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What is a Cyber-Physical System: Definitions and Models Spectrum

Each time a relevant proposal occurs, existing perspectives, concepts or fundamentals are confronted by emergent ones. The Industry 4.0 and its promoted production control systems based on Cyber-Physical Systems (CPS), made splash new potentials for the binomial human and technology (equipments and its settings).

Several authors explore the envisaged required more physical and digital connection to announce interesting transformative changes, where self-configure and adaptive machines sustain the application of corrective decisions.

This paper exposes a spectrum of existing CPS definitions and models and contributes with the fundamentals for an effective intelligent CPS (I-CPS), where a double loop learning process, allows its supporting software algorithms to be changed or reprogrammed. Instead, not only self-configure machines but its configuring software, too.

Keywords: *Industry 4.0; Cyber-Physical System; Double-loop learning; CPS Definitions; CPS Models; CPS Spectrum*

1. INTRODUCTION

The development of cyber-physical systems (CPS), more concretely cyber-physical production systems (CPPS) (CPPS will be the subject in this paper under the common designation CPS), is a critical issue for Industry 4.0.

The CPS concept is conceived as a new generation, or a paradigm, for future control systems. Not only resilient control systems with auto-generated interfaces [1], but rich full context-aware control systems that offer innovative settings for timely corrective changes .

A future CPS scenario will not face only more sensors and actuators and their connectedness, but a set of much more autonomous units (generalized as 'things') that, being not necessarily integrated, cooperate, are composable and, essentially, allow in-state dynamic reconfiguration or programming, towards a resilient and adaptable IT ecosystem, "(...) *a special type of system of systems in which multiple systems with various degrees of autonomy achieve common goals while adapting to the given environment…*(…)" [2]. Seen as a new perspective for existing technology-based solutions, but now with effective refactoring patterns, applicable to much more than software components. For instance, both, full physical processes and computations must be reconfigurable or redesigned too.

In essence, CPS started being computation and physical processes integration, where (…) Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa (…) [3].

There are some concerns related with the "(…) *nondeterministic behaviour of humans in human-in-the-loop control systems* (…)" [1] or resilient control systems and self-adaptive machines [4], however, no evidences were found (in the literature review) for the awareness about computational components reprogramming or realigning, that we believe is essential to get autonomous learning CPS, or intelligent CPS.

Due to: i) the many perspectives and definitions for CPS and their potentials in manufacturing and many other domains; ii) the lack of common understanding of CPS in those domains; and iii) the belief that the emergent context of global digitalization reached from Industry 4.0 and Internet of Things, requires a more intelligent CPS, made this research, and the consequent proposal of an original CPS logical architecture model, pertinent challenge.

In this paper there are presented 1) a CPS logical architecture, and 2) the CPS definitions "spectrum", as the main and original contributions.

At the end of the paper, a selection of the CPS definitions, by a number of authors, are presented in support of the model and "spectrum" defined.

The remainder of this paper is therefore organised as follows. The problem between normative (or prescriptive) definitions and descriptive definitions, of CPS, are shortly considered in Section 2. Section 3 describe main CPS modelling approaches, in which the proposed CPS logical architecture model is proposed, followed by Section 4 that explores CPS definitions and models Spectrum, that highlight the differences of the existing CPS definitions. The conclusions of the paper **are in Section 5, followed by the References and the** Annex containing the selection of the CPS definitions and their characterization within the context of CPS definitions and models Spectrum.

Received: May 2019, Accepted: June 2019
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doi: 10.5937/fmet1904663P

2. ON DEFINITIONS: NORMATIVE VS. DESCRIPTIVE DEFINITIONS

Definitions have the function of exact description of something, of some phenomena or object, without possibility of changing it. If the definition would change, it would mean that another definition is created, and so on ad infinitum. To make the process simpler, i.e. to extend the meaning of one definition, the concept of synonyms has appeared as somethings that have different names for the same meaning.

However, what is real (true) is that there is a very small number of true (ideal) synonyms, and these are usually found in defining natural phenomena. The differences in meanings in synonyms in other areas are even greater, although these, appear as true (ideal) synonyms. E.g. "firm" and "company" are considered almost undoubted synonyms in the management and organisation literature, but these two synonyms could, and do, contain significant differences.

The conclusion is that the majority of synonyms are "false" synonyms, which only in certain characteristics have similarity, while in others (characteristics) are quite different. In accordance with the previous, definitions could be also seen as the real ("ideal") definitions, as happened in e.g. natural sciences (e.g. mathematics, physics, chemistry) (although it is shown that sometimes even these are not correct in certain characteristics and situations, but this is in relatively small numbers), while in other fields definitions function as the false synonyms, meaning these are context sensitive. For example, in one case "cooperation" would mean one, and in another case would mean something different, and so far.

At the present state of the theory, we could find two types of definitions, normative, or prescriptive, and descriptive:

- Normative, or prescriptive – The normative, or prescriptive, definitions are those in which it is prescribed how something should be in reality. Normativity denotes theory, ordering and truth.

However, the practice (the "praxis") shows that the reality is not always the same as it is prescribed and for this reason is necessary new description of that same reality, or, a new term is necessary. In this way we came to the new (linguistic) concept and it is "descriptive definition" which considers description and descriptive analysis of phenomena or objects in different "spheres" (domains, fields, circumstances) and contexts. That is, definitions are, as it is said above, context sensitive.

- Descriptive – The descriptive definitions are those in which the reality is escribed and analysed in different "spheres" (domains, fields, circumstances) and contexts.

Exactly because of sensitivity on context, the normative definitions are not sufficient, i.e. the normative definitions are not sufficiently efficient and effective to describe all diversity and complexity of contexts in hic appear, or emerge, those moments in which a definition is necessary.

In accordance with the above, the only solution is resort to descriptive definitions, which by their nature, but also by the own nature of the phenomena and objects of the definition cn only be descriptive.

It, by itself, therefore, implies that the situations for definitions are variables, and definitions, following that variability, can only to describe them. I.e. the descriptive definitions, and not prescriptive definitions, or how it should be.

Thus, this is the approach by the authors of this paper in defining CPS concept.

3. CPS MODELLING

3.1 A review of CPS modelling approaches and issues

Modelling represents a critical process on all technical development issues. Having behaviour simulation and (predicted) results analysis, will surely contribute for zero defects [5], even on prototyping stage. However, the inherent and intrinsic complexity of emergent CPS scenarios, the application of common patterns for modelling (Model-Based-Design, Model-Driven-Development) are quite faraway for being adequate. Indeed, having physical, computation, dynamic and human based systems that need to be represented and correlated, where context, information field, dynamic (re)organization, real-time and feedback loop between any of those entities must be considered, makes the effective CPS Modelling a challenge, by itself [6].

Several different models are explored, all using taxonomies-based diagrams (ePtolemy II (https://ptolemy.berkeley.edu/books/Systems/)), or multilayer of entangled logical or functional components [7], basically. However, a globally recognized CPS reference model is not there, yet!

The common architecture of a CPS comprises models of physical processes as well as models of the software, computation platforms and networks. The feedback loop between physical processes and computations encompasses sensors, actuators, physical dynamics, computation, software scheduling, and networks with contention and communication delays. Modelling such systems with reasonable fidelity is challenging, requiring inclusion of control engineering, software engineering, sensor networks, etc. Additionally, the models typically involve a large number of heterogeneous components. Composition semantics becomes central [8].

In CPS many things happen at once. Physical processes are compositions of many things occurring at the same time, unlike software processes, that are deeply rooted in sequential steps. Abelson and Sussman [9] describe computer science as "procedural epistemology," knowledge through procedure. In the physical world, by contrast, processes are rarely procedural. In other words, the physical processes are compositions of many parallel processes. Measuring and controlling the dynamics of these processes by orchestrating actions that influence the processes are the main tasks of embedded systems. Consequently, concurrency is intrinsic in CPS. Many of the technical challenges in designing and analysing embedded software stem from the need to bridge an inherently sequential semantics with an intrinsically concurrent physical world [8].

Thus, the progressive attention to CPS represents a new "context" based on the emergent communicational and processing capabilities that did not exist before.

The current tools and approaches available for modelling CPSs are either analytical and/or logical means. The former typically focus on the components and provide less support for system-level conceptualization and compositionality issues. The latter typically operate with multi-level abstractions and do not consider the physicality (attributes or properties) of the components or the system as a whole [8]. Automated or semiautomated processes can, under certain circumstances, synthesize implementations from models. But the intrinsic heterogeneity and complexity of CPS stresses all existing modelling languages and frameworks [7,10,11].

This vision actually corresponds to the CPS definition in [12]: “Cyber-Physical Systems (CPS) is an integration of computation with physical processes whose behaviour is defined by both cyber and physical parts of the system. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa”, which explicitly requires non-fixed connections, the connections in continuous changes [13]. The majority of CPS definitions found in literature have a more relaxed definition, implying fixed connections [14,17], or at most requiring changing only the “physical” part of the CPS, see e.g. [13,18].

Being, according to literature, CPS definitions very general, some identified features allow to understand their characterization and grading their behaviour around topics like openness, control, automation, adaptability, efficiency and effectiveness (human active in the dynamics of CPS) [19].

The emergent attention or concerns around *Communication, Integration, Digitalization, Miniaturization, Personalization, Sustainability* (and others), support the profitability of investments (human and material), the reuse of legacy equipment, the energy efficiency, processes reorganization (and others),are all essential pillars for nowadays CPS relevance. However, still persist the scenario of a complex puzzle of, on one hand, no necessarily integrable and tightly integrated systems, and on the other hand that, technically, demands to computer engineering (SOA (Service-Oriented Architecture) and AOA (Agent-Oriented Architecture)) and electronics (sensors and actuators) to redefine their (inter)relations.

The computational and communicational capacity of existing (and forecasted) infra-structures and systems, force new challenges and promotes new paradigms on integration and collaboration [20]. Different adaptability and autonomy will be required, where mentioned “systems societies” [21] need to be transformed on transparent (ubiquitous) and effective systems! Industry 4.0, Internet of Things and Big Data represent clear demonstrations of that!

3.2 CPS logical architecture

A new CPS logical architecture, following the vision, and the definition, proposed in [11], is proposed (Figure 5).

However, considering the unambiguous existing CPS models, published in the literature, and the new requirements of expected CPS, there could be identified other CPS models, and definitions, which are considered as special cases, or “relaxed”, or reduced, models and definitions, comparing with the model referred in the above paragraph (Figure 5).

These all could be described, grouped, and denominated as following:

1) Production Systems (PS), or Manufacturing Systems (MS) – “PS/MS”, where physical infra-structures are managed and controlled by multiple information systems (ERP, BOM, MES, etc. on the “higher” levels of control, but also the “lower” levels of control such as servo-control and other embedded control functions). All these information systems, providing the feedback loops, are by the nature “digital”, making them a “digital part” of the system, Figure 1. However, this type of the “traditional”, or “conventional”, control systems are not considered as the CPS systems. One of the reasons is that while the so-called “primitive”, or “low level”, feedback loops could be realized in real time, the “higher level” feedback loops in traditional manufacturing systems, are realized in batch mode, or offline mode, which I snowadays considered as limitation, and which lead to tconception of the CPS (in fact, this type of the system (traditional PS/MAS) is not necessary to discuss within the CPS issue, except for the reasons of reference (in order to demonstrate the paradigmatic difference of the CPSs) and from the reason of “closure” of the CPS systems definitions classification);

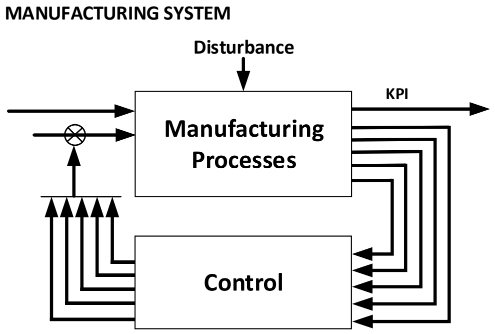

Figure 1. Logical Architecture of the “classical”, or “conventional”, Production or Manufacturing System – PS/MS

2) Classical Cyber-Physical Systems – “CPS^0” where physical infra-structures and digital systems are related and cyclically controlled (feedback loop) providing Adaptability, reconfigurability, fast responsiveness, and robustness are some advantages of CPS, once traditional systems cannot “respond quickly enough to a large-scale system because of the lack of agility and dynamic behavior, which are necessary to address complex and changeable system environments” [22]. In other words, the main difference between traditional manufacturing systems (PS/MS) without CPS, and manufacturing systems with CPS, is the CPS capability of real time control loops (decision making) concerning adaptability, reconfigurability, fast responsiveness, and robustness, i.e. with additional functionalities of capability for “feedback loops where physical processes affect computations”. These “old” functionalities, but now

in a qualitative new way, providing real-time responsiveness, are provided by recurring to new generation of emerging computation technologies such as cloud and ubiquitous computing, Internet of Thing, Web 2.0 3.0 and 4.0, Fast Internet, and similar. Actually, all these "emergent" computational technologies require, almost without exception, recurring of "outdoor" services, while remaining "lower level" control loops are still embedded in the "traditional" control modules within the PS/MS "doors" (indoor). This is the reason why the CPS intrinsic computational part is figured as separated, represented a "DIGITAL 0" level (in line with denomination of CPS^0), while the "object" PS/MS, denominated as the "Object Manufacturing System" , still keeps a part of traditional "control" module, represented as the "PHYSICAL LEVEL" in the context of the CPS usual definition of composition of "physical" and "digital" parts (although the "physical" part of the CPS still contains embedded low level (digital) control block) These differences imply specific logical functional architecture of the CPS (in comparison with traditional manufacturing system PS/MS logical architecture in **Error! Reference source not found.**) presented in Figure 2.

The "Simulation", that, basically, reacting to input states, allows the simulation of changes applied to all CPS, allows the analysis of the impact of environment changes (data from previous processing, disturbances, etc.) in the manufacturing process. Aggregating the past, present and predicted data and exploring advanced algorithms, will support the CPS's "physical part" reconfigurability capacity. Thus, the CPS "physical" part – "Object Manufacturing System" reconfiguration and its core services reprogramming, can be explored and production results realigned and anticipated. The need of continuous simulations comes from the permanent evaluation of results along the time, in which each state must be seen as a new instance off all system, having previous state as input, as well as new environment conditions, intended (forced variances) or not (disturbances), Figure 2. The functional change of the Object Manufacturing System is provided by the advanced simulation tools oriented to CPS and Industry 4.0 requirement.

The test-bed of digital machine twins (i-machines) is one of them, allowing systems to deal continuously and dynamically with it, reconfiguring it at any stage of the manufacturing process.

It is to notice in the Figure 2, and subsequent figures of CPS logical architectures, that the fine arrows represent the inputs and outputs of the systems' modules /blocks. The thick arrow (in blue) represents the system as output from the intrinsic CPS "digital" part (from the level "DIGITAL 0") from the module "Object System Model Generator" and that will substitute the Control module of the PS/MS, i.e. of the Object System of the CPS, in Figure 2.

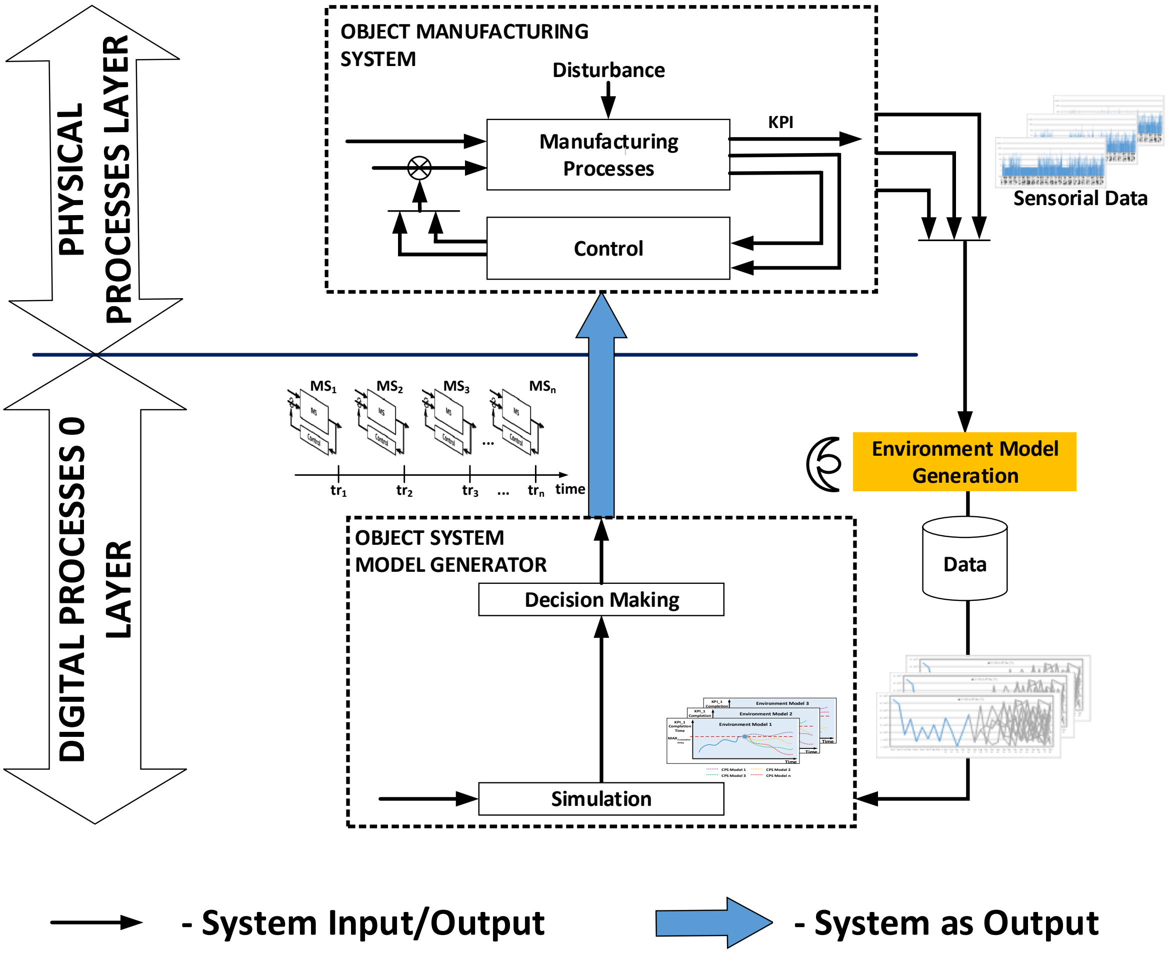

Figure 2. Logical Architecture to model a CPS^0

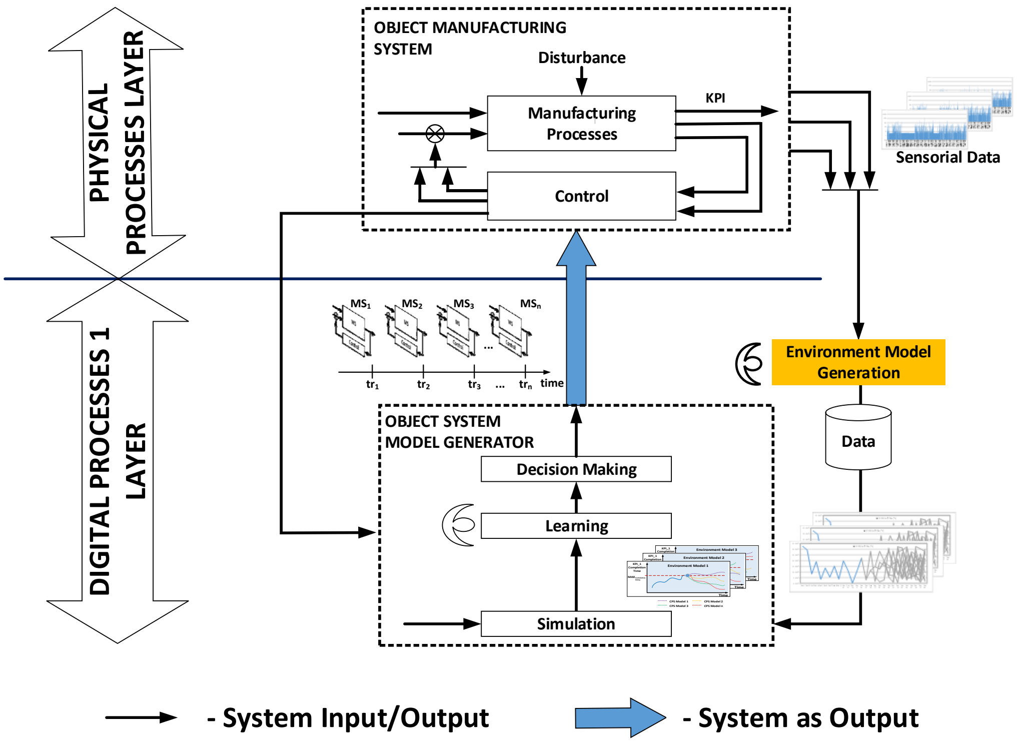

Figure 3. Logical Architecture to model a CPS^1

3) Cyber-Physical Systems with physical part and digital part integrated, where a single loop learning can affect (or change) the physical part (settings, schedules, etc.) – “CPS^1”. The logical architecture of this type of CPS models is an extension of the CPS^0 logical architecture with embedding the Learning module, as figured in Figure 3. The new “computational” module, with embedded “Learning” module, form a second type of the CPS’s “computational part of the CPS, denominated as the “DIGITAL 1” level (in line with denomination of CPS^1). The learning module provide structural reconfiguration of the “Object Manufacturing System” Control module.

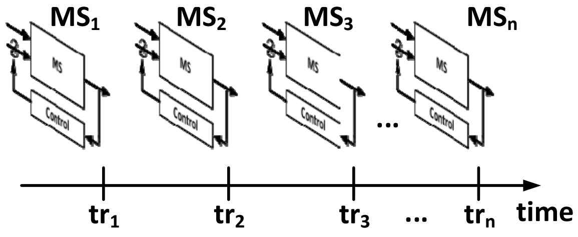

Figure 4. A “single loop” Learning, together with Simulation processes, allows functional and structural reconfiguration of the Object Manufacturing System Control module, i.e. the CPS’s computational part “affects” the CPS’s “physical” part

The Learning, similarly with the CPS^0 model, aggregating the past, present and predicted data and exploring advanced algorithms of artificial intelligence interface learning strategies [23], fuzzy logic ranking, multi-criteria-decision, deep learning and others, will support the learning capacity. The need of continuous learning (similarly to the CPS^0 models) comes from the permanent evaluation of results along the time, in which each state must be seen as a new instance off all system, having previous state as input, as well as new environment conditions, intended (forced variances) or not (disturbances). The structural change is provided by the well-known learning algorithms mechanisms, within the sub-module “Learning”.

The new Control module, that will substitute the old one, is generated through the learning process that outputs the new Control module. This happens in a sequence, due to changing environment and contexts, as depicted in Figure 5.

4) Cyber-Physical Systems with double loop learning – CPS^2, where digital part can be changed (adjusted) to better control the physical part. In this model, it is introduced another level of “digital”, with the second “Learning” module, that has capacity to learn about the Learning module in the CPS^1 model. The learning process about another learning process (“Learning about learning”) is called in literature the “2nd loop learning”. This second learning module is embedded in the module denominated “Computational System Model Generator”. The new “computational” module, together with the “computational” module described in the CPS^1 architecture model, form the third, far more complex, type of the CPS’s “computational” part, denominated as the “DIGITAL 2” level (in line with denomination of CPS^2). In this way, it is provided that the data from the CPS’s “physical part”, i.e. from the “Object Manufacturing System”, affect the learning process itself, i.e. the learning algorithms themselves, in the CPS^1 model, i.e. affect the CPS’s “computational” part. The subsequent CPS architecture logical model is presented on the Figure 5.

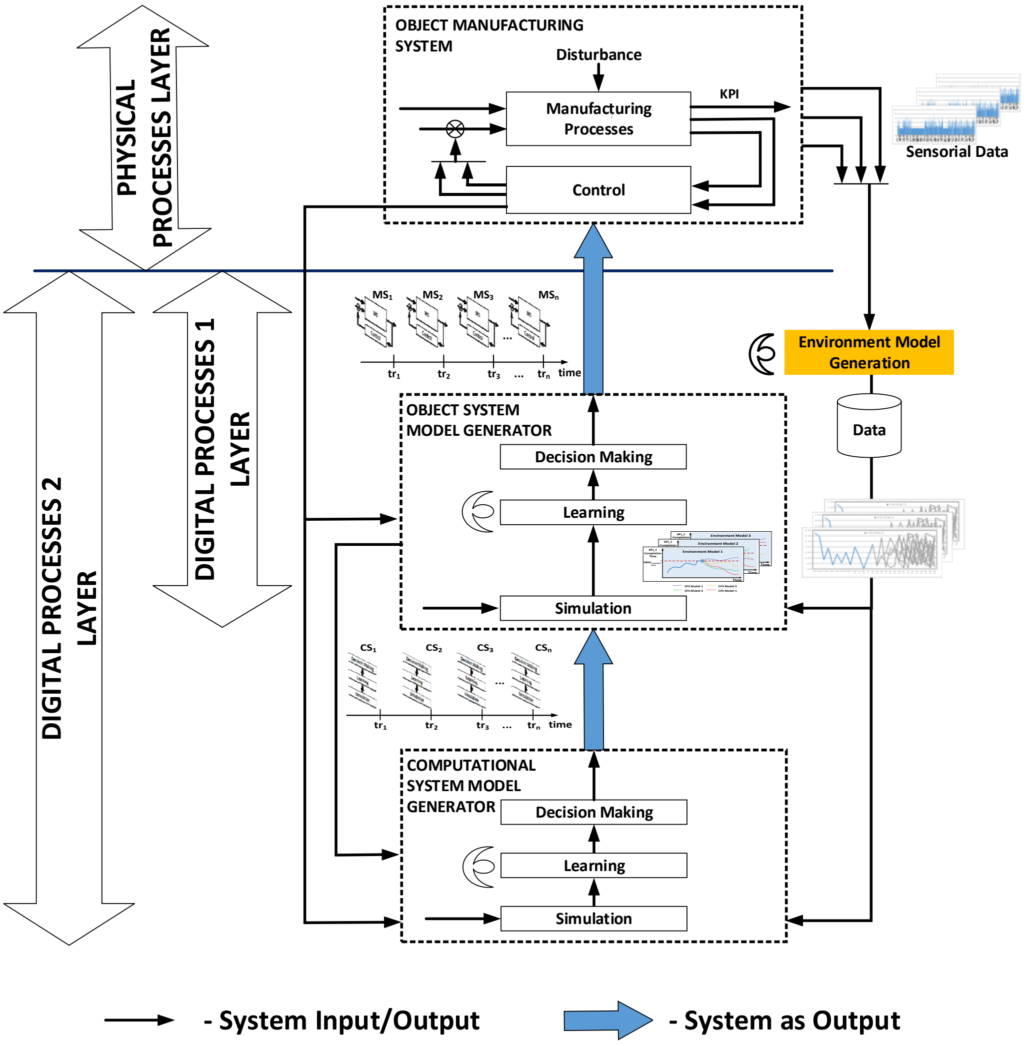

Figure 5. Logical Architecture to model a CPS^2

Again, the “2nd loop learning” Learning module, similarly with the CPS^1 model, aggregating the past, present and predicted data and exploring advanced algorithms of artificial intelligence learning strategies, fuzzy logic ranking, multi-criteria-decision, deep learning and others, will support the further learning capacity. The need of continuous learning (similarly to the CPS^1 models) comes from the permanent evaluation of the learning within the “1st loop learning”, simulations and decision making results along the time, in which each state of the “1st loop learning”, simulation and decision making mechanisms must be seen as a new instance of all system, having previous state as input, as well as new environment conditions, intended (forced variances) or not (disturbances). The structural change of the CPS’s computational part is provided by the well-known learning algorithms mechanisms, within the sub-module “Learning” within the “Computational System Model Generator”.

The new “Object System Model Generator” will substitute the old (previous) one. This happens in a sequence, due to changing environment and contexts, as depicted in Figure 6.

By theCPS2 architecture model, it is fully satisfied the requirement for the CPS model in accordance with the vision, and definition, in which the CPS is defined as the system with “**feedback loops where physical processes affect computations and vice versa**”.

Note: The notations for the CPS architecture models denominations, CPS^0, CPS^1, CPS^2, are inspired by the notations for denominations of the curves continuity types, namely C^0, C^1, C^2, in analytic geometry, and subsequently in computer graphic models in CAD.

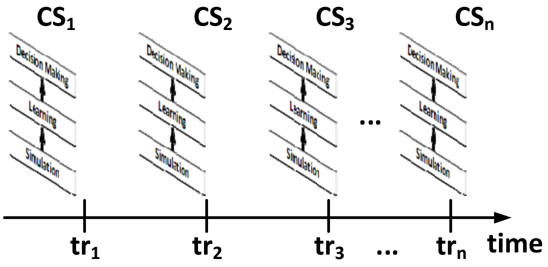

Figure 6. A “second loop” Learning, allows functional and structural reconfiguration of the CPS’s Computational System, i.e. the CPS’s physical part “affects” the CPS’s “computational” part.

4. CPS DEFINITIONS AND MODELS SPECTRUM

There are many CPS definitions, with associated corresponding CPS models classes, that could be grouped in few classes by their qualitative features, and ordered by their complexity and applicability, making a CPS definitions "spectrum".

The CPS definitions "spectrum" represents a CPS definitions taxonomy.

(Employing the term "spectrum" is inspired by Milgram's and Kishino's introduction of the term "mixed-reality spectrum" for description of the taxonomy of mixed reality visual displays, in [24].

4.1 Towards CPS definitions Spectrum

At one end, presented as the left end, of this "spectrum", are definitions of "classical" PS/MS (not subject of discussion in this paper), which logical architecture is presented on the Figure 1.

Following, on the next, second, place are definitions of the type CPS^0 (Figure 2), addressing the most simple CPS models and their definitions, such as: " … smart systems that include engineered interacting networks of physical and computational components …" [14], or "…physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core" [15], similarly in [16] and [17] which include, or permit, the CPS architectures "based on fixed connections due to the traditional philosophy inherited from mechatronics" [13].

At the other end, the right end, of the "spectrum" there could be find definitions of yjetypeCPS^2 (Figure 5), such as "… [CPS] is an integration of computation with physical processes whose behaviour is defined by both cyber and physical parts of the system. Embedded computers and networks monitor and control the physical processes, **with feedback loops where physical processes affect computations and vice versa**" [12] [*Note: bold letters by the authors of this paper*], which explicitly requires non-fixed connections, the connections in continuous changes, implying that the architectures with fixed connections are not true CPSs. The definitions and the models of the type CPS^2 are the most complex in this part of the spectrum.

Therefore, a more demanding definition of CPS requires features that both physical and computational systems affect and change each other, making a system with systemic relationship, implying a totally new implementation paradigm, and for which the former definition is just a special case.

Analysing the CPS approaches and models in the literature, it could be identified that there are many of the type CPS^1 (Figure 3), representing the functionality of physical part of the CPS system reconfigurability, e.g. in [13,18], locating these approaches/models in the "middle" of the CPS definition "spectrum". This type of definitions/models is the most populated in the literature at the moment.

However, a CPS approach/model, of the type CPS^2, that embed changing the computational system by the physical system, is not found.

4.2 Linear domain of the CPS definitions and models Spectrum

The CPS models, and corresponding definitions, presented in the previous section 3., including the "traditional" PS/MS, namely PS/MS, CPS^0, CPS^1, and CPS^2, could be ordered linearly, which is easy to verify, due to "additive" nature of incorporation of new modules or functionalities, forming a CPS definitions Spectrum.

Due to the "linear" order of these types of CPS definitions/models, this part of the CPS spectrum will be called the "linear domain of the CPS definitions and models spectrum". A figurative presentation of this part of the spectrum is given in Figure 7. All this linear characterization of CPS are represented synchronically in Figure 7.

It is important to notice that the CPS models of the types CPS^1 and especially CPS^2, due to inclusion of learning capacities, could be denominated as well as "Intelligent CPS", in short, I-CPS.

Further, considering the single loop learning in CPS^1 and the second loop learning in CPS^2, further detailing in denominations would be as I-CPS^1 and I-CPS^2 respectively, also alternatively as I^1-CPS and I^2-CPS, Figure 7.

Consequently, the CPS models without learning, i.e. the CPS^0 model type, in order to keep consistency in denominations for the whole domain (spectrum) could be denominated as I-CPS^0, or I^0-CPS, Figure 7.

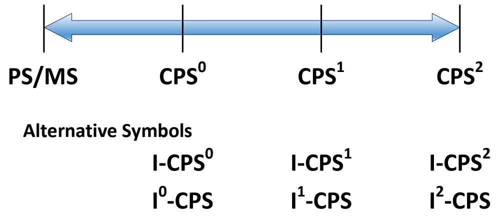

Figure 7. Linear domain of the CPS definitions and models spectrum,

4.3 Dynamic domain of the CPS definitions and models Spectrum

Considering the existing industrial systems and literature definitions, we grade synchronically (Figure 8**Error! Reference source not found.**) a cross-domain nearly spectrum of cyber physical systems as: (a) CPS (classical cyber physical systems), (b) CPS-AMS (CPS Augmented Manufacturing Systems), (c) M-CPS (Mixed CPS); (d) CPS-VMS (CPS Virtual Manufacturing Systems) and (e) I-CPS (Intelligent CPS).

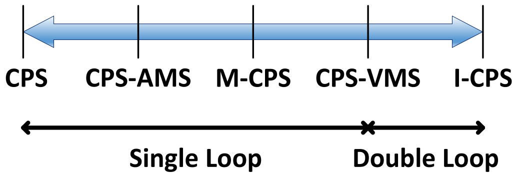

Figure 8. Dynamic domain of the CPS definitions and models spectrum, or cross-domain nearly spectrum of CPS

Globally, existing CPS move around the classical CPS models, of the types CPS^0 and CPS^1, which are, basically, physical components and their controlling systems that can reconfigure the control module of the object manufacturing system. A local technological ecosystem involving machines, sensors, cooperation and automation, for a specific domain with small-scale, systematic and tangible assets, where analysis of local results can be considered (feedback loops) to improve the system. Furthermore, CPS-AMS explore augmented reality assets, using real-time data coming from integrated sensors (context-aware) and CPS-VMS explores virtual reality on scenarios of simulation. M-CPS can be the most common of nowadays CPS where mixed reality, technology and autonomous controlling systems are explored, towards corrective measures. However, all these CPS are based on a single loop learning [25], ignoring the real causes in their full scale.

The effective learning instead, happens only if a double loop learning occurs "…rising individual capability to take effective action..." [25], [26], that objectively means, the CPS controlling systems can be changed by itself. If there is continuous learning, an inteligent, effective, collaborative and systemic CPS, with abstract or intangible assets, prepared for cross and large-scale domain is possible, this is an I-CPS. The announced Intelligent Manufacturing [27,28] of Industry 4.0 and Internet of Things, for being credibly, must consider I-CPS support, i.e. the CPS^2 models.

Since the relationship between the linear definition of CPS (Figure 7. Linear domain of the CPS definitions and models spectrum,) and the nearly spectrum (Figure 8. Dynamic domain of the CPS definitions and models spectrum, or cross-domain nearly spectrum of CPS

) is not simple, we believe the need to extend the linear domain of spectrum with "CPS^N", to deal with the scenario of complexity, uncertainty and dynamism that reality generates [29], the common context awareness. Indeed, there must be possible to continuously redesign or reprogram the controlling systems' supporting algorithms, and therefore, a new instance of CPS, potentiating *n-loop learning models*. This agile capacity to learn against uncertainty or unpredictable context fits clearly exponential growth model solutions, whose implementation will have to follow hybrids lines of classical and quantic algorithms (referring to the quantic algorithms inspired by [30,31].

4.4 CPS definitions and models spectrum

We believe that *n-loops learning* supports a synchronic spectrum of CPS, where new instances of more efficient CPS are generated.

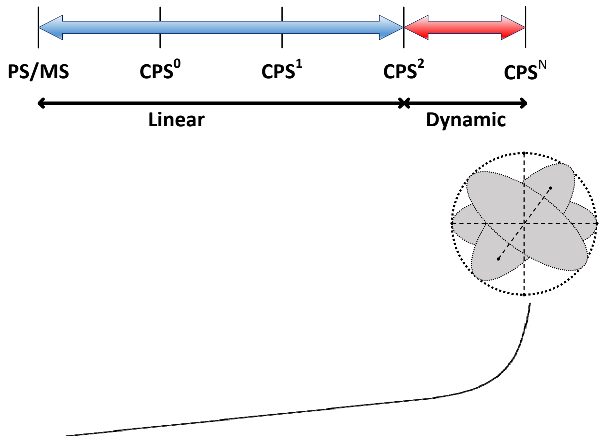

Figure 9. CPS definitions and models spectrum, integrating the both, linear and dynamic parts of the spectrum domain.

Each new CPS instance fits a linear characterization (PS, CPS^0, CPS^1, CPS^2) and a tenue dynamic border on its model that allows the instance behaving differently in a different time, exploring virtual, augmented and intelligence for learning, and since able to evolve. The full CPS definitions and models spectrum, integrating the both, linear an dynamic parts of the spectrum domain, is given in the Figure 9!

It is represented figuratively the linear "growth" and the part of the exponential "growth" in complexity of the CPS definitions and models, finishing with a "quantic" model of the CPS definitions and models space (inspired by the Bloch's sphere [38]).

5. CONCLUSIONS

The Industry 4.0 represents an emergent context for industrial activities, where physical equipment, controlling processes and supporting information systems are closer than ever. Once more, the new technological capacities, that arise faster and continuously, play a key role on this announced transformative paradigm.

The exploration of distributed architectures for increasing the computational processing capacity that allows, indeed, the mature or innovative artificial intelligence, big data and others advanced algorithms to be applicable, the ease digital communication and connectivity, and integration of advanced electronic devices to sensor more and more things, point to the scenario where controlling all production life-cycle, from preparation, the execution, to the final results evaluation, is a continuous loop of learning and realignment to fit the context uncertainties. The Cyber-Physical-Systems (CPS) represent such scenario's supporting systems.

Since there are many CPS definitions, models or frameworks, this research focused on the identification of their characteristics and classifies them in a spectrum of approaches or applications.

Although this spectrum perspective has not been emphasized before, existing definitions of CPS remark that their logical and functional behaviour are, indeed, wide-ranging spectrum application.

Believing that self-adaptive machines or processes are required, but unachievable if their supporting systems are not reprogrammable, a continuous double-learning loop is needed. The defects can be anticipated or corrected, but more important than that is the mitigation of the cause of it, the expected path to the I-CPS, the intelligent CPS. This research describes the models of such complex and effective evolving learning systems.

Annex I shows a synopsis of literature selected definitions and their positioning in presented CPS synchronic spectrum. The classification stems from the CPS main features, behaviour and supporting technologies. The grouping of criteria based on the exploration of virtual or augmented reality support, the learning and intelligence capacity, cyber/physical integration and other particularities that can improve the system, such as training.

Finally, it is expected that the research presented, especially considering the proposed CPS architecture logical model, that includes double-loop learning will contribute to the future CPS reference model and CPS meta-model.

ACKNOWLEDGMENTS

This work has been supported by FCT – Fundação para a Ciência e Tecnologia, Portugal, within the Project Scope: UID/CEC/00319/2019

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ШТА СУ САЈБЕР-ФИЗИЧКИ СИСТЕМИ (СФС): „СПЕКТРУМ“ ДЕФИНИЦИЈА И МОДЕЛИ

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Сваки пут када се деси релевантан предлог новог концепта, постојеће перспективе, концепти или њихове основе суочавају се са овим који се појавио. Индустрија 4.0 и системи контроле производње које Индустрија 4.0 промовише, засновани на Сајбер-Физичким Системима (СФС), генерисали су нове потенцијале за бином човек - технологија (опрема и њена употреба).

Неколико аутора истражује предвиђену и захтевану релацију физичког и дигиталног како би најавили трансформативне промене од интереса, где ауто-конфигуришуће и ауто-адаптативне машине и системи подржавају примену корективних одлука.

Овај рад излаже „спектрум“ постојећих СФС дефиниција и модела и доприноси основама за један ефиектниван интелигентни СФС (И-СФС), где процес учења са двоструком повратном спрегом омогућава да се његови софтверски алгоритми промене или репрограмирају. Уместо тога, не само ауто-конфигуришуће машине и системи, већ и ауто-конфигуришући софтвер.

Annex I

Industrial Cross-Domain nearly spectrum of CPS

Position in spectrum	Reference	Definition	Comment /Observation / Note
CPS-AVS	[32]	*(...) CPS is the merger of ‘‘cyber’’ as electric and electronic systems with ‘‘physical’’ things. The ‘‘cyber component’’ allows the ‘‘physical component’’ (such as mechanical systems) to interact with the physical world by creating a virtual copy of it. This virtual copy will include the ‘‘physical component’’ of the CPS (i.e., a cyber representation) through the digitalization of data and information. By this, CPS can be assumed as a range of transformative technologies to manage interconnected computational and physical capabilities (...)*	Virtuality Cyber/Physical Integration No learning
M-CPS	[33]	*(...) CPS embraces smart elements or machines who has the augmented intelligence and ability to communicate each other to make part of planning, unique or non-repetitive tasks. These smart elements, for instance, can control the needs of workpieces, alter the manufacturing strategies for the optimal production, choose (if already exists) or find a new strategy all by themselves. These elements will build their own network (...)*	No effective Intelligence Single-loop learning Cyber/Physical Integration Systematic
CPS	[34]	*(...) CPS includes autonomous vehicles, medical systems, process control, robotics and so on□—□wherever physical systems (“things”) and cyber systems (IT-based systems) are combined (...)*	Cyber/Physical Integration No learning
CPS	[35]	*(...)* Cyber-Physical Systems (CPS) is defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities *(...)*	Cyber/Physical Integration No learning
M-CPS	[36]	*(...) Cyber-Physical Systems (CPS) are systems composed by a physical component that is controlled or monitored by a cyber-component, a computer-based algorithm. Advances in CPS technologies and science are enabling capability, adaptability, scalability, resiliency, safety, security, and usability that will far exceed the simple embedded systems of today. CPS technologies are transforming the way people interact with engineered systems. New smart CPS are driving innovation in various sectors such as agriculture, energy, transportation, healthcare, and manufacturing (...)*	No effective Intelligence Cyber/Physical Integration Single-loop learning
CPS	[32]	*(...) Cyber-physical systems (CPS) are a collection of transformative technologies for managing interconnected physical and computational capabilities (...)*	Cyber/Physical Integration Single-loop learning
M-CPS	[37]	*(...) Cyber-Physical Systems are a next-generation network connected collection of loosely coupled distributed cyber systems and physical systems monitored/controlled by user defined semantic laws. Here, cyber systems are collections of control logic and sensor units, while physical systems are collections of actuator units. CPS is the merger of cyber (electric/electronic) systems with physical things. CPS helps mechanical systems to perceive the physical world, process these perceptions as data on computers, make calculations, and inform systems to take actions to change process outcomes (...)*	Cyber/Physical Integration Single-loop learning
CPS-AMF	[38]	*(...) Cyber-Physical Systems (CPS) is a computerized networking system that integrates with physical processes. The lack of theoretical foundation in CPS has resulted with this study, which aims to provide a holistic view of Cyber-Physical Systems and its integration with Augmented Reality (AR) as a decision support tool in the pre-construction stage (...)*	Cyber/Physical Integration Single-loop learning Augmented Reality

CPS-AMF	[39]	*(...) MAR-CPS: Measurable Augmented Reality for Prototyping Cyber-Physical Systems (...)*	Cyber/Physical Integration Single-loop learning Augmented Reality
CPS-VMF	[40]	*(...) Cyberphysical System with Virtual Reality for Intelligent Motion Recognition and Training (...)) with intelligent sensor data mining and motion analysis. It can be potentially used for next-generation rehabilitation due to its cyber controlled, automatic motion analysis (...)*	Cyber/Physical Integration Single-loop learning Virtual Reality Training
M-CPS CPS-VMF	[41]	*(...) Cyber Physical System (CPS) together with Internet of Things, Big Data, Cloud Computing and Industrial Wireless Networks are the core technologies allowing the introduction of the fourth industrial revolution, Industry 4.0 (...) realistic virtual models mirroring the real world are becoming essential to bridge the gap between design and manufacturing (...)*	Real Time Cyber/Physical Integration Single-loop learning Virtual Reality Training

Position in spectrum	**Reference**	**Definition**	**Comment /Observation / Note**
CPS	[42]	*(...) Cyber-Physical Systems (CPSs) integrate the dynamics of the physical processes with those of the software and communication, providing abstractions and modeling, design, and analysis techniques for the integrated whole (...)*	Cyber/Physical Integration Single-loop learning
M-CPS	[43]	*(...) Manufacturing Cyber-Physical System (M-CPS) is envisioned to handle the actual operations in the physical world while simultaneously monitor them in the cyber world with the help of advanced data processing and simulation models at both the manufacturing process and system operational levels (...)*	Cyber/Physical Integration Single-loop learning
M-CPS CPS-VMF	[44]	*(...) A sensor-packed manufacturing system in which each process or piece of equipment makes available event and status information, coupled with market research for true advanced Big Data analytics, seem to be the right ingredients for event response selection and operation virtualization, and thus moving manufacturing operations closer to the cloud manufacturing paradigm (...)*	Cyber/Physical Integration Single-loop learning Virtual Reality
I-CPS	[3]	*(...) Cyber-physical systems (CPS) are integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa (...)*	Cyber/Physical Integration double-loop learning

Literature references for learning CPS