Cyber-Physical Integration of PCB, Harness, and System Assembly Lines

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Abstract – To enhance the characterisation of cyber-physical system (CPS) characteristics by utilizing embedded components. The method facilitates micro-miniaturization and improves stability by enabling the integration of electronic components into printed circuit boards (PCBs). Due to the complexity of printed circuit board (PCB) manufacturing and the significant impact of social factors, integrated checking is necessary to ensure and enhance production quality. Over the past few decades, the printed circuit board (PCB) industry has had some of the fastest growth. Due to the complexity of printed circuit board (PCB) manufacturing and the significant impact of social factors, integrated checking is necessary to ensure and enhance production quality. Due to rapid changes in consumer preferences and advances in electrical technology, electronics, particularly home automation equipment, are becoming increasingly obsolete. Printed Circuit Boards (PCBs) are the fundamental components of modern electronic devices. The final product's functionality and dependability are directly affected by how effectively it is assembled. The printed circuit board (PCB) is no longer a remote location. It is connected to power units, sensor networks, and other components using a variety of wire harnesses. There is more to these harnesses than just "cable bundles." It is possible to enhance the characterisation of cyber-physical system (CPS) characteristics by utilizing embedded components. The method facilitates micro-miniaturization and improves stability by enabling the integration of electronic components into printed circuit boards (PCBs). Combining computer and physical processes results in cyber-physical systems (CPSs). Devices enable seamless connection between the virtual and physical worlds. In these systems, computer components interface with the physical world to enable real-time communication and decision-making. Cyber-physical systems (CPS) are interconnected systems that more closely integrate fundamental and computational components. As the computer components can observe both the system and its environment, computers can continuously provide feedback to help govern the system and alter its environment.

Keywords – Printed Circuit Boards (PCBs), Cyber Physical System (CPS), Printed Circuit Board Assembly (PCBA), Internet of Things (IoT), Automatic Optical Inspection (AOI), Cyber-Physical Vehicle Systems (CPVSs)

1. Introduction

The most crucial component of all sophisticated electronic devices is the printed circuit board assembly (PCBA). Still, it can only function well when it is correctly connected with other systems both within and outside the device [1]. In this case, knowing how to connect cables and wire harnesses is helpful. Several crucial components serve as the brains of an electronic device, ensuring steady power and information transfer [2]. The engineers' ability to integrate these meticulously crafted components with the printed circuit board assembly (PCBA) will determine the final product's utility, robustness, and efficacy [3]. As connectors transport data and power, cable and wire harness assemblies are crucial components of any electrical system. Typically, a cable assembly consists of two or more wires or cables joined at one or both ends [4]. Devices are designed to perform a specific task, usually joining two disparate components or devices. The primary task is to maintain and safeguard several electrical connections [5]. Harnesses are more intricate systems designed for routing and safety within a gadget or automobile, whereas wires are typically straightforward point-to-point connections [6]. Selecting the appropriate form and materials for these assemblies is crucial. Premium components are necessary for long-lasting performance, to prevent electrical issues, and to maintain signal integrity, particularly in challenging environments [7]. These components include sturdy connectors, appropriate conductor gauges, and robust insulation [8]. The overall safety and reliability of the device could be significantly compromised by intermittent connections, short circuits, or early failures resulting from poor design or material selection [9]. The most crucial component of any contemporary computer device is the printed circuit board assembly, or PCBA. It facilitates communication between various system components, processes data, and manages operations [10]. Even the most sophisticated external connections and devices would not function without a robust, well-designed printed circuit board assembly (PCBA) [11]. Since the printed circuit board assembly (PCBA) is so crucial, it is naturally influenced by the type and quality of its external connections, particularly those made with cable and wire harness assemblies [12]. Through the printed circuit board assembly (PCBA), these assemblies transmit and receive data, power, and control information. The appropriate operation of these linkages is crucial [13]. A cyber-physical system (CPS) represents a novel perspective on what occurs when computer and physical systems cooperate without issues [14]. A variety of computers and networks that enable various forms of communication, sophisticated data processing and decision-making, and engagement comprise the cyber portion of a cyber-physical system (CPS). The modelled natural and physical systems, such as the environment, human behaviour, safety, boundaries, and events, are the focus of the physical section [15]. Cyber-Physical Systems (CPS) have become a significant aspect of our everyday lives due to the proliferation and popularity of the Internet of Things (IoT), Industry 4.0, autonomous systems, and Smart-X technology [16]. Smart grids, unmanned intelligent aerial aircraft, emergency response systems, healthcare systems, and intelligent transportation systems all rely on cyber-physical systems (CPS). Since cyber-physical systems (CPS) integrate both digital and physical components, they are unique [17]. Cyber-Physical System (CPS) has historically been viewed as the expansion and advancement of several well-known research fields. Technologies consist of distributed real-time systems, wireless sensor networks, networked control systems, and integrated complex systems. There are now several kinds of computers besides desktop computers [18]. The low cost of compact, energy-efficient devices and computation-capable components has been crucial to this advancement. As a result, tiny devices that can be integrated into real-world systems have been developed in the field of embedded computers [19]. These devices not only facilitate computer-based system administration and control but also provide mechanisms for adapting systems to changing environmental conditions. As these devices proliferate, the concept of cyber-physical system (CPS) has expanded [20]. Groups of computers that can observe, manage, communicate with, and alter the physical systems in their immediate environment are known as cyber-physical systems, or CPS [21]. Many cyber-physical systems (CPSs) are real-time systems because they must perform calculations in real time. Such systems depend on the accuracy of computations at a specific moment in time. It means that outcomes are legitimate only if they are accurate in both logic and timing [22]. Like physical systems, virtual and real systems must cooperate in the actual world. Embedded system networks in the real world often consist of a computer, several sensors, and occasionally motors [23]. In these systems, the computer is typically composed of distributed components, and communication between them is crucial. The computer needs to use a separate network to connect to other computers of the same type [24].

A cyber-physical system (CPS) combines real processes, computation, and communication. Physical processes can be observed in engineering (aerospace, automotive, and civil infrastructure), physical and chemical processes (materials design, chemical processing), socio-technical systems (financial systems, computer networks), biological systems, and entertainment systems (miniature helicopters, robotic pets) [25]. Physical processes fall into one of five categories: fluid dynamics, biology, mechanics, electricity, or ecology. It presents many opportunities and issues when computers and physical processes are combined [26]. The system aims to function correctly, which in human-involved systems might mean either ensuring that all users receive a minimum level of service quality (progress) or encouraging users to interact with the system as little as possible [27]. Physical processes occur constantly and on a variety of scales in space, time, and other dimensions. Most cyber components either function independently or are connected [28]. Real-time computing, the foundation of the integration paradigm, has expanded as systems have gotten more complex in terms of requirements and control. The control and systems sectors have developed into collaborative groupings [29]. Both conventional embedded systems and control systems reinvented using new methods, connected to the internet of things (IoT), are included in the cyber-physical system (CPS). Given their ability to manipulate the physical environment, cyber-physical systems (CPSs) can be viewed as the next stage in the evolution of the internet of things (IoT). Combining cyber-physical systems (CPS) with conventional embedded and control systems opens new possibilities [30]. The internet of things (IoTs) includes cloud computing, RFID (Radio Frequency Identification), and wireless sensor networks. It allows for dependable data processing and transmission. Conversely, a cyber-physical system (CPS) is a scalable, dependable control solution that integrates computer, communication, and internet of things (IoT) technologies [31]. While the internet of things (IoT) focuses on information processing and transmission, the cyber-physical system (CPS) provides robust control and sensing capabilities [32]. The cyber and physical components of a cyber-physical system (CPS) may be connected across time and space, and they may cooperate and act differently depending on the circumstances [33]. The discipline of computational process science encompasses mechatronics, computer theory, the Internet of Things (IoT), wireless sensor networks, cybernetics, design, and process science. Feedback loops are utilized in embedded systems to aid with control. The cyber-physical system (CPS) and the internet of things (IoT) are both built on similar ideas; however, the cyber-physical system (CPS) sets a higher level between its actual and digital portions [34]. Cyber-physical systems (CPSs) are clearly depicted as a framework of interconnected components with physical inputs and outputs, in contrast to the self-contained devices typical of embedded systems. Cyber-physical systems (CPSs) are used across a variety of fields, including industrial automation, healthcare, aircraft management, distributed energy systems, and control technology. Cyber-physical systems (CPSs) will improve the economy and alter the current functioning of real engineering systems [35].

2. Literature Review

For devices to function correctly, every step of the technology-making process is crucial. Wire harnesses and printed circuit boards (PCBs) are two essential components that are frequently combined to create functional computer systems [36]. A wire harness is an arrangement of wires, cables, and connectors that provides power or electrical signals to various components of an electronic system. Wire harnesses facilitate connections, save space, and shield wires from wear and damage [37]. Connectors consolidate wires into a single unit to facilitate the installation and maintenance of electrical devices [38]. To create a functional electronic device, a printed circuit board (PCB) assembly assembles electronic components such as integrated circuits, resistors, and capacitors [39]. Such parts can transmit electrical power and signals to various system components when they are connected to the printed circuit board (PCB) [40]. Most electronic gadgets have robust construction and well-designed circuits thanks to printed circuit boards (PCBs). Together, they enable the creation of strong, reliable, and effective systems that power our everyday gadgets [41]. Due to the precision of printed circuit board (PCB) assembly and the safety and communication provided by wire harnesses, manufacturers can develop innovative solutions in a variety of industries, including consumer electronics and vehicles [42]. Combining the three Cs—calculation, communication, and control—is the first step in modeling cyber-physical systems (CPSs). These are logical and discrete (cyber entities) and systems, both natural and man-made, governed by the laws of physics (physical entities). Sensors and motors connect the two objects. Sensors, computers, and the physical world are all intricately connected in cyber-physical systems (CPSs) [43].

Shu et al. [2024] describe how manufacturing firms have increasingly adopted sophisticated technologies across various manufacturing system applications in response to the Industry 4.0 revolution to boost output. Significant changes are occurring at the workstation and system levels due to advances in automation and robotics, as well as improved access to data and faster data processing and decision-making. High-precision manufacturing, self-optimization and self-configuration, digital operations management, high-mix, low-volume production, and human-machine interaction are among the new developments making the manufacturing industry more complex and dynamic. Manufacturers must reconsider and adapt their procedures and tactics, particularly regarding the role of human labor, if they are to succeed in this globally interconnected and rapidly evolving world. A human-centered cyber-physical manufacturing environment has been established through the integration of intelligent sensors and networked production equipment. As more and more factories become automated and digitalized, collaboration between intelligent systems and their operators is crucial to maximizing production efficiency. One widely held belief about the future of research on human-machine symbiosis is that automation and humans will be able to collaborate more effectively and leverage one another's skills. Additionally, the manufacturers use in-process inspection to maintain high product quality and obtain prompt feedback on manufacturing process issues in advanced manufacturing [44].

Ouided Hioual et al. [2023] describe cyber-physical systems (CPS) as systems that track and regulate processes by combining real-world components with computer and communication technologies. Systems operating in dynamic contexts must manage concerns such as shifting consumer demands, device malfunctions, and environmental changes that may impact service quality. To truly address these issues, researchers must develop adaptive cyber-physical systems (CPS) that can respond intelligently, optimize resources, and modify their architecture at any time. Cyber-physical systems (CPS) are complex systems that monitor and control physical processes by combining real-world components with computer and communication technology. Among the sectors that frequently use these tools are industries, energy, transportation, and healthcare. Cyber-physical systems (CPS), which can process data, control devices, and synchronize communication in real time, have evolved from discrete computers into highly complex, dynamic systems. Technology facilitates communication between the physical and digital worlds. Cyber-physical systems (CPS) become increasingly essential for boosting output, optimizing resource utilization, and making sound decisions as their capabilities and complexity increase. Although computers are composed of several components that operate at various levels of abstraction, cyber-physical systems (CPS) differ significantly from conventional systems. Things are made even more difficult by the fact that the real world is so unpredictable and changeable. Therefore, ensuring that the design and development of cyber-physical systems (CPSs) can manage this complexity while still adhering to regulations is one of the most significant issues. These are autonomous systems that can monitor their environment, identify problems or changes, and adjust their behaviour to continue operating and fulfil performance requirements [45].

Oliver Kwan et al. [2022] describe that over the past few decades, the printed circuit board (PCB) industry has experienced some of the fastest growth. Due to the complexity of printed circuit board (PCB) manufacturing and the significant impact of social factors, integrated checking is necessary to ensure and enhance production quality. The market for printed circuit boards (PCBs) has expanded significantly in tandem with the rapid growth of the global electronics industry. Printed circuit boards (PCBs) require significant effort, involve complex manufacturing processes, are highly precise, can be altered in many ways, and incur substantial end-of-life costs. As a result, it is even more crucial to consider the entire printed circuit board (PCB) production process, including the workers, equipment, materials, and settings used. However, the expansion of printed circuit board (PCB) examination is being impeded by two significant issues. The first is the currently in use automatic optical inspection (AOI) systems. These systems prioritize examining products for defects over identifying issues. Linking fault types to their causes for diagnostic purposes may alert employees to potential problems and prevent errors in production processes, which is beneficial for companies looking to increase output and quality. However, identifying flaws necessitates a thorough comprehension of the entire production process, which is challenging with actual printed circuit board (PCB) systems. Secondly, inspections lack sufficient expert guidance [46].

Timon Hoebert et al. [2019] describe that to meet the increasing need for mass customization, modern assembly systems must be updated with new technologies and techniques. Automation components that can join the system on their own are expected to benefit significantly from a cyber-physical system (CPS) that can self-assemble. Large, intricate production systems with multiple components are frequently used to produce commodities. Putting things together is one of the most costly and time-consuming aspects of production lines. It is primarily due to the unpredictable nature of the components and the complexity of the processes involved. When demand fluctuates in terms of quantity and product diversity, things get much more difficult. Although there are more products and their life cycles are becoming shorter, manufacturing systems are currently undergoing a paradigm transition. It necessitates the production of highly tailored, fast-delivery, and reasonably priced items. In such a case, the production processes for either cutting or assembling the product need to be adaptable enough to satisfy the final product's requirements. The movement of materials between the tools and the assembly stations also calls for a more flexible logistics approach. Right now, the only practical solution to a paradigm shift appears to be robotics. Rapid setup of robots and their accessories is required, as is the collection and analysis of process data. It must be possible to organize and execute actions independently [47].

Joerg Franke et al. [2016] describe that cost reduction, quality standards, functional integration, and miniaturization primarily drive the electronics manufacturing industry. Cyber-physical manufacturing networks may alter future production of electrical and mechatronic products. Traditional production engineering is undergoing significant change as the shift from automated production processes to intelligent production networks becomes increasingly likely. Production lines are increasingly automated and interconnected today, particularly in the electronics sector. The quality and efficiency of production lines are monitored and graded at the plant or business level using an integrated approach. However, the complexity of production necessitates new regulations to improve process control, deploy more sophisticated technology, and increase manufacturing productivity. Initially, the foundation materials are printed using solder paste. High output and high automation are characteristics of the solder paste printing process. At least one assembly machine then places electrical components on the printed circuit boards (PCBs). To expedite production, the feeder delivers the precise quantity of pieces required to the assembly machine. The final stage involves physically and electrically connecting the printed circuit board (PCB) and the electronic components. The solder paste needs to be significantly above its liquidus temperature at all joints, and the process control should ensure the components do not overheat [48].

3. Research Methodology

To ensure that the lines that assemble printed circuit boards (PCBs), wire harnesses, and entire systems function seamlessly, design science research leverages cyber-physical systems (CPS), digital twins, the industrial internet of things (IIoT), and AI-driven analytics. The technique makes use of a layered cyber-physical system (CPS) design, which consists of [49]:

- **Physical manufacturing processes -** Cyber-physical systems (CPS), which combine real-world and virtual computers, have revolutionized the industrial sector. The integration has increased the productivity, efficiency, and flexibility of production processes [50]. Advances in computer, transmission, and sensor technologies over the last few decades have altered the definition of a cyber-physical system (CPS). Initially, the primary focus of production-level cyber-physical system (CPS) applications was automation and control systems [51].

- **Cyber modeling and analytics -** Technologies such as wireless communication, sensor tracking, embedded computing, and large-scale data processing have advanced significantly in recent years. Together, these technologies now form a system that integrates physical processes, communication, and computing. Perception, communication, and computation are always inherent in the physical process. The physical apparatus becomes linked and information-rich as a result. A cyber-physical system (CPS), a kind of mixed autonomous system, is produced using this technique. Numerous industries employ cyber-physical systems (CPS), including innovative grid management, intelligent manufacturing, city traffic forecasting, and healthcare system operations. A cyber-physical system (CPS) is now closely intertwined with human existence and societal advancement [52].

- **Closed-loop feedback and control –** Three distinct closed-loop cyber-physical systems (CPS) were demonstrated for the first time. It involves event-driven control, network slowness, and disruptions [53]. A new event-triggered scheme with fewer triggers than other schemes is created by adding a disturbance term, thereby lengthening the triggered times [54]. Computers, communication, and control technologies have all advanced significantly during the past few decades. Consequently, the field of cyber-physical systems (CPS) has expanded and gained recognition [55]. The latest generation of intelligent systems has applications in industrial robots, smart grids, aerospace, and many other fields. By incorporating computer, sensing, and communication capabilities into physical objects, a cyber-physical system (CPS) integrates control, computation, and communication [56]. It allows real-time management of bodily processes. Both portable sensor-actuator networks and computer networks must be able to manage a variety of control scenarios [57].

Both qualitative and quantitative evaluations of the efficacy of system-level integration are conducted using performance metrics like throughput, defect rate, and energy consumption. The proposed approach consists of four interconnected layers [58]:

- **Physical Layer –** (printed circuit boards (PCBs), wiring leads, and system assembly tools) Cyber-physical system (CPS) integrates real-world activities with computer-based functions. Networks and embedded computers employ feedback loops to monitor and manage physical processes. To influence physical processes and have physical processes affect computations. These software-based systems must function consistently, dependably, securely, effectively, and in real time while interacting with the outside world. Because their hardware and software components are intricately linked, cyber-physical systems (CPS) are inherently distinct. Cyber-Physical Systems (CPS) provide intelligent decision-making, real-time monitoring, and enhanced automation. They have a significant impact on a wide range of industries, including smart cities, manufacturing, transportation, and healthcare. Sensors and motors make up most of this layer. Sensors detect machine indicators, which are then modified. The actuators, on the other hand, move objects by fusing an energy source with electrical impulses [59].

- **Sensing & Data Acquisition Layer** – (Integrated machine and sensor interfaces) The 5C model—connection, conversion, cyber, cognition, and configuration—helps us comprehend the operation of cyber-physical system (CPS) and the flow of data between them [60]. From data collection to self-adaptation and optimization, each level of the system denotes a higher level of expertise. The fundamental components of a cyber-physical system (CPS) include data networks, sensors, actuators, embedded processors, and control algorithms [61]. These components facilitate the monitoring and control of physical processes using a closed-loop feedback system. Sensing the physical system's state, implementing control algorithms, and using actuation to make the physical system perform as desired are the primary responsibilities of the core cyber-physical system (CPS) area. The four primary components of a comprehensive cyber-physical system (CPS) are the physical system, actuation, control, and sensing. A closed-loop feedback control technique is employed to achieve the intended physical outcomes. This closed-loop feedback process governs sensing and acting, two crucial components of a cyber-physical system (CPS). Control algorithms can operate in fully set or independent modes, and they can be distributed, decentralized, or centralized. To achieve the intended physical outcomes, co-design of cyber-physical communication across the cyber-physical barrier is required to enable cyber and physical systems to communicate and connect [62].

- **Cyber Layer** – (Digital twins, analytics, and AI models) cyber-physical system (CPS) is an engineered system that integrates computational elements with physical processes. Cyber-Physical System (CPS) leverages sophisticated algorithms and real-time data analysis to monitor and control physical processes. By embedding intelligence into physical objects and environments, a cyber-physical system (CPS) enables machines to make autonomous decisions, adapt to changing conditions, and optimize performance in numerous ways. A cyber-physical system (CPS) has significant potential for innovation and transformation across various sectors. It enables interaction between digital and physical components, which drive advancements in manufacturing, transportation, healthcare, energy, and beyond. Data is gathered by the dedicated modules of the bodily systems in various devices within the cyber-physical system (CPS). The collected data is assured of its accuracy by dedicated data acquisition modules and is transferred to the information processing module as required by the services to apply various data processing functions, e.g., statistical processing, security, and feedback control. This layer serves as the storage base for the cyber-physical system (CPS) and is distributed between the Fog and the Cloud, depending on the nature of the data and the time required to process it [63].

- **Control & Decision Layer** – (Feedback-based regulation and flexible scheduling) To monitor and manage physical processes in real time, a cyber-physical system (CPS) integrates computer algorithms with networked devices and physical processes. This technology facilitates communication between humans and machines by connecting the actual and virtual worlds. Cyber-physical systems (CPS), which include smart grids, self-driving cars, healthcare systems, and industrial automation, enhance safety, efficiency, and decision-making through automation and connectivity. Complex systems comprising both computer and physical components that collaborate in real time to accomplish specific tasks are known as Cyber-Physical Systems (CPS). Hardware and software components combine to form cyber-physical systems (CPS). A cyber-physical system (CPS) is a system that tracks and controls physical processes using both computer and physical components. These systems improve the safety, dependability, and functionality of physical systems by integrating sensing, actuation, computation, and communication [64].

Every location appears to have its own system and activities:

$$U_{PCB} = \sum_{j=1}^{m} (U_j^{process} + U_j^{delay})$$

where:

$U_j^{process} = processing\ time\ at\ station\ j$

$U_j^{delay} = waiting\ or\ buffering\ delay$

A combinatorial complexity metric is employed to demonstrate complexity:

$$E_K = \sum_{p=1}^{q} (W_p . V_p)$$

Where: $V_p = wire\ length$, $W_p = Number\ of\ wires\ of\ type\ p$

The expression for assembly time is:

$$U_{system} = U_{pcb\_install} + U_{harness\_routing} + U_{testing}$$

A pipeline for real-time data is created:

$$B(r) = \{B_{pcb}(r), B_{harness}(r), B_{system}(r)\}$$

where: B(r) = synchronized streams of production data at time r.

Each twin continuously updates state variables:

$$V_{r+1} = f(V_r, Z_r, C_r)$$

where: C_r = disturbances (machine faults, delays), V_r = system state, Z_r = control inputs

Methodological Flow Summary

Physical Manufacturing → Sensing → Digital Twin → AI Analytics → Feedback Control → Optimized Production

As it integrates close ties between computer and physical activities, cyber-physical systems (CPS) are regarded as a crucial technology for the creation of future industrial systems [65]. Many individuals believe that the economy and society can benefit significantly from the widespread adoption of cyber-physical systems (CPS) across industries. Since most cyber-physical systems (CPS) require several components to function, it is challenging to explicitly code the connections between system components while also accounting for the complex interrelationships that occur when things go wrong. Therefore, certain technologies and techniques are required to facilitate the construction of large-scale cyber-physical systems (CPS) with resources dispersed throughout the world. A model-based method could help create a self-configurable cyber-physical system (CPS) [66]. When a system automatically adapts its configuration to changes in its environment, it is said to self-configure. Developers don't need to do anything because an autonomic service manager automatically distributes this system configuration to available hardware resources [67]. To add plug-and-play components to the cyber-physical system (CPS) without requiring complex human intervention or a unique setup procedure, it is crucial to have reliable auto-configuration management. The elements of a cyber-physical system (CPS) require an environmental representation, such as an ontology that explains the concepts and their relationships in the application domain, to perform their functions. The components of a cyber-physical system (CPS) can agree on how to understand shared concepts in an open environment by using ontologies, a robust knowledge management approach [68].

4. HALLENGES AND FUTURE TRENDS IN CYBER-PHYSICAL SYSTEMS

5. CHALLENGES AND FUTURE TRENDS IN CYBER-PHYSICAL SYSTEMS

4. Challenges, Characteristics, and Future Trends in Cyber Physical Systems (CPS)

The success of the cyber-physical system (CPS) catalyst project depends on ensuring the security of systems that interact with one another and resolving privacy and security issues that arise when real and virtual entities collaborate. Building trust, dependencies, and composite, reusable services in smart and connected cities that are still in the design stages presents some challenges. The challenges include gathering, analyzing, and exchanging data from many sources across domains such as agriculture and the environment; ensuring that healthcare devices are reliable and trustworthy; and safely integrating IoT sensors, middleware, and actuators at scale. Enhancing the transdisciplinary integration of cyber and physical components is crucial to assessing the effectiveness of the cyber-physical system (CPS) and ensuring its feasibility, practicality, and security. Cyber-physical systems (CPS) are distinct from "cybersecurity." A cyber-physical system (CPS) is composed of many systems from various domains that collaborate through autonomous models. The unpredictable behaviour of these systems creates a wealth of study opportunities. At the forefront of emerging technology are cyber-physical systems (CPS), which integrate the digital and physical worlds.

By combining computerized and real-world processes, cyber-physical systems (CPS) open new growth opportunities across industries such as healthcare, transportation, and smart cities. As these systems become more complex, their ability to manage security, privacy, and interoperability concerns will determine how well and frequently they are used. Improving dependable design techniques, increasing computer speed, and ensuring that cyber-physical systems (CPS) function properly in critical scenarios should be the primary objectives of future research to increase their use. The ongoing development of cyber-physical systems (CPS) will undoubtedly have a significant influence on how society and technology evolve throughout time. Lastly, research on cyber-physical systems (CPS) is expanding rapidly and attracting individuals who wish to apply and address issues across a variety of fields, including healthcare, autonomous vehicles, smart cities, infrastructure management, Industry 4.0, environmental and agricultural systems, logistics, and more. Since the issues arising from maintaining many apps are constantly evolving, there don't appear to be any restrictions on how far growth can go. Due to the rapid evolution of cyber-physical systems (CPS), planning, governance, and policy research are emerging fields of study receiving significant attention to ensure these systems can collaborate reliably. The actual and virtual worlds are connected by the cyber-physical system (CPS). Cyber-physical systems (CPS) communicate with the physical world using sensors and integrated computing. The core of the cyber-physical system (CPS) lies in control and computation. The cyber-physical system (CPS), for instance, maintains the following characteristics [69]:

- **Cyber capabilities across all physical component**s: Exactly as crucial as the concept's design is the system's actual design. It involves developing and measuring the hardware, managing it, establishing connections, and inspecting the system [70]. Due to its increased automation and management, the cyber-physical system (CPS) requires optimal network coverage [71].

- **Networked at extreme and numerous scales:** Cyber-physical systems (CPS) collect and arrange data using sensors and controllers. Numerous industries, including healthcare, long-distance communication, industrial automation, and personal transportation systems, require networks to function [72]. Such industries require a new kind of communication that provides structure and permits flexibility when used online to effectively utilize data [73]. To fulfil demand and maintain quality of service (QoS), cyber-physical systems (CPS) require a wide range of networking levels [74].

- **Numerous spatial-temporal constraints:** Thought of as 3C technology, the cyber-physical system (CPS) incorporates connectivity, processing, and control with the real world. It requires that the components of the cyber-physical system (CPS) communicate with one another both spatially and temporally [75]. Limitations such as event detection and action selection must be appropriately implemented to ensure accuracy in both time and space [76].

- **Unique computational and physical substrates:** As cyber-physical systems (CPS) may adapt to changing configurations and interact with their physical environment in real time to meet specific requirements, they require specialized computing capabilities [77]. The physical substrate must coincide with the development as it occurs during the calculation [78].

- **Elevated automation and closed control loops across various scales:** As cyber-physical systems (CPS) must be able to adapt to changing circumstances in real time and receive an increasing amount of data, self-learning takes place [79]. An essential component of the system's operation is automation. The purpose of the cyber-physical system (CPS) is to control the control object [80]. The control component of the cyber-physical system (CPS), which is crucial for feed-forward control loops, is essential to dynamic systems [81].

- **Open system:** The open-system aspect of the cyber-physical system (CPS) enables it to autonomously adapt to its environment, create rules based on domain standards, and modify the external physical environment to conform to those rules [82].

5. Internet of Things (IoT), Cyber Physical System (CPS), and Applications of Cyber Physical System (CPS)

The internet of things (IoT) is enhanced by the cyber-physical system (CPS), which leverages IoT design to make it more intelligent and interactive. In addition to facilitating communication between humans and machines in both the real and virtual worlds, cyber-physical systems (CPS) include conventional embedded and control systems that are unaffected by novel approaches [83]. Among other things, they increase awareness and aid in comparison, prediction, reconfiguration, and repair. In specific contexts, cyber-physical systems (CPS) and the internet of things (IoT) must continue to improve [84]. Real-Time Physical Systems (RTPS) that employ an effective feedback control strategy that accounts for dynamic changes and real-time elements. A processor built for a basic model controls the vast cyber-physical system (CPS). The goal of the internet of things (IoT) is to provide decentralized control to connected end devices. The internet of things (IoT) and cyber-physical systems (CPS) share many characteristics, such as the capacity to sense, compute, store, and link to other devices [85]. The cyber-physical system (CPS) has been enhanced with new communication and control techniques to improve its fundamental attributes, including long-term use, safety, and security [86]. Wireless connections and advanced communication technologies have expanded and enhanced the use of cyber-physical systems (CPS), which are well-suited to the internet of things (IoT). These technologies include wearable devices, healthcare sensors, and cloud-based innovative systems. In the context of the internet of things (IoT), cyber-physical systems (CPS) examine the interplay between innovative systems, user-centered and interactive applications, optimization in IoT-enabled CPS, and control of distributed systems. Due to increased demand and improved performance, the cyber-physical system (CPS) needs to be enhanced. The implementation of cyber-physical systems (CPS) improves the performance of the internet of things (IoT). Numerous fields employ cyber-physical systems (CPS) to increase the adaptability, effectiveness, dependability, and self-sufficiency of large-scale systems [87]. Cyber-physical systems (CPS) are simpler to use in some field applications due to these advantages. Numerous specialized areas of cyber-physical systems (CPS), including new technologies, system architecture, manufacturing techniques, system design and modeling, and real-world applications, might use some development. As a cross-disciplinary cyber-physical system (CPS), it can be applied in nearly any field. Cyber-physical systems (CPS) have numerous applications, such as energy management, education, medical devices, process control, smart homes, Industry 4.0/smart manufacturing, wearable technology, transportation systems, traffic prediction, and weather and environmental monitoring [88].

5.1 Environmental Monitoring

Wireless sensor networks are a crucial component of cyber-physical systems (CPS). Sensor nodes placed strategically in various locations are used by a cyber-physical system (CPS) to monitor the environment with human assistance. The environmental equilibrium is broken when these sensor nodes detect natural and man-made disasters, such as fires, flooding, hazardous gas releases, and excessive rainfall. Unusual ecological conditions and the resulting system issues are addressed via a framework that facilitates communication between the cyber-physical system (CPS) and its environment. Real-time world monitoring technologies use cloud computing, multi-agent systems, and wireless sensor networks (WSNs). The cyber-physical system (CPS) paradigm offers flexibility and scalability by leveraging technologies to operate in a dynamic environment. A wireless sensor network (WSN) is used within the three-layer structure of a cyber-physical system (CPS) to gather data from physical nodes equipped with sensors. Higher layers can then receive this data, enabling data analysis and decision rules to monitor the cyber-physical system (CPS) performance [89].

5.2 Transportation System

Smart transportation deals with real-time information analysis. Autonomous driving vehicles, vehicular cyber-physical systems (VCPS), and Intelligent transportation are significant advancements in the transportation domain that build on cyber-physical systems (CPS). Autonomous driving vehicles show almost no fatalities compared to human-driven vehicles, ranging from cars to planes. For traffic measurement, a privacy-preserving point-to-point function is used, in which the number of traveling vehicles is measured based on their geographical locations by intelligent cyber-physical road systems. Bit arrays are used to collect data, and maximum likelihood estimation (MLE) is used to obtain the measurement result. The co-optimization and co-regulation schemes for both cyber and physical resources are considered by examining time-varying sampling patterns, sensor scheduling, control mechanisms, feedback scheduling, and motion planning and resource allocation for cyber-physical vehicle systems (CPVSs). Predicting road traffic has been one of the most valuable applications of cyber-physical systems (CPS) and has proven to be highly accurate. Here, an in-the-loop operator is added to the framework so that, based on the prediction, traffic at a specific location can be prevented, and a retrospective analysis can be performed to prevent road traffic [90].

6. Conclusion

The goal of this research is to develop cyber-physical systems (CPS) that can adapt to changing environments. It emphasizes the importance of maximizing resources, making quick configuration changes, and responding wisely to maintain excellent service quality. The inspection system employs prescriptive intelligence to identify the issue and determine a solution, descriptive intelligence to provide a framework for manufacturing printed circuit boards (PCBs), and predictive intelligence to detect and anticipate defects. To create personalized goods, real-time changes in production processes require flexible, adaptable material flow systems and assembly equipment. To meet these demands, cyber-physical systems (CPS) must be able to automatically plan and execute tasks. They also need to be capable of self-creation. In contemporary industry, control system design is typically carried out independently of hardware and software specifications. Control programs for a particular system architecture are then created by hand.

Furthermore, standard industrial robot systems lack the flexibility to adjust to the demands of new, constantly evolving, and increasingly complex production processes. Research into cyber-physical systems (CPS) and the advancements they have enabled have driven the development of numerous new IT trends, including the Internet of Things (IoT), cloud computing, big data, the Industrial Internet, and Industry 4.0. A new method for inspecting printed circuit boards (PCBs) is required to support smart manufacturing. Because they integrate the digital and physical worlds, cyber-physical systems (CPS) are the most advanced technology. By combining computerized and real-world processes, cyber-physical systems (CPS) open new growth opportunities across industries such as healthcare, transportation, and smart cities. As these systems become more complex, their ability to manage security, privacy, and interoperability concerns will determine how well and frequently they are used. Improving dependable design techniques, increasing computer speed, and ensuring that cyber-physical systems (CPS) function properly in critical scenarios should be the primary objectives of future research to increase their use. Cyber-physical systems' (CPS) ongoing development will undoubtedly have a significant impact on how society and technology evolve.

References

1. Petkov, Nikolay, and Malinka Ivanova. "Printed circuit board and printed circuit board assembly methods for testing and visual inspection: a review." *Bulletin of Electrical Engineering and Informatics* 13, no. 4 (2024): 2566-2585.

2. Lanzisera, Steven, Andrew R. Weber, Anna Liao, Dominic Pajak, and Alan K. Meier. "Communicating power supplies: Bringing the internet to the ubiquitous energy gateways of electronic devices." *IEEE Internet of things journal* 1, no. 2 (2014): 153-160.

3. Ghosh, Shajib, Antika Roy, Nitin Varshney, Patrick Craig, Md Mahfuz Al Hasan, Sanjeev J. Koppal, Hamed Dalir, and Navid Asadi Zanjani. "SHIELD-PCB: securing hardware inspection with enhanced learning and defense against

adversarial examples in printed circuit boards images." In *Applications of Machine Learning 2024*, vol. 13138, pp. 116-123. SPIE, 2024.

4. Umeda, Shinji, Noboru Ishii, Noriaki Horiguchi, Makoto Maeda, Takumi Yamaguchi, Hideo Tanaka, Hiroshi Niinobe et al. "Underground power cable, distribution cable, overhead transmission line, industrial cable and their accessories." *Furukawa Review* 32 (2007): 2-20.

5. Samaila, Musa G., Miguel Neto, Diogo AB Fernandes, Mário M. Freire, and Pedro RM Inácio. "Challenges of securing Internet of Things devices: A survey." *Security and Privacy* 1, no. 2 (2018): e20.

6. Hoang, Duc NM, Sang Yoon Park, and Jong Myung Rhee. "Comparative Analysis of Traffic-Reduction Techniques for Seamless CAN-Based In-Vehicle Network Systems." *Electronics* 12, no. 4 (2023): 998.

7. El Guerraf, Abdelqader, Imane Ziani, Sana Ben Jadi, Ali El Bachiri, Mohammed Bazzaoui, El Arbi Bazzaoui, and Farooq Sher. "Smart conducting polymer innovations for sustainable and safe food packaging technologies." *Comprehensive Reviews in Food Science and Food Safety* 23, no. 6 (2024): e70045.

8. Nzenwa, E. C., and A. D. Adebayo. "Analysis of insulators for distribution and transmission networks." *American journal of engineering research (AJER)* 8, no. 12 (2019): 138-145.

9. Constantinescu, Cristian. "Intermittent faults and effects on reliability of integrated circuits." In *2008 Annual Reliability and Maintainability Symposium*, pp. 370-374. IEEE, 2008.

10. Jillek, W., and W. K. C. Yung. "Embedded components in printed circuit boards: a processing technology review." *The International Journal of Advanced Manufacturing Technology* 25, no. 3 (2005): 350-360.

11. Lewis, Shane, Asfaw Bekele, Tushar Tike, and Vineeth Bastin. "Characterization study of strain generated during press fit connector insertion in printed circuit board assembly." *Proceedings of SMTA Int.* (2016): 25-29.

12. Maria, A., and K. Srihari. "A review of knowledge-based systems in printed circuit board assembly." *The International Journal of Advanced Manufacturing Technology* 7, no. 6 (1992): 368-377.

13. Wang, Chia-Nan, Nhat-Luong Nhieu, and Tien-Anh Pham Viet. "Enhancing efficiency in PCB assembly for the leading global electronics manufacturing services firm: a TRIZ and Ant Colony Optimization approach." *The International Journal of Advanced Manufacturing Technology* 133, no. 11 (2024): 5529-5552.

14. Kim, Kyoung-Dae, and Panganamala R. Kumar. "Cyber–physical systems: A perspective at the centennial." *Proceedings of the IEEE* 100, no. Special Centennial Issue (2012): 1287-1308.

15. Hehenberger, Peter, Birgit Vogel-Heuser, David Bradley, Benoît Eynard, Tetsuo Tomiyama, and Sofiane Achiche. "Design, modelling, simulation and integration of cyber physical systems: Methods and applications." *Computers in Industry* 82 (2016): 273-289.

16. Vermesan, Ovidiu, Peter Friess, Patrick Guillemin, Martin Serrano, Mustapha Bouraoui, Luis Pérez Freire, Thomas Kallstenius et al. "IoT digital value chain connecting research, innovation and deployment." In *Digitising the Industry Internet of Things Connecting the Physical, Digital and VirtualWorlds*, pp. 15-128. River Publishers, 2022.

17. Hamzah, Muzaffar, Md Monirul Islam, Shahriar Hassan, Md Nasim Akhtar, Most Jannatul Ferdous, Muhammed Basheer Jasser, and Ali Wagdy Mohamed. "Distributed control of cyber physical system on various domains: a critical review." *Systems* 11, no. 4 (2023): 208.

18. Gunes, Volkan, Steffen Peter, Tony Givargis, and Frank Vahid. "A survey on concepts, applications, and challenges in cyber-physical systems." *KSII Trans. Internet Inf. Syst.* 8, no. 12 (2014): 4242-4268.

19. Cecílio, José, and Pedro Furtado. "Wireless sensors in heterogeneous networked systems." *Wireless Sensors in Heterogeneous Networked Systems* 2 (2014): 39-59.

20. Rai, Rahul, and Chandan K. Sahu. "Driven by data or derived through physics? a review of hybrid physics guided machine learning techniques with cyber-physical system (cps) focus." *IEEe Access* 8 (2020): 71050-71073.

21. Ashibani, Yosef, and Qusay H. Mahmoud. "Cyber physical systems security: Analysis, challenges and solutions." *Computers & Security* 68 (2017): 81-97.

22. Shrivastava, Aviral, Patricia Derler, Ya-Shian Li Baboud, Kevin Stanton, Mohammad Khayatian, Hugo A. Andrade, Marc Weiss, John Eidson, and Sundeep Chandhoke. "Time in cyber-physical systems." In *Proceedings of the eleventh IEEE/ACM/IFIP international conference on hardware/software codesign and system synthesis*, pp. 1-10. 2016.

23. Stankovic, John A., T. E. Abdelzaher, Chenyang Lu, Lui Sha, and Jennifer C. Hou. "Real-time communication and coordination in embedded sensor networks." *Proceedings of the IEEE* 91, no. 7 (2003): 1002-1022.

24. Stankovic. "A perspective on distributed computer systems." *IEEE Transactions on Computers* 100, no. 12 (1984): 1102-1115.

25. Sztipanovits, Janos, Xenofon Koutsoukos, Gabor Karsai, Shankar Sastry, Claire Tomlin, Werner Damm, Martin Fränzle, Jochem Rieger, Alexander Pretschner, and Frank Köster. "Science of design for societal-scale cyber-physical systems: challenges and opportunities." *Cyber-Physical Systems* 5, no. 3 (2019): 145-172.

26. Vlachos, Dionisios G. "A review of multiscale analysis: examples from systems biology, materials engineering, and other fluid–surface interacting systems." *Advances in Chemical Engineering* 30 (2005): 1-61.

27. Smith, C. Estelle, Bowen Yu, Anjali Srivastava, Aaron Halfaker, Loren Terveen, and Haiyi Zhu. "Keeping community in the loop: Understanding wikipedia stakeholder values for machine learning-based systems." In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1-14. 2020.

28. Sanislav, Teodora, and Liviu Miclea. "Cyber-physical systems-concept, challenges and research areas." *Journal of Control Engineering and Applied Informatics* 14, no. 2 (2012): 28-33.

29. Buttazzo, Giorgio. "Research trends in real-time computing for embedded systems." *ACM SIGBED Review* 3, no. 3 (2006): 1-10.

30. Xu, Hansong, Wei Yu, David Griffith, and Nada Golmie. "A survey on industrial Internet of Things: A cyber-physical systems perspective." *Ieee access* 6 (2018): 78238-78259.

31. Wang, Lihui, and Xi Vincent Wang. "Latest advancement in CPS and IoT applications." In *Cloud-Based Cyber-Physical Systems in Manufacturing*, pp. 33-61. Cham: Springer International Publishing, 2017.

32. Blasch, Erik, Ivan Kadar, Lynne L. Grewe, Richard Brooks, Wei Yu, Andres Kwasinski, Stelios Thomopoulos, John Salerno, and Hairong Qi. "Panel summary of cyber-physical systems (cps) and internet of things (iot) opportunities with information fusion." In *Signal Processing, Sensor/Information Fusion, and Target Recognition XXVI*, vol. 10200, pp. 171-188. SPIE, 2017.

33. Baheti, Radhakisan, and Helen Gill. "Cyber-physical systems." *The impact of control technology* 12, no. 1 (2011): 161-166.

34. Agarwal, Rupanshi, Akash Sanghi, Gaurav Agarwal, Amit Kumar Gupta, and Kamal Upreti. "Integrating intelligence: The convergence of computer science and engineering in cyber–physical systems." In *Big Data Analytics and Intelligent Applications for Smart and Secure Healthcare Services*, pp. 49-67. CRC Press.

35. Möller, Dietmar PF. "Introduction to cyber-physical systems." In *Guide to Computing Fundamentals in Cyber-Physical Systems: Concepts, Design Methods, and Applications*, pp. 81-139. Cham: Springer International Publishing, 2016.

36. Kumar, Amit, Pooja Pathak, Vijay Kumar Dwivedi, and Dilip Kumar Sharma. "Designing IoT-Enabled Circuits for Non-Contact Liquid Infusion in Infectious Patient Care." In *2023 International Conference on Advances in Computation, Communication and Information Technology (ICAICCIT)*, pp. 701-706. IEEE, 2023.

37. Kellermann, Helmut, Géza Németh, Jörg Kostelezky, Kai L. Barbehön, Fathi El-Dwaik, and Ludwig Hochmuth. "Electrical and Electronic System Architecture: Communication Network, Power Distribution System, Central Services and Wiring Harness." *ATZextra worldwide* 13, no. 8 (2008): 30-37.

38. Li, Shuaibing, Binglei Cao, Jin Li, Yi Cui, Yongqiang Kang, and Guangning Wu. "Review of condition monitoring and defect inspection methods for composited cable terminals." *High Voltage* 8, no. 3 (2023): 431-444.

39. Jillek, W., and W. K. C. Yung. "Embedded components in printed circuit boards: a processing technology review." *The International Journal of Advanced Manufacturing Technology* 25, no. 3 (2005): 350-360.

40. Tang, S. C., S. Y. Hui, and Henry Shu-Hung Chung. "Coreless planar printed-circuit-board (PCB) transformers-a fundamental concept for signal and energy transfer." *IEEE Transactions on Power Electronics* 15, no. 5 (2000): 931-941.

41. Buechley, Leah, Mike Eisenberg, Jaime Catchen, and Ali Crockett. "The LilyPad Arduino: using computational textiles to investigate engagement, aesthetics, and diversity in computer science education." In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 423-432. 2008.

42. Chakraborty, Moupali, Jeff Kettle, and Ravinder Dahiya. "Electronic waste reduction through devices and printed circuit boards designed for circularity." *IEEE Journal on Flexible Electronics* 1, no. 1 (2022): 4-23.

43. Vu, Tuyen V., Bang LH Nguyen, Zheyuan Cheng, Mo-Yuen Chow, and Bin Zhang. "Cyber-physical microgrids: Toward future resilient communities." *IEEE Industrial Electronics Magazine* 14, no. 3 (2020): 4-17.

44. Wang, Shu, and Roger J. Jiao. "Smart In-Process Inspection in Human–Cyber–Physical Manufacturing Systems: A Research Proposal on Human–Automation Symbiosis and Its Prospects." *Machines* 12, no. 12 (2024): 873.

45. Azeri, Nabila, Ouided Hioual, and Ouassila Hioual. "Enhancing Self-Adaptive Cyber-Physical Systems using Federated Machine Learning." In *TACC*, pp. 108-119. 2023.

46. Wang, Yutong, Jiangong Wang, Yansong Cao, Shixing Li, and Oliver Kwan. "Integrated inspection on PCB manufacturing in cyber–physical–social systems." *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 53, no. 4 (2022): 2098-2106.

47. Merdan, Munir, Timon Hoebert, Erhard List, and Wilfried Lepuschitz. "Knowledge-based cyber-physical systems for assembly automation." *Production & Manufacturing Research* 7, no. 1 (2019): 223-254.

48. Kaestle, Christopher, Hans Fleischmann, Michael Scholz, Stefan Haerter, and Joerg Franke. "Cyber-physical electronics production." In *Industrial Internet of Things: Cybermanufacturing Systems*, pp. 47-78. Cham: Springer International Publishing, 2016.

49. Charter, Todd. "Human-centered intelligent monitoring and control of industrial systems: A framework for immersive cyber-physical systems." UVicSpace Home (2024).

50. Zhang, Kunwu, Yang Shi, Stamatis Karnouskos, Thilo Sauter, Huazhen Fang, and Armando Walter Colombo. "Advancements in industrial cyber-physical systems: An overview and perspectives." IEEE Transactions on Industrial Informatics 19, no. 1 (2022): 716-729.

51. Rossit, Daniel Alejandro, Fernando Tohme, and Mariano Frutos. "Production planning and scheduling in Cyber-Physical Production Systems: a review." International journal of computer integrated manufacturing 32, no. 4-5 (2019): 385-395.

52. Wilson, A. N., Abhinav Kumar, Ajit Jha, and Linga Reddy Cenkeramaddi. "Embedded sensors, communication technologies, computing platforms and machine learning for UAVs: A review." IEEE Sensors Journal 22, no. 3 (2021): 1807-1826.

53. Berger, Christoph, Alexander Zipfel, Stefan Braunreuther, and Gunther Reinhart. "Approach for an event-driven production control for cyber-physical production systems." Procedia CIRP 79 (2019): 349-354.

54. Ding, Lei, Qing-Long Han, Xiaohua Ge, and Xian-Ming Zhang. "An overview of recent advances in event-triggered consensus of multiagent systems." IEEE transactions on cybernetics 48, no. 4 (2017): 1110-1123.

55. Park, Kyung-Joon, Rong Zheng, and Xue Liu. "Cyber-physical systems: Milestones and research challenges." Computer Communications 36, no. 1 (2012): 1-7.

56. Zhou, Ji, Yanhong Zhou, Baicun Wang, and Jiyuan Zang. "Human–cyber–physical systems (HCPSs) in the context of new-generation intelligent manufacturing." Engineering 5, no. 4 (2019): 624-636.

57. Sastry, S., & Iyengar, S. S. (2005). Real-time sensor-actuator networks. International Journal of Distributed Sensor Networks, 1(1), 17-34.

58. Rahman, Arifur, and Rafael Reif. "System-level performance evaluation of three-dimensional integrated circuits." IEEE transactions on very large scale integration (VLSI) systems 8, no. 6 (2002): 671-678.

59. Duan, Pengfei, Ying Zhou, Xufang Gong, and Bixin Li. "A systematic mapping study on the verification of cyber-physical systems." IEEE Access 6 (2018): 59043-59064.

60. Yin, Dao, Xinguo Ming, and Xianyu Zhang. "Understanding data-driven cyber-physical-social system (D-CPSS) using a 7C framework in social manufacturing context." Sensors 20, no. 18 (2020): 5319.

61. Zeadally, Sherali, Teodora Sanislav, and George Dan Mois. "Self-adaptation techniques in cyber-physical systems (CPSs)." *IEEE Access* 7 (2019): 171126-171139.

62. Guan, Xinping, Bo Yang, Cailian Chen, Wenbin Dai, and Yiyin Wang. "A comprehensive overview of cyber-physical systems: From perspective of feedback system." *IEEE/CAA Journal of Automatica Sinica* 3, no. 1 (2016): 1-14.

63. Iqbal, Rahat, Faiyaz Doctor, Brian More, Shahid Mahmud, and Usman Yousuf. "Big Data analytics and Computational Intelligence for Cyber–Physical Systems: Recent trends and state of the art applications." *Future Generation Computer Systems* 105 (2020): 766-778.

64. Wan, Jiafu, Min Chen, Feng Xia, Li Di, and Keliang Zhou. "From machine-to-machine communications towards cyber-physical systems." *Computer Science and Information Systems* 10, no. 3 (2013): 1105-1128.

65. Tao, Fei, Qinglin Qi, Lihui Wang, and A. Y. C. Nee. "Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison." *Engineering* 5, no. 4 (2019): 653-661.

66. Zhou, Yuchen, F. Richard Yu, Jian Chen, and Yonghong Kuo. "Cyber-physical-social systems: A state-of-the-art survey, challenges and opportunities." *IEEE Communications Surveys & Tutorials* 22, no. 1 (2019): 389-425.

67. Müller, Hausi A., Holger M. Kienle, and Ulrike Stege. "Autonomic computing now you see it, now you don't: Design and evolution of autonomic software systems." In *International Summer School on Software Engineering*, pp. 32-54. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006.

68. Vermesan, Ovidiu, Arne Bröring, Elias Tragos, Martin Serrano, Davide Bacciu, Stefano Chessa, Claudio Gallicchio et al. "Internet of robotic things–converging sensing/actuating, hyperconnectivity, artificial intelligence and IoT platforms." In *Cognitive hyperconnected digital transformation*, pp. 97-155. River Publishers, 2022.

69. Yun, Huitaek, and Martin BG Jun. "Immersive and interactive cyber-physical system (I2CPS) and virtual reality interface for human involved robotic manufacturing." *Journal of Manufacturing Systems* 62 (2022): 234-248.

70. Wolf, Wayne H. "Hardware-software co-design of embedded systems." *Proceedings of the IEEE* 82, no. 7 (2002): 967-989.

71. Molina, Elias, and Eduardo Jacob. "Software-defined networking in cyber-physical systems: A survey." *Computers & electrical engineering* 66 (2018): 407-419.

72. Dey, Kakan, Ryan Fries, and Shofiq Ahmed. "Future of transportation cyber-physical systems–Smart cities/regions." *Transportation cyber-physical systems* (2018): 267-307.

73. Lamb, Roberta, John Leslie King, and Rob Kling. "Informational environments: Organizational contexts of online information use." *Journal of the American Society for Information Science and Technology* 54, no. 2 (2003): 97-114.

74. Mourtzis, Dimitris, and Ekaterini Vlachou. "Cloud-based cyber-physical systems and quality of services." *The TQM Journal* 28, no. 5 (2016): 704-733.

75. Ahmadi, Ahmadzai, Ali Hassan Sodhro, Chantal Cherifi, Vincent Cheutet, and Yacine Ouzrout. "Evolution of 3C cyber-physical systems architecture for industry 4.0." In *International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing*, pp. 448-459. Cham: Springer International Publishing, 2018.

76. Afshar, Saeed, Andrew Peter Nicholson, Andre Van Schaik, and Gregory Cohen. "Event-based object detection and tracking for space situational awareness." *IEEE Sensors Journal* 20, no. 24 (2020): 15117-15132.

77. Tavčar, Jože, and Imre Horvath. "A review of the principles of designing smart cyber-physical systems for run-time adaptation: Learned lessons and open issues." *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 49, no. 1 (2018): 145-158.

78. Hooks, Daniel E., Torsten Fritz, and Michael D. Ward. "Epitaxy and molecular organization on solid substrates." *Advanced Materials* 13, no. 4 (2001): 227-241.

79. Horváth, Imre, and Jože Tavčar. "Designing Cyber-Physical Systems for Runtime Self-Adaptation: Knowing More about What We Miss..." *Journal of Integrated Design and Process Science* 25, no. 2 (2022): 1-26.

80. Harrison, Robert, Daniel Vera, and Bilal Ahmad. "Engineering methods and tools for cyber–physical automation systems." *Proceedings of the IEEE* 104, no. 5 (2016): 973-985.

81. Fagcang, Haesul, Richard Stobart, and Thomas Steffen. "A review of component-in-the-loop: Cyber-physical experiments for rapid system development and integration." *Advances in Mechanical Engineering* 14, no. 8 (2022): 16878132221109969.

82. Vasiljev, Yury S., Violetta N. Volkova, and Vladimir N. Kozlov. "The concept of an open cyber-physical system." In *International Conference Cyber-Physical Systems and Control*, pp. 146-158. Cham: Springer International Publishing, 2019.

83. Haldorai, Anandakumar. "A review on artificial intelligence in internet of things and cyber physical systems." *Journal of Computing and Natural Science* 3, no. 1 (2023): 012-023.

84. Magade, Krishananjali, and Amit Sharma. "Significant role of IoT in cyber-physical systems, context awareness, and ambient intelligence." In *The Next Generation Innovation in IoT and Cloud Computing with Applications*, pp. 16-34. CRC Press, 2024.

85. Ji, Ram, Devanand Padha, Yashwant Singh, and Surbhi Sharma. "Review of intrusion detection system in cyber-physical system based networks: Characteristics, industrial protocols, attacks, data sets and challenges." *Transactions on Emerging Telecommunications Technologies* 35, no. 9 (2024): e5029.

86. Jiang, Yuchen, Shen Yin, and Okyay Kaynak. "Data-driven monitoring and safety control of industrial cyber-physical systems: Basics and beyond." *IEEe Access* 6 (2018): 47374-47384.

87. Khater, Heba M., Farag Sallabi, Mohamed Adel Serhani, Ezedin Barka, Khaled Shuaib, Asadullah Tariq, and Mohamad Khayat. "Empowering healthcare with cyber-physical system—a systematic literature review." *IEEE Access* 12 (2024): 83952-83993.

88. Khaitan, Siddhartha Kumar, and James D. McCalley. "Design techniques and applications of cyberphysical systems: A survey." *IEEE systems journal* 9, no. 2 (2014): 350-365.

89. Jabeur, Nafaâ, Nabil Sahli, and Sherali Zeadally. "Enabling cyber physical systems with wireless sensor networking technologies, multiagent system paradigm, and natural ecosystems." *Mobile information systems* 2015, no. 1 (2015): 908315.

90. He, Yi, Alireza Jolfaei, and Xi Zheng. "Cyber-physical systems in transportation." In *Intelligent Cyber-Physical Systems for Autonomous Transportation*, pp. 129-149. Cham: Springer International Publishing, 2021.