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The Evolution of Cyber-Physical Systems referenced in its requirements: Literature Review

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Abstract

We are currently experiencing the fourth Industrial Revolution in terms of Cyber-Physical Systems (CPS). These systems are industrial automation systems that allow many innovative features through its network and access to the cyber world, changing our daily lives. New solutions like CPS isolate different ones according to the existing communication and engineering technologies. The first definition of the term CPS was presented in 2006, due to the understanding of the growing importance of the interactions between interconnected systems and the physical world, and in 2008, this concept was disseminated and new studies formed to emerge, define and define which the main requirements that CPSs have to meet are. In this context, the present article aims to present a study to identify, based on the analysis of the literature, the main requirements that PHCs must address. The research development methodology was based on the explanatory type, through bibliographic research and a mixed approach using the systematic literature review. The results obtained show a chronological evolution of the fundamental requirements for CPSs, of which the functionality, autonomy, efficiency, robustness, security, integration, remote diagnosis and client stand out. This progress is related to the global technological evolution, as well as the increased application of these systems.

Keywords: Cyber-Physical Systems, CPS, Literature Analysis, Requirements

1. INTRODUCTION

In recent years, Cyber-Physical Systems (CPS) have not only become an important direction of academic research and development and the scientific community, but are also expected to become the priority development industry field of the business community. The development of CPS research and application is of great importance to accelerate the integration of industrialization and information technology (LIU et al., 2017).

The CPS refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. The ability to interact and expand the capacities of the physical world through computing, communication and control is a key factor for future technological developments (BAHETI; GILL, 2011).

CPS follows the trend of having information and services everywhere and is inevitable in today's highly interconnected world (MARWEDEL; ENGEL, 2012). Lately, CPSs are being developed that are part of a future world connected in a global network, in which products, equipment and objects interact with embedded hardware and software beyond the limits of single applications (ACATECH, 2011).

The first definition of the term CPS was presented in 2006, due to the understanding of the growing importance of interactions between interconnected computing systems and the physical world (WANG; TORNGREEN; ONORI, 2015). In 2008, this concept was disseminated (LEE, 2010; WAN et al., 2010; GUNES et al., 2015), and new studies began to emerge, aiming to identify and define the main requirements that PHCs should have.

In this context, this article aims to present a study aiming to identify, from the analysis of the literature, the main requirements that the Cyber Physical Systems must contemplate.

2. THEORETICAL FRAMEWORK

2.1. CPS Concept

The term CPS was introduced in 2006 in the United States, with the understanding of the need for interaction between the physical and computerized world (WANG; TORNGREEN; ONORI, 2015). This conception emerged to be a paradigm of studies and research, influenced by control, communication and computing (PARK, 2012).

This discipline covers knowledge and principles of computational and engineering disciplines (networks, controls, software, human interaction, learning theory, such as electrical, mechanical, chemical, biological, physical sciences, engineering and information (ACATECH, 2011; KRAMER, 2014)

The first definition for this term was disseminated in 2008 showing that CPSs are physical and computer interactions interconnected to communication networks, which perform the monitoring, performance and control of physical processes (LEE, 2010; WAN et al., 2010; GUNES et al., 2015).

Gill (2010) portrays the CPS as physical, biological and engineering systems whose operations are integrated, monitored and/or controlled by a computational nucleus, with computing being associated with the communication network interconnected to the physical elements. The core is an embedded system, responding in time and performing frequent distribution.

Conti et al. (2012) describes CPSs as the transformation of embedded, highly integrated and networked systems, enabling networked devices to monitor, detect and act with the real world.

Baheti and Gill (2011) and Liu et al. (2017) consider CPSs with a new era of systems of computational and physical capabilities that interact with humans. Sannislav and Miclea (2012), corroborate that this concept will be able to develop a new perspective that exceeds the time, space and dimensions currently known.

2.2. CPS Features

The CPS is one of those responsible for facilitating Industry 4.0 (BERGER et al., 2016). According to Grabler and Pöhler (2017), CPS is the evolution of embedded systems, since embedded systems are not necessarily interconnected. The divergence must be highlighted, what presents the main differentiation is the interaction with the physical environment (MARWEDEL; ENGEL, 2012)

These systems are made up of networks, such as sensors, actuators, control processing units and communication devices (CARDENAS; AMIN; SASTRY, 2008; WANG; VURAN; GODDARD, 2008).

The CPSs have as functions: collection, processing, evaluation and saving of physical data using sensors and interacting with the processes using actuators, makes connection and use of global data and dedicated multimodal man-machine interface (HUANG, 2008; BARNUM; SASTRY; STANKOVIC , 2010; WAN et al., 2011; SHI et al., 2011; GUNES et al., 2015).

According to Lee (2008), Sha et al. (2009) and Acatech (2011), the CPS is characterized by: Cyber capacity in each physical component and resource restrictions; Multiple and extreme networks; Time and space scales; Dynamic reconfiguration; High automation and closed-loop control; Reliable and certified operation; Integrated cyber and physical components with a focus on learning and adaptation, higher performance, self-configuration.

According to Sanislav and Miclea (2012), the CPS can be defined by 5 points: Input and feedback from / to the physical environment; Distributed management and control; Real-time performance requirements; Large geographical distribution without physical security components in several locations; Large-scale control systems.

Unlike other information and communication technologies, the CPS is a complex system, requiring greater integration and has the following attributes: functionality, reliability, security, cost, stability, performance, efficiency and work in real time (KIM; KUMAR, 2012; SANISLAV; MICLEA, 2012; BROY; SCHMIDT, 2014).

Liu et al. (2017) describe CPS as major requirements: robustness, self-organization, self-maintenance, security, remote diagnosis, real-time control, autonomous navigation, transparency, predictability, efficiency, model correction, interoperability, global tracking, responsiveness to internal and external changes.

CPS developers and users need confidence to run, Rajkumar et al. (2010) and Park (2012) also emphasize this trust brought by the CPS system and Baheti and Gill (2011) consider it as a combination of requirements, such as: reliability, security, usability and privacy.

Dumitrescu, Juergenhake and Gausemeier (2012) point out the relevance of intelligent systems, the adaptability of autonomous interaction, robustness to work dynamically and react to problems, anticipation of strategies and focus on customer requirements and Grabler and Pöhler (2017) add importance interaction with other devices.

As these are systems that act strongly in real time and have a high complexity of specification analysis, a structure should be designed in which critical security information and services are guaranteed by small subsets and that these are frequently specified and verified (WANG; VURAN; GODDARD, 2008).

As the CPS are not constantly in operation in controlled environments, they must be designed in a robust, capable and agile manner in unscheduled conditions, being able to adjust to possible problems arising from the subsystem, despite the uncertainties and errors of detection and control. (LEE, 2008; WAN et al., 2010). According to Wang, Vuran and Goddard (2008), the open loop structure allows the error to spread throughout the system chain, thus, loops must be closed in the cyber and physical sphere, being able to effectively be adverse uncertainties, failures and attacks.

For CPSs, it is necessary to readjust existing concepts so that computer and physical integration can be achieved. Giving priority to the issue related to time. Currently, it does not require that computation be faster in these systems, but that decision-making is made at the fundamental moment, so time is not a quality factor, but a necessity (LEE, 2010).

Notoriously, it is clear that traditional networks are not enough to support CPS applications, so integrated transmission networks are used. In most cases, a CPS system includes two or more communication networks, thus being known for its high level of heterogeneity in the composition of the system's devices (WAN et al., 2010; ACATECH, 2011).

The supports for the CPSs provide the resources of computing, communication, precise control, remote cooperation and autonomy (KRAMER, 2014).

CPSs are designed for a network with physical equipment, involving the work of units, for example in the manufacturing process, they include machines, storage systems and installations that are capable of carrying out information exchange independently, creating autonomous actions and controlling themselves between the same. In order to impact manufacturing and the entire product or process life cycle. This equipment and physical components are different from software and hardware (ACATECH, 2011; KAGERMANN; WAHLSTER; HELBIG, 2013).

The systems are designed to bring about significant changes in the realization of comprehensive controls in complex industrial processes and in production control systems (LEE, 2008; GRABLER; PÖHLER, 2017).

With the computational and physical interaction, involving human beings, physical capacity is increased, bringing new possibilities for technological developments and also being increasingly applied in the manufacturing sector (BAHETI, GILL; 2011; LIANG et al., 2018).

The CPSs make it possible to transform conventional machines into intelligent machines, these machines have the ability to coordinate technologies and improve overall performance (MONOSTORI, 2014; CAO; ZHANG; CHEN, 2017).

3. RESEARCH DEVELOPMENT METHODOLOGY

The research development methodology was based on the explanatory type, in this type of research the main objective is to provide greater proximity to the fact to be researched, making it more understandable and constructing new hypotheses, involving bibliographic surveys of experienced researchers in the given subject, assuming the design of bibliographic research (GIL, 2007).

The bibliographic research is carried out based on surveys of theoretical references and analyzed from publication in books and scientific articles, collecting knowledge and information, with the advantage of allowing a high range of sources that must be analyzed to ensure reliability (FONSECA, 2002; GIL, 2007).

Using a mixed approach, being a combination of qualitative and quantitative. Qualitative research involves obtaining descriptive data, aiming to deepen the phenomenon and provide a greater level of detail

(GOLDENBERG, 1997; BOGDAN; BIKEN, 2003; CRESWELL, 2007). The quantitative research, on the other hand, proposes the measurement of the information obtained, in order to develop a general explanation of the subject, portraying the research target (FONSECA, 2002).

There was the use of systematic literature review which is a scientific investigation, these reviews are retrospective observational studies or experimental studies of recovery and critical analysis of the literature, following 4 fundamental steps: planning, collection, analysis and result, according to table 1 (TRANFIELD; DENYER; SMART, 2003; DENYER; TRANFIELD, 2009).

Table 1: Planning, collection, analysis and result

Steps	**Step by Step**
Planning	- Research definition / research objective - Identification of search terms - Selection of the database - Definition of search criteria
Collection	- Application of search criteria - Application of selection criteria
Analysis	- Application of relevance criteria
Result	- Presentation of results

Tranfield, Denyer and Smart (2003)

3.1. Planning

The research aims to survey and identify the main requirements of the CPS. The search term selected was "cyber physical system" and was searched in the Portal da Capes database.

One of the criteria for the search filter was the period, starting in 2008 when the theme started to be disseminated until the year of the research in 2018. Other criteria considered were the material being an article, having the journal reviewed in pairs and be related to Engineering.

3.2. Collect

The Capes database was accessed, the search term, period and search filters were applied.

Inserting the search term "cyber physical system" the quantities of 1315 articles were found and after limiting the period, applying the filters by the article, reviewing the journal in pairs and being related to Engineering, the number of articles found reduced to 95 and these were selected for the analysis stage.

3.3 Analysis

With the articles collected, at this stage criteria were determined for the analysis of the studies.

First, it was necessary to read the titles and abstracts, when there was no coherence with the researched topic CPS, the material was removed from the analysis.

After that, the articles kept were read in their entirety, going through another analysis, where only the articles that explained the requirements of a CPS were kept, resulting in 64 articles on the purpose of the research.

With this total of citations, the main requirements were evidenced by several researchers on the subject, considering: performance with the physical environment, complexity, integration, functionality, reliability, security, cost, stability, performance, efficiency, robustness, remote diagnosis, work in time real, autonomy, transparency, predictability, model correction, interoperability, global tracking, usability, privacy, interaction, improvement in customer service, ability to respond to internal and external changes.

Due to the complexity of the CPS, some requirements were identified and through the analysis carried out it was verified that there are relationships between them, that is why 8 relevant requirements that form the groups were determined, as they cover the others mentioned, as shown in Table 2.

Table 2: Main CPS requirements

Group	Requirements
Security	Security, Privacy, Transparency and Reliability
Functionality	Functionality and performance with the physical environment
Integration	Integration, Interaction, Usability, Complexity and Interoperability
Remote diagnostics	Remote diagnostics, Model correction, Ability to respond to internal and external changes, Global tracking
Autonomy	Autonomy, Real-time work, Predictability
Efficiency	Efficiency, Performance
Robustness	Robustness, Stability
Customer	Cost and Improvement in meeting customer requirement

Tables 3, 4, 5, 6, 7 and 8 present the definitions related to the requirements in CPS systems presented.

Table 3: Definition of the security requirement in CPS systems

Requirement	Definition
Safety	Security is considered one of the most important requirements, since every organization is concerned with protecting its intellectual properties and operational goals from a malicious attack that could alter its cybernetic structure. But non-operational targets should also be assessed, such as measurements collected by sensors that can be confidential, and only authorized persons should be aware of this information. Some forms of attacks on CPS are sending false information to sensors and controllers, this information can be about process parameters, measurements, frequencies, times and incorrect identifications, thus changing the real specifications. It is also possible to interrupt the operation of sensors and controllers, obstruct communication channels, compromise devices and send data, so it is important to create algorithms in order to avoid these accidents, bringing greater privacy and reliability. These attacks can also be directed at quality control systems for inadequate evaluation, product design problems delaying launch, security risks for operators, among others.

Table 4: Definition of the functionality requirement in CPS systems

Requirement	Definition
Functionality	CPSs bring advantageous, numerous and innovative features, which come from working with complex physical environments through sensors and other devices, capable of converting physical properties, such as pressure, temperature and detection of mechanical movements.

Table 5: Definition of the integration requirement in CPS systems

Requirement	Definition
Integration	It basically consists of the integration of physical infrastructures with information technology incorporated into the internet, communication services, control and cloud solutions. The complexity of these systems is increased when they interact in different domains and also when data sources have different meanings, units and values between variation of machines and devices, also increasing the challenge of usability and interoperability. Because of this high complexity, it is necessary to understand and analyze all the existing interaction of physical and computational

	components, knowing that unique and traditional networks are not satisfactory for this support. There are two types of integration, vertical and horizontal. Vertical integrates systems at different levels, for example devices, controllers, data analysis and ERP. The horizontal integrates machines with other manufacturing resources in the field, such as robots, AGV's and machine tools)

Table 6: Definition of the remote diagnostic requirement in CPS systems

Requirement	Definition
Remote diagnostics	CPSs must perform condition monitoring, diagnosis and remote control, being essential in products, factories, networks and smart logistics Interacting directly with the physical world, its behavior must be changed automatically in the face of changes in environmental conditions, operational and external contexts, making decisions and making corrections

Table 7: Definition of the autonomy requirement in CPS systems

Requirement	Definition
Autonomy	The interaction with the physical environment has to be done autonomously, being able to detect, make decisions and control. These systems operate in real time and are fully autonomous, providing self-calibration (performs the calibration itself), self-adaptation (automatically adapting), self-awareness (knowledge of one's own status and internal data), self-description (comprehensive knowledge about the dynamic structure and the infrastructure of the total system), self-maintenance (identifies the need for maintenance and performs it), self-optimization (monitoring of parameters and optimizes them) and self-monitoring (monitoring of own data and performance), thus bringing greater predictability.

Table 8: Definition of the customer requirement in CPS systems

Requirement	Definition
Customer	CPSs assist in the implementation of customer requirements and demands, customizing products according to the specific individual needs of consumers. These automated systems adapt to the specifications of all types of users. In addition, with this technology, the customer is able to interact and virtually track the product in real time and the company is able to react to changes in the markets, bringing greater agility and customer service.

	A relevant additional point and a return to the customer is the cost reduction, since these systems optimizing the processes, consequently reduce times and costs and allow monitoring costs throughout the chain. It also brings greater improvement to the processes, improving the quality of the products.

3.4. Results and discussions

Table 9 shows the chronology of research on CPSs, identifying the main requirements of this system identified by the authors.

Table 9: Main characteristics of CPS systems

	Functionality	Autonomy	Efficiency	Robustness	Safety	Integration	Customers	Remote Diagnostics
Lee (2008)	X	X	X	X				
Wan et al. (2010)	X	X	X	X				
Rajkumar et al. (2010)			X		X			
Baheti e Gill (2011)	X	X			X			
Park (2012)		X	X		X			
Marwedel e Engel (2012)	X		X	X	X			
Dumitrescu, Juergenhake e Gausemeier et al (2012)		X		X	X			
Kim e Kumar (2012)	X	X	X	X	X	X	X	
Sanislav e Miclea (2012)	X	X	X	X	X	X	X	
Broy e Schmidt (2014)	X	X	X	X	X	X	X	X
Liu et al (2017)	X	X	X	X	X	X	x	X

As can be seen, the first research by Lee (2008) and Wan et al. (2010) on CPSs, show that the main requirements are related to functionality, autonomy, efficiency and robustness.

Rajkumar et al. (2010), Baheti and Gill (2011), Park (2012), Dumitrescu et al. (2012) already identify and signal that an important requirement in CPS systems is security, since in previous research they were not presented and / or identified.

Kim and Kumar (2012), Sanislav and Miclea (2012), Broy and Schmidt (2014) and Liu et al (2017) present in addition to the necessary requirements for CPSs related to security, functionality, integration, autonomy, efficiency and robustness, others additional requirements for remote diagnostics and customers.

4. CONCLUSIONS

This research aimed to identify and present, from the analysis of the literature, the main requirements that CPSs must contemplate, and an expansion of the necessary requirements for CPSs as a function of time can be observed, related to the global technological evolution, as well as as the increased application of these systems.

When the concept and definition of CPSs emerged, the first researches showed that the main requirements of these systems were related to functionality, autonomy, efficiency and robustness.

Subsequently, research added the requirement of security, as one of the important attributes, in order to guarantee the privacy, transparency and reliability of data and information.

And finally, recent research additionally presents the requirements related to remote diagnosis, in which interaction with the physical environment is carried out autonomously, and customers, in which they assist in the implementation of customer requirements and demands, personalizing the products to the individual and specific needs of consumers.

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