Cyber Physical Systems – Overview and Evolution
A tool for continuous evolution of systems

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Abstract Developing and maintaining great products and services comes with the challenges including trade-offs, dynamics, details, time pressure and economics. The revolution in the context of machines, often termed as Industry 4.0 symbolizes smart factories. Industry 4.0 is being characterized by ubiquitous and mobile internet, smaller and more powerful sensors and computing getting cheaper, artificial intelligence and machine learning. All these leverage the pervasive power of digitalization and information technology. The merger of Information Technology with Operational Technologies. Cyber Physical Systems merges computing, communication and control into an integrated form. The purpose of this paper is to discuss the reference models and architectures discussed in 5C architecture and C2PS reference architectures and develop insights on the skills, competencies and projects worth watching.

Index Terms Simulation, Cyber Physical System, Cloud, Internet of Things, Control Systems, Industrial Internet.

I. INTRODUCTION

Developing and maintaining great products and services comes with the challenges including trade-offs, dynamics, details, time pressure and economics [1]. Innovation has turned into more dynamic forms including collaborative or co-creation through a combination of standards, open architectures and open source. [2]. The revolution in the context of machines, often termed as Industry 4.0 symbolizes smart factories.

Industry 4.0 is being characterized by ubiquitous and mobile internet, smaller and more powerful sensors and computing getting cheaper, artificial intelligence and machine learning. It is this fusion of these technologies and their interaction across physical, digital and biological domains that makes the fourth industrial revolution different from previous revolutions. All these leverage the pervasive power of digitalization and information technology [3].

Many a barrier has been broken. For instance Software Architecture now considers Intelligent, Connected Systems as the paradigm [4]. A recent NASSCOM conference discussed the trend as Connected, Autonomous, Shared and Electric (CASE) [5]. The merger of Information Technology with Operational Technologies have led to several knee jerk reactions like - 'A bunch of IT guys invading the factory floor'. From a Control Systems practitioner standpoint, control systems getting closer to mainstream standards and technologies including web and information modeling. From an Information and Communication Technology(ICT) specialist, the view is about modernizing the Control Systems or Automation Systems space with latest technologies. While many consider data as the new oil, very few seem to be focused on extracting potential value from captured data. In case of manufacturing it is as low as 20 to 30 percent. A Smart City or Smart Grid or a Smart Factory requires the best of the converging worlds and need a shared vision. The architectural concerns and their differences are shown in Fig. 1 to facilitate an appreciation across the two practices. As Gaynor states, an appreciation of systems is necessary [6].

Characteristic	Systems	IT Applications
Time to market	1 Year and reducing	Much less, even in the range of months
Target Market	Specific market segments driven by reliability and cost factors	Targeted at applications more to improve productivity.
Expected Lifetime	10-30 years	1-5 years
Relevant owners	Phase wise owners from operator, engineer, end customer, decommissioning engineer	Owners could vary across projects.
Legacy support/Backward Compatibility Requirements	Strong requirements due to huge investments required	Weak requirements due to the fact that an IT implementation could reduce current operating cost.
Shutdown permitted	Shutdown only permitted as part of planned maintenance. Else could lead to losses	Shutdown is permitted within tolerance benchmarks.
Safety Critical	Yes, considering human lives and huge investments to be protected	Few implementations are safety critical, but not necessarily

Fig. 1. Comparison of Concerns in Systems and IT Applications.

Cyber Physical Systems becomes significant in this context. Brend Kramer explains origins of Cyber from Greek word Kubernetis meaning control skills. This evolved to English word govern [7]. Stipanovic characterizes Cyber Physical Systems as a new research direction at the intersection of physical, biological, engineering and information sciences. In short they integrate the dynamics of physical processes with those of software and communication providing abstractions and modeling design and analysis techniques for the integrated whole. The interactions lead to need for new techniques in design due to the concepts taking physical and virtual forms leading to new emerging scenarios otherwise called emergence. The disciplines involve embedded systems, computers and communication [8].

As in Fig. 2, the CPS merges the 3Cs computation, communication and control into an intelligent closed loop system between the physical world and the information world [9]. Though the initial use cases had more to do with Virtual Reality, Computer Vision and Immersed experiences, the field is fast evolving to support Systems across their Lifecycle.

One of the milestone works in the area is discussed by Michael Strage in the concept of Serious Play way back in 1999 [10]. The two publications discussing CPS in detail are the one discussing 5C Architecture which defines Cyber Physical Systems in detail and presents how Cyber Physical System and its layers act as transformative technologies for managing interconnected systems [11]. These bring together the Information Technology (IT) aspects and the Operational Technologies (OT) prevalent in manufacturing and power plants using control systems.

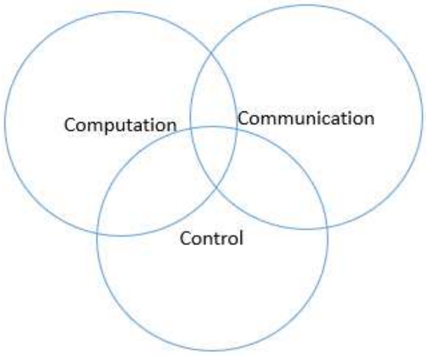

Fig. 2. Convergence of 3C's.

These systems have the following characteristics:

1. Closely Integrated.
2. Cyber Capability in every physical component and resource constrained.
3. Networked at multiple extreme scales.
4. Complex at multiple temporal and spatial scales.
5. Dynamically reorganizing/reconfiguring
6. High degrees of automation, control loops must close.
7. Operation must be dependable certified in some cases.

The purpose of the paper is to briefly navigate through the finer details of convergence as seen from two publications of 5C Architecture and C2PS, discuss the competencies and skills, ideas to kickstart action and future.

II. Overview

The 5C Architecture defines two main functional components:

1. Advanced Connectivity which ensures real-time data acquisition from physical and information from physical space.
2. Intelligent Data Management Analytics and Computational capability that constructs the cyber space.

As in Fig. 3, below, the Cyber Physical System is considered at various levels;

1. Smart Connection Level.
2. Data to Information Conversion Level.
3. Cyber Level.
4. Cognition Level.
5. Configuration Level.

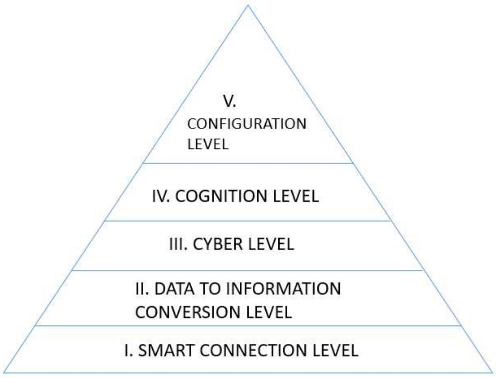

Fig. 3. 5C Architecture Model.

Each of these levels is described in detail in next steps:

I. Smart Connection Level
This level is about acquiring accurate and reliable data from machines and their components. The data measured by sensors are obtained from controllers and from enterprise manufacturing systems. The various types of data and selection of sensors play an important role here.

II. Data to Information Conversion Level
This level is about inference from data leading to meaningful information. This is used for prognosis and health management by calculating health value, estimating remaining life etc.

III. Cyber Level
This level acts as a central information hub with data being pushed from multiple sources or machines. This level uses special analytics to show the capability and comparison across multiple devices and systems.

IV. Cognition Level
This level is about generating thorough knowledge of the monitored system and proper presentation for good decision making.

V. Configuration Level
This is feedback from cyber space to physical space and acts as supervisory control to make machine self-configurable and self-adaptive.

III. Detailed Considerations

One of the architectural patterns of applying Cyber-Physical Systems is the digital twin. Dr. Michael Greaves in his book Virtually Perfect book, introduced the term digital twin.[12]. As per Greaves, the Digital Twin concept model consists of three main parts: a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that ties the virtual and real products together. We can collect operational data, and continuously improve the intelligence of the digital part by learning from operational data analysis. These can later be included back into factory simulation. In a recent publication on Cyber Physical Systems the authors introduce a Reference Architecture for building a Cyber Physical System based on Cloud using digital twin architecture termed C2PS [13].

As in Fig. 4, the architecture model approaches it by considering Cloud or Distributed Consideration as the primary consideration. The key elements of physical element include Network Interfaces, Power Supply, Sensors, Functional Unit/Functions, Data Store, Observation and Actuators. In the Cyber thing, these elements turn out to be virtual. There can be three types of interactions physical-physical, cyber-cyber and cyber-physical.

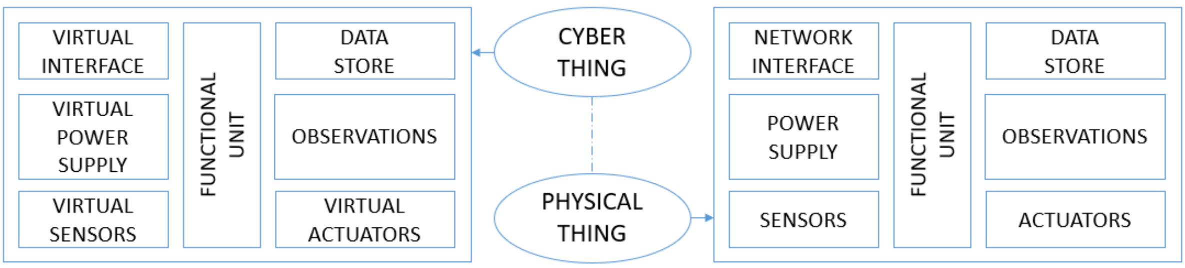

Fig. 4. C2PS Architecture.

Software defined elements play a significant role considering the Cloud or Distributed Systems as the primary approach [14]. The author and team once identified an architectural approach to start with using the capabilities of open hardware like Raspberry Pi and Open Network Emulators using Software Defined Networks like Mininet [15].

IV. EMERGENCE OF STANDARDS AND FRAMEWORKS

Standards include CPS Framework Release from NIST [16]. The Framework sees CPS going beyond a conventional product, system and application design traditionally conducted in the absence of significant or pervasive interconnectedness. CPS could include System of Systems and due to complexity and multiple systems emergent behaviours can be many. CPS could go far beyond current applications including cross-domain ones. Connectedness could have impact on being trustworthy. There is a need to be able to accommodate a variety of computational models and support variety of communication. Heterogeneity can lead to complexity. Timing is a major concern and the operating environment has a major role to play.

As in Fig. 5, the CPS Conceptual Model includes major concerns over Reliability, Security, Resilience, Safety, Confidentiality, Privacy. The Reference Model considers the industrial Internet of Things (IIoT) Reference Model, IEEE P2413 working group, OneM2M as inter-operability enabler, Cyber Security Research Alliance (CSRA), NIST Privacy Engineering, IEEE 802.1 TSN-Time Sensitive Networking, OPC-Unified Architecture, Time synchronization using IEEE 1588, Industrial Internet Consortium and Open Platform. 4DIAC a Project using IEC 61499 is also one of the aspects getting developed as part of the CPS work. At an abstract level, CPS can be deployed to enable and control- the flow of energies, the flow of material, the transportation of objects or goods, the movement of objects, the flow of signals, the conversion of energies, material and signals. The aspects of CPS considerations spans across Functional, Business, Human and Trustworthiness. The Prominent concerns include Performance and Safety properties as to avoid hazards.

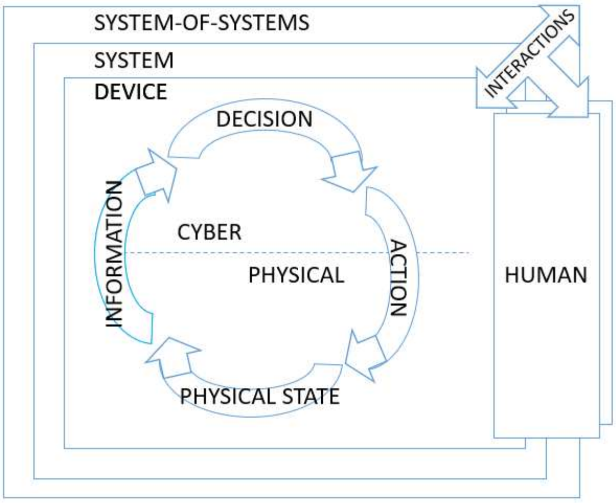

Fig. 5. CPS Conceptual Model.

V. OPPORTUNITIES, COMPETENCIES AND SKILLS

While machines can enable us to be more human, an agile transformation is essential [17]. 'What we need is an entrepreneurial society in which innovation and entrepreneurship is normal, steady and continuous'-Peter Drucker. Continuous experimentation as an approach to Products and Systems is discussed by Jan Bosch in his Three layer product model [18]. The endless possibilities of experimentation empowering the world is the focus of Chris Anderson's book Maker Revolution [19]. This leads us to a three - axis view as in Fig. 6 with Digital and machine driven Transformation in x-axis, the experimentation system on y-axis and agile transformation on z-axis. Cyber Physical Systems would play a significant role as Experimentation System, thereby enabling faster evolution,also ability to gain confidence of users over time.

The research challenges include Design considering reliability, A Systems Perspective, and Human considerations including safety and trustworthiness [20]. There is much research required to better understand the relationship between cognitive cycle of the human operator and that of CPS built and operated by humans.

The type of skills and the tools required to operate in this ecosystem include a good understanding of web technologies, communication technologies and embedded systems. Cross-pollination is essential to necessitate knowledge building. These teams need to have a good grasp of algorithms, data science from an application perspective.

Two projects worth watching are 4DIAC and the one from Blair. 4DIAC is part of Cyber Physical System platform projects and Built on the IEC 61499 standard. This project provides an engineering approach based on eclipse and a runtime which runs on Raspberry Pi called FORTE [21]. Blair et al builds on the Power System Standards of IEC 61850 and maps the same to Web protocols like HTTP [22]. The open source nature of these projects facilitate further collaboration. An approach using Design Thinking to facilitate faster incremental feature additions could be applied [23].

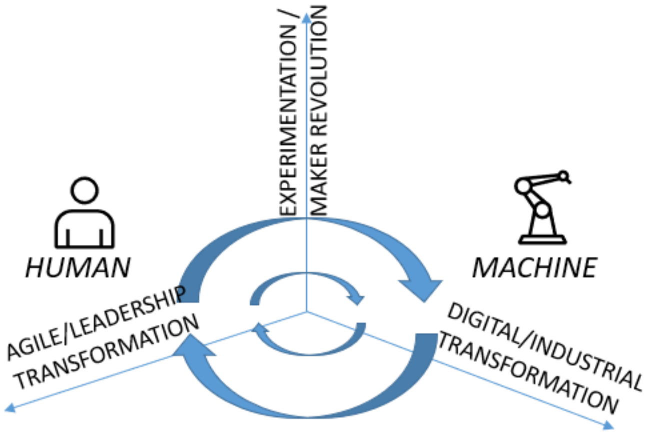

Fig. 6. Three Axis View.

VI. SUMMARY

Cyber Physical Systems have the ability to play a major role in continuous experimentation in systems. They empower organizations to perform data exploration faster. These systems expand themselves from Smart Factories to Smart Cities, Smart Grids and Healthcare thus delivering innovative experiences to customers. When augmented with intelligence they enable learning from real world, thus having increasing their impact. An iterative approach applying Design Thinking can be considered to unravel benefits.

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Ten Rules for the Good Life

Never put off till tomorrow what you can do today.
Never trouble another for what you can do yourself.
Never spend your money before you have it.
Never buy what you do not want because it is cheap; it will never be dear to you.
Pride costs us more than hunger, thirst, and cold.
Never repent of having eaten too little.
Nothing is troublesome that we do willingly.
Don't let the evils which have never happened cost you pain.
Always take things by their smooth handle.
When angry, count to ten before you speak; if very angry, count to one hundred.

Thomas Jefferson

Eight Things You Can Learn in 10 Minutes That Will 10x Your Productivity

How to prioritize
How to get everything out of your head
How to separate urgent from important tasks
How to focus on one thing at a time
How to live the 80/20 life
How to own and defend your time
How to stop being a perfectionist
How to measure your inputs and results!

Source: https://medium.com/kaizen-habits/habits-you-can-learn-in-10-minutes-that-will-make-you-more-productive-for-the-rest-of-your-life-b428015becfb