unless the timestamp is very recent, it does not provide information about where the products are now, or, for example, adjust delivery estimation date and time. If we can link the goods to the transportation vehicles, then we only need to track the vehicle to track the products, which is a common practice in logistics applications and used by big logistics companies such as Tao Bao and Jin Dong.

In the case study, two types of tracking devices were installed in vehicles, and their location was tracked every 10 s. One of these devices was a custom-tailored device that can use either NBIoT (Narrow Bant IoT) or LTE-M (Long-Term Evolution—Machine Type Communication) for data communications, and the other was an off-the-shelf device, which uses 4G communications. Despite both device types using TCP/IP communications, the cellular network technologies that they use have different constraints related to coverage, data rate, and delivery delay. Also, these two devices use different Application-Level protocols and data PDU (Protocol Data Unit) formats.

Even though these two CPS devices have different specifications and features, the objective was to present the logistics management applications and a homogeneous view of the devices. Therefore, the architecture that was chosen to support this application was based on that presented by the authors in [52]. Using this architecture, as presented in Figure 1, it is possible to perform the integration of these devices and send their data in real time as required.

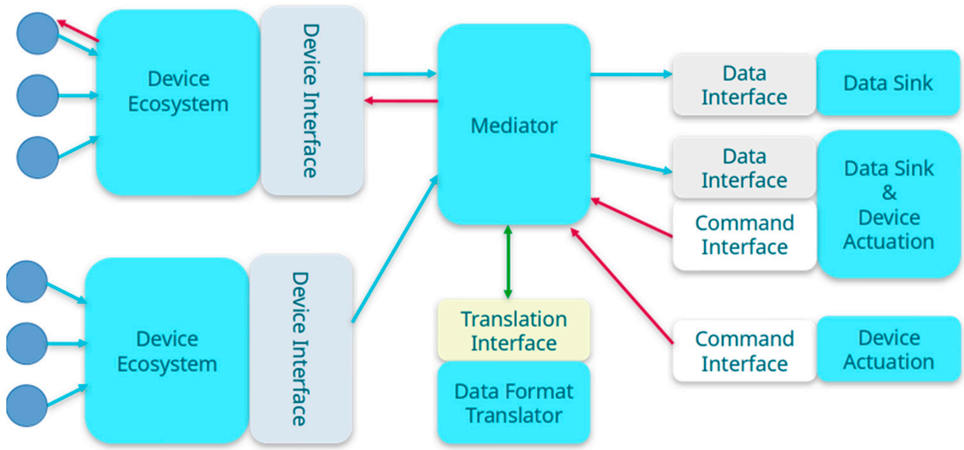

Figure 1. Generic architecture for CPS Framework.

5.1. Generic Architecture for CPS Framework

To comply with the above requirements, the architecture that was chosen to support this application was based on that presented by the authors in [52], which is a generic architecture for a CPS Framework. Using this architecture, as presented in Figure 1, it is possible to perform the integration of any type of device and send its data in real time, as required. It also allows for the integration of data sinks such as data visualization interfaces, databases, business logic implementation applications, etc.

This architecture comprises a central component (Mediator) that routes information between Devices (connected to Device Ecosystems) and Data Sinks. This component also routes commands between components that can actuate in devices (Device Actuation) and the CPS devices. For data exchange between the components of the architecture and the Mediator, a set of Interfaces was defined. Device Ecosystems use the Device Interface to send data to the mediator and to receive commands from it. For each data transmission protocol that needs to be supported, a Device Ecosystem must exist. Devices that use the same protocol can share the same Device Ecosystem (independently of their make or model), therefore making the integration components of the architecture reusable.

Besides this integration at the protocol level, integration at the data compatibility level must also be ensured. To accomplish this, an interface to connect Data Format Translators (the Translation Interface) was defined. Data from devices are translated into a common format that can be then sent to the data sinks (using the Data Interface) or translated again into a particular format needed by the Data Sink.

Because CPS devices need to receive commands (e.g., an actuation command or a configuration-related request), a Command interface was designed.

With this architecture, if we have N device types and M data sink types, instead of having N × M integration solutions, which would result in an ad-hoc integration between device and data sink, we will have N + M integration solutions.

A reference implementation of this Framework was developed, where the Mediator component was implemented using Java and packed in a Docker container, making it ready to use and integrated in projects that require this component. To make the integration easier, two integration libraries were developed, one using Java and another in Python. These two libraries implement the communication interfaces, using gRPC, and allow system integrators not to need to care about the details of the communications between the architecture components.

5.2. A Generic Application for Asset Tracking

Based on the generic CPS Framework presented in the above section, an Asset Tracking Platform, which was used in the case study, was developed. This platform allows us to monitor in real time the location of vehicles, to know some basic information (e.g., operational status, total distance, total number of trips), and to see historical information about the trips of the vehicles. A block diagram of this platform is presented in Figure 2. This architecture is open enough to plug in new micro-services that implement different types of business logic. In the current use case, the objective is to have a generic platform that allows for the tracking of vehicles; however, simply by adding a module that can relate the tracked vehicle to a given product, it can then become a product tracking platform, and so on.

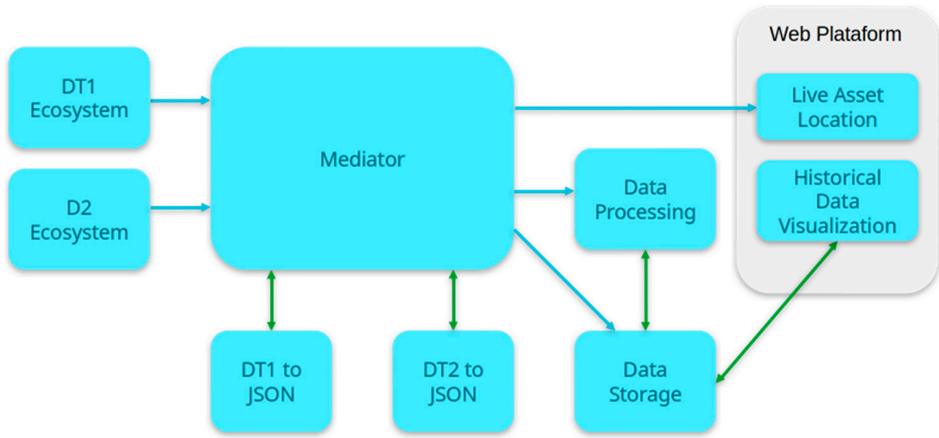

Figure 2. Block diagram of Asset Tracking Platform.

As above mentioned, two types of devices were used in this case study. One of these device types, hereafter DT1, is a custom-tailored device that uses a custom proprietary Application-Level protocol, as used by the authors in [52,53], to transmit the data. Support for this protocol is provided by the DT1 ecosystems, which handle all data transfers between the device and the cloud. Similarly, there is an ecosystem to handle the communications between the second type of device, hereafter referred to as DT2, which uses a plain socket to send information. These two ecosystems will provide the integration of the devices at the communications protocol level.

DT1 and DT2 transmit information in two different formats, which are not the same. This means that the information needs to be adapted before being sent to the data sinks. To provide this translation, and therefore compatibility at the data format level, two translators that translate between the DT1 and DT2 data formats to a common JSON format were developed ("DT1 to JSON" and "DT2 to JSON").

Data from the devices are then sent to the data consumers that use it without needing to have knowledge about the original data transmission protocols or data format. For the use case, these consumers are as follows: a Data Storage service, which stores data sent from devices; and an application that processes the information and detects when the vehicle started or stopped a route (mentioned in the below images as "rides"). This detection is made both by decoding start/stop events that the DT1 devices send and analyzing the ignition, speed, and GPS data from the DT2 devices. The result of the processing is also sent to the Data Storage. To display data from the vehicles rides and their position in real time, a Web Platform was developed. This Web Platform is also used to display historical data stored in the Data Storage.

To fit in several mobility-related use cases, ranging from asset tracking to shared mobility applications, the Web Platform was built to be the most generic as possible. The information displayed by this application has two sources: the real-time data, related to the current vehicle position, which are sent directly by the Mediator as the data arrive from the devices, for Live Asset Location; and the historical data and other information related to vehicles that are retrieved from the Data Storage.

Figure 3 presents a detail of the platform, where the status of the tracked vehicles is presented. In this view we have on the right side a map that displays the last location reported by each vehicle, and on the left a filter that allows the user to select the vehicle to see on the map by operational status.

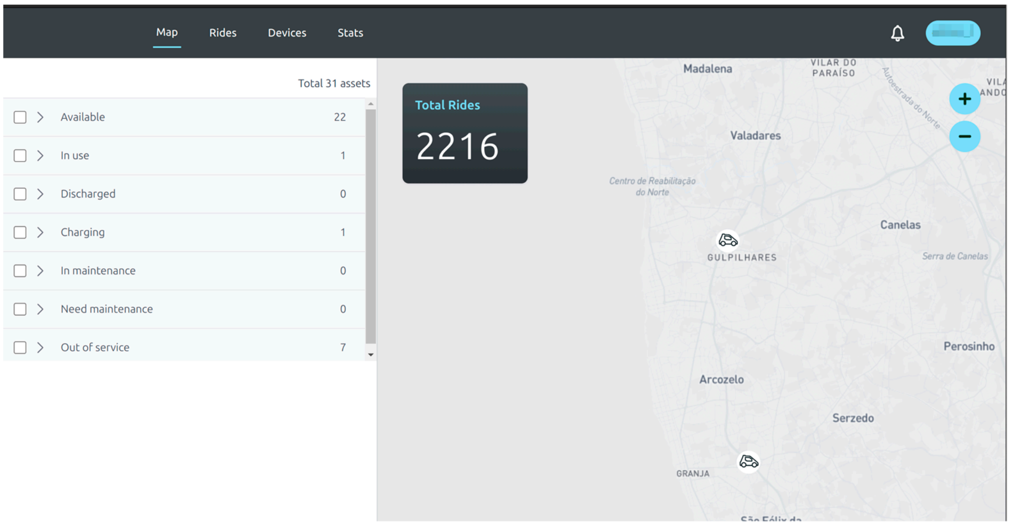

Figure 3. Generic overview of platform.

A detailed view of the vehicles that are available on the platform is presented in Figure 4. In this view, we can see some basic information about the vehicle, such as its unique identifier, license plate, status (in use, stopped, or charging—for electrical vehicles), the total distance, and the total number of trips/rides.

Figure 4. Detail of the list of vehicles.

Selecting one of the vehicles will show the user the list of trips (Figure 5) related to that vehicle; for each trip, the user can visualize a map with data from that trip.

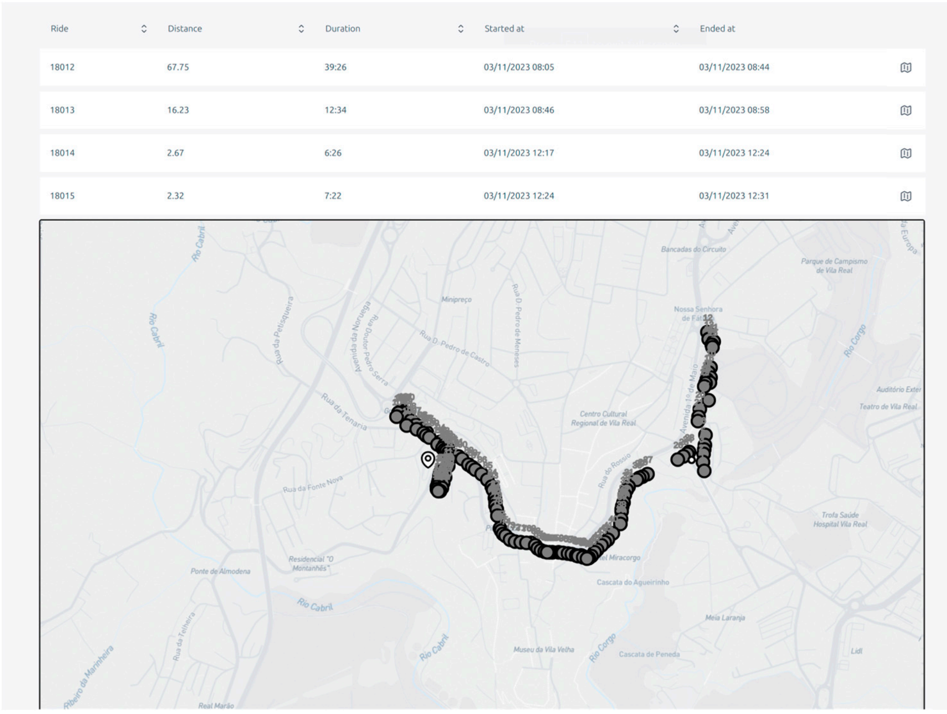

Figure 5. Detail of a track recorded by the platform.

6. Conclusions and Future Challenges

The vision outlined by Industry 4.0 for the future of production systems is driven by the aspiration to achieve a more personalized production process. This necessitates flexible and modular systems, with the fundamental components being Cyber–Physical Systems (CPSs). The concept of these systems, originating in the field of embedded systems, has been tailored to fit the framework of Industry 4.0.

From an Industry 4.0 overview, CPSs can be seen as the convergence between the physical and virtual worlds. Therefore, CPSs can be characterized as systems reliant on embedded software with the capacity to access physical data and influence physical processes through sensors and actuators.

Data acquired by the CPS devices, installed in the vehicles used in the case study, were processed and stored independently of their source (device type, used protocol, data format, etc.). This case study was used as a proof of concept of the presented framework for the integration of CPS devices and logistics applications. However, although this framework has been mainly tested in mobility-related applications, its scope can be extended beyond mobility- and logistics-related applications.

To analyze the proposed Framework for CPS devices, applied to logistics applications, the following two metrics were analyzed.

- Adaptation to several use cases: the platform that was implemented around the proposed framework has as an objective the tracking of vehicles (including logistics vehicles); however, the architecture allows other applications to be added (as Data Sinks) to add extra features. For example, several types of product scanners can be added to the architecture, each one connected to a specific ecosystem, which sends information to the Mediator. This information is then sent to the Data Processing applications and to the Data Storage to track products.
- Easy integration of data sources and applications: the architecture was developed having in mind the easy integration of any data source to any data sink. Besides the use case presented in this paper, this architecture is being used as an integration component in applications related to mobility and sustainability.

If we look from the perspective of performance in terms of time, the maximum delay that is expected in the data transmission is around 15 s, for those nodes using NBIoT, which is a delay that is acceptable for asset tracking in logistics applications. This time is not dependent on the architecture, but on the network technology. A preliminary measurement to the platform delay was made, using an ecosystem flooding the Mediator with GPS coordinates messages and a Data Consumer to receive these data. This test had as a result a delay in the order of 200 microseconds in a computer with an 11th Gen Intel(R) Core(TM) i7-1185G7 @ 3.00 GHz PC, with 16 GBytes of RAM, running Ubuntu Linux 22.04 and Java 11.

The major achievements of this work were the development of a framework, and a reference implementation, that allows for both speeding up the process of building logistics-related platforms or speeding up the process of integrating new features into an existing platform. This framework also allows for the integration of new data sources into already existing applications, without the need to refactor these applications. Also, the overhead added by the framework is minimal and does not impact the real-time needs of the logistics platforms.

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