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CPS-BOK: Body of Knowledge for Cyber-Physical System

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Abstract. *Aiming at the management of Cyber-Physical Systems (CPS) evolution during the development cycle of their components, integration phase, and maintenance in operation, this paper presents a Body of Knowledge named of CPS-BOK (Body Of Knowledge for Cyber-Physical System). Considered the core technology of Industry 4.0 and IoT (Internet of Things), a CPS was firstly defined as the integration of computational and physical processes, evolving to managing interconnected physical assets and computational resources involved in a collaborative complex System of systems. In this context, the system requirements are usually defined in isolation by parts of the system in a very abstraction level, being very difficult to be verified during the system life cycle. The proposed CPS-BOK defines a methodology for evaluation of CPS design, implementation, and maintenance by means of a framework oriented to the CPS business.*

Key-words: cyber-physical systems, architecture, model, framework, body of knowledge, evaluation methodology, internet of things.

1. INTRODUCTION

Cyber-Physical System (CPS) is considered as an emerging component for Industry 4.0 and IoT (Internet of Things) solutions, in addition to the state-of-the-art of these systems. Initially, the CPS was considered as the remote embedded system that sends information to the server computer. With technological evolution, the interconnection options have grown up and now are important keys in these systems. This scenario increases the system complexity level leading to the need for proper management of parts, interconnections, and integration between physical and virtual worlds. For this reason, project models are useful to represent the aspects of interconnection and complexities of the parts, which simplifies their evaluation under the perspective of CPS maturity.

The term maturity is *"the state of being fully grown or developed"*[Fraser et al. 2002]. Capability maturity models (CMMs) are tools used to assess the capability of an organization to perform the key processes required to deliver a product or a service. Since the development of the Capability Maturity Model, maturity models have been applied in many other fields, such as product design safety[Strutt et al. 2006]. Another example of maturity model applied to product design is classified as "performance-by-construction" maturity level[Campos and R. Haverkort 2015] . Significantly, they can be used, both as evaluating tools and as a product improvement tool. In the context of this paper, the best of definition is the "performance-by-construction" maturity level, were the key processes required by maturity model is extended for the process, techniques, and practices (CPS-BOK) required by the highest level of CPS dependability that should be driven the CPS business requirements.

Aside from not being essentially a management model of CPS projects, this work was inspired in project management and continuous improvement models such as the PDCA cycle[Moen and Norman 2009] [Swamidass 2000] to propose a body of knowledge capable of representing the most complex aspects of CPS. The main goal is to increase the maturity of these systems, consequently improving in reliability and availability.

The term Cyber-Physical Systems (CPS) was first presented at a National Science Foundation (NSF) workshop in 2006, performed in Austin, Texas, USA [Lee 2006]. The term was defined as integrations of computational and physical processes. In 2007, author Edward A. Lee cites again the term in his technical report, "Computing Foundations and Practice for Cyber-Physical Systems: A Preliminary Report" [Lee 2007] confirming the earlier definition. Subsequently, the definition was extended to include the communication process. [Cooperation 2013] [of Science and Engineering 2011]

CPS represents a new generation of systems that are both interconnected and collaborative, offering to citizens and businesses a wide range of innovative applications and services [Cooperation 2013]. Nowadays, the CPSs are considered as transforming technologies, which focus on the management of the physical assets and computational resource that compose interconnected systems. The CPS discipline has attracted much attention from researchers in recent years. In addition to intelligent factories, new challenges are being proposed in the area of health [Zhang et al. 2017], intelligent networks [Liu et al. 2016], intelligent transport [Syed et al. 2012], intelligent houses [Kuang et al. 2014], intelligent buildings and cities [Gurgen et al. 2013].

With the main purpose of advanced connectivity, intelligent information management and the analytical and computational capacity of the cyberspace, which guarantees real-time acquisition, analysis and feedback, a CPS consists of three functional components [Marwedel 2018]: 1) Embedded Systems; 2) Communication Technology; 3) Pervasive/Ubiquitous Computing.

The figure 1 shows a relational diagram of the functional components of CPS. However, the CPS discipline deals with generic issues and the categories presented in figure 1 are very abstract and not specific enough for general implementation purposes. It is possible to find some works in the literature that present an approach to planning and implementation, however the largest number of scientific papers related to the theme is applied to industry 4.0 or do not deal with important details in communication or pervasive/ubiquitous computing.

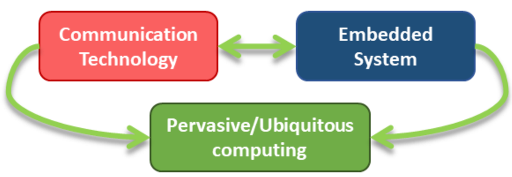

Figura 1. Main Functional Elements of CPS [Marwedel 2018] (©European Commission)

In 2006 Peter Mardwedel presented the first edition of his book entitled Embedded System Design, with the main objective of providing an overview of the design of embedded systems and relating the most important topics of embedded systems design to each other [Marwedel 2006]. In his book, even without the CPS concept, Peter proposes a guide to planning embedded systems, concepts that he later applies in the second and third editions of his book. The work can be considered pioneering and reference, however it deals superficially with the planning process of these systems, in additional the communication and pervasive computing and in a profound way the concepts of embedded systems.

After the work of Peter Mardwedel, many other works were presented with the objective of proposing an architectural model for CPS, however focusing on manufacturing and industry 4.0, as can be seen in the articles "The Cyber-Physical Systems Architecture for Industry 4.0-based manufacturing systems "[Lee et al. 2015]," An improved cyber-physical systems architecture for Industry 4.0 smart factories "[Jiang 2018]. As can be seen, these studies do not address the entire life cycle[Huang 2009] of a critical CPS, such as in the health area or the monitoring of environmental variables for the prevention of natural disasters.

Thus, a main research question that we intend to answer with this work is: *How to increase CPS maturity with reliability and availability properly required by the business?*

The present work addresses this research question presenting a Body of Knowledge, CPS-BOK (Body of Knowledge for Cyber-Physical System), which covers the whole life cycle[Huang 2009] of a CPS, from an extension of the concepts of continuous improvement proposed in the methodology PDCA [Moen and Norman 2009] [Swamidass 2000] (Plan, Do, Check, Act) to improve the maturity these systems. For this, the CPS-BOK include 4 guidelines, nominated: CPS-AMD (CPS Architectural Model Design), CPS-FMK (CPS Framework), CPS-EMM (CPS Evaluation Maturity Model) and CPS-IMM (CPS Increase Maturity Model).

The paper is organized as follows. Section 2, methodology present the guide CPS-BOK as a model capable of representing the aspects of interconnection and complexities of the parts. Section 3 presents a summary of the evaluation of an observational network for environmental data collection typified as CPS. Finally, Section 4 presents the conclusions and future perspectives.

2. CPS-BOK METHODOLOGY

The need of this Body of Knowledge directed at CPS was raised during the evaluation of the environmental data collection system of CEMADEN (National Center for Monitoring and Natural Disasters), a center linked to the Ministry of Science, Technology, Innovation and Communications (MCTIC) of the Government Federal of Brazil.

CEMADEN has a network for environmental data collection, which operates 24 hours a day, with more than 4000 equipment spread throughout the Brazilian territory. This network is typified as a Critical CPS since it has the role of saving lives.

Given the characteristic of CEMADEN's observational network, work was begun to qualify the architecture used in the implementation of the network. The purpose of this qualification was to evaluate the potential risks of failures and improve the reliability and resilience of the network. Based on these needs there was a significative difficulty to find in the literature a model/reference guide so that the structure could be evaluated and improved. This difficulty was the key to the development of this Body of Knowledge in order to surround the entire life cycle of a critical CPS project such as the case of CEMADEN.

Before the development approach, a bibliographic review was carried out with the objective of finding models/guides of reference or works that could collaborate in the development of the Body of Knowledge CPS-BOK.

2.1. CPS-BOK: Body Of Knowledge for Cyber-Physical System

The CPS-BOK proposal is to present a complete Body of Knowledge, from the planning to the disposal of the Cyber-Physical System, that is, covering the whole life cycle[Huang 2009] of the development of a system.

The figure 2 presents the CPS-BOK mapping for the systems development life-cycle.

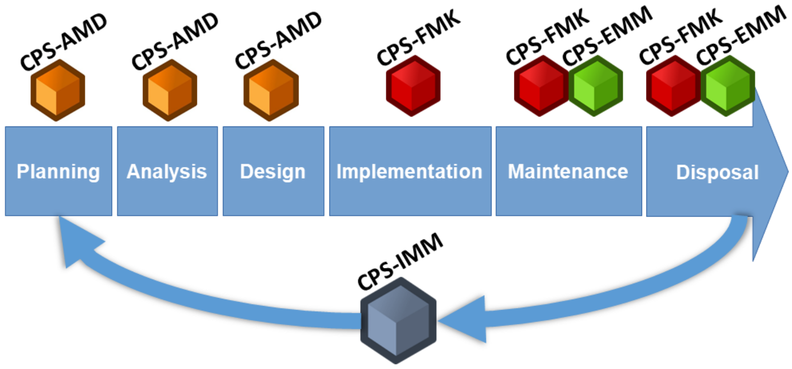

Figura 2. Mapping from CPS-BOK to SDLC

The CPS-BOK intends to present an evolutionary methodology, inspired by the PDCA cycle[Moen and Norman 2009] [Swamidass 2000], which would allow the construction of a system starting from a lower level of maturity to the highest level, aligned with the main business objectives of a CPS system. The figure 3 presents an adaptation of the PDCA cycle[Moen and Norman 2009] [Swamidass 2000] for the CPS-BOK methodology.

As in the PDCA Cycle[Moen and Norman 2009] [Swamidass 2000], the evolutionary cycle of the CPS-BOK proposes the CPS-AMD (Plan) as the system planning and design process. This involves identifying objectives or purpose and designing an architecture. The CPS-FMK (DO) step includes activities for implementation, in which the CPS-AMD components are implemented, aiming at creating the system. The CPS-EMM (Check) step focuses on monitoring of the results obtained with the previous steps to verify the adherence of the system to the proposed levels of architectural maturity. As with the PDCA[Moen and Norman 2009] [Swamidass 2000], it is also possible at this stage to identify problems and elements for improvement. The cycle is completed with the CPS-IMM (Act) stage, which integrates the learning generated by the whole process, which will be used to raise the level of maturity in a new iteration of the CPS-BOK evolutionary cycle.

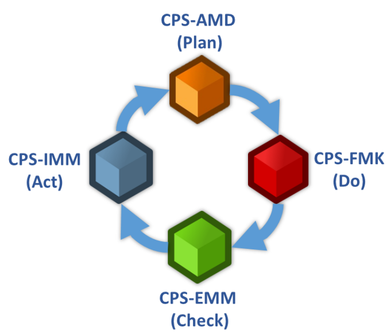

Figura 3. CPS-BOK evolution cycle

2.1.1. CPS-AMD: Architecture Model Design

The CPS-AMD proposes a conceptual framework as a guideline for the planning and design of a system, where the three functional components of the CPS are treated as critical elements for the success of the business. The CPS-AMD guide has 3 basic dimensions:

(a) **Cyber-Physical System Dimension:** Displays the functional components of CPS [Marwedel 2018];
(b) **Business Requirements Dimension:** Proposes a set of requirements types to be evaluated in each of the dimensions.
(c) **Functional Attributes Dimension:** Proposes a set of architectural elements that each of the functional components of CPS should present, driven by business requirements.

As shown in figure 4, the combined 3 dimensions aims to increase the maturity of system implementation, improving system quality, maintainability, availability, and resiliency.

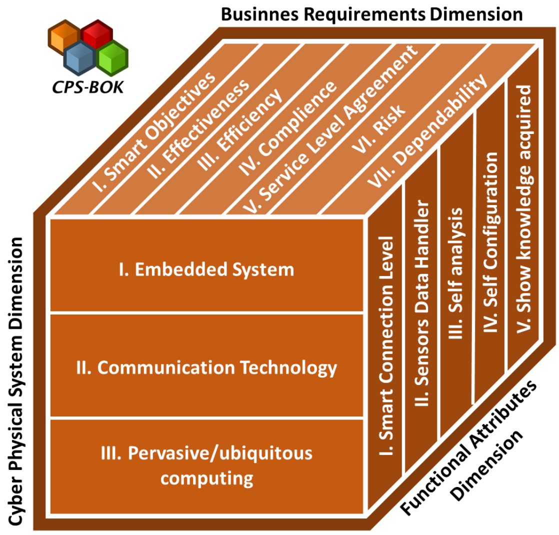

Figura 4. Cubic representation of CPS-AMD

2.1.2. CPS-FMK: Framework

It is a guideline for the implementation of the Cyber-Physical System project, which proposes the architectural components being instantiated. The figure 5 presents a synthesis of the architecture proposed by the CPS-FMK in parallel with the diagram proposed in the 5C architecture [Lee et al. 2015], which extended and benefited by the experience of this model. The 5C architecture presented here clearly defines, through a sequential workflow manner, how to construct a CPS from the initial data acquisition, to analytics, to the final value creation [Lee et al. 2015].

2.1.3. CPS-EMM: Evaluation Maturity Model

The CPS-EMM presents a guideline, based on concepts of the "performance-by-construction" maturity level[Campos and R. Haverkort 2015], for evaluating projects of the Cyber-Physical System, qualifying the maturity of the construction of the project. The CPS-EMM guide proposes a model that maps and correlates the fundamental elements of the CPS-AMD and CPS-FMK guides to maturity levels, as shown in figure 6. The main objective is to monitor the results

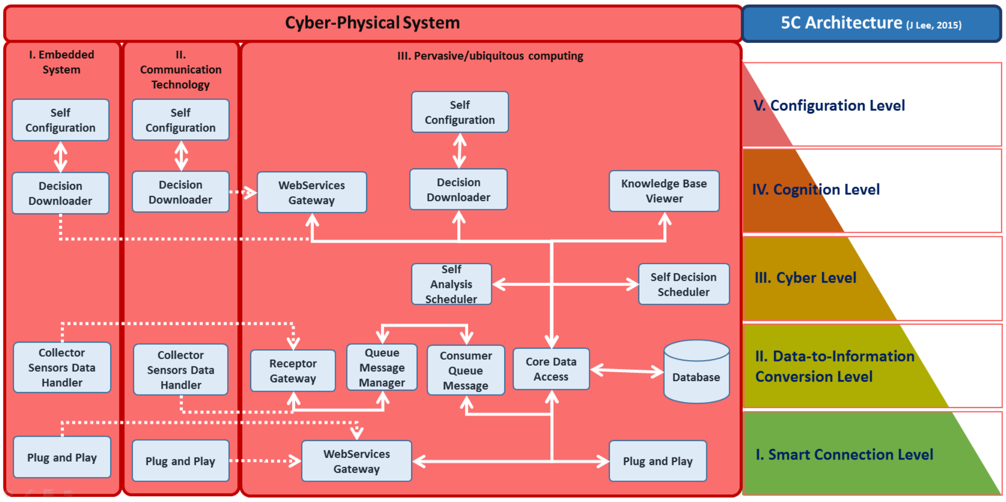

Figura 5. CPS-FMK implementation diagram

obtained with the steps CPS-AMD and CPS-FMK to verify the adherence of the system to the proposed levels of architectural maturity. At this stage it is also possible to identify problems and elements to be improved.

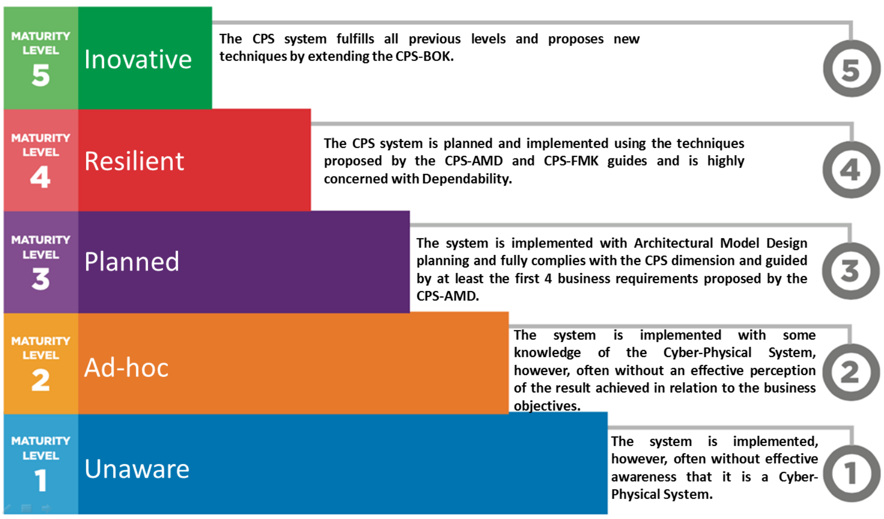

Figura 6. CPS-EMM implementation diagram

2.1.4. CPS-IMM: Increase Maturity Model

The CPS-IMM presents a set of good practices that integrate the learning generated by the entire process of planning and implementing the system and where corrective actions are taken based on what has been verified. That is, one must correct the faults found in previous steps. Then, after investigating the causes of these faults or deviations and after acting to solve them, the cycle must be restarted in order to increase the maturity of the CPS.

3. CEMADEN: A CASE STUDY

The Brazilian National Center for Monitoring and Alert Natural Disasters - CEMADEN, created has the mission to monitor the natural hazards in susceptible risk areas of Brazilian counties to natural disasters and issue alerts with the final objective to reduce the number of fatal victims and material loss in whole country. This monitoring is performed through environmental parameters that make up the prediction of possible natural disaster warnings. This characteristic qualifies the CEMADEN's observational network as a critical CPS and public safety. After evaluation, we came to the conclusion that the CEMADEN's observational network meets all the typical requirements of a CPS, covering the 3 elements of the CPS dimension from CPS-AMD. However the network has been fully implemented with CPS unawareness, there was no architectural planning and finally, it does not provide elements that address the dependability of the system. Based on this evaluation, the CEMADEN's observational network is considered at level 1 of maturity (Unaware), although the business critically requires at least at level 4 of maturity (Resilient) CPS-EMM. Details of the evaluation is not presented due to sake of space, but, special care is needed in terms of the reliability and availability of the CEMADEN network in order to increase maturity level.

How to increase CEMADEN's CPS maturity with reliability and availability properly required by the observational network for monitoring and alert natural disaster? To reach maturity level 4, the observational network would need to be redesigned on the basis of the CPS-BOK, reusing the existing infrastructure. Remembering that the network is at level 1, so the process of increasing maturity should begin with CPS-IMM. In this step, all failures must be evaluated in conjunction with business requirements so that all learning can be integrated into the process. This step is one of the most important because its result will guide the next steps, that is, it will define the quality required for the maturity evolution. The next step is the CPS-AMD, which, based on the generated analysis of the CPS-IMM, should present the evolution planning of the CPS systems. In this step the fundamental requirements will be evaluating to increase desired CEMADEN's CPS maturity, such as Dependability Requirements. Following the process, the next step is the implementation using the CPS-FMK. This step materializes the planned system. The correct implementation represents the success of CPS. The CPS-FMK suggests important components for CEMADEN, such as the "Collector Data Handle" and the "Self Analysis Scheduler". These components are responsible for generating reliability, availability metrics and, most importantly, predicting possible failures. This information is important to ensure strategic management of the observational network, mainly improving the efficiency and effectiveness of maintenance. Finally, in order to ensure that the implementation was successful, the CPS-EMM should be performed. This step will assess the maturity achieved after the evolutionary cycle of the CPS-BOK.

4. CONCLUSION

This work presents in a synthetic form the proposed CPS-BOK, which is a methodology for evaluation CPS design, implementation, and maintenance by means of a framework oriented to the CPS business. Organized in a set of guidelines, CPS-BOK support evolutionary analysis of the elements of a CPS under perspectives of development and maintenance as well. A preliminary application of CPS-BOK in CEMADEN observational network has demonstrated it is a useful approach. The next step of this work is to validate the applicability of CPS-BOK in other domains.

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