Cyber Physical Systems: Theory and its Applications

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Abstract:- Cyber Physical Systems (CPS) are a new research subject that has piqued the interest of many scientists. It is transmuting the way people interact with established systems. Beginning with a definition of CPS, the paper goes on to examine the necessity for these systems to be implemented in many application areas, as well as the research hurdles of establishing an acceptable formalism that represents more than networking and information technology.

Keywords:- *Cyber-Physical Systems, Architecture, Modeling, Design, Dependability.*

I. INTRODUCTION

We can engage with people and obtain relevant information from all over the world in a very short amount of time by using the Internet. As a result, the Internet has changed the way we conduct research, conduct studies, run our businesses and services, and even have fun. There is, however, a disconnect between the cyber world, where information is exchanged and updated, and the physical world, where humans live. In addition, the sector has been changed by a digital revolution during the previous two decades. This shift isn't a decision; it's a result of long-term economic and technical developments that have produced an environment that allows for and necessitates a wide range of new capabilities. Some early examples of a new system generation (e.g., quality, safety, and efficiency critical infrastructure; integrated, self-optimizing transportation systems and vehicles; environmentally friendly and energy efficient air planes and automobiles; advanced health care via increased automation, integrating smart devices, etc.) have resulted from technological advances in recent decades. These early instances highlight the need for a new generation of systems known as Cyber-Physical Systems (CPSs) that encompasses more than networking and information technologies, as well as the integration of information and knowledge into physical things. A new generation of intelligent and autonomous systems could be produced by integrating perception, communication, learning, behavior generation, and reasoning into such systems (CPS-Steering-Group (2008)).

The following is a breakdown of the paper's structure. Section 2 examines the notion of CPS, which was just introduced, from a variety of perspectives, including definitions, characteristics, and attributes. Section 3 highlights the need for the CPSs implementation in various application areas and their characteristics for several of these domains. The research issues in defining an acceptable formalism for these classes of systems are presented in Section 4. (CPSs). The core of the paper and the subject of section 5 is a discussion of the state of the art in the primary CPSs research areas: generic architecture, design principles, modelling, dependability, and some implemented examples and finally section 6 marks the conclusion for the research made in this paper.

II. LITERATURE REVIEW

Cyber-physical systems comprises of sensors, actuators and systems which are connected through a high-fidelity network, adding to the functionalities of the system, such as real-time data transfer, which allows the interaction between various systems. The interaction of the physical and computational components leads to futuristic implementations of Internet of Things (IoT). Real time applications which can manage many environmental datasets are supported by CPS and IoT. In recent times , more developments in CPS have improved the association between humans and CPS in the loop. Distinctive ideas related to CPS have been explored such as proposing an intelligent CPS, reducing bandwidth and increasing the energy efficiency of integrating mechanisms which supports autonomy and adaptation. We have several benefits of this CPS. For instance, self adaptation, fault-prediction and autonomy.

III. CPS CONCEPT

The newly coined CPS term will be required to enable the construction of a modern vision for social services that transcends time and location to hitherto unseen dimensions (CPS-Steering-Group (2008)). CPS is the junction of computation and physical processes, rather than the merger of the physical and the cyber (Lee and Seshia, 2011). Shankar Sastry of the University of California, Berkeley, gave a complex CPS definition in 2008: "A cyber-physical system (CPS) integrates computing, communication, and storage capabilities with monitoring and/or control of entities in the physical world, and must do so reliably, securely, efficiently, and in real-time."

CPSs are not typical embedded systems or real-time systems, today's sensor networks, or merely desktop applications, but they do have several distinguishing properties, as Huang (2008) points out and as shown below: (1) Cyber capabilities in every physical component; (2) Networked at multiple and extreme scale; (3) Dynamically reconfiguring/reorganizing; (4) High degrees of automation, control loops must close; (5) In some cases, operation must be dependable and certified; (6) Cyber and physical components are integrated for learning and adaptation, higher performance, self-organization, and autoassembly.

The following core properties define CPSs, as they do all information and communication systems: (1) functionality; (2) performance; (3) dependability and security; and (4) cost. Usability, administration, and adaptability are three more aspects that influence system dependability and security. The following are the main characteristics of CPSs: (1) Input and feedback from/to the physical environment-protected communication channels exist; (2) Management and distributed control - federated method (3) Requirements for real-time performance; (4) A wide geographic distribution with no physical security components in diverse locations; (5) Control systems with a very high size (SystemOfSystems - SoS).

IV. APPLICATION DOMAINS

Cyber-physical systems have a number of benefits: they are efficient and safe, and they allow individuals to collaborate to create complex systems with new capabilities. Critical infrastructure control, safe and efficient transportation, alternative energy, environmental control, telepresence, medical devices and integrated systems, telemedicine, assisted living, social networking and gaming, manufacturing, and agriculture (Huang (2008), Lee (2008)).are just a few of the domains where cyber-physical technology can be used. Water supply (storage, treatment, transport and distribution, waste water); electricity generation, transmission and distribution; gas production, transport and distribution; oil and oil product production, transport and distribution; and communications are examples of critical infrastructure.

The paper Wan et al. (2010) present some requirements that CPSs should meet based on the business sectors in which they will be used: automotive, environmental monitoring/protection, aviation and defence, critical infrastructure, and healthcare (Table 1). The physical platforms, which support CPSs, offer the five capabilities listed below: computing, communication, precise control, remote cooperation, and autonomy.

Unlike traditional embedded systems, CPSs interact directly with the physical world, making environmental change detection and system behaviour adaption major difficulties in their design.

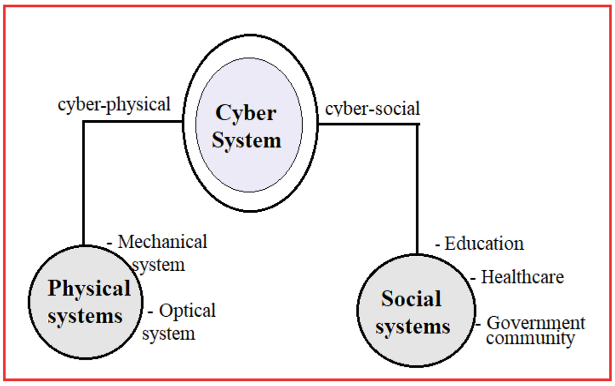

Fig 1: Domains

V. RESEARCH CHALLENGES

Communications and networking, systems theory, mathematics, software engineering, computer science, and sensors are examples of isolated sub-disciplines. As a result, several modelling tools and formalisms are used to build and evaluate digital systems. In order to make adaptable analysis, each representation emphasises some characteristics while ignoring others. Formalism often depicts either cybernetic or physical processes as essential to create CPSs, but not both.

The following paragraphs outline the primary research directions required in the CPSs sector, which is currently in its early stages:

- *Abstraction and Architecture:*

Innovative methods to abstractions (formalisms) and architectures are needed to enable control, communication, and computation integration for the rapid design and implementation of CPS.

They should enable the flexible, efficient, and robust integration and interoperability of diverse systems that make up CPSs. (Baheti and Gill (2011)).

- *Distributed Computations and Networked Control:*

It refers to new frameworks, algorithms, methods, and tools for time-and event-driven computing, software, variable time delays, failures, reconfiguration, and distributed decision support systems that are designed to meet the high reliability and security requirements for heterogeneous cooperating components that interact through a physical environment (Baheti and Gill (2011)).

- *Verification and Validation:*

Hardware and software components, as well as the systems they create, must progress beyond their current state and achieve a high level of reliability, re-configurability, and certification when applicable. The research directions include new models, algorithms, methodologies, and tools for verifying and validating software components as well as the overall system from the early design stage (Baheti and Gill (2011)).

The following scientific problems in the realm of CPSs were also noted in the CPS Steering Group Report from March 2008 (CPS-Steering-Group (2008)): (1) In design flows, realign the abstraction layers - abstractions must encompass physical concepts like time and energy. These improvements to the levels of abstraction will enable the creation of calculations with physical properties and physical system dynamics that are resistant to implementation errors. (2) The creation of semantic foundations for the composition of heterogeneous models and modelling languages that explain various physics and their associated logics; (3) The development of a new concept of compositionality in heterogeneous systems that enables the design of huge, networked systems that satisfy critical physical features and reliably offer desired functionality; 4) The creation of a technology for partially compositional property prediction; (5) The development of a model-based, exact, and predictable technology foundation for system integration. (6) The creation of a new infrastructure for CPS design automation that is nimble; (7) The development of new open architectures for CPSs that will allow the development of national-scale and global-scale capabilities; (8) The development of architectures and tools for reliable CPSs made up of unreliable components and resilient CPSs that will withstand malicious attacks from the cyber or physical domains. To shorten design timelines and boost CPS confidence, these designs should make use of open systems technologies. Table 21 in CPS-Steering-Group (2008) emphasises the importance of some of the aforementioned difficulties for several of the CPSs' target industries: aviation, defence, automotive, energy, and healthcare.

VI. RESEARCH AREAS

CPS research is focused on the following areas at the international level: the definition of a generic architecture, the definition of CPS design principles in their application domains, CPS modelling, CPS dependability assurance, and CPS implementation (for critical infrastructure control and beyond).

A. *Generic Architectures for CPSs*

The architecture of a CPS should ensure that cyber and physical elements are treated equally. The software architecture is a nice place to start, but the concept should be expanded to CPS by creating new vocabulary for physical and cyber-physical aspects that are needed to understand system behaviour.

The paper Prototype Architecture for Cyber-Physical Systems" (Tan et al. (2008)) present a representative prototype architecture of the CPS concept, which highlights the cyber world represented by events/information as an abstraction of the real physical world governed by semantic laws, evolving the typical architecture of embedded systems and aligning it to current technological requirements. The following is revealed by this architecture: (1) Global Reference Time - supplied by the next-generation network and acknowledged by all CPS components; (2) Event/Information Driven - events are "raw facts" provided by sensor units/humans or "actions" performed by actuator units/humans, and information is an abstraction of the physical world created by system control units or humans through event processing. (3) Quantified Confidence - a mechanism for calculating the certainty of events/information at any given time; (4) Publish/Subscribe Scheme: Each CPS control unit subscribes to important events/information depending on its system purpose, and also publishes events/information as needed. (5) Semantic Govern Laws - These laws, which have the event-condition-action form, accurately control system behaviours in the context of the environment based on user-defined situations or scenarios; (6) New Networking Techniques - establish a global reference time, as well as new event/information routing and data management schemes.

The paper "A Software Architecture for Next-Generation Cyber-Physical Systems" (West and Parmar (2006) proposes to build a CPS based on a software architecture composed of a collection of application-specific services that organises itself using the most appropriate communication and isolation methods between services. In the development and verification of a software system for a given application, the software architecture must take into account the automatic composition of services in order to satisfy the application restrictions, given underlying hardware restrictions, as well as the hardware heterogeneity.

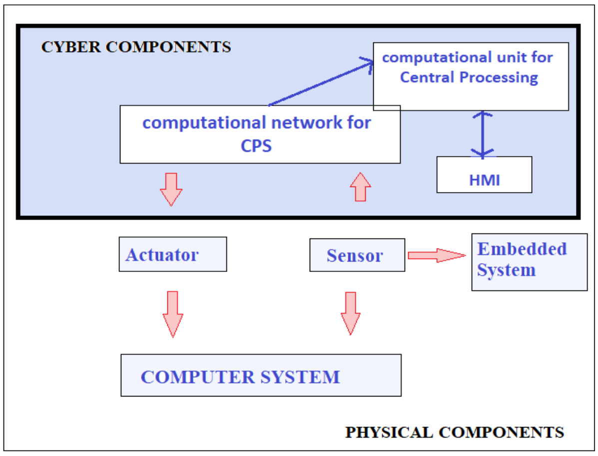

Fig 2 : Basic Architecture of CPS

B. *CPSs Design Principles*

Because CPSs are still in their infancy, there are a few scientific studies in the specialist literature (Sha et al. (2008), Huang (2008), Lee (2008), Baheti and Gill (2011)) that seek to establish specific design principles of these systems in their domains of application.

The study "Cyber-physical Systems in Industrial Process Control" (Wang et al. (2008)) delves into the design concepts of large-scale systems with heterogeneous components that can be solved using a new unifying network and control theory. The study looks at real-time operation in a heterogeneous system, which necessitates a unified theory of real-time operation that incorporates both existing and unique conclusions.

Control, systems, and software engineering are three main disciplines that are increasingly needed in the design of complex systems and CPSs. Due to the heterogeneity of CPSs, the study "Composition of Cyber-Physical Systems" (Sztipanovits (2007)) states that the design decomposition by orthogonal parts of the problem cannot be implemented in the case of CPSs. Compositionality in the design process is also limited by the substantial interdependencies between the CPS components. The system interdependencies must be abstracted, which can be accomplished through the creation of new modelling tools.

C. *CPS Modeling*

The modelling of CPSs is crucial to the implementation of these systems. In recent years, modelling has progressed, resulting in the emergence of "meta-modeling" techniques and a suite of "meta-programmable" tools that enable the introduction of domain-specific modelling languages, providing system designers with modelling concepts and notation tailored to the application domain. Sztipanovits (2007) shows how to use these modelling tools in CPSs modelling.

There is a semantic representation of the CPS interdependencies utilising semantic models implemented using multi-agent approaches (Talcott et al. (2008)). It propose event-based semantics as the cornerstone for CPSs semantics in their study "Cyber-Physical Systems and Events." (Talcott et al. (2008) For the following reasons, event-based semantics were chosen: (1) Rather than an internal state, the events address interactions between components and observations. This allows for higher-level specification and reasoning while also allowing for easy integration with more detailed data. (2) The events represent the concept of causal partial order, which reflects the physical reality that deciding a linear order for occurrences separated in space is impossible (and should not depend on it). Talcott et al. (2008) provide two compositional models, one for autonomous agents and one for interactive agents, in their work. The interactive agent paradigm appears to provide the kind of interaction required in CPSs. Modeling of CPSs must take into account the interaction of physical and cyber components, as well as communications, necessitating the creation of a formal framework for analysing these systems.

Bujorianu and Barringer (2009) present a formal methodology termed "Hilbertean formal methods" to give a denotational semantics for these systems in their paper "An Integrated Specification Logic for Cyber-Physical Systems." The technique blends denotational semantics with an algebraic model for physical processes to demonstrate the CPSs paradigm's holistic perspective, and it has the following major features: (1) It ensures consistency when dealing with deterministic and stochastic models; (2) It is built on a domain theoretic semantics; and (3) Environment features are specified as type classes.

D. CPSs Examples

Even if the CPS foundations have not yet been defined, there are research centres that have built previous examples of CPSs or have posed CPS development problems in specific application areas. In this part, we'll look at two cases.

Implemented CPSs for critical infrastructure control have been studied (Flores et al. (2008), Morris et al (2011). The research on CPS for energy infrastructure monitoring and control from the north of the United States is presented in the publication "Engineering Future Cyber-Physical Energy Systems: Challenges, Research Needs, and Roadmap" (Flores et al. (2008)). This system necessitates the integration of several heterogeneous physical levels and decision control networks, mediated by decentralised and distributed sensor/actuator structures coupled with an intelligence level, resulting in the development of a new modelling paradigm for advanced CPSs for energy with embedded security and distributed control.

A CPS for real-time hybrid testing of civil structures is shown in the publication "Cyber-Physical Systems for Real-Time Hybrid Structural Testing: A Case Study" (Huang et al. (2010)).

Hybrid testing combines the structure's physical components with computation models of other known structural components, greatly outperforming simply numerical or empirical methods. The CPS is unique in that it has a reusable design and is written in the C++ programming language, allowing both cyber and physical components to be integrated flexibly using XML-based configuration requirements. (West, R. and Parmar, G. (2006)).

VII. CONCLUSIONS

The article provides a brief overview of the current state of the art in the creation of CPSs, or future engineering systems, to which several governments (e.g., the United States and the European Union) are paying more attention by providing a variety of financing options. The authors will strive to establish a framework to ensure the dependability attribute of these systems by evaluating their behaviour, starting with this paper, which highlights the necessity to construct CPSs in many application areas, the research hurdles, and early achievements in this field. The evaluation entails the creation of a CPSs event-driven multi-agent model capable of combining physical and cyber components and allowing for the accurate assessment of their interdependencies. There is a robust need for unifying terminologies and system framework. Methodology of abstraction and robust theory both are needed in conceptualization, implementation and testing of CPS.

FUTURE SCOPE

Cyber-physical systems (CPS) is an booming terminology and it will transform how humans will interact with physical world CPS can be a further contribution to the challenges of our society and are exceedingly relevant in fields of applications. Economic sectors where CPS will bring dynamic changes majorly are manufacturing, healthcare, transportation etc.CPS can be referred to as the next general purpose technology that can bring industrial revolution.

REFERENCES

[1]. Avizienis, A., Laprie, J.C., Randall, B., and Landwehr, C. (2004). Basic concepts and taxonomy of dependable and secure computing. *IEEE Transactions On Dependable And Secure Computing*, 1, 11-33.
[2]. Baheti, R. and Gill, H. (2011). Cyber-physical systems. *The Impact of Control Technology*, 161-166.
[3]. Bujorianu, M. and Barringer, H. (2009). An integrated specification logic for cyber-physical systems. In *Proceedings of 14th IEEE International Conference on Engineering of Complex Computer Systems*, 291-300.

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[4]. CPS-Steering-Group (2008). Cyber-physical systems - executive summary. URL: http://varma.ece.cmu.edu/summit.
[5]. Flores, A., Quiles, E., and et. al. (2008). New formulation through arti_cial neural networks in the diagnosis of faults in power systems - a modular approach. In *Electronics, Robotics and Automotive Mechanics Conference 2008*, 411-416.
[6]. Huang, B. (2008). Cyber physical systems: a survey.
[7]. Huang, H.M., Tidwell, T., and et. al. (2010). Cyber-physical systems for real-time hybrid structural testing: a case study. In *Proceedings of ICCPS10*, 69-78.
[8]. Lee, E.A. (2008). Cyber physical systems: design challenges. *Technical report no. UCB/EECS-2008-8.*
[9]. Lee, E.A. and Seshia, S.A. (2011). *Introduction to embedded systems - a cyber-physical systems approach*. LeeSeshia.org.
[10]. Lin, J., Sedigh, S., and et.al. (2011). A semantic agent framework for cyber-physical systems.
[11]. Lin, J., Sedigh, S., and Miller, A. (2009a). A general framework for quantitative modeling of dependability in cyber-physical systems: a proposal for doctoral research. In *2009 33rd Annual IEEE International Computer Software and Applications Conference, 668-671*.
[12]. Lin, J., Sedigh, S., and Miller, A. (2010). Modeling cyberphysical systems with semantic agents. In *Proceedings of 34th Annual IEEE Computer Software and Applications Conference Workshops*, 13-18.
[13]. Lin, J., Sedigh, S., and Miller, A. (2009b). Towards Integrated Simulation of Cyber-Physical Systems: Case Study on Intelligent Water Distribution. In *2009 Eighth IEEE International Conference on Dependable,*
[14]. *Autonomic and Secure Computing, 690-695*.
[15]. Morris, T.H., Srivastava, A.K., and et. al. (2011). Engineering future cyber-physical energy systems: challenges, research needs, and roadmap.
[16]. Sha, L., Gopalakrishnan, S., and et.al. (2008). Cyber-physical systems: a new frontier. In *2008 IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing*.
[17]. Sztipanovits, J. (2007). Composition of cyber-physical systems. In *Proceedings of the 14th Annual IEEE International Conference and Workshops on the*
[18]. *Engineering of Computer-Based Systems (ECBS'07).*
[19]. Talcott, C., Wirsing, M., and et. al. (2008). Cyber-physical systems and events. *Software-Intensive Systems*, 101-115.
[20]. Tan, Y., Goddard, S., and Perez, L.C. (2008). A prototype architecture for cyber-physical systems. *SIGBED Review*, 5(1).
[21]. Wan, K., Man, K.L., and Hughes, D. (2010). Specification, analyzing challenges and approaches for cyber-physical systems (CPS). *Engineering Letters*, 18(3).
[22]. Wang, Y., Vuran, M.C., and Goddard, S. (2008). Cyberphysical systems in industrial process control. *ACM SIGBED Review - Special issue on the RTSS forum on deeply embedded real-time computing*, 5(1).
[23]. West, R. and Parmar, G. (2006). A software architecture for next-generation cyber-physical systems. In *Position Paper at the NSF Cyber-Physical Systems Workshop*.
[24]. Woo, H., Yi, J., and et. al. (2008). Design and development methodology for resilient cyber-physical systems. In *Proceedings of The 28th International Conference on Distributed Computing Systems Workshop*, 525-528.
[25]. Zhang, Y., Yen, I., and et. al. (2009). Optimal adaptive system health monitoring and diagnosis for resource
[26]. constrained cyber-physical systems. In *Proceedings of the 20th International Symposium on Software Reliability Engineering*, 51-60.