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Cyber-Physical Production Testbed: Literature Review and Concept Development

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Abstract

Many researchers use virtual and simulation-based testbed technology for research in production and maintenance optimization. Although, the virtual environment produces good results, it cannot imitate the unexpected changes that occur in actual production. There are very few physical testbeds emulating actual production environment. The aim of this paper is to present a concept of a cyber-physical production testbed based on review of Cyber-Physical Systems (CPS) testbeds in research. The testbed consists of a semi-automatic production line equipped with system monitoring tools, data analysis capabilities and commercial software. This testbed will be used for demonstration of data acquisition for production and maintenance prioritization. Additionally, the testbed will be used for research in IoT platforms for production optimization.

Keywords: Cyber-Physical Systems; Production; CPPS-Testbed; Industry 4.0; Smart Manufacturing;

1. Introduction

The emergence of concepts like Industry 4.0 and smart manufacturing has led many manufacturing companies towards integration of automation and information systems, stimulating a paradigm shift from automated manufacturing to intelligent manufacturing [1,2] leading to realization of *smart factories*. Smart factories are enabled by introduction of *Internet of Things (IoT)* and *Internet of Services* in manufacturing constituted of *cyber-physical systems* (CPS) [3]. Cyber-physical Systems (CPS) are autonomous physical systems that are interconnected with other systems in the

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environment by integrating the physical components and processes with cyber world of computation and networking and have the ability to collect and evaluate data, communicate with other systems in their environment and initiate actions to perform operations intelligently [4]. CPS application are found in factory automation, medical systems, power grids, aerospace and transportation. CPS in manufacturing or *Cyber-Physical Production Systems (CPPS)* are combination of sub-systems constituted of autonomous and cooperative elements in form of robots and work-stations connected to each other[5]. These sub-systems are situation dependent of each other though all levels of production from processes though machines up to production and logistics networks [5,6]. CPPS consists of smart machines, warehousing systems, digitalized production facilities with end-to-end ICT-based (Information & Communication Technology) integration and will lead to smarter and connected processes for agile and efficient production [7,8].

The problem with CPS, particularly with CPPS research is lack of integrated testing of different parts and aspects together as a system. One possible solution to solve this problem is to use CPPS testbeds for integrated testing, validation and verification with realistic platform and controlled industrial environment. Such use of testbeds provides opportunities to test new technologies before actual industrial applications. Manufacturing companies around the world have been encouraged to invest into industrial projects and research for enabling the realization of smart factories [5]. Initiatives like Learning Factories provide a good platform for such investments. Learning factories are already being used for education and training purposes in subjects like energy efficiency, manufacturing and service operations processes[8,9]. Cyber-Physical Production Systems will also lead to sustainable production. The end-to-end engineering and intelligent cross-linking of products and processes in CPPS will lead to more sustainable industrial value creation on all three sustainability dimensions: economic, social and environmental [10]. The allocation of resources on basis of intelligent cross-linked processes and value creation modules will lead to realization of efficient resources allocation [10].

This is done by studying the use of CPS is in current literature (from 2007 to 2017). The paper is divided as follows, Section 2 presents the Literature review, section 3 results and lastly a concept of Cyber-Physical Production Testbed (CPPS-testbed) being built at Stena Industry and Innovation Lab (SII Lab) of Chalmers University of Technology is presented in section 4.

2. Literature review

The aim of this literature review is to analyze use of cyber-physical systems testbeds in research. Moreover, the literature review focuses on finding the current status of use of cyber-physical systems testbeds in production.

2.1 Methodology

The paper follows a systematic literature review approach. A systematic literature review shall be able to identify relations, gaps and inconsistencies in the literature [11,12]. It shall also be able to establish the progress of existing research and give direction for further research. As Cyber-Physical Systems is a continuously developing topic involving multiple engineering and technology disciplines, a systematic review approach will help in examining the trends and categorize the continuous ongoing research in field of cyber-physical systems testbeds. This approach will also help in formulating the concept for the proposed cyber-physical production testbed. The results from the qualitative research done in literature review is used for developing the concept of CPPS presented in this paper. The concept development focused on explaining the integral aspects of a CPPS.

2.2 Identification of keywords and search terms

The main search for relevant publications was carried using Scopus search on November 28, 2017. Two set of searches were carried out with different sets of keywords. In first search, the keywords used were ‘Cyber’ ‘Physical’ ‘Production’ ‘Tested’. In second search, the keywords used were ‘Cyber’ ‘Physical’ ‘Testbed’. The search was limited to Article titles, Abstracts and Keywords. Only Conference papers and Articles in English language were considered in this study.

2.3 Findings

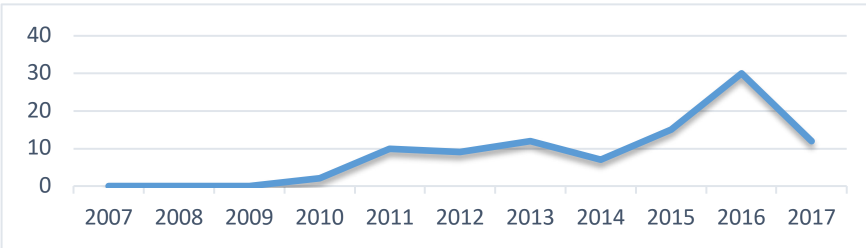
In first search, a total of 9 documents were found. Out of the 9 papers, 6 were conference papers, 2 were articles and a book chapter. Such a low number of documents highlights the few number of CPPS testbeds in research. Such low numbers in first search promoted the search for CPS testbeds included in second search.

In the second search, a total of 242 documents were found until November 28, 2017. As the papers focus on use of testbeds in research, the search was further narrowed down by limiting it to keyword "Testbeds". In total 97 articles were used in literature study. The findings were further classified according to major technological disciplines of cyber-physical systems shown in table 1. The aim of the classification was to find subject areas with the maximum use of cyber-physical testbeds.

Table 1. Technology wise distribution

Discipline	Number of Articles	Percentage of total
Electrical grids	19	20.21 %
Cyber security	22	22.45 %
Network & Communication	17	17.35 %
Robotics & Manufacturing	8	8.16 %
IoT, Web & Cloud computing	6	6.12 %
Simulation based	10	10.20 %
Other	15	15.31 %

Fig. 1: Year of Publication



3. Results

Majority of use of testbeds in CPS research focuses on its applications. As the area of application of Cyber-Physical Systems is wide, so is the research. Use of testbeds for research in Cyber-Physical Systems ranges from Unmanned Aerial Vehicles (UAV's) to collaborative robots, from smart grids to critical infrastructures and from industrial communications to cloud computing. As CPS is a combination of various sub-systems consisting of sensors, networks, embedded systems etc. its emergence has led to research and development of embedded systems, controls and networks, communication and computing. This branched research contributes to development of CPS systems but most of the work is still simulated or the focus is on the sub-components of a cyber-physical systems [13]. Several universities and research institutions are developing CPS testbeds for assessing security and vulnerability of power grids and power systems. CPS testbeds from the findings are divided according to their application areas and are presented below.

3.1 CPS testbeds with focus on Smart Power Grids

One of the major area of cyber-physical systems and testbeds research is electrical power system grids. The power systems in different parts of world are going though revolutionary changes in both architecture and operating principles. Most of the work in smart grid testbed research focus on the system architecture. Researchers have been developing and implementing different types of system architectures on testbeds consisting of simulation, emulation and physical components. The new generation of power grids require a resilient and robust communication backbone to support the changes in system architecture which is provided by extensive use of information technology [14]. The increasing use of information technologies in modernization of electrical grids has opened up the possibilities of attacks on these grids. Researchers are using smart grid testbeds extensively for research on security of power systems and control with modern communication systems. The PowerCyber testbed at Iwo State University is used to test vulnerability of the system to cyber-attacks and assessment of impact of cyber-attack [15,16]. These testbeds are also used for testing, verifying and validating various complex grid models. A survey on smart grids testbed provides a detailed information on lists of smart grid testbeds and their targeted research areas [17].

3.2 CPS testbeds with focus on Cyber Security

Researchers have been using testbeds for Cyber security research which is a major concern due to increasing use of internet and computers in functioning of critical infrastructures like smart power grids, water management and transportations infrastructures [18,19]. A result of a cyber-attack on a smart grid may result in its stability issues with change in current flow, faults in transmission lines etc. To answers such concerns and asses the security of cyber-physical systems, the European Union has developed an experimental testbed platform called EPIC [20]. Various attack scenarios on critical infrastructures are studied on testbed in [21] along with the involvement of human factor. Testbed at South Dakota State University (SDSU) is used for experimentation to study effects of a cyber-attack and its impact on the system voltage. The change in real and reactive power generation due to the attack is also demonstrated. Mitigation of the attack using optimal power flow is presented in [22]. SCADA systems are important part of industrial communications networks and widely used in critical infrastructures. Cyber-attacks on SCADA and similar industrial communications systems and networks system is further discussed in [23,24]. A hybrid testbed for cyber security assessment based on cloud computing is developed in [25].

3.3 CPS testbeds with focus on Network and Communication

Communication is considered as the backbone of CPS. CPS research in communication manly focuses on use of UAV's as testbeds and to demonstrate Machine to Machine (M2M) communication [26]. UAV based testbed research focuses on different components of CPS like network, sensing and communication technology. UAV testbeds in form of drones are used for testing and implementing object tracking algorithms, autonomous navigation of UAV's [27], [28]. Development of CPS has led to increase in development of cloud manufacturing technologies [29]. A CPS testbed is developed by connecting two manufacturing sites with local area networks consisting a total of 7 machines with cloud over internet. The testbed uses MTConnect communication method for data acquisition on manufacturing status and demonstrates 3-D printing and monitoring of the printing process [29]. Human-in-loop is also an important aspect of cyber-physical systems. Testbeds are used to verify and validate control algorithms for human-in-loop assistive robots with focus on elderly care [30]. In [31], the authors present a testbed focusing on communications between hardware and software components of a Cyber-Physical System.

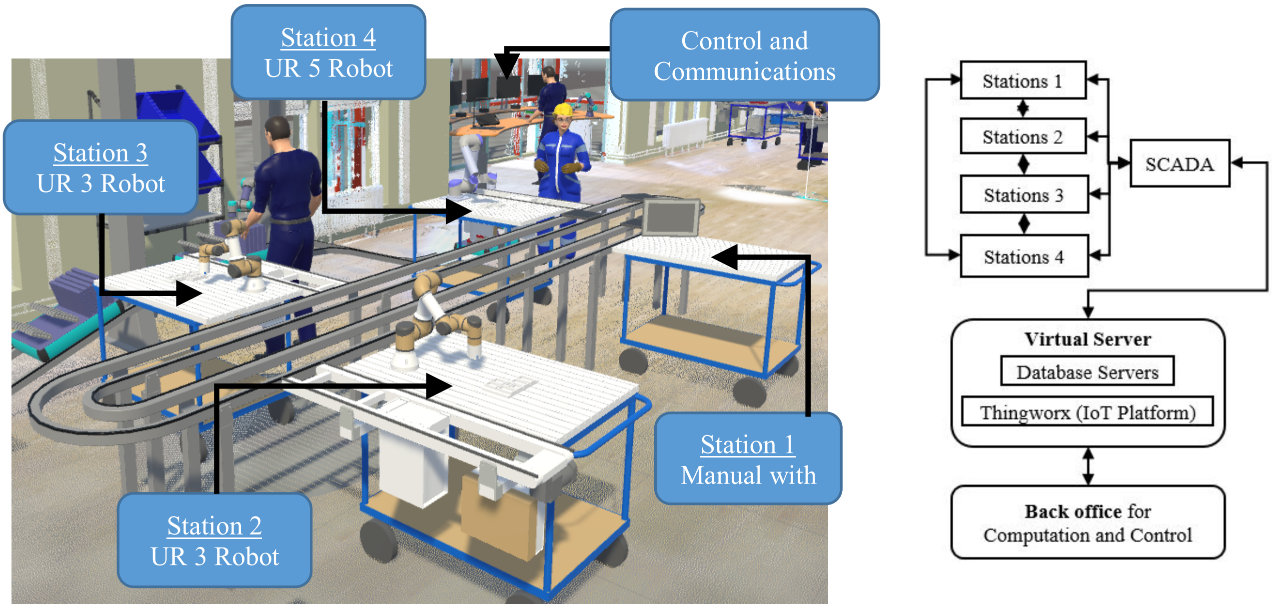
The results show a wide range of use of testbed application in CPS research. Many examples of use of testbeds in CPS research have been discussed. CPS testbeds reviewed are use technology like SCADA systems, different machine-to-machine communication techniques, and Collaborative robots etc. which have application in a CPPS. These aspects are used in concept development. The challenges like cyber-attacks are also faced by CPPS systems, though these challenges are not in scope of the proposed concept.

4. Concept development

Based on the results of testbed literature review and their use in research focusing on industrial applications, the proposed tested is developed with the objective of creating industrial environment for research. The testbed includes technology that is used in industry along with emerging technologies. The combination of new and old technologies provides a unique platform to solve existing industrial problems and an opportunity to focus on future challenges. The primary goal of this testbed is to serve as a platform for cross-disciplinary research of cyber-physical production systems. The testbed will also be used as a learning factory for educating students, academic and industrial partners on topics like smart factory, cyber-physical production systems, etc.

Inspired from the testbeds discussed in above sections, the proposed testbed is divided into three parts to focus on three the important aspects of the testbed viz. cyber, physical and communication. The first part consists of physical components of the testbed. Second part consists of network and communication of the testbed and third part consists of computing and cyber capabilities of the testbed.

Fig. 2: Layout of the testbed is presented on left side and communications flow on right side



Part 1: Physical Production Platform

The testbed production platform resembles a semi-automatic production line consisting four work-stations. Human operators on some work-stations will work together with robots or collaborative robots (cobots). Cobots are type of robots designed for working together with humans and are widely used in industry [32]. We use cobots manufactured by Universal Robotics, Station 2 and 3 are equipped with UR3 robot and station 4 is equipped with UR5 robot. Station 1 is manually operated by an operator.

Part 2: Network and Communication

The communication and network part elaborates on the connectivity of the testbed providing the link between the cyber and physical components of the CPPS-testbed. Use of PLC and sensors in testbeds is highlighted in [33]. In [34], the authors explain seamless integration of PLC (Programmable Logic Controllers) into an Industry 4.0 production environment. Use of PLC in CPS testbeds is highlighted in [17]. Soft-PLC in form of HMI (Human-Machine Interface) unit capable of performing the tasks of a PLC are used in the testbed [35]. Beijer iX T7B HMI has a built-in Soft-PLC and provides the closed loop connection capability of a PLC along with visualization of data and status of the process. The OPC Unified Architecture (UA) or IEC 61499 is a generic and open standard protocol for machine to machine interface widely used in industrial communication and in automation for establishing connectivity between different hardware and software platforms [36,37]. UPC UA communication protocols are used in this testbed for establishing communication between different software applications and hardware components for data acquisition and process control. Wireless communication between the cyber and physical components is established over Wi-Fi access points. IEEE 802.11ac Wi-Fi standard is used to achieve seamless wireless connection [37]. Application of RFID in production is discussed in [38] and for positioning in smart factories in [39]. Along with RFID tags, Sensors are very important part of automated industrial setup. Sensors have a wide range of application from data collection, machine and process monitoring to communication and thus play a very important role in process control, computation and optimization [40]. PwC revels over 35% of manufacturing industry in US is using sensors for data acquisition [41]. IFM 289 conductive sensors are used in testbed to control production flow, initiate robot operations and simultaneously for data acquisition along with RFID system manufactured by Vilant which is used for positioning and movement tracking of pallets on the conveyor belt.

Part 3: Computation and Cyber platform

Use of testbeds for research in cloud computing and computation is discussed in section 3.2 and 3.3. The computing and cyber platform is hosted in a designated area called “Back office” (Fig.2) resembling the management and control center of an industrial setup. Three computer workstations equipped with latest Intel Core-I9-7900X processers are used for analysis and control of the production system testbed. The Core-i9 processors are capable of providing ample processing power to run simulations and IoT applications simultaneously. A commercial data acquisition system and *Computerized Maintenance Management System (CMMS)* is also used in the testbed for data acquisition, system monitoring and control. Increased use of internet in manufacturing lead to creation on internet of things. In manufacturing, Internet of Things (IoT) is defined as an ecosystem of interconnected, uniquely identifiable physical devices and software components with the ability of data exchange with other devices over a network with limited human intervention. It can also be used to visualize seamless interaction of cyber and physical worlds [42]. Thingworx IoT Platform developed by PTC is used in the testbed [43]. Production simulation software AutoMOD by Applied Materials, Inc. is used for simulating production systems and emulating it in the testbed setup.

Three important aspects of the testbed and their characteristics have been briefly discussed in this section. The use of sensors and RFID technology along with advance technology like IoT and computation part highlights the capabilities of testbed to focus on combining old and new techniques.

5. Discussion

From the results of literature review, a steady growth in used of testbeds in CPS research and publication is implicated as shown in figure 1. Although there is a steady growth in use of testbeds in CPS research, many of these testbeds focus on the sub-component level research. The component or discipline specific research lacks integrated multi-disciplinary approach of research in CPS, especially in field of production which involves various disciplines like robotics & manufacturing, networking and communication IoT, simulations etc. Research on sub-component levels like robotics, AGV’s, cloud computing, network and communication, simulation, IoT, etc. has a wide range of application in production. This research can be combined together to study the integration and effects of different sub-components and technologies together, especially in case of CPPS where all these sub-components are crucial in functioning of the system. Such integrated approach will not just help in studying and overcoming effects and limitations of CPPS, Use of such combined integrated approach in form of testbed for production research will help in mitigating the resistance of manufacturing companies to elevate their production processes to industry 4.0-compalient [7]. The testbed presented as a concept in this paper will contribute to the integrated approach on CPPS research. Use of sensors and SCADA systems along with IoT will help in addressing problems related to integration of new and old technology. Using simulations and CMMS with-in the testbed will help in determining the impact of such techniques in industry. The final report on industry 4.0 recommends training and continuous professional development as priority areas for implementing industry 4.0 [3]. Besides being used as a production setup for training and research in CPPS and industry 4.0, the testbed will also be used as learning factory for educating students and researchers. The areas of research for the proposed testbed focuses on collaborative robotics, factory automation, maintenance, simulation, communication and Internet of Things.

Conclusion

Use of testbeds for promoting and enabling realization of CPPS in industry is an exciting and important research in field of digitalized manufacturing. This paper describes the concept of CPPS testbed with industrial capabilities inspired from literature review. The review of testbeds highlighted the specific approaches from different disciplines which needs to be combined to realize CPPS application in industry. The results also indicated the wide application of testbeds and their use in testing and validating research, which led to the formation of the CPPS testbed concept. The testbed concept combines different aspects of CPS and promotes integrated approach for research in CPPS. Such approach provides the necessary technological basis for facilitating realization of CPPS. Use of CPPS testbeds in research will not just help solving existing problems but also lead to new methods and techniques which will help in enabling CPPS on a wide range of industries.

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