CYBER-PHYSICAL SYSTEMS: PRINCIPLES AND ARCHITECTURES: A REVIEW

Viren Babulal Shah
Research Scholar
Department of Commerce and Management
Sunrise University, Rajasthan.
getviren@gmail.com

Dr. Rajpal Singh
Research Guide
Department of Commerce and Management
Sunrise University, Rajasthan.

Abstract

Researchers are working on CPS designs and models in an effort to improve system performance and realize the full potential of the system as Cyber-Physical Systems (CPS) are becoming more and more prevalent in both business and academia. The goal of this study is to provide a comprehensive overview of the modeling and designing CPS projects carried out during the last five years. We outline three main categories of CPS, including smart cities, smart manufacturing, and smart healthcare. We also provide an overview of the most current models and architectures for each class. We identified a number of outstanding problems and potential future research topics based on the reviewed literature.

Keywords- *CPS Model, CPS Architecture, Cyber-Physical Systems, Smart Healthcare, Smart Manufacturing, Smart City.*

INTRODUCTION

Cyber-physical systems (CPS), often known as smart systems, are interconnected networks of electronic and mechanical parts. These technologies will serve as the cornerstone of our vital infrastructure, serve as the base for new and evolving smart services, and enhance many aspects of our quality of life. "CPS has the power to drastically alter all facets of existence. Some of the concepts that have already come into use include driverless vehicles, robotic surgery, intelligent buildings, a smart electric grid, smart manufacturing, and implanted medical devices. The development of CPS throughout time allowed for a wide range of applications in several disciplines. As a result, it created a need for standards to create precise CPSs and reference designs, as well as models to specify the ideal methods for deployment and implementation.

In an effort to address recent challenges, such as heterogeneity, interoperability, and security, new designs and architectures that enable coherent integration of communication, control, and computation for CPS deployment have been proposed at various levels of abstraction. However, as a result of new difficulties being made possible by new technology, new models and architectures will be required. In this essay, we review the architectural and CPS model proposals made during the last five years. This paper's main contributions include: 1) presenting the key CPS application classes; 2) analyzing and comparing the existing CPS architectures; 3) contrasting the most recent design approaches for CPS with respect to their models, tools, benefits, and validation; and 4) highlighting the current research challenges and outlining our vision for fruitful research. We go into more depth on the goals we covered in the last section.

CPS CLASSES

This section develops the main application classes of CPS.

Smart Healthcare: Healthcare systems now have a better degree of dependability and flexibility because to the CPS revolution. The availability of smart operating rooms and hospitals, live image-guided surgery, and dynamic configurable/controllable sensors and medical equipment has made it simpler and "smarter" for caregivers to monitor, control, or even follow patients.

Smart Manufacturing: With regard to next-generation smart manufacturing, CPS is playing a key role. The phrase "smart manufacturing" refers to a state of production where intelligence is generated by model-based simulation, model-based optimization, and real-time transmission and analysis of data from across the product lifecycle. Numerous academics have focused on smart manufacturing, which has emerged as a necessary trend. As a result, several definitions, architectures, frameworks, and models as well as research problems were put forward.

Smart City: An example of a cyber-physical socio-technical system is a smart city. It describes a city that use ICT to provide effective services and enhance the quality of life for residents. A cyber-physical infrastructure, new software platforms, and rigorous guidelines for mobility, security, safety, privacy, and the processing of enormous volumes of acquired data are all necessary to enable such a Smart City scenario.

CPS ARCHITECTURES

The design phase is regarded as the most crucial step in the implementation of CPS since it directly affects system performance. There isn't, however, a single framework for all CPS applications. Many other architectural designs have been suggested, including multi-tier architectures, cloud-based designs, and SOA-based designs. The two primary factors that affect the suggested architectures are (1) the system needs (such as real-time, security, resilience, etc.) or (2) the application specifics (such as medical, manufacturing, power grid, etc.). In our study, we concentrate on the second method, which groups various designs into the four categories indicated above.

Innovative Healthcare A cloud and big-data architecture for HEALTH-CPS was presented by Zhang et al. They used a three-tier approach to solve the problem: data gathering, management, and application service layer. The major goal of this project is to demonstrate how big data analysis and cloud computing may improve the efficiency of the healthcare system. A model-based architecture for Medical CPS was presented by Silva et al. It consists of three basic models: controller, device, and patient models. The creation of test cases for developers' apps will be aided by these verified models. The authors also created a controlled experiment based on a real-world clinical situation to verify the architectural components. A layered architecture for smart health analytic services was presented by Sakr et Elgammal. Data connection, data storage, management layer, analytic layer, and display layer are the four key layers that make up the suggested architecture. Numerous use cases and applications scenarios have been offered for approval.

A centralized healthcare CPS design with four primary layers—the physical layer, the communication layer, the intelligent service layer, and the data analysis layer—was created by Sultanovs et al. The design strives to enhance both the quality of the patient's care and their support, from monitoring to automating the process. The architecture still need testing and validation, however.

Innovative Manufacturing To address the typical CPS problems and allow intelligent production, Liu et Jiang proposed a CPS architecture in the shop floor. Three layers make up the suggested architecture: physical configuration, middleware, and compute layer. To test their design, a small-scale adaptable automated manufacturing line was used as an example. Bagheri et al. suggested a 5C CPS architecture as a unified framework with five levels, including connection, conversion, cyber, cognition, and configuration, in the same general direction. The design uses sophisticated analytics rather than a formal CPS deployment to increase the efficiency and resilience of production systems. An analysis of a case study with an intelligent band-saw monitoring system was used to verify the design.

To maintain security at each tier of the industrial CPS (management layer, supervision layer, RT control layer, and physical layer), Huang et al. suggested a four-layer security architecture. As a case study, a networked water level control system (NWLCS) on the AADL simulation environment was presented. By bridging the boundaries between CPS, cloud computing, and manufacturing, Liu et al. proposed a new paradigm for cyber-physical manufacturing clouds. The proposed service is based on CPMC's resource layer, resource virtualization layer, core cloud layer, and application layer oriented layered architecture. A test-bed based on the described architecture of the CPMC with two production locations was created and assessed using various scenarios for factory operations. Additionally, Chaplin et al. proposed a distributed software architecture for Evolvable Assembly Systems.

The Smart City A multi-level design for smart cities was proposed by Gaur et al. Data collecting, data processing, data integration and reasoning, device management, and alarms are the four key layers that make up the suggested architecture. The architecture uses Dempster-Shafer uncertainty reasoning principles and semantic web approaches to take use of large amounts of data from smart cities. A few real-world situations have been discussed without a relevant case study being provided to support the design. Tang et al. presented a layer-based fog computing architecture to serve a wide range of applications and services in smart cities. Data centers, intermediate computing nodes, edge computing nodes, and sensor networks on essential infrastructure make up the four levels that the solution splits into a smart city design. For the architectural validation, many case studies have been examined utilizing smart pipeline monitoring system. Anthopoulos suggested a standard multi-tier ICT smart city architecture in order to promote sustainability, creativity, and standardize smart city design. It is made of five layers: the natural environment, hard infrastructure (not based on information and communications technology), hard infrastructure (based on ICT), services, and soft infrastructure. The architecture must be tested and validated, nevertheless. To overcome the challenge of combining sophisticated systems that make up smart cities in one design, Clement et al. developed a service-oriented reference architecture for smart cities. As a case study, an abstract SG was given.

CPS MODELS

The complexity and volume of CPS applications make it very challenging to develop such systems. In order to develop complicated behavior features of the system and provide a clear vision for creating CPS applications, researchers have shed light on model-based techniques. In fact, several strategies, techniques, and tools for modeling cyber-components and physical processes have been developed. Therefore, we review the model-based design approachrelated activities that have been done.

Innovative Healthcare To address one of the complex problems in healthcare systems, resource allocation, Oueida et al. introduced a clever healthcare reward-based approach. Patient satisfaction, owner satisfaction, and resource satisfaction are the three concepts that the model revolves around. Through a number of simulations and experiments, the reward-based model has been shown to be accurate. Silva et al. have established a paradigm for safeguarding patient security throughout the evaluation and validation of medical CPSs. A patient's model dynamics and vital signs produced by statistical regression models will be built. Over the suggested baseline patient model, the model has been verified.

Polu introduced a flexible healthcare system that uses data mining methods and remote sensor modules using multi-agent modeling. increasing contact between patients, caregivers, and clinicians via mobile computers. The six primary agents in the proposed multi-agent system are the patient watching agent, the authentication agent, the administrator agent, the supervisor agent, the caretaker agent, and the decision support agent. Big data has been suggested as a use in the medical area by Hao et al. They use N-ary formal concept analysis to describe the large-scale medical cognitive system with the goal of enabling high-quality, systematic massive data representation and association. Real-world situations must be used to test and verify the model.

TABLE-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	Abstract SG case study	[16]

	architecture		

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

Smart Manufacturing: Along the production life-cycle, Weyer et al. provided a framework that provides flexible connection, interaction, and synchronization between CPS and multidisciplinary simulation. The framework was created using a three-tier design, which includes an application, logic, and data layer. It has received industry validation in the car sector. Shin et al. [23] suggested a big-data analytical approach to forecast the tolerance efficiency of power usage in manufacturing. The model used MTConnect for monitoring data and STEP-NC for planning data. A prototype has been put into use with a case study on turning machining to validate it. A component data model built on UML and utilized in an assembly system process was suggested by Strang and Anderl. The concept makes it possible to store information about numerous system components. As a result, several judgments might be made using this data. An example of simulating one stage of the assembly of a pneumatic cylinder has been provided in order to highlight the advantages of this component data model. A unified reference model for smart manufacturing (Unified Reference Model - Map & Methodology (URM- MM)) that would promote ecosystem advancements was developed by Takahashi et al. after discussing several reference models for smart manufacturing. The authors want to put the model through additional testing via case studies and refinements since it is still in its early stages of development.

Smart City: To serve as the basis for developing blueprints for smart cities, Abu-Mata designed a software reference architecture for them based on SOA and software engineering disciplines. Eight perspectives of a meta-model, comprising capability view, participation view, location view, service view, data view, application view, infrastructure view, and business process view, were described using UML. An integrated conceptual model for a smart city was given by Fernandez-Anez et al. to reflect the crucial role stakeholders play in creating smart cities and addressing urban difficulties. The model has been tested in the smart city of Vienna.

A general conceptual model for smart cities based on multi-agent systems was explored by Longo et al. It consists mostly of many viewpoints and descriptions detailing different ways to implement smart cities, including their applications, features, interfaces, behaviors, standards, etc. The model outlines the most crucial guidelines and specifications for creating an architecture for smart cities. For cloud service providers, Sarkar et al. developed an intelligent decision-making methodology to get around the challenge and complexity of selecting the optimal security rules that are compatible with research on smart cities. Multivariate normal distribution, a statistical technique, is the foundation of the suggested model. There are other techniques for optimization, such as the fuzzy multi-objective optimization methodology and the Bat algorithm. A genuine data set of hosting Plans of Enterprise Cloud 4C has been utilized to verify the model.

CHALLENGES AND CONCLUSIONS

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

- At first look, it's clear that multi-layer and service-oriented architectures—the majority of which concentrate on big-data analysis and cloud computing—are the most prevalent in practically all classes. As a result, it makes more sense given the rapid development of various data analysis techniques and the vast data produced by CPS. Nevertheless, future contributions must take into account a security issue.
- Furthermore, it is crucial to talk about data heterogeneity. Almost all architectures were ready to address this issue, and the majority of them incorporated cloud computing and data-driven technologies as solutions.
- The inherent variety, concurrency, and temporal sensitivity of CPSs also provide several modeling challenges. According to the present study, we can see that a lot of the modeling work being done now lacks the necessary semantic strength to effectively address these issues.

TABLE -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	Fuzzy Multi-Objective	Hosting plans dataset	[29]

	model	Optimization		

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

Each model does, in fact, concentrate solely on one component, and only a handful attempt to provide a cohesive model for a particular class. Big data analysis combined with formal approaches might take care of this issue.

Finally, it is important to note that almost all of the contributions included in the survey focused on modeling the cyber component of CPS. However, modeling the physical and cyber components to work together while taking into account the social and computational aspects of the application is more fascinating.

With new technologies and new diverse contexts, CPS have seen increasing attention over the last ten years and will continue to expand in the next years. As a result, the need to standardize and combine CPS designs and models remains a crucial issue. We quickly identified the three main classes in CPS. We also examined several designs and modeling approaches for these classes. We demonstrated that there is still considerable work to be done for CPS data processing and CPS deployment, and that most of the present modeling work has sufficiently robust semantics to appropriately handle CPS difficulties.

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