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A Review on Cyber-Physical Systems: Models and Architectures

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***Abstract*—The increasing proliferation of Cyber-Physical Systems (CPS) in industry and academia bring researchers to work on CPS architectures and models seeking for enhancing the performance and gaining the full potential of the system. This work aims to provide a holistic view of the initiatives done during the last five years in modeling and designing CPS. We define three major classes of CPS covering Smart Healthcare, Smart Manufacturing, and Smart City. We also provide a review of the recent developed architectures and models for each class. Based on the surveyed literature, we identified many open issues and we suggested possible future research directions.**

***Index Terms*—Cyber-Physical Systems, Smart Healthcare, Smart Manufacturing, Smart City, CPS Architecture, CPS Model.**

I. Introduction

CYBER-PHYSICAL SYSTEMS (CPS) or "smart" systems are interacting networks of physical and computational components. These systems will provide the foundation of our critical infrastructure, form the basis of emerging and future smart services, and improve our quality of life in many areas. *"The potential of CPS to change every aspect of life is enormous. Concepts such as autonomous cars, robotic surgery, intelligent buildings, smart electric grid, smart manufacturing, and implanted medical devises are just some of the practical examples that have already emerged"* [1]. The emergence growth of CPS led it to encompass many domains and enabled various applications in different areas. Thus, it opened the need for standards to design an accurate CPS and reference architectures, as well as models to define the best practices for implementation and deployment.

Novel approaches for designs and architectures that empower coherent integration of communication, control, and computation for CPS deployment were proposed in different level of abstractions seeking for resolving new encountered challenges, such as, heterogeneity, interoperability, and security, etc [1], [17]. However, new technologies will enable new challenges, thus new models and architectures will be needed. In this paper, we summarize the architectures and models of CPS proposed, during the last five years. The main contributions of this paper are: 1) Presenting the main application classes of CPS, 2) Analyzing and Comparing the existing CPS architectures, 3) Comparing the recent design approaches for CPS with respect to their models, tools, benefits, and validation, and 4) Highlighting the current research challenges and provide our vision for promising research. In the next section, we detail the discussed objectives.

II. CPS Classes

This section develops the main application classes of CPS.

1) Smart Healthcare: The revolution of the CPS brings healthcare systems to a higher level of reliability and flexibility. Indeed, the task of monitoring, controlling the medical devices or even following the patients has become more easier and 'smarter' for caregivers by providing smart operating rooms and hospitals, live image-guided surgery, and dynamic configurable/controllable sensors and medical devices [2].

2) Smart Manufacturing: CPS is taking a central role in new-generation smart manufacturing. *"The term smart manufacturing refers to a future state of manufacturing, in which real-time transmission and analysis of data from across the product life-cycle, along with model-based simulation and optimization, create intelligence to yield positive impacts on all aspects of manufacturing"* [3]. Smart manufacturing has took the attention of many researchers and has become an inevitable trend. Thus, many definitions, architectures, frameworks, models were proposed as well as research challenges.

3) Smart City: A Smart City can be considered as a Cyber-Physical Socio-Technical System. It refers to a city that uses ICT to provide efficient services and improve the life of citizens. *"Enabling such a Smart City setting requires a cyber-physical infrastructure combined with new software platforms and strict requirements for mobility, security, safety, privacy, and the processing of massive amounts of collected data"* [4].

III. CPS Architectures

Due to its direct impact on the system performance, the design process is considered as the most critical aspect in CPS deployment. However, there is no unified system framework designed for all CPS applications. Many architectures have been proposed: cloud-based architecture, SOA-based architecture, multi-tier architectures. The proposed architectures depend mainly on two facts: (1) *the system requirements* (e.g. real time, security, resiliency, etc.) or (2) *the application details* (e.g. medical, manufacturing, power grid, etc.). In our work, we focus on the second approach which classifies different architectures based on the four mentioned above classes.

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1) Smart Healthcare: Zhang *et al.* [5] presented a cloud and big-data architecture for HEALTH-CPS. Their solution consists of three-layer: data collection, management, and application service layer. The main purpose is to show the strength of big-data analysis and cloud computing in enhancing the performance of the healthcare system. Silva *et al.* [6] introduced a model-based architecture for Medical CPS. It comprises three main models: patient models, device models, and MCPS model (controller). These validated models will help developers to make test cases for their applications. Further, the authors developed a controlled experiment of a clinical scenario to validate the architecture elements. Sakr et Elgammal [7] proposed a layered architecture for smart health analytic services. The proposed architecture comprises mainly four layers including: data connection, data storage, management layer, analytic layer, and the presentation layer. Many applications scenarios and uses cases have been presented for validation.

Sultanovs *et al.* [8] developed a centralized healthcare CPS architecture that consists of four main layers: physical layer, communication layer, intelligent service, and data analysis layer. The architecture aims to improve the patients treatment quality as well as their assistance from monitoring to automating the treatment process. However, the architecture still need test and validation.

2) Smart Manufacturing: Liu et Jiang [9] introduced a CPS architecture in shop floor to deal with the common CPS challenges and enable intelligent manufacturing. The proposed architecture consists of three-layer architecture: physical connection, middle-ware, and computation layer. A small-scale flexible automated production line was taken as an example to validate their architecture. In the same direction, Bagheri *et al.* [10] presented a 5C CPS architecture as unified framework enclosing five layers: connection, conversion, cyber, cognition, and configuration. The architecture aims to enhance efficiency and resiliency of manufacturing systems using advanced analytic over formal deployment of CPS. The architecture has been validated over a case of study about intelligent band-saw monitoring system.

Huang *et al.* [11] proposed a four layer security architecture for industrial CPS to preserve security at each layer of the industrial CPS (management layer, supervision layer, RT control layer, and physical layer). A networked water level control system (NWLCS) on AADL simulation environment was introduced as a case study. A new Paradigm of Cyber-Physical Manufacturing Cloud was introduced by Liu *et al.* [12] that targets reducing the gaps between CPS, cloud computing, and manufacturing. The proposed service is an oriented layered architecture of CPMC which divided into: resource layer, resource virtualization layer, core cloud layer, and application layer. A test-bed based on the presented architecture of CPMC with two manufacturing sites was developed and evaluated over distinct factory processes scenarios. Also, an Evolvable Assembly Systems software distributed architecture was presented by Chaplin *et al.*

3) Smart City: Gaur *et al.* [13] presented a multi-level architecture for smart cities. The proposed architecture is composed of four main layers: data collection, data processing, data integration and reasoning, device control and alerts. The architecture aims to exploit big volumes of smart city data using semantic web techniques and Dempster-Shafer uncertainty reasoning rules. Some real-time scenarios have been described without presenting a real case study to validate the architecture. In order to support a big number of applications and services in smart cities, Tang *et al.* [14] proposed a layer-based fog-computing architecture. The solution divides a smart city architecture into four layers: data centers, intermediate computing nodes, edge computing nodes, and sensing networks on critical infrastructure. Distinct case studies have been studied using smart pipeline monitoring system for the architecture validation. To enable sustainability, innovation and standardize smart city design, Anthopoulos [15] proposed a common multi-tier ICT smart city architecture. It has been divided into five layers: composed from Natural Environment, hard Infrastructure (Non ICT-based), hard infrastructure (ICT-based), services, soft infrastructure. However, the architecture needs test and validation. Clement *et al.* [16] proposed a service-oriented reference architecture for smart cities to overcome the difficulty of integrating intelligent systems composed smart city in one architecture. An abstract SG was provided as a case study.

IV. CPS Models

The increasing number of CPS applications and their complexity made the design of such systems a very difficult task. Therefore, researchers shed the light on model-based approaches to help constructing complex comportment aspects of the system and afford a good vision for designing CPS applications. Indeed, different methodologies, techniques and tools were proposed for modeling cyber-components and physical processes. Hence, we survey works that have been done in model-based design approach.

1) Smart Healthcare: Oueida *et al.* [18] presented a smart healthcare reward-based model to overcome one of the difficult challenges in healthcare systems which is resource allocation. The model turns around three satisfaction terms: patient satisfaction, owner satisfaction, and resource satisfaction. The reward-based model has been validated through several experiments and simulations. Further, Silva *et al.* [19] defined a model for ensuring the safety of patients when testing and validating medical CPSs. Vital signs generated using statistical regression models and a patient's model dynamics will be created. The model has been validated over the proposed baseline patient model.

Using multi-agent modeling, Polu [20] presented a versatile healthcare system that incorporates remote sensor modules and data mining techniques. Using mobile computing for enhancing interaction among patients, caretakers, doctors. The proposed multi-agent system comprises six mains agents: patient observing agent, authentication agent, administrator agent, supervisor agent, caretaker agent, and decision support

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TABLE I
SUMMARY OF CPS ARCHITECTURES

Application	Architecture	Validation	Contribution
1	Layered cloud and big-data architecture	Testbed based on Robot technology	[5]
	Model-based architecture	Controlled experiment of a clinical scenario	[6]
	Layered architecture	Field tests applications scenarios and uses cases	[7]
	Layered centralized architecture	/	[8]
2	Layered architecture	Small-scale production line case study	[9]
	5C-based architecture	Intelligent bandsaw monitoring system case study	[10]
	Layered security architecture	Simulation of a networked water level control system	[11]
	Layered Service-Oriented architecture	Testbed of CPMC with two manufacturing sites	[12]
3	Layered architecture	/	[13]
	Layered distributed fog-computing architecture	Smart pipeline monitoring system case studies	[14]
	Multi-tier architecture	/	[15]
	Service-oriented architecture	Abstract SG case study	[16]

CPS Applications: 1. Smart Healthcare, 2. Smart Manufacturing, 3. Smart City.

agent. Hao *et al.* [21] proposed an application of big-data in medical field. They model big medical cognitive system using N-ary formal concept analysis aiming to enable systematic and high-quality big-data representation and association. The model needs to be tested and validated over real scenarios.

2) Smart Manufacturing: Weyer *et al.* [22] proposed a framework that enables flexible connection, interaction, and synchronization between CPS and multi-disciplinary simulation along the production life-cycle. The framework was built under three-tier architecture: application tier, logic tier, and data tier. It has been validated within an automotive industry.

A big-data analytic model was proposed by Shin *et al.* [23] in order to predict tolerance efficiency of power consumption in manufacturing. The model used STEP-NC for planning data and MTConnect for monitoring data. For validation, a prototype has been implemented with a case study on turning machining. Strang et Anderl [24] proposed a component data model based on UML and used in an assembly system process. The model enables storing data about various system components. Therefore, this data could be used for making various decisions. To demonstrate the benefits of this component data model, an example of simulating one assembling step of a pneumatic cylinder has been presented. Takahashi *et al.* [25] discussed various reference models on smart manufacturing and proposed a unified reference model for smart manufacturing (Unified Reference Model - Map & Methodology (URM-MM)) which would support ecosystem developments. The model is still in its early stage of development and the authors would bring it to more test through case studies and more enhancements.

3) Smart City: Abu-Mata [26] defined a software reference architecture for smart city based on SOA and software engineering disciplines to serve as the foundation to create smart cities blueprints. A meta-model with eight views was presented using UML including: capability view, participation view, place view, service view, data view, application view, infrastructure view, and business process view. Fernandez-Anez *et al.* [27] presented an integrated conceptual model for a smart city to mirror the important mission of stakeholders in developing smart cities and facing urban challenges. The model has been validated on vienna smart city.

Longo *et al.* [28] discussed a generic conceptual model for smart cities based on multi-agent system which consists mainly from several views and descriptions explaining distinct means of smart city, especially uses, characteristics, interfaces, behaviors, standards, etc. The model frames the most important standards and requirements for designing a smart city architecture. Sarkar *et al.* [29] proposed an intelligent decision making model for cloud service provider to overcome the difficulty and the complexity of choosing the best security policies that fits-in to be explored on smart city. The proposed model is based on a statistical method called multivariate normal distribution. Other methods like fuzzy multi-objective optimization technique and Bat algorithm are also used for optimization. To validate the model, a real data set of hosting Plans of Enterprise Cloud 4C has been used.

V. CHALLENGES AND CONCLUSIONS

We outline the research challenges that could improve CPS architectures and models as follows:

- At first glance, we can easily notice that multi-layer architectures and service-oriented architectures are the most used in almost all classes, where most of them focus on big-data analysis and cloud computing. Thus, it makes more sense due to the speedy growth of different techniques of data analysis as well as the big-data generated from CPS. Nevertheless, a security concern must be taken into consideration in future contributions.
- Further, data heterogeneity is an important issue to be discussed. Almost every architecture had the willing to overcome this challenge and most of them introduced cloud computing and data-driven technologies as a way of handling this challenge.
- Furthermore, the intrinsic heterogeneity, concurrency, and sensitivity to timing of CPSs poses many modeling challenges. Based on the current survey, we can notice that much of the current work in modeling has insufficiently strong semantics to adequately address these problems.

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TABLE II
SUMMARY OF CPS MODELS

Application	Model	Tool (theoretical or technical)	Validation	Contribution
1	Reward-based model	Maximum Reward Algorithm	experiments and simulations	[18]
	Safety ensuring model	Statistical regression models	Baseline patient model with evaluation	[19]
	Multi-agent model	/	/	[20]
	Big medical cognitive model	N-ary formal concept	/	[21]
2	Three-tier model	/	Volkswagen automotive production	[22]
	Big-data analytic model	STEP-NC, MTConnect	Turning machining case study	[23]
	Component data model	UML	Sim pneumatic cylinder assembling step	[24]
	Unified Reference Model	/	/	[25]
3	Multi-View Meta-Model	UML	/	[26]
	Conceptual model	/	Vienna Smart City strategy	[27]
	Multi-agent system model	/	/	[28]
	Intelligent decision making model	Fuzzy Multi-Objective Optimization	Hosting plans dataset	[29]

CPS Applications: 1. Smart Healthcare, 2. Smart Manufacturing, 3. Smart City

Indeed, each model focuses only on one aspect, and few of them aim to provide a unified model for a specific class. Relying on formal methods in combination with big data analysis might handle this aspect.

- Finally, it is worth mentioning that almost all the surveyed contributions were focusing on modeling the cyber part of CPS. Whereas, it is more interesting to model the physical and cyber parts to fit together and covering the social and computational dimensions of the application.

CPS have known significant interest in the last decade, and will continue to grow over the next years with new technologies and new heterogeneous environments. Thus, seeking for unifying and standardizing CPS architectures and models still a major concern that must be considered. At a glance, we defined major three classes in CPS. Further, we analyzed several architectures and modeling techniques for these classes. We showed that much of the current work in modeling has insufficiently strong semantics to adequately address CPS challenges and that there is still much work to be done for CPS data analysis and CPS deployment.

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