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Cyber–physical systems: Extending pervasive sensing from control theory to the Internet of Things

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ABSTRACT

Essentially, the emerging term "Cyber–Physical Systems (CPS)" is an architectural paradigm in which the pervasive sensing technologies represent a fundamental part. Originally defined in the computer sciences domain, the term Cyber–Physical Systems has been adapted to very different domains such as the control theory or electronic engineering. Even, some authors understand CPS as a particular scenario of the Internet of Things (IoT) based on pervasive sensing. Furthermore, recently, some works propose a definition for CPS including all the features described in the different domains. In this paper we provide a comprehensive analysis of the nature and characteristics of the different proposals, discuss the recent attempts to standardize CPS, and review the state-of-the-art on CPS for each technological domain. We compare those different proposals on CPS, discuss about some related terms and technologies and conclude by describing the main research challenges in the area.

1. Introduction

Essentially, the emerging Cyber–Physical Systems (CPS) are feedback control systems based on pervasive sensing [1]. Thus, CPS embody a vision of physical devices (sensors, actuators and sensor-enable mobile devices) performing feedback control loops, where devices provide and receive information from a control system which executes a certain application. In general, it assumes physical devices are seamless integrated into daily living objects, making up the called embedded systems or embedded devices.

The presence of feedback loops supported by a pervasive sensing infrastructure is the common characteristic to all proposals on CPS. From this common core, and depending on the considered technological domain, CPS may be focused on very different issues such as improving the integration level in embedded devices, building real-time applications or providing customized services in the context of the Internet of Things (IoT). Then, around each vision, authors have identified different lines in CPS research, have proposed specific architectures and have described particular solutions addressing the concrete problems of CPS in their area.

Furthermore, very recently (final months of 2013), the main standards organizations (such as the International Organization for Standardization – ISO – and the European Telecommunications Standards Institute -ETSI-) have created public working groups in order to become CPS into a standard technology. The pioneer in these efforts was the National Institute

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of Standards and Technology -NIST-, which proposed in its first conclusions (published in September 2015) [2] a horizontal architecture for CPS including all previous proposals. As a result, very different works can be found under the name of Cyber–Physical systems.

Moreover, CPS are currently maturing from its origin as research paradigm to a variety of commercial products [3,4]. CPS have many potential applications from smart infrastructure (grid, water, gas, etc.) and smart health care to smart manufacturing and smart transportation, where pervasive sensing is indispensable [5]. These applications have an important potential to benefic companies, societies and, in general, human lives.

Due to the relevance of CPS, different review papers about this topic have appeared in the literature during the last ten years. However, because of the extended use (and certain abuse) of the paradigm "Cyber–Physical Systems" nowadays, it is necessary a new effort to collect and organize the proposed contributions, considering the special circumstances that surrounds the term (lack of agreement about its definition, confusion with similar concepts and previous terms, the interest of the technological researchers on adjusting their ideas to this new paradigm, etc.). In fact, some of previous review works [6,7] propose or defend a particular definition of CPS which is employed as a framework to select the contributions to be referred. As a consequence, they offer a partial vision of this new paradigm. On the other hand, different review works about special topics related to CPS have been reported: self-adaptation [8], security [9], modeling [7], etc. These papers use to be exhaustive and very useful, but they do not offer a global context (it would be interesting, for example, to know if all reviewed contributions understood CPS in the same way or if all authors envision the same type of systems). A third group of surveys [10,11] is focused on future challenges and current trends (or similar issues). The objective of these papers, nevertheless, is not to offer a review about the state-of-the-art but to detect tendencies and problems to be solved. Finally, a great number of survey works [5,12–15] indicates the existence of different definitions and visions for CPS, and sometimes even the different defended architectures are analyzed, but, due to the enormous number of different proposals and the difficulties to classify them, reviewed works are usually organized depending on the application scenario (vehicular systems, medical environments, etc.), mixing works based on different concepts of CPS (which, as we are seeing, even include different elements and components). Therefore, in this paper a new comprehensive review of Cyber–Physical Systems is provided, considering all proposed definitions and visions. Reviewed works include not only which are directly referred as belonging to CPS, but also proposals about topics whose relation with CPS is not clear (Machine-to-Machine, Wireless Sensor Networks...) and other works which fit the different requirements to be considered as CPS. A first explanation of the global context is provided, identifying the elements which may compose CPS and proposing a classification for contributions related to CPS based on the ideas of the Eindhoven Institute for Research on ICT (so proposals inspired by a common definition of CPS are presented together). Finally, as a novelty, not only research works are reviewed but also standardization initiates, which (possibly) will determine the future of CPS.

The rest of the paper is organized as follows. Section 2 introduces the main components of CPS, their features and their relation with the different technological domains. Most important aspects on CPS, which are going to be reviewed from different approaches, are also presented here. Section 3 reviews CPS as defined in control theory, and analyzes the state-of-the-art on the main research challenges. Section 4 presents CPS as understood in computer sciences. Section 5 is focused on communication engineering and its proposals, works, and solutions on CPS. Finally, Section 6 presents the vision of the standards organizations on CPS, as well as the published preliminary conclusions. Finally, Section 7 presents the main future challenges in CPS research and Section 8 concludes the paper.

2. Overview of cyber–physical systems

Works on CPS have helped to the definition of new and extremely interesting emerging technologies in pervasive sensing. However, in the last months Cyber–Physical systems has become into an extremely popular term [15]: the original definition has been extended [16], new concepts and elements (such as virtual sensors) have been added [17], etc. In that way, learning about the composition of CPS might be a complicated task, as many different proposals can be found.

Therefore, in this section we list and describe all the elements which could be part of Cyber–Physical Systems, and show how combining these elements in different proportions it is possible to obtain the main approaches identified in CPS sciences. Moreover, most important aspects on CPS are identified, and a brief summary about how each topic is addressed from each one of the listed approaches is provided.

2.1. Elements in cyber–physical systems

A deep analysis of all possible elements which may be part of CPS should be based on the study of all proposed application scenarios in research literature. However, in 2014, the Eindhoven Institute for Research on ICT (EIRCT) identified the six components which, occasionally, have been used to make up CPS [18]: physical world, transducers, control components, data analytics elements, computation elements and communication components. Although this proposal has not been communicated (until now) in a regular scientific journal, (as we are seeing) it is a powerful instrument to categorize in a coherent way all the existing definitions and works about CPS. Using the ideas of the EIRCT, a genuine review methodology and a survey with a totally new approach to all exiting works may be provided (as we are able to study all the contributions supported by a common understating of CPS together).

The physical world includes all the elements with which the other components in the system cannot communicate explicitly (i.e. the elements with which cyber components cannot establish a dialog by means of engineered methods and solutions). As it is one of the main characteristics of CPS, cyber elements must interact with the physical world. However, while cyber components may communicate directly among them through common protocols, interfaces or access technologies (a paradigm known as "explicit interactions"), interactions among cyber components and elements in the physical world have to be performed through sensors and actuators, whose outcomes are processed (using, for example, learning techniques, probably one of the most important aspects of CPS that are being studied) in order to infer the state of the physical world and make decisions (a paradigm known as "implicit interactions"). More formally, in explicit interactions, each one of the agents to be communicated "informs" in a certain level of abstraction what it expects the others to do (by means of textual messages, using a GUI, speech input, etc.) [19]. On the contrary, implicit interactions are based on actions performed by the agents that are not primarily aimed to interact with the others, but they understand as input [19,20]. Then, elements in the physical world interact with the other components in the system by means of sensors and actuators which sense and influence them and analyze their behavior [20].

Depending on the application domain, the physical world may be limited to some specific elements or not. In the most general case, the physical world includes two parts: the physical system and the physical environment [21]. The physical system includes all the engineered devices (such as production systems or programmable controllers) which ideally are co-designed with the rest of the CPS, but also might be an existing legacy system. The physical environment refers to physical phenomena relevant to the system (raining, temperature in a room, etc.) [12]. People are a particularly important element in the physical world. Thus, systems that consider humans as part of the physical world are known as *Human-in-the-loop systems* [22]. Basically human-in-the-loop systems can be classified in three categories depending on the role occupied by humans [22]: (i) systems where humans may control the operation [23] (in that point CPS connect to software-defined networking — SDN — [24]), (ii) systems where humans are only passively monitored [25] and (iii) hybrid systems of the previous [26]. In contrast to the physical world, the rest of the components in a CPS it is said belong to the cyber world or cybernetics.

Transducers refer to the pervasive sensing platform. It includes sensors, actuators and sensor-enable mobile devices organized in one or several networks [12]. Transducers usually are organized in nodes which may include sensors, actuators, processors, communication capabilities and batteries [27]. These nodes are seamless integrated into daily-living objects creating the next generation of embedded devices [12]. At logical level, it is common to suppose that sensors and actuators are grouped in two different networks (see Fig. 1). Pervasive sensing platform is responsible for acquiring data from the physical world, and transmit that information to the control components. Besides it receives data from the control components and must act on the physical world in the adequate way. In general transducers are organized as a wireless network, although wired solutions are also possible. Moreover, transducers may be intelligent, virtual and/or distributed. Nowadays, however, intelligent transducers are much common than virtual or distributed nodes. In particular, intelligent transducers (more commonly named as smart transducers) [28] are seamless integration between sensors (or actuators) and processors, so a new device being able to self-adapt to the environment and perform some initial processing actions is obtained. IEEE 1451 standard defines and proposes different solutions to interact with this type of transducers, such as the Transducer Electronic Data Sheets (TEDS) [29], which allow the self-description of transducers and their plug-and-play connection.

Control components group all the hardware and software elements focused on managing the pervasive sensing platform. These components acquire data from sensors, perform local processing and control the actuators in order to reach the wanted state in the physical world [21]. Control tools typically present a continuous dynamic, although depending on the application in CPS they also may present a discrete behavior inherited from computing systems [27]. In general, these tools must make possible to control "by design" the behavior of the pervasive sensing platform [30]. Clearly, due to the distributed architecture of pervasive sensing platforms, control components used to be decentralized too (although that is not mandatory) [31].

Data analytics elements include all software programs focused on processing, filtering, and storing the information from the different control components. In the past, these elements used to be considered part of control components and/or computation elements. However, the increased integration between the cyber and physical world presents important challenges which deserve to be treated independently [31]. Besides, most of these challenges (such as the huge amount of information produced and the heterogeneity of the generated data) are addressed by specific technologies like Big Data. For all that, important institutions as the EIRCT are considering data analytics elements as an independent component of CPS [18]. These elements perform pattern recognition, decision-making, predictive analysis and machine-learning, among other capabilities. If necessary, they also include visual analytics for controllers, managers or general users [21].

Computation elements include a heterogeneous group of elements belonging to computer sciences. Technologies such as computational models; action-oriented, realistic, timely goals [21]; rigorous timing models for microprocessors [32,33], real-time computing [34] and virtualization [18] are part of this group. These components are usually employed to adapt the system to internal and external changes through "switching" between different operation "modes". As a result, CPS might be considered as a hybrid system [27]. Finally, this group also includes security techniques and policies, from secure hardware [35,36] to pure software solutions [37] and hybrid approaches [38].

Communication components refer, basically, a group of technologies focused on Internet services. Some examples of the elements included are cloud-computing [39], service composition [40], future wired and wireless technologies for supporting the connectivity [41], energy efficient protocols [42], machine-to-machine communications (M2M) [43] and intelligent mobility management [44].

Fig. 1 shows a generic holistic view for CPS where all the previous components are considered. As we are seeing later simpler views are possible depending on the considered technological domain.

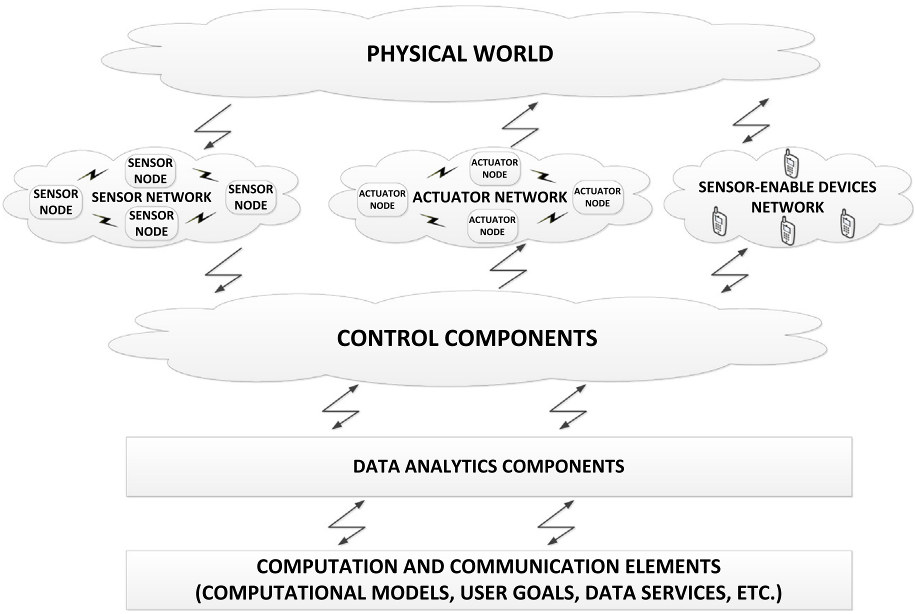

Fig. 1. Holistic view of CPS.

2.2. Main approaches in CPS sciences

CPS has been addressed from different views by the scientific community [12]. There exist several proposals and definitions, some of them extremely specific and focused on a particular scenario as [45]. However, among all these proposals it may be also found approaches with a great impact and to which several authors have contributed. Without being exhaustive, it is noteworthy the proposals of (i) Lee [34] which describes CPS as "integrations of computation and physical processes"; (ii) Rajkumar [46] which proposes CPS as "physical and engineered systems whose operations are monitored, coordinated and integrated by a computing core"; (iii) Marwedel [47] which describes them as "embedded systems together with their physical environment" and (iv) Kim [27] which says "CPS are the next generation of engineered systems in which computing, communication and control technologies are tightly integrated".

As can be seen, proposal (i) is focused on the processes, while the others are focused on the systems. Moreover, proposal (iv) does not consider the physical world in the definition, while in the others is one of the main parts. On the other hand, proposals (iii) and (iv) highlight the improvement of the integration level while (i) and (ii) are focused on the synchronization of cyber and physical world.

As a popular term CPS are understood in different ways by different authors, therefore trying to fix a uniform definition is useless [48]. Nevertheless, the EIRCT proposes that all approaches in CPS (from more famous to which are only developed by the authors who proposed them) can be classified into four main groups depending on the elements which the authors consider as part of CPS [18]. In this work, we identify these four groups with the main research areas in telecommunication engineering: control theory, computer sciences, communication engineering, and vertical systems.

The simplest architecture for CPS belongs to control theory. In this area, CPS are understood as a composition of the physical world, transducers and control components. In some specific applications simple data analytics elements are also considered [49,50], although it is not the regular situation. The importance of CPS in control theory has been showed in many studies such as [10,51–53] and others such as the above-mentioned Marwedel's [47], Sztipanovits' and Gill's [54], which understands CPS as "physical, biological and engineered systems whose operations are integrated, monitored, and controlled by a computational core".

The oldest proposal on CPS is due to computer sciences researchers. In fact, the term CPS was coined around 2006 at the National Sciences Foundation (NSF) together with the Berkeley University [1]. It is probably the view which has had the greatest impact, with several related projects running since 2008 [3,55,56]. In this area CPS are understood as a composition of the physical world, transducers, control components and computer sciences elements. Specialists on hybrid systems, new computational models, real-time applications and predictive models (among others) support this vision. The definition proposed by E. Lee in his famous position paper "Cyber–physical systems; are computing foundations adequate?" [34] is the base of contributions in this technological domain.

The probably least developed approach is due to communication engineering. This view is focused on hardware, services and embedded devices, so CPS are understood as a combination of transducers, control components, some data analytics elements, computer science elements and communication components. In this approach, the physical world is considered to be outside the system's limits (i.e. it is not considered a part of CPS, but an environment that surrounds them and whose changes they are aware of). Approaches such as proposed by Kim [27] belong to this technological domain. Researches in this

Table 1
Composition of CPS in the different technological domains.

	Control theory	Computer sciences	Communication engineering	Vertical system
Physical world	✓	✓	✓	✓
Transducers	✓	✓	✓	✓
Control components	✓	✓	✓	✓
Data analytics elements	Sometimes	Sometimes	Sometimes	✓
Computation elements		✓	✓	✓
Communication components			✓	✓

area tend not to include the word "Cyber–Physical Systems" in their works, although the proposed technologies could be considered a contribution in this field (as Wireless Sensor Networks [57], M2M communications [43], etc.). Thus, the number of works about CPS in communication engineering is much fewer than in other areas.

Finally, vertical approach for CPS considers the entire stack, from end-user customized services and computational models, to the pervasive sensing infrastructure and the physical world. Then, in this area, CPS are understood as a combination of all the components mentioned in Section 2.1. This theory of CPS is mainly supported by the standard organizations (such as the NIST) [21] and some research institutes as the EIRCT [21]. This perspective for CPS is the newest, proposed around 2013, but due to its great potential has been rapidly spread [48].

Table 1 summarizes the composition of CPS depending on the technological domain considered. As can be seen the underlying pervasive sensing infrastructure and the control components are the common elements to all proposals. Any case, it is clear that CPS are something more than just control tools [18], traditional embedded systems, real-time applications and/or desktop applications [58], and represent a new type of systems which are not available yet but which will have a great impact on the world [18,46].

In this context, CPS are characterized by some common aspects to all approaches, which makes them very different from any other previous engineered system. In particular, CPS involve some of the most modern techniques and popular research topics: learning solutions (especially those related to pattern recognition), context-aware systems, self-configuration and self-adaptation techniques, mobile solutions and fault-tolerant implementations (among other). However, although important aspects are common to all approaches, each technological domain addresses them from a different point of view. Below, a brief analysis of this situation for each aspect is provided.

First, context-awareness is defined as the ability of systems (specifically mobile systems) to link their operation with changes in the environment [59]. Consequently, it is an intrinsic characteristic to CPS. However, while telecommunication researchers try to define system architectures being able to manage the devices' context [39]; control theory authors look for an optimum stable control algorithm (or function) including as much context information as possible [60].

Secondly, machine learning is a pretty old concept referring the ability of computers to learn without being explicitly programmed [61]. Nowadays, is a specific field belonging to computer sciences, so these authors contributed the most to this area with respect to CPS (defining adaptive physical models [6] and hybrid automatons [62] among other works). Control theory researchers are also interested in the topic, specifically if humans are monitored (a type of human-in-the-loop systems [25]).

Self-configuration and self-adaptation are properties which allow devices to automatically perform the installation procedures to get the basic operational parameters and to obtain the necessary information for operation; modifying its configuration in an autonomous way without restarting or stopping the system operation when an unexpected change occurs [63,64]. Although autonomic computing studies (computer sciences) consist of bringing to a given system the self-* properties [65], in the particular case of CPS, communication engineering authors are the most prolific on the topic (usually, moreover, in applications related to industrial scenarios [66]).

Fault-tolerance is the ability of systems to operate regularly in case of a failure event [67]. This property is very important in critical systems (such as energy control infrastructures), but it is rarely required to CPS (although some CPS applications are also critical [68]). In this context, computer sciences authors are almost the only ones which have developed proposals in this topic (and, most of them, related to security [69]).

Finally, mobility is a very famous property of systems being able to modify its position (logical or geographical) without having to modify or interrupt its regular operation [70]. Although it is not a mandatory requirement, devices integrated into CPS are usually considered mobile. Thus, most authors working on CPS address problems associated with mobility. Control theory researches (for example) investigate the impact of fluctuations due to mobility in the control loop stability [71]. Computer sciences authors enhance traditional solutions (such as authentication) to be applied to mobile CPS [72]. And communication engineers propose different mechanisms (e.g. protocols) to support mobility in CPS [73].

2.3. CPS or the internet-of-things

Many concepts and technologies are relatively similar to CPS: embedded systems [74], wearable technologies [75], legacy systems [76] and Industry 4.0 [66,77,78], pervasive sensing [79], machine-to-machine communications [80], etc. The relation between CPS and some of them is often confusing. Some other terms are often associated to CPS, such as cloud

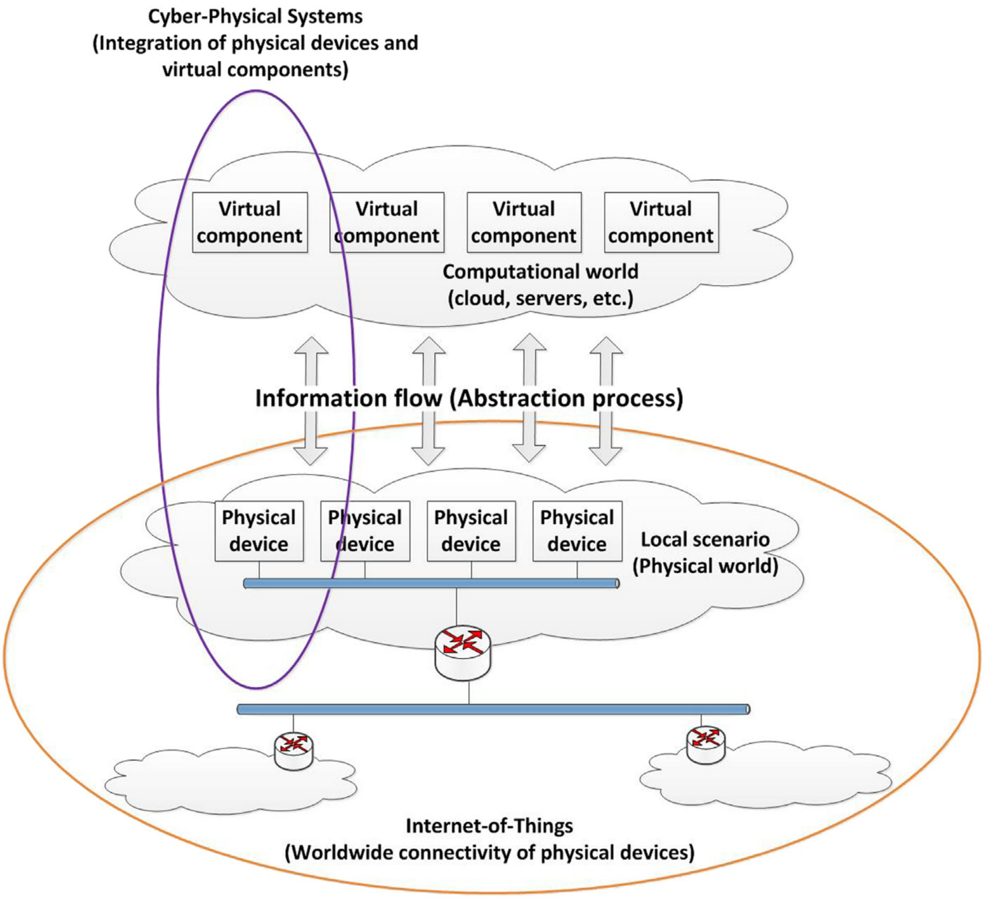

Fig. 2. Relation between CPS and IoT.

computing [81], pervasive computing [82] or system-of-systems [83,84], while "Internet of Things" shares very similar characteristics to CPS.

The term "Internet-of-Things" (IoT) represents the idea of several objects which, through unique addressing policies, are able to interact with each other and cooperate with their neighbors to reach some goals [85]. As we are seeing, this definition is similar in some aspects to CPS (networked devices, common goals, etc.); however there is not any official correspondence between CPS and IoT, so various theories about the relation between both terms may be found.

In [86], Koubâa identified that the frontier between CPS and the IoT is not clearly defined since both concepts have been driven in parallel from two independent communities, although they have always been closely related. In general, four main theories are discussed nowadays.

First, some authors propose CPS and IoT are independent concepts [74], which refer different realities. Thus, in [87], Chen identifies four topic which become different CPS and IoT: (i) CPS work in a close-loop manner, (ii) the network scale of CPSs is not as large as IoT, (iii) in CPS it is necessary a deep integration between the cyber and physical world, and (iv) CPS may not necessarily be connected to Internet (although this last point depends on the considered technological domain, as we are seeing).

In this group, other authors defend both terms are related to the same general scenario, but represent different views. For them, IoT has a horizontal view (i.e. IoT scenarios only consider hardware components and the technologies to communicate them) focused on creating a global network of daily living objects with worldwide connectivity. On the other hand, CPS has a vertical approach including from networked physical devices to computational models, control policies or data services [74] (see Fig. 2).

Other authors propose that IoT and CPS refer the same reality. In this group all opinions are not equal. Some authors defend that both terms are interchangeable because they always were synonyms. Others think they are synonyms because IoT is being smoothly extended from RFID technologies to something more general [88]. Finally, some authors think both refer to the same but IoT is more supported by European and Chinese researchers and CPS by American organizations [74].

A third group of authors, thinks that IoT, CPS, and the rest of similar terms are only "buzzwords" for referring the future totally connected world [88]. Finally, other researchers defend CPS belongs to IoT, so CPS is only a new pattern or particular scenario of IoT [13].

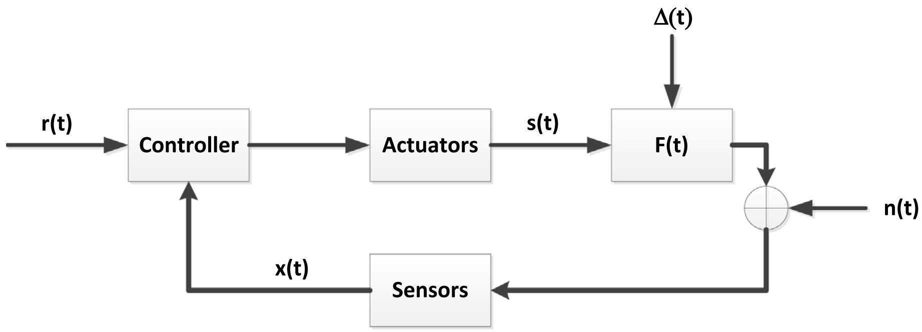

Fig. 3. Block diagram for a general controller.

3. Cyber–physical systems in control theory

Control theory is the branch of engineering that deals with the methodologies and tools for modifying the behavior of dynamic systems as desired. One of the most extended ways of applying control is by means of feedback loops, whose inputs are provided by a pervasive sensing platform [89]. This particular area of control theory is known as feedback control theory.

As we said in the introduction, CPS are, basically, feedback control systems based on pervasive sensing. Therefore, researchers on feedback control theory rapidly adopted the CPS paradigm in order to design the next generation of control systems.

In this section we review the basis of feedback control theory, describe the main research lines on CPS from the point of view of control experts, and present the most important contributions made in the cited lines.

3.1. Problem description

In the most general (and realistic) case, the problem of designing a controller is to correctly model the response of the system under control when its inputs are modified, as well as the inputs which must be applied to the system to obtain a certain response. Generally speaking, the objective of a controller is to make the temporal evolution of some process or system, $x(t)$, behaves in a desired way by manipulating in time some input, $s(t)$. For example, in the pasteurization process the liquid has to be heated and cooled various times following a specific pattern. The temporal evolution of temperature $T(t)$, then, has to be controlled to follow this pattern by varying the intensity level $I(t)$ of the refrigeration system.

Depending on the definition of $x(t)$ and $s(t)$ the objective might be to keep $x(t)$ close to some equilibrium point (a regulator problem) or to keep $x(t) - r(t)$ close to some equilibrium point, with $r(t)$a reference temporal evolution (a servo problem) [90]. Thus, the formula modeling the temporal evolution of a controller is as follows [89] (1).

$$x(t) = (F(t) + \Delta(t))(s(t)) + n(t). \tag{1}$$

In that expression (1), $n(t)$ is an unknown noise or disturbance, $F(t)$ the transference function and $\Delta(t)$ represents unknown perturbations in the transference function. Fig. 3 shows a block diagram for a general controller. As can be seen, systems in control theory (including the proposed CPS) present a continuous dynamics, as the physical time (which is continuous) governs these systems.

In a really common practical problem not only $n(t)$ and $\Delta(t)$ are unknown, but also the transference function $F(t)(\cdot)$ [91]. In many cases, the temporal evolution $x(t)$ cannot be expressed explicitly as in expression (1), as it is the solution of a differential problem without analytical solution. In these cases, the mathematical formulation of the control problem used to be as seen in expression (2).

$$\dot{x}(t) = F_t(x(t)) + u(t) \tag{2}$$

where $x(t)$ is the output temporal evolution and $u(t)$ is the controller signal. The unknown disturbances are considered null. This situation is typical of feedback systems where the appearance of $\dot{x}(t)$ is only due to the mathematical model as it has not a real existence in the physical world [92].

Systems as described in Fig. 3 are usually based on Programmable Logic Controllers (PLC), a type of microcontroller specifically designed to be integrated in feedback control systems. These devices can be networked, but as they are factory-centered (geographically dispersed locations cannot be connected), networks present a high rate and delays are negligible. Then, design techniques may be the same if controllers are networked or not. This type of networked PCL is usually known as Distributed Control Systems (DCS) [93].

Sometimes, however, feedback loops are closed through a shared network, creating the called Networked Control Systems (NCS) [94], which can be deployed in geographically dispersed locations. PLC, DCS and NCS are not new concepts, and usually are considered as legacy control systems [12].

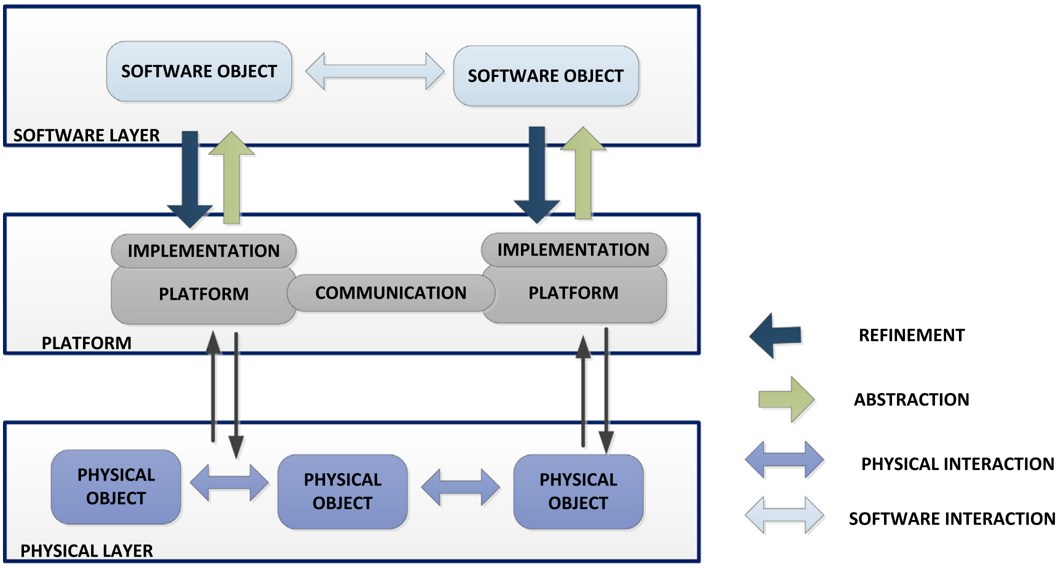

Fig. 4. Layers in CPS along [99].

Nevertheless, the named above legacy systems face some challenges, such as the impact of the network-induced delays in the stability of NCS, which may be addressed using the CPS paradigm. Moreover, traditional legacy systems and new CPS share several characteristics, although CPS entail requirements far beyond the expectation of legacy control systems [12,54]. Therefore, in several scenarios CPS can improve the performance of traditional systems, integrate existing legacy systems in a uniform infrastructure or directly replace the traditional feedback control systems [95,96].

3.2. CPS in control theory: The basis

As can be seen in Fig. 3, feedback control systems are made of controllers and sensors and actuators (the pervasive sensing platform), so the proposed architectures for CPS in control theory usually follow this scheme (see Fig. 4) Thus, the main definitions for CPS in control theory use to remark aspects such as the control processes, sensing capabilities or the physical world. Apart from the proposals cited in Section 2.2 [47,54], it must be mentioned the definition proposed by Sztipanovits [97] which describes CPS as "a computer system that processes and reacts to data from external stimuli from physical world and make decision that also impact the physical world". This definition is important because it considers, besides control components and the pervasive sensing platform, data analytics elements, so more complicated control systems can be developed using the CPS paradigm (such as some alternatives to SCADA systems [98]).

The definition of a reference architecture for CPS is a pending challenge (see Section 7). However, some authors have tried to address this issue. In the case of CPS in control theory, the proposed architectures are simple. In Fig. 4 can be seen the architecture proposed by Sztipanovits [99], which is one of the most used in CPS for control theory [100–102]. It consists of three layers: the physical layer corresponds to the physical world, and groups a collection of objects whose behavior is determined by physical laws; the second layer (called "platform") comprises the hardware elements (the pervasive sensing platform); and the third layer (the software layer) involves all the control algorithms, methodologies, etc. Similar architectures are described in other works such as [103].

CPS in control theory present a collection of particular characteristics which define the system operation. Some of these characteristics are common, as we are seeing, to all CPS (independently of the technological domain or application); others, however, are particular of the control theory domain. In [58,103,104] authors identified the following six characteristics for CPS in control theory:

- Cyber capabilities are deployed in the every element in the platform: the software is embedded in the hardware.
- Components in CPS are closely integrated.
- CPS are networked.
- CPS show dynamically reorganizing/reconfiguring: CPS, as very complicated systems, must have adaptive capabilities.
- Control loops in CPS must be closed. In CPS the most advanced feedback control technologies have to be widely applied.
- Operation must be dependable, and certified in some cases.

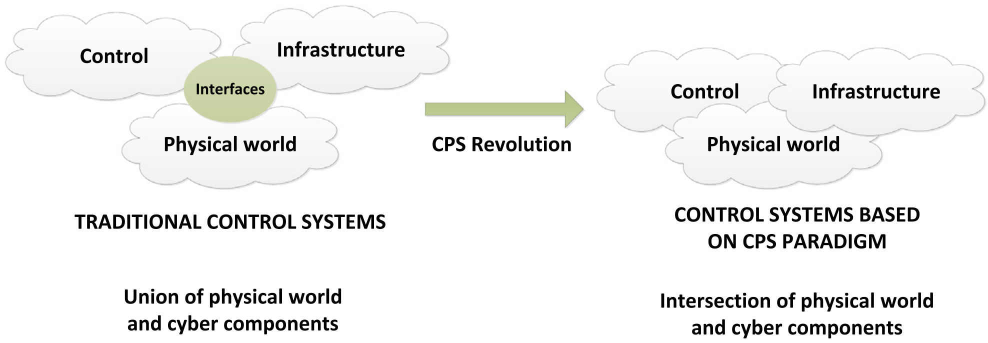

Fig. 5. Evolution from legacy control systems to CPS.

3.3. Research topics on CPS and control theory

Reviewing the works on CPS in control theory [93,95,96] two main research lines can be identified [18]. The first tries to obtain high-performance control system; the second tries to reach a deep penetration of sensing and actuation into the physical world. In the first line, the challenges which are usually addressed are: the obtaining of a much tighter integration among the different components (see Fig. 5) and the creation of robust systems being able to work under uncertainty and complexity. In the second line, the definition of new *miniaturizing techniques* and the *improvement in the processing capabilities* integrated in sensors and actuators are the most common topics.[1]

Some authors have proved that the Moore's law practically resolves the challenges related with the second research line [18,105]. Therefore, most works on CPS are focused on obtaining high-performance control system.

The *creation of high-performance systems* through the *increment of the integration level* among the different components in CPS is usually addressed by selecting only two components and trying to embed one of them in the other.

The most common topic is trying to integrate control policies in the pervasive sensing platform. Traditionally, control policies are completely independent from the infrastructure, and they are programmed after deploying the system [106]. This approach, however, is not valid to meet the characteristics expected from CPS, because of their intrinsic complexity and dynamical behavior. To meet those characteristics and being able of applying complex control policies, the control processes, the physical world and the pervasive sensing infrastructure must be modeled together In this context, the most challenging situation in CPS modeling is to select a set of consistent models for physical environment, software, hardware, etc. In this way, one very interesting topic on CPS research is model definition, creation and integration. In [107], for example, it is proposed a really successful new framework for *CPS modeling* called "CPS modeling integration hubs". The work describes a new methodology and modeling environment for CPS, including a core composed of architecture, verification, analysis, hardware and software models (together with a requirement repository) which may be complemented with new modules if required. The selected modeling language is based on ModelicaML [108]. It is a remarkable work, as authors have tested the proposal with good results by modeling power grids, microrobotics or vehicle management [109,110].

Other important topic is network integration in control systems. CPS propose a scheme where networks are part of the control components, and latency requirements and storage restrictions are not only addressed with network engineering, but also using knowledge about the physical processes [18]. However, compared with legacy control systems, CPS for control theory are still at an elementary stage [6]. Thus, related to the inclusion of networks in the control components, usually only one topic is addressed: the *sample scheme* [27]. The traditional approach consists of sampling the physical world periodically or at predetermined instants. However, CPS allow implementing "control-on-demand" policies [18] which enable an important saving of resources as energy. For example, in the called event-based control systems, sampling is only triggered when a certain event occurs (formally that is named as Riemann or Lebesgue sampling [111]) and the called self-triggered control systems can decide the intervals when the physical signals may be unsampled and the appropriate instant to sample it again [112–114].

The creation of *robust systems* being able to work under uncertainty and complexity is basically focused on the impact of networks uncertainties (noise, delays, packet losses, etc.) in the studies about *CPS stability* (extremely important in feedback systems). In order to include the network-induced delays in traditional stability models, several proposal have appeared: some of them based on lossless channels in which the packet priority is dynamically modified [115,116] or the maximum transmission interval is limited [117]. Others propose mathematical analysis such as Lyapunov exponents [118], hybrid systems [119] (see Section 4) or asynchronous dynamical systems (ADS) [120]. Finally, the most realistic proposals consider channels with losses, modeled as Markov chains [121] or channels with additive Gaussian noise [122–125]

Finally, apart from the main research lines, two additional groups of contributions may be found: on the one hand, contributions on the main CPS aspects and, on the other hand, miscellaneous topics of which we are reviewing the most usual ones: *decentralized systems* and control techniques for CPS.

[1] Boldface words are used to emphasize the main research topic in each technological domain.

With respect to the key aspects identified in Section 2.2, context-awareness is maybe the most studied topic in control theory. In general, works on this topic deal with the problem of making a control decision considering (at least) all the relevant information about the context [126]. In order to create a stable control loop, between the information acquisition and the actuation it must pass a limited time, so different proposals in order to reach these objectives may be found. Some works propose a predictive scheme [126], while others (focused on human environments) deal with fuzzy control techniques (the human activities are considered context information) [60]. Furthermore, proposals about human environments are also the basic scenario for machine learning works in control theory. In fact, one of the most challenging scenarios for control theory is human control, as human behavior is quite random and complex. Thus, in works about the human-in-the-loop problem, pattern recognition techniques for human activity inferring (a type of machine learning solutions) are usually included [127]. In general, it seems that Bayesian networks are the most adequate technique, so control application for humans tend to consider them [25,128]. Recent works about self-adaptation in relation to CPS in control theory are sparse. In this context, self-adaptation is usually named as "self-tuning", understood as the ability of control systems to modify its internal parameters in order to optimize an objective function [129]. Typical works on this topic are not specifically designed to CPS although they may be applied to this field. Mathematical analysis about the undelaying dynamical problems (stability, fixed points, etc.) are the main contribution in papers on self-tuning systems [130,131]. On the contrary, fault-tolerant control is a very popular topic, although most contributions are pretty similar. The basic idea is to construct a control parametric function, being able to recover the stability (partially or totally) if any malfunction event appears [132–134]. Finally, different proposals on control with CPS including mobile nodes have been reported. First works on the topic tried to control mobile robots by means of parametric functions [135] (recently similar papers have been also published [136]). Nowadays however, the interest is generally focused on Wireless Sensor Networks (WSN) with mobile nodes, and the fluctuations due to mobility [137,138]. In [71], for example, it is proposed a new control loop scheme for mobile nodes, where the WSN is connected to both, the input and the output of the controller (traditionally it is only connected to the input).

With respect to the miscellaneous topics, in fact, decentralized (distributed) control systems are also usually threated in works on CPS [139] Sometimes these works are specifically focused on large-scale systems [140], or on optimal control [141] or real-time applications [142]. On the other hand, specific *control techniques for CPS* have been also proposed: new design methodologies based on achieving the balances among robustness, schedulability and power consumption [143] have appeared; particular controllers involving resilient power junction have been designed [144] and specific problems and application have been investigated [145,146].

As CPS for control theory present the simplest architecture, and control systems are interesting for industrial companies, this technological domain is the one with the greatest real application for the CPS nowadays. One of the most promising fields is *Smart Manufacturing* [12]. CPS in the future industry (now being developed, for example, in Germany) will help to improve efficiency, productivity and safety and to create new forms of flexible work and collaboration [147].

4. Cyber–physical systems in computer sciences

The term "Cyber–Physical Systems" emerged around 2006, when it was coined by Helen Gill at the NSF [7]. Very soon, in the domain of computer sciences, E. Lee [34] was the first who wondered about the validity of traditional assumptions in computer sciences for the next technological revolution. As result, computer sciences are the domain where most contribution can be found to CPS (from theoretical results to industrial projects).

In this section we review the origin of CPS, the most remarkable theoretical results on CPS in this technological domain and the main research lines for CPS in computer sciences.

4.1. The origin of CPS

In the physical world, the time passes inexorably and it is intrinsically concurrent. However, nowadays, abstractions in computer sciences do not reflect these properties. Lee argued that technical progress is impossible while abstractions in computer sciences and properties of the physical world do not match [11]. CPS is the proposed solution to bridge that abstraction gap.

CPS are usually related to "cyberspace" (used by William Gibson in the novel Neuromancer), however, the roots of the term CPS are older and deeper [1]. CPS comes from the word "cybernetics", which was coined by Norbert Wiener [148]. Wiener derived the term from the Greek $\kappa\upsilon\beta\varepsilon\rho\nu\tau\eta\varsigma$ (kybernetes), meaning governor, pilot or rudder [1]. Although the mechanisms he used did not involve digital computers, some authors claim [1,7] that the basis of his work are similar to those used today in a huge variety of computer-based systems.

Unlike in control theory, where sensing technologies have been traditionally employed, in computer sciences pervasive sensing was introduced by CPS. Actually, the Wiener's notion of cybernetics was deeply rooted in closed-loop feedback, so CPS moved to computer sciences the traditional pervasive sensing and actuation technologies from feedback control.

Although all approaches for CPS show a technology that deeply connects the physical world with the cyber world [148], computer sciences experts claim their approach for CPS is more foundational and durable than the others, because it does not refer to either implementation approaches (as in communication engineering) nor particular applications (as in control theory).

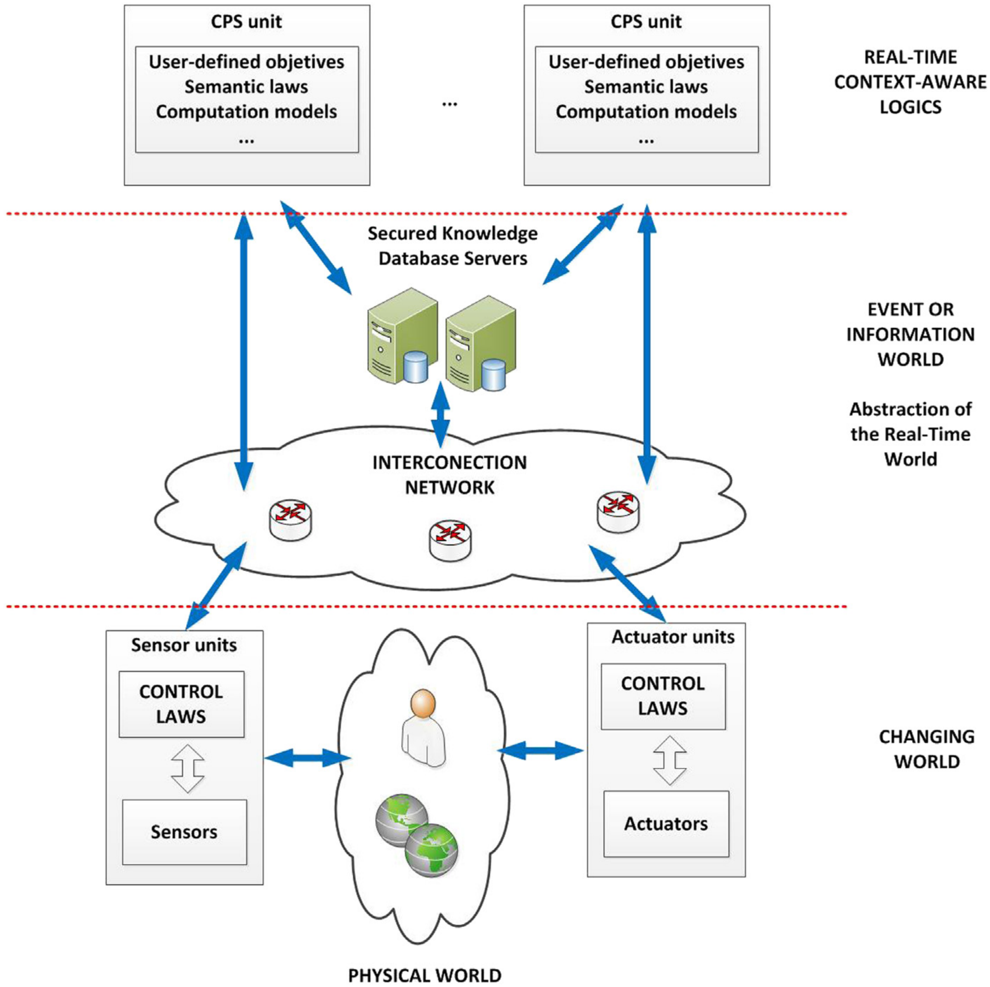

Fig. 6. Layers in CPS along [155].

Most experts on CPS in computer sciences agree with the original definition [149–152]. So, "a cyber–physical system is an integration of computation with physical processes. Embedded computers monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa". For these authors, CPS is about the intersection, not the union, of the physical world and the cyber components.

4.2. Theoretical results

As we said, most authors in computer sciences agree with the definition proposed by E. Lee for CPS. However, other interpretations, with much less impact, have been propounded. In [46], for example, "CPS are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing core". Despite these differences, the way in which authors view CPS in computer sciences is similar. Actually, integration of electronic components in physical objects is not new. Embedded devices [153] have been successfully employed in many sectors such as automotive, aircraft control, games or home appliances. Nevertheless, these devices used to be "closed boxes" that do not offer any service to the outside. The radical transformation authors on CPS from computer sciences envision comes from connecting several of these devices, over which complex software applications are deployed [154].

Architectures for CPS in the computer sciences domain are more complex than the ones presented in the control theory domain; mainly because they used to include computation elements such as semantic technologies or context-aware applications. Fig. 6 shows the prototype architecture for CPS described in [155], which is one of the most cited proposals [156–158]. In control theory architectures are usually designed following implementation criteria (external systems in one layer, hardware in other one and software in the third one). However, in computer sciences all layers include hardware and software elements, and architectures used to be designed depending on the abstraction level.

As it can be seen in Fig. 6, the proposed architecture consists of three different layers. The first layer (called "changing world") includes all elements with continuous dynamics and which behavior is controlled by physical laws, i.e. the physical world, transducers and control components (embedded in the sensing platform). The second layer (the information world)

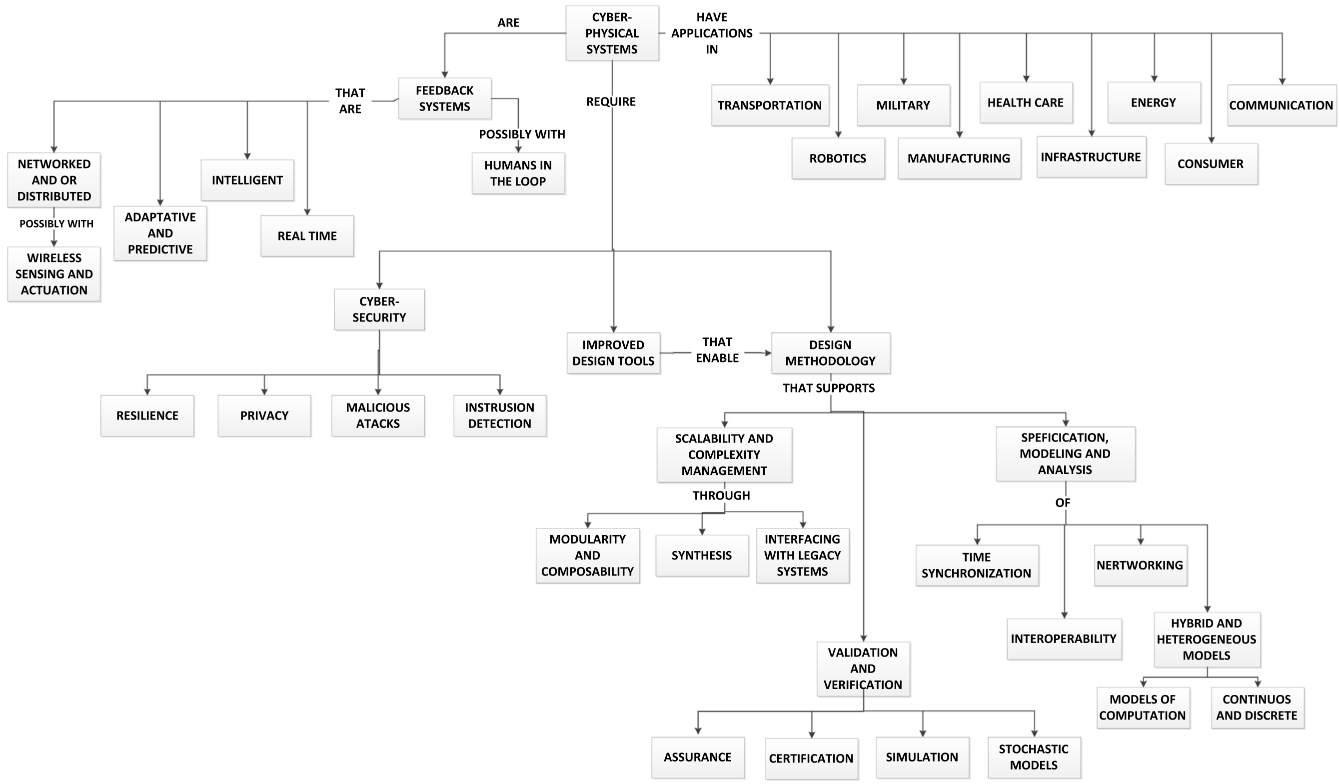

Fig. 7. CPS: the concept map. Source: Berkley University.

contains some simple data analytics elements which translate from "raw facts" (events) produced by sensors and actuator to abstract information used in computing elements. Finally the third layer (real-time context-aware logics) models at high-level the changing-world and determines at real-time the system's behavior. In the third layer computational algorithms would run in parallel with processes in the physical world, so CPS must coordinate two "types of time" [159] (contrary to what happens in control theory, where only the physical time is considered).

The characteristics that must show a system to truly be a CPS have been also deeply investigated. Although many proposals may be found, there exists a certain agreement about the necessity a system to show the following four characteristics to be a CPS [160]:

- Heterogeneity: CPS may include several types of devices. The underlying pervasive sensing platform must be able to incorporate and configure sensor nodes (with a certain amount of memory), mobile devices (such as smartphone) and networked servers.
- Unreliable networking: Devices in the pervasive sensing platform are usually connected through low-power wireless communication technologies such as 802.15.4 [161] and Nordic [162]. These technologies show a high rate of packet loss and CPS may be able to work under these circumstances.
- Mobility: In CPS mobility must be supported. In general devices in CPS interact opportunistically, as the movement may be determined by unpredictable factors such as the human behavior.
- Tight environmental coupling between the system and the external world. In CPS the system border tends to be unclear [18].

The creation of the "Cyber–Physical Systems Virtual Organization" (CPS-VO) in the U.S. [163] has allowed deepening in the conceptual issues on CPS following the computer sciences approach. In particular, we must remark the concept map proposed by the Berkley University which summarizes the characteristics, requirements an application of CPS [164]. In Fig. 7 we include a graphic presentation of that concept map.

Fig. 7 contains two important characteristics about CPS in computer sciences, not showed before, which must be remarked. First, nowadays, as we said in the introduction, CPS is a particular application of pervasive sensing. However, although all current works on CPS include a sensing platform [165,166], computer sciences experts also envision other types of interaction between the physical and the cyber world (unknown today), then CPS in Fig. 7 are "system possibly with wireless sensing and actuation". And, second, traditional feedback systems (including CPS for control theory) are reactive: the system receives a stimulus and it reacts [47]. However, CPS in computer sciences may be also predictive: the system reacts to a future stimulus in order to avoid, modify or cause it [167]. This new philosophy requires technologies to analyze all data available (from the past and present) and predict the future. In this point, CPS joins with Big Data and similar solutions [18].

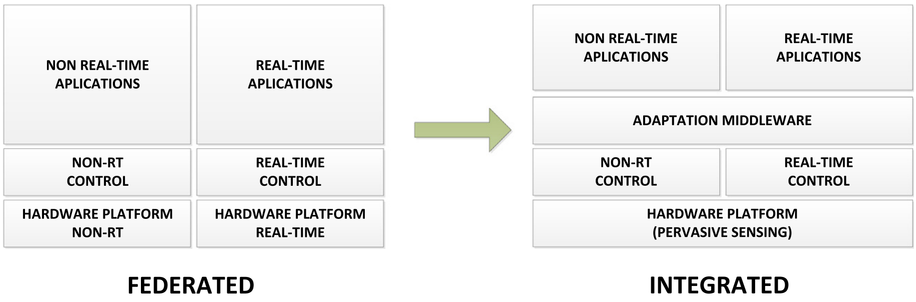

Fig. 8. Evolution from traditional federated systems to integrated CPS.

4.3. *Research topics on CPS and computer sciences*

Research lines on CPS in the computer sciences domain are much more numerous than in control theory. In general terms, each box in Fig. 7 represent a research topic which involves various specific technical challenges. For example, three issues arise with the pervasive sensing platform (named as "wireless sensing and actuation" in Fig. 7): *data models* for distributed sensor data [168], *location of sensors* and actuators, and *time synchronization* [164].

However, some works have identified the main research lines in CPS in the computer science domain. Namely [27]: hybrid systems, distributed systems, real-time applications and security. Other topics, such as certification, have been scarcely investigated, and only preliminary reports on the state of the art have appeared [154].

A hybrid system is one system which mixes continuous dynamics and discrete dynamics. As CPS in computer sciences include both the physical world (continuous dynamics) and computing elements (discrete dynamics), usually they are designed, analyzed and validated as *hybrid systems*. The most simple hybrid systems employed in the CPS sciences are switched system. These systems switch among various continuous operation modes, along a control signal [169]. Overall, with these systems the stability is studied [170]. A more general framework for CPS are hybrid automaton (HA) which allows designing complex dynamics. Several mathematical formalisms for HA and CPS have appeared: from works about general issues [171], to studies for CPS specification [172] and validation [173]. Particularly important are frameworks for algorithm verification, which allows validating the behavior of software to CPS "in theory" [174]. Furthermore, well-known results bout HA complexity, such as the concepts of simulation and bisimulation [175,176], are being used in order to reduce the intrinsic complexity to CPS when analyzing them. Finally, HA also allow automatic synthesizing of CPS given a specification and using supervisory control [177], game theory [178], piecewise-affine hybrid systems [179] or discrete-time linear systems [180]. Based on hybrid systems and HA have appeared for algorithm validation [181] and system synthesis [182].

CPS are intrinsically distributed (see Fig. 7). Therefore, one of the most important issues on CPS is verifying the behavior in the global system. However, due to the complexity of the problem, no general solution has been proposed. In particular studies about the correctness in distributed CPS are mainly focused in automobile traffic control systems [183,184]. Besides, works about the design of *distributed CPS* have appeared, for example for automated traffic intersection [185]. All these works, however, use pencil–paper techniques [186,187], and automated methods would be valuable.

CPS executes *real time applications*. In order to enable real-time working, CPS must include three technologies [27]: real-time scheduling, real-time systems and real-time networking. In all these areas there exist classical results which are applicable to CPS, and new results specific of CPS.

In real-time scheduling many results are classical proposal, now applied to CPS [188–190]. However, with the objective of supporting temporally predictable execution of the computing tasks in CPS, some authors have proposed intelligent algorithms. These algorithms must order adequately all the computing tasks in a CPS, so that all temporal constraints of the task are fulfilled. Among other proposals, it may be found real-time queuing techniques [191], real-time scheduling for distributed systems [192,193], techniques of resource reservation for real-time applications [194] and real-time scheduling algorithms for embedded systems [195].

In respect of real-time systems, CPS face integrating different types of applications (real-time and not real-time) over the same pervasive sensing platform [18], moving from a federate approach to an integrated approach (see Fig. 8). To overcome such issue, middleware based on the proper abstractions from the system complexities are used [27,184].

One of the best known examples of these adaptation middleware is the Common Object Request Broker Architecture (CORBA) [196]. It allows the interoperability among software objects running in different machines in a heterogeneous distributed environment. There exist other proposal, such as real-time CORBA [197], which includes real-time scheduling. Etherware [183] is a middleware to be deployed in large-scale networked feedback systems. OSA+ [198] is another middleware for distributed real-time embedded systems. Finally, some authors have proposed programming languages for real-time systems such as the successful Signal [199] and Esterel [200].

The last element related to real-time application in CPS is real-time networking. This issue has been widely studied, and most results employed in CPS are solutions of the state-of-the-art [201,202]. However, some specific proposals such as routing protocols for real-time pervasive sensing platforms [203,204] are sometimes investigated.

Security is basic for systems which pretend to control critical infrastructures such as transport, health care or military equipment [205,206]. Thus, many works on particularities [9,207] of security in CPS and its vulnerabilities have appeared [208,209]. Mainly, CPS tend to be distributed and involve thousands of embedded system which, moreover, may operate at real-time, so intelligent analysis cannot be easily made. Some generic proposals are about including security in the physical world [210], and other maintain the traditional scheme of detecting attacks [211,212]. However, most works on safe CPS are focused on specific implementation for Electric Power Grid [213–215].

A special case of security solutions for CPS are which are specifically designed to CPS including mobile nodes. At this point, one of the most important identified aspects of CPS is addressed. In general, in computer sciences works, mobility is considered as any other characteristic to be included in the models [216]. However, in the case of security, mobility has a special recognition. In particular different soft signature technologies (typically certificateless techniques) have been defined [72,217,218]. Following this line, we are reviewing the state-of-the-art in the other key aspects of CPS in relation to computer sciences. Context-awareness is not the most common topic in works about CPS in computer sciences. However, some contributions have been reported. In particular ontologies describing the different information fields that describe a context have been proposed [219,220]. Additionally, logical rules, (semantic) algorithms and procedures in order to process the context information (adding variables, comparing contexts, etc.) have been described [221]. Machine learning, on the contrary, is a very popular issue. Three main types of contributions may be found. First (and probably the most common approach) different machine learning techniques are proposed with the objective of detecting cyber-attacks and intruders in CPS. Pattern recognition technologies based on Markov's chains [222] or Bayesian inference [223] are common, but other proposals such as neural networks may be also found [224]. The second topic related to machine learning is physical model creation [6]. As describing systems as complicated as CPS may be a difficult task, different instruments to assist CPS designers to perform this activity have been proposed, several of them based on machine learning techniques [225]. The third and last topic is research on hybrid automatons. Hybrid automatons combine traditional finite state machines with logical rules and machine learning techniques in order to reason about the state of the physical world [62]. It is a common approach for CPS applied to natural and social sciences (biology, education, etc.). With respect to fault-tolerant systems, the most interesting works about cyber–physical applications belong to the computer sciences domain. In particular, advanced solutions (usually mathematical models) to keep CPS operating under the planned constraints by means of an external control (even in case of a failure event) have been reported [69]. As closure, self-configuration and self-adaptation policies are not usually addressed in a separated way as, in computer sciences, CPS are adaptive by default. However, in 2016 a team of Swedish computer science researchers proposed a systematic methodology and algorithm to study the state-of-the-art on the self-adaptation technologies for CPS [8]. Only a small number of the reviewed references are provided, but conclusions are remarkable. For example, they found that self-adaptation is understood in very different ways (as reconfigurability, reliability or interoperability among other possibilities); and that most self-adaptation technologies for CPS are integrated into high-level applications and are based on mapping functions.

Finally, other interesting topics addressed in the research literature are CPS simulation [226], where even a simulator called CyPhySim [227,228] has been developed, and modeling [7,229].

5. Cyber–physical systems in communication engineering

The use of the term CPS in communications engineering is very recent and low. Experts on communication engineering use to employ older terms such as smart environments, Internet-of-Things (IoT) or Sensor Networks which may all fall under the CPS design umbrella [230]. However nowadays it is not clear the relation between these terms and CPS (see Section 2.3). In general, communication engineering experts understand CPS as a particular scenario of IoT where the underlying hardware is a pervasive sensing platform and where Internet services allow creating feedback control loops [13].

In this section we briefly review the characteristics of CPS in communication engineering, as well as the main research topics.

5.1. Characteristics of CPS in communication engineering

Definitions of CPS in communication engineering are not very common. In general, however, they are focused on the Internet Services and the underlying devices (the traditional embedded devices). One example of these definition is proposed by Kim [27] which says "CPS are the next generation of engineered systems in which computing, communication and control technologies are tightly integrated".

Works about the characteristics of CPS are works much more exhaustive. In [14], for example, they are identified sixteen basic characteristics a system much show to be considered as CPS. Some of these characteristics are common to other approaches, but others are particular of the communication engineering domain (although they optionally could be also present in other domains). Table 2 classifies the cited characteristics as they appear or not in other domains. Similar characteristics have been proposed in other works such as [231].

Architectures for CPS in communication engineering may be presented following a network-like scheme or a logical stack. In Fig. 9 it is presented a network-like architecture described originally in [232].

Table 2
Characteristics of CPS in communication engineering.

Non-particular characteristics	Specific characteristics
Components in CPS include various encapsulations, materials, software types, dynamics, etc.	Components in CPS may present both pre-defined and ad-hoc connections.
CPS must join the digital part and an analog part.	CPS should implement various problem-solving strategies.
CPS are heterogeneous systems.	CPS must build knowledge from both built-in formal knowledge (obtained from the pervasive sensing platform) and knowledge generated by artificial intelligence.
CPS should present some level of intelligence.	CPS include distributed decision-making.
CPS may change their behavior dynamically.	CPS should support distributed problem solving.
Components in CPS are open systems.	CPS should be context-depending.
Components in CPS have to reorganize themselves depending on the circumstances.	CPS present different spatial scales and temporal ranges.
CPS must be able to learn from history and be unsupervised.	
Different strategies to maintain the integrity, security and reliability of CPS should be implemented.	

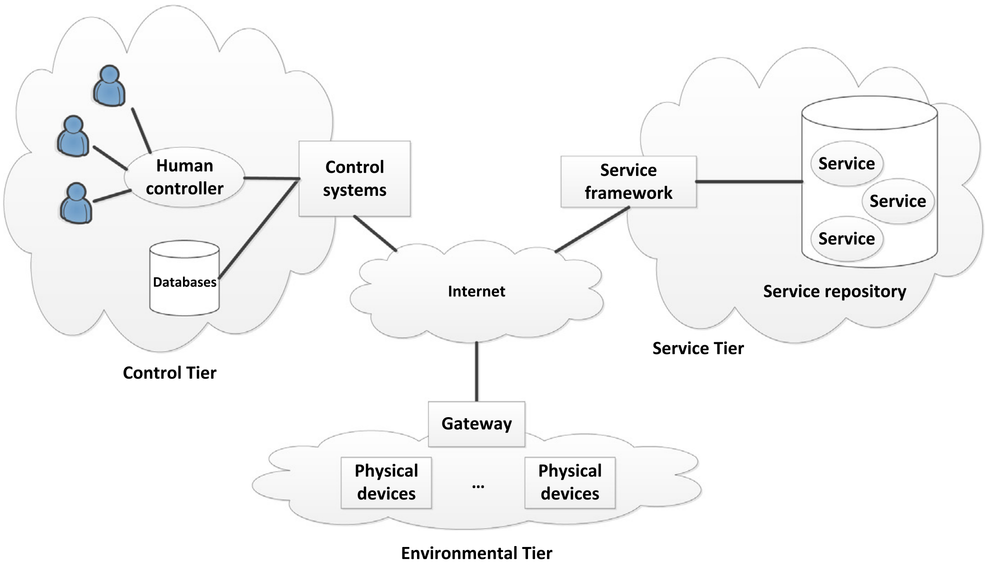

Fig. 9. Architectures for CPS in a network-like scheme [232].

As can be seen, the architecture is similar to other proposals for generic Internet services [233], including three entities (hardware platform, control and end-user services) connected through the Internet. In some cases, each entity is, at same the time, described as a collection of sub-nets or networked servers, creating a hierarchic architecture [210].

On the other hand, Fig. 10 shows a proposed architecture for CPS [234] with a great impact (described as a logical stack including very common and famous technological such as OSGi [235] and JNI [236]). In this case, the architecture also presents three layers: the physical layer includes the hardware devices, the second provides control and the third is dedicated to service provision. All layers (as well as the humans or machine which uses the services) are communicated through the Internet (or local-area network, depending on the case). In this approach the physical world are not considered part of the system.

Other architectures for CPS in communication engineering, similar to which showed in Figs. 9 and 10, may be found in [231] and [13].

5.2. Research topics on CPS and communication engineering

Research topics on CPS in communication engineering include all the issues traditionally related to IoT, (Mobile) Wireless Sensor Networks (WSN) or Machine-to-Machine Communications. Nevertheless, as the relation among these concepts and CPS is not clear, usually they are treated independently [237]. Any case, many works have tried to compile the state-of-the-art in these topics [238–242].

CPS and IoT share many research topics and usually almost any solution produced for one scenario is directly applicable to the other. In this field, most complicated issues, such as the self-configuration of heterogeneous hardware platforms are not usually addressed (in this case a possible solution might be found in [87], where network configuration is based on the concept of "reputation" of a node). The most common topics, then, are related to data services. Particularly important

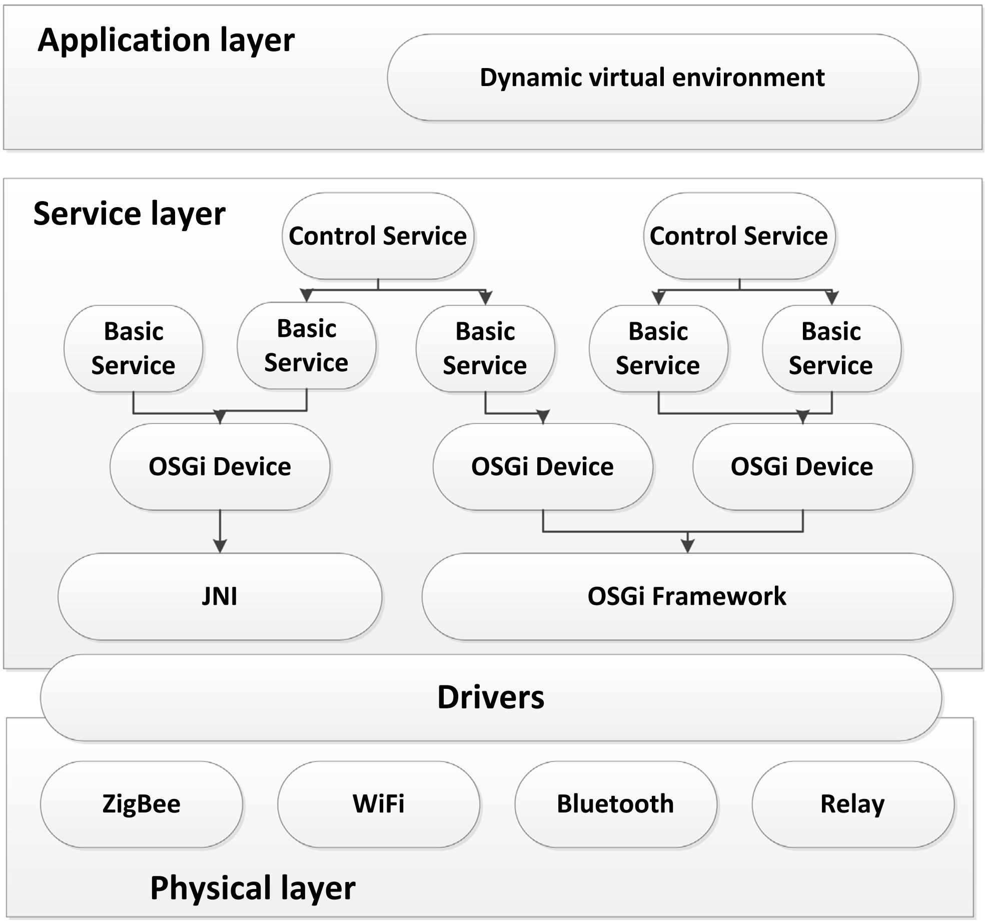

Fig. 10. Architectures for CPS in a logical stack [234].

are the topics of service composition, service management and service access [85]. In CPS, the most investigated solution for *composed services* is expressing them as Business Process Execution Language (BPEL) executable files, where each task calls a service (composed – as workflows could be nested – or simple) [243]. *Service management* in CPS is usually based on semantic technologies and the definition of different concepts of Quality-of-Service [244,245]. *Service access* in CPS is especially challenging due to the different interfaces offered by end-devices. Two basic solutions are usually proposed: embedded TCP/IP stacks in all devices [246] and translation layers which adapt a generic web services language (offered to the applications) to the specific interfaces of the different devices [247].

Related to (Mobile) Wireless Sensor Networks, the most popular topic is the definition of *energy-efficient routing protocols* [248]. Some proposals are based on specifically adapted traditional unicast protocols [249]. Others propose new approaches, being especially important GPS-based approaches [250]. Another important problem in WSN is *modeling the coverage area* of sensors. In order to completely cover a certain extension, sensors must be properly placed. The problems associated with this issue have been deeply investigated [251], and some mathematical approaches proposed [252]. The problem of *replacing batteries* [253], techniques to *sleep sensors* [254] and technologies to *filter automatically the relevant information* while routing packets are also usual topics [255].

Research on *device-to-device communications (D2D)* is also a very important topic, as it is one of the most promising fields on communications engineering (it is applied to CPS, IoT and mobile networks, among other areas). Based on this technology, mobile nodes in a CPS may be networked and coordinate to better understand the environment and relate to the physical world in a more efficient way. Historically, D2D communications were defined to enable multi-hop relays in cellular networks [256]. However, nowadays, several different proposals may be found. In relation to CPS, enhanced studies about peer-to-peer communications based either on mobile communications (typically LTE) [257] or on wide-area radio access technologies [258,259] are the most interesting works. Usually, power consumption [260], traffic offload [261], or the number of concurrent D2D links [262] are the most interesting variables to enhance. Nevertheless, other topics are also relevant. For example, the inclusion of QoS or power constraints in session negotiation [263], as well as the use of new generation multicast technologies [264,265], are promising proposals.

Finally, in M2M communications most popular research topics are the analysis of *new radio-access technologies* (RAT) for low-power, low-rate communications and/or massive access communications. Some proposals are based on mobile communications [266], but most of them are based on Home-area networks (HAN) such as Bluetooth [267] and, mainly, ZigBee or IEEE 802.15.4 [268,269].

Although, as we said above, self-configuration of heterogeneous hardware platforms is not usually addressed, other types of self-configuration and self-adaption are successfully investigated. In particular, different works about how to address self-* properties in CPS for industrial applications may be found [66,270,271]. Typically, these proposals obtain a pyramid-like architecture where self-adaptation is placed in the top level. Works about self-adaptable (sometimes understood as self-aware) hardware architecture for cyber–physical devices have been also reported [271,272]. The last common topic about CPS self-adaption in communication engineering is the creation of middleware layers to support the self-* properties [273]. In order to finish this section we are reviewing the existing literature on the other key aspects of CPS. The definition of architectures and functional implementations of CPS is also common in relation to context-awareness. Architectures being able to store and manage context information [39] and/or provide context-dependent services (in medical environments, for example) [274,275] are common. Moreover, very recently (2017), context-aware sensing and actuation based on CPS (a technology which allows systems to require, obtain and use in an intelligent way context information) has also received attention [276] (applied, for example, to vehicular systems [277]). Fault-tolerance is rarely required to CPS, but it has been exhaustively investigated in WSN. About this topic, most works propose different fault-tolerant routing or topology-management protocols [278–280], but fault-tolerant WSN applications (specially for critical scenarios such as medical environments) may be also found [281]. With respect to mobility, communication engineers defined in 2013 the concept of "mobile CPS" [73]. In the same paper, the authors propose different protocols to support the mobility of cyber–physical nodes. Originally identified with crowdsensing systems, mobile CPS are now a well-known term, and many applications and works about "CPS and mobile computing" have appeared [282–284] (most of them focused on protocols and solutions to integrate both functions). Finally, machine learning and CPS is not a primary research topic for communication engineers. In general, works including learning techniques use them as instruments to build a bigger system (which is the research target). In fact, learning techniques are commonly employed in smart (or cyber) manufacturing systems [285] or in the called Cyber–Physical Production Systems (CPPS) [286].

6. Standardizing cyber–physical systems

CPS paradigm has received a great support from academia, institutions, governments and industries since the beginning. In Section 4 we cited some organizations such as the NSF or the CPS-VO (both from the U.S.), although the European Union through the Advanced Research and Technology for Embedded Intelligence Systems (ARTEMIS) project [287] and the European Commission through the Horizon2020 program [288] have also greatly supported the CPS revolution. As a result of this governmental support, the main standards organizations have included the CPS (one way or another) in their agendas. In this section we are reviewing the different attempts to standardize CPS and we compare all approaches reviewed in this work.

6.1. Overview of CPS and standards organizations

Basically, three standards organizations have addressed the challenge to normalize the CPS: the International Organization for Standardization (ISO), the European Telecommunications Standards Institute (ETSI) and the National Institute of Standards and Technology (NIST). Other important institutions such as the German Academy of Science and Engineering are also working on CPS [289], but its results do not have the consideration of standards.

The ISO, in collaboration with the International Electrotechnical Commission (IEC), created in 2012 a standardization special working group (SWG) [290] to develop a standard on the Internet-of-Things (IoT). Strictly, the ISO is not working on CPS, however, as we saw in Section 2.3, more and more authors show that IoT and CPS are different perspectives of the same concept. One of the purposes of the ISO is, precisely, to determine how much similar IoT and CPS are.

The SWG for IoT, named first as ISO/IEC JTC 1/SWG 5 and later as ISO/IEC JTC 1/SWG 10, was established in 2012 at the 27th plenary meeting of ISO/IEC JTC 1 [291] in China. ISO's vision of CPS is similar to the approach of communication engineering, so the collaboration between the SW10 and the SW7 (dedicated to Sensor Networks) is official [292]. Nowadays, two important documents have been publicly distributed: an IoT mind map [293] and a report about differences of IoT, M2M, and CPS [294] (both published in the final months of 2014). However, no result about architectures, applications, etc. is public yet.

The ETSI is totally focused on communications and networking in the context of IoT and CPS. In particular, this organization is responsible of the standards about Machine-to-Machine (M2M) communications [295]. This technology (among others) is widely employed in CPS, however, the ETSI, nowadays, is not working in standardizing CPS as a whole.

Finally, the NIST, is totally focused on standardizing CPS as a particular technology, different from any other proposal [2]. Its vision of CPS is different from all the previous, and includes all the components cited in Section 2, so all the different approaches for CPS are included in the NIST's proposals. The CPS Public Working Group was established in 2014 and in September 2015 it generated its first public results. The NIST has proposed a notational architecture for CPS, has tried to fix the vocabulary and is trying to develop the key problems of CPS.

Table 3 compares the action of the different standards organizations.

Table 3
Comparison among the action for standardizing CPS in different organizations.

Topic	ISO/IET	ETSI	NIST
Element standardized	Internet-of-Things	Machine-to-Machine communications	Cyber–Physical Systems
Start date	2012	2009	2014
Objective(s)	Developing definitions for IoT and vocabulary. Developing a reference architecture for IoT. Developing other IoT relevant standards such as IoT use-cases, network level technologies, or interoperability.	Developing and maintaining standards about: Requirements (ETSI TS 102 689). Functional architecture (ETSI TS 102 690). Interface descriptions (ETSI TS 102 921).	Developing a consensus definition, reference architecture, and a common lexicon and taxonomy. Ensuring that timing, dependability, and security are considered as first order design principles.
Current state	Active, last publication on January 2015. Next standards announced: IoT — Definition and Vocabulary ISO/IEC (ISO/IEC NP 20924). IoT — Reference Architecture (AWI 30141).	Active, last publication on March 2016.	Active, last publication on September 2015.
Published documents	Preliminary report [294].	Technical Specification (TS) and Technical Report (TR) published for all topics (not European standard) [295].	Draft for the CPS framework [296].

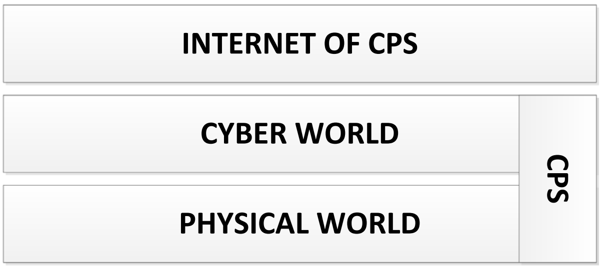

Fig. 11. "Internet of CPS" NIST vision.

6.2. *The case of the NIST*

The NIST define "Cyber–Physical Systems or "smart" systems as co-engineered interacting networks of physical and computational components" [297]. In that way, the NIST sees CPS as a vertical system which may include, eventually, any other implementation belonging to any other technological domain. Moreover, the NIST is leading a wide program to advance on CPS, including the Cyber–Physical Systems Public Working Group (CPS PWG), formed by NIST in 2014. This group has identified five key areas in CPS [2]:

- Vocabulary and Reference Architecture
- Use Cases
- Timing
- Cybersecurity and Privacy
- Data Interoperability

Only contributions in two areas have been published. First it has been published a report about timing [298] where different technologies such as IEEE 1588 Precision-Time Protocol (PTP), general concepts such as the phase delay and standard as the ITU T Recommendation G.8264 are reviewed. Second a report about a general framework for CPS has been distributed [210]. In this report, the NIST shows the idea of an "Internet of CPS" where systems deployed in different part of the world may interact, offer services to the others, etc. (see Fig. 11). Besides, a functional decomposition of these systems is also proposed [296], and a template to describe CPS is also included.

Moreover, the NIST has proposed a notational architecture for CPS (see Fig. 12) and now is investigating the different characteristics which present CPS. The proposed architecture consists of six layers and six transversals capabilities which must be included in each layer. The first four layers in the stack match with four of the explained components in Section 2.

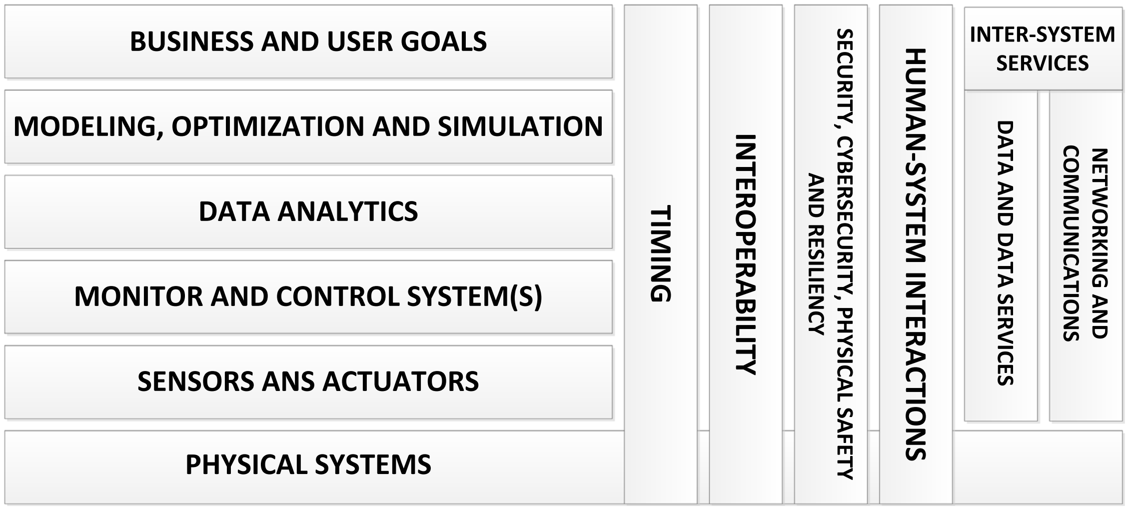

Fig. 12. NIST's notational architecture for CPS.

The fifth layer (Modeling, optimization and simulation) develops and maintain the dynamical computational models. The sixth layer (Business and user goals) refers to the measurable goals defined by users which must be reached. With respect to the transversals capabilities, all of them are well known, except the "Internet-system services", with this name, the NIST refers the connection between the local CPS and the Internet of CPS it envisions.

The proposals and documents of the NIST are extremely new, so few works considering those results have been published [48].

6.3. Comparative study

Once reviewed the main four approaches for CPS, in Table 4 we compare the principal characteristics of CPS in each one.

Besides, once reviewed the most relevant works on the different key aspects of CPS identified in Section 2.2 for each one of the technological domain, Table 5 presents a comparative study as a summary.

7. Future research challenges

Although architectures, applications and research lines for CPS depend on the considered technological domain, most challenges in CPS sciences are common for all approaches. As Internet has changed the way in which we communicate with others, CPS will change the way in which we deal with the physical world [27]. The challenges which must be addressed to support that revolution range from fundamental scientific and engineering issues to institutional and societal topics [299].

Many reports have identified research opportunities [299], scientific challenges [299,300], technological barriers [300] and business opportunities [301] for CPS. In this Section we compile and describe some of the most remarkable challenges identified, and propose new promising areas for research.

7.1. Scientific and engineering challenges

The creation of CPS as a new type of engineered systems needs to address various scientific and technical challenges:

- Technical solutions for obtaining integrated heterogeneous systems are needed [299]. CPS contains many heterogeneous components, some of them distributed, which have to work together to create the expected performance. Mainly, modeling languages and a rigorous semantics are needed for describing the interactions (physical, computational and communications) among heterogeneous devices. Another approach consists of constructing systems with components designed in different domains and sectors without the advantage of any common standard. This second vision, however, is much more challenging and nowadays is far beyond the state-of-the-art [96].
- New pervasive sensing architectures being able of providing services (for top-down applications) and data (for traditional bottom-up applications) are required, in order to support the enormous variety of application in CPS.
- Methodologies to address the complexity intrinsic to CPS have to be developed [27]. Languages for modeling the system characteristics and behavior at different abstraction levels and independently of the application domain are needed. Besides automatic tools to transform models, compose application, build and deploy the components and incorporate verification and validation capabilities are required [302,303].

Table 4
Comparison among the different approaches for CPS.

Element	Control theory	Computer sciences	Communication engineering	NIST
Type of the dynamics	Continuous	Hybrid	Discrete	Hybrid
CPS are understood as...	Improved networked control systems	Integration of computational and physical process	Framework for advanced Internet-services	Networked smart systems
Number of layers in reference architectures	3	3	3	6
Layers in reference architectures	Physical world Hardware Software	(Different abstraction levels) Physical world Information Logics	Physical platform Network and control Services	(Different capabilities) Physical world Sensors Control Data analytics Models User goals
Research topics	Incrementing the integration level (new models, and new sample schemes) Building robust systems New control techniques Data services (service access, composition and management)	Hybrid systems Distributed CPS Timing Security Simulation Modeling Improvements in the pervasive sensing platform (models for distributed data, time synchronization and sensors location)	Wireless Sensor Networks (energy-efficient protocols, coverage models, batteries replacement, etc.) M2M and D2D communications (new RAT) Real-time applications (RT scheduling, RT systems and RT networking)	CPS Framework Reference architecture for CPS Cybersecurity Data interoperability Use cases

- Deep and extensive theoretical works addressing the dynamics of CPS are required [27]. The complex dynamics generated by the tight relation among cyber and physical worlds are unexplored. Significant theoretical results are necessary to allow understanding the behavior of communications, computation, control and applications when working unified [304].
- Models representing the different types of devices are also needed (remarking, overall, the interfaces and the interaction capabilities).
- Advance towards human-focused applications over CPS, facing three main challenges [22]. First a comprehensive understanding of the complete list of human-in-the-loop applications is needed. As we said in Section 2.1 all human-in-the-loop application can be classified in three types, however, due to the complicated human behavior and its great dependency of the external conditions a richer taxonomy [305,306] is needed. Second, automatic tools to create models of human behaviors are also necessary. Applying existing toolboxes for computer networks to systems involving humans is essential to deploy CPS in the real world [307,308]. Finally, the traditional feedback control scheme has to be modified properly to incorporate humans. The human models could be placed in several locations (outside the loop, inside the controller, inside the transducers, in various locations, etc.), and theoretical and practical results about the different options must be generated [309].
- New scheduling politics for pervasive sensing platforms are necessary, allowing devices to discover their capabilities and self-manage their resources [310].
- Appropriate software platforms, APIs and Integrated Development Environments (IDEs) are required. The development of reliable, scalable and evolvable CPS needs tools at various levels of abstraction in order to hide the underlying complexity (distributed components, reconfigurations, etc.) to high-level developers [311].
- Methodologies for measuring the system performance have to be developed [299]. Verifying the performance, security and other requirements block the development of CPS. Nowadays, validating CPS capabilities is extremely costing, so new approaches and tools are necessary [53].
- A new generation of pervasive sensing technologies has to be developed [230]. Integrating pervasive sensing platforms in CPS involves two main challenges. First a specific model for the sensors and actuators life-cycle has to be

Table 5
Comparison among the typical works on the key aspect for the technological domains.

Topic	Control theory	Computer sciences	Communication engineering
Context-awareness	Stable control algorithms (or functions) considering context information (using predictive techniques or fuzzy control)	Ontologies for context information and algorithms to process and compare that information.	Context-aware sensing Architecture for context-ware CPS Context-aware service provision
Machine learning	Pattern recognition for human activity detection	Cyber-attacks detection by means of pattern recognition Instruments based on learning for physical model creation Hybrid automatons	Smart manufacturing Cyber–Physical Production Systems (employed as technology belonging to large systems)
Self-adaptation and self-configuration	Mathematical analysis of dynamics describing "self-tuning" systems	Adaptive models to support self-* properties Systematic methodology and algorithm to study the state-of-the-art	Middleware creation supporting self-* properties Self-adaptable architecture definition Self-adaptable hardware platforms
Fault-tolerance	Description of parametric control functions being able to correct the effect of failures	Mathematical analysis of solutions to keep CPS under the regular operation constraints	Fault-tolerant routing protocols for WSN Fault-tolerant WSN for critical applications
Mobility	Control systems for mobile robots Enhanced feedback control loops for mobile WSN	Regular models for CPS including mobility considerations Special security solutions for mobile nodes in CPS	Definition of "mobile CPS" Crowdsensing Integration of CPS and mobile computing

Table 6
CPS challenges along the application.

Application	Challenges
Aviation and defense	Mainly, new security protocols have to be designed. Extremely precise control components are also necessary. Developing a technology for high power technology will be important.
Healthcare	A new generation of analysis, synthesis and integration technologies are required. Interoperability algorithms will be also basic in the future.
Critical infrastructure	Mainly, extremely precise control components are necessary. New developing methodologies in order to guarantee the quality of the software will be also desirable.
Environment monitoring	Obtaining improved pervasive sensing technologies is the main challenge: reaching low-power consumption, the creation of disregarded systems and very precise in time platforms are the most important issues.
Automotive	Developing a technology for high power technology will be, in practice, the only challenge for future.

defined [312,313], specially indicating the consequences in higher layers of the variations at low-level. And, second timing in CPS is one of the most important topics, synchronizing the pervasive sensing infrastructure, and the other components in CPS, is a challenging situation [314].

Finally, in Table 6 we describe some additional challenges which depend on the particular application of CPS considered: aviation, defense, healthcare, critical infrastructure, environment monitoring and automotive [160].

7.2. Institutional and societal challenges

The revolution of CPS is not only technological, but also social and economic, as they will change the way in which people relate with the environment. Thus, the public institutions and the general society must address various challenges [299]:

- The trust of society on CPS performance, opportunities and value must be strengthened. Actions to assure that CPS are trustworthy and secure, as well as properly information campaigns to integrate the general society in the CPS revolution are pending.
- An effective model of governance must be agreed. CPS may be large-scale systems, including international applications controlling critical infrastructures such as transport, energy, health, etc. Organizations to provide both local and global regulations are necessary. These institutions will publish standards, will manage future issues on interest-conflicts and will enhance the development of CPS from the public sector with the appropriate economic incentives.
- New business models have to be investigated. The Internet revolution has changed, in many ways, the economy. CPS will transform the economy deeper than any previous technology. Those new business models, however, are not well-defined yet. This lack of proved business model seems to be blocking investments in new deployments and CPS research.
- Professionals on CPS are necessary. CPS have a cross-disciplinary nature. Then, professional knowing about mathematics, statics, engineering, computer sciences, sociology, etc. are essential to start the CPS revolution. Nowadays, there is a lack of concentrated and multi-disciplinary educational programs oriented to develop CPS. In the past, the academic world has faced similar challenges, as with the integration of Internet sciences or, more recently with bio-engineering.

8. Conclusions

Cyber–Physical Systems are a particular application of pervasive sensing technologies, where feedback control loops are deployed as end-user application. However, as a popular word, CPS are understood in different ways in different technological domains. Thus, understanding the characteristics and impact of CPS is a very complicated task.

In this work we have reviewed the elements which may be part of CPS, and, after describing the origin of CPS and its relation with Internet-of-Things, we have introduced the four main approaches for CPS existing today: control theory, computer sciences, communication engineering and vertical systems. For each domain we have explained the reference architectures with more impact, described the characteristics of CPS and review the state-of-the-art in the main research lines. Besides, we have reviewed the recent attempts to standardize the CPS. Finally, we also have discussed the main future unsolved challenges.

Originally defined in the computer sciences domain, the term CPS rapidly evolved towards other areas, increasing the dispersion in the architectures, characteristics, use-cases and, even, future challenges described for CPS. This phenomenon has been enhanced by the appearance of other terms (such as Industry 4.0, Internet-of-Things or Wireless Sensor Networks) not clearly separated from CPS, and used sometimes as synonyms. The interest of the standards organizations in normalizing the CPS will help in the future to reduce the ambiguity which surrounds that term. In particular, the efforts of the NIST in fixing a common architecture, vocabulary and reference architecture are helping companies and researchers to clearly shaping CPS technologies.

In conclusion, nowadays many equally important proposals for CPS are found. However, in the next future, the use of CPS paradigm in practical technologies and the creation of new standards related to CPS will help to narrow the scope and boundaries of these systems.

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Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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