Concept and Implementation of a Cyber-Physical Digital Twin for a SMT Line

W. D. Lin[1], M. Y. H. Low[1]
[1]Singapore Institute of Technology, Singapore
(David.Lin@SingaporeTech.edu.sg)

Abstract - **This paper conducted research on the concept design and implementation of a cyber-physical digital twin system for manufacturing. Based on literature reviews and industry requirements for a cyber-physical digital twin system for manufacturing, this paper proposed a concept design architecture of a cyber-physical digital twin system and its implementation methodology. An application of building a cyber-physical digital twin system for a Surface-Mounted-Technology (SMT) line is illustrated based on the proposed concept and framework. The basic requirements of the proposed cyber-physical digital twin system are divided into three layers, i.e. operations layer, visualization layer, and intelligence layer. Operations layer is about systems modeling of the physical processes and establishing connections with the cyberspace. Visualization layer is related to the collection and displaying of the historical and present data in a visual manner. The intelligence layer is the ability to conduct data analytics and decision makings to identify patterns and bottlenecks, reduce waste, perform predictive maintenance, etc. A proof of the concept prototype is developed based on the proposed cyber-physical digital twin system for a SMT line.**

Keywords – **Industry 4.0, Cyber-physical Digital Twin, Real-Time Simulation, Manufacturing, SMT line**

I. INTRODUCTION

For decades manufacturing technologies have been advancing rapidly riding on the wave of revolution of information and communication technology (ICT). Many past manufacturing technologies were the extended results of ICT, such as computer numerical control (CNC), computer-aided design (CAD), computer-aided manufacturing (CAM), and computer integrated manufacturing (CIM) etc. In recent years, the emergence of Industrial IoT and Cyber-Physical System (CPS) brought up the worldwide new challenges and opportunities for the convergence of manufacturing technologies and ICT under the theme of Industry 4.0 [1].

Following the Industry 4.0 initiative, one of the applications of CPS into the next generation of manufacturing systems is emerging and referred to as cyber-physical production system (CPPS). Under the scheme of CPPS, more and more machines and devices will be connected with each other, allowing them to communicate and interact with one another, creating an intelligent and autonomous manufacturing system [2].

The vision of CPPS is to enable manufacturing systems to perform tasks autonomously and improve their performance by machine learning [3]. Ultimately the manufacturing systems are able to communicate with each other, trigger actions collaboratively with minimum human interventions, and build up revolutionary novel business models and create values [4].

CPPS enables dynamic processes to be adaptive, self-corrective, and capable of responding to demands in real time instead of the traditional pre-programmed logic. With the applications of innovative Industry 4.0 technologies, the manufacturing industry advances into the fourth industrial revolution which will greatly improve their productivity, efficiency and versatility [5]. Among the key technologies of CPPS, a cyber-physical digital twin is one of the ideas that was conceptualized with the help of CPS, IIoT, big data analytics and simulation technologies [6].

With the support of real-time speed, data analytics will be more accurate and responsive for predictive analysis and other forms of in-depth data analytics [7]. Advanced analytics will enable companies to uncover new ways to improve their processes and operations. For instance, predictive analysis is able to detect potential issues before causing disruptions of operations and support predictive maintenance along the way. As long term benefits, it will increase profits by lowering downtime, reducing chokepoints, etc.

The purpose of this paper is to carry out research on exploring the concept of cyber-physical digital twin and its applications, especially in the manufacturing industry. In this paper, we proposed a novel cyber physical digital twin system architecture, which is consisting of three inter-connected layers, i.e. operations layer, visualization layer, and intelligence layer. The rest of the paper is organized as below: Section II is a literature review, followed by the description of the proposed cyber-physical digital twin architecture for manufacturing in Section III. Section IV demonstrates the implementation of a prototype cyber-physical digital twin system for a SMT line, and Section V concludes the paper.

II. LITERATURE REVIEW

The notion of Digital Twin was defined in the context of product lifecycle management by Michael in 2003 [8]. With a digital twin, companies can analyze and diagnose the operation processes in real-time operating conditions, optimize its performance and maintenance in real time, and make confident predictions about future performances. The ultimate goal is to improve productivity, reduce the cost, and risk of unplanned downtime. The idea of digital twin has taken off only in recent years with the advancement of ICT technologies and as sensors have become cheaper and the cloud has delivered almost limitless, low-cost storage

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space. Digital twin is one of Gartner's Top 10 strategic technology trends for 2018 [9].

Digital twin can be regarded as a revolutionary breakthrough of the traditional simulation. Digital twin is able to perform simulation based on the real-time data while the traditional simulation requires the user to manually input the parameters and static information required to run the simulation. As a digital twin is capable of automatically gather real-time information from the physical processes, it helps companies to save time and costs when applying simulation technology. With a digital twin, it also increases the accuracy of results as compared to traditional simulation which is tedious, time-consuming and allows room for human-error and usage of obsolete data [10].

In addition to increased accuracy and reduction in time and cost, a digital twin is capable of interacting with the physical assets and performing a bilateral communication to control and modify the physical processes. Updating the physical processes and logics through a digital twin can be either autonomously or with human interactions [11].

Digital twin is a virtual representation of the physical objects, processes and real-time data involved throughout a product lifecycle [12]. It can be applied in a wide variety of contexts and serves various objectives at the facility level, shop floor level and product level. A digital twin can track both the historical and current behavior, and predict the future behavior of a physical product, production assets, and the infrastructure in a cyber-virtual environment to support decision makings for complex dynamic manufacturing processes [13].

A major challenge in designing a cyber-physical digital twin is in determining the optimal level of details and varieties of connectivity in creating a digital twin model. In a real-time dynamic manufacturing environment, it is easy to get lost in the complexity of an advanced manufacturing environment with thousands of different types of sensors and lots of different branded digital devices, let alone the massive amount of manufacturing processes and technologies to be modelled.

There exists no standard digital twin system architecture that can fit the large variety of manufacturing systems. Instead, some companies provide software as basic digital twin development tools. According to MarketsandMarkets™ (2017) [14], some of the major companies operating in the global digital twin market are General Electric, IBM, Microsoft, Oracle, PTC, ANSYS, and Siemens AG. These software are mainly general purpose tools for developers to develop specific solutions to companies.

Cyber-physical digital twin system is relatively new to the manufacturing sector, and the concept is yet to be accepted and implemented in the manufacturing sector of Singapore. The academic versions of conceptual system architecture still need further fine-tuning and proof of concept before actual implementation within a real-life legacy manufacturing system. This paper is to conduct research to support the concept design of an Industry 4.0 cyber-physical digital twin system and its implementation for the manufacturing system.

III. PROPOSED CYBER PHYSICAL DIGITAL TWIN FRAMEWORK FOR MANUFACTURING

Based on the literature reviews, the purposes of a cyber-physical digital twin and a traditional simulation model have some overlapping points such as visualization of the factory processes and simulation of the day-to-day operations. However, it is important to understand the distinction between them, and evaluate the potential of using an existing simulation software as a cyber-physical digital twin development platform rather than creating a bespoke software.

A cyber-physical digital twin needs to be designed and developed based on a set of requirements elicited from the industry companies. Compared with the prevalent strategy of off-line simulation, the cyber-physical digital twin system is expected to conduct time-sensitive data analysis and simulation experiments with more accurate results.

The architecture design of the proposed cyber-physical digital twin system aims to overcome the limitations of current electronics manufacturing system, such as the lack of predictive ability and intelligence capabilities [15].

As shown in Fig.1, the cyber physical digital twin will be the core of the system architecture, which is built upon a real-time simulation platform to support decision-making applications, such as production planning and inventory planning. In the meantime, the cyber-physical digital twin is interfaced with SCADA system, manufacturing execution system, and distributed physical space manufacturing resources such as production lines and equipment. At the operational level, a shop-floor modular tracking system is providing the visibility at the shop floor level.

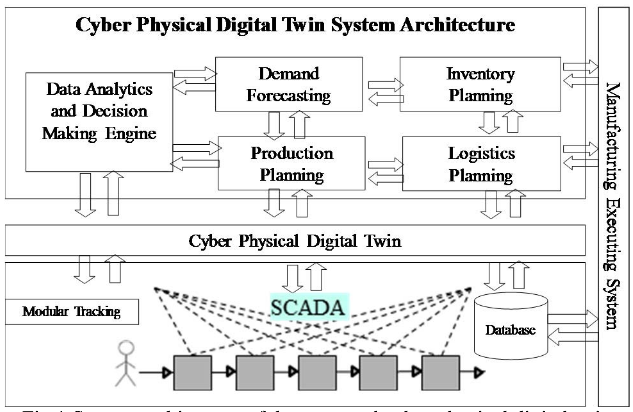

Fig.1 System architecture of the proposed cyber physical digital twin system

Thus, there are three layers of modules required in the proposed cyber-physical digital twin system. These three layers of modules are listed by the sequence of operation, visualization, and intelligence and will be described below.

A. Operation Layer

As a foundation of any digital twin system, it needs to gather, collect and track all the physical assets on the shop floor. The traditional assets tracking methods are not efficient as it requires manual searching of locations and attributes of assets such as quantities and status.

The proposed modular assets tracking system at the operational layer is designed to automate the assets tracking process for tracking shop floor assets, including equipment or inventory of materials. An example of using such modular tracking system is for kitting the spare parts through a pick-to-light system, which dynamically tracks all kitting materials, and allows automated locating components, and would thus decrease the process timings, motion waste and learning curve. In addition, it would also increase the accuracy and productivity rate.

B. Visualization Layer

Traditionally many companies use standalone simulation package as silo applications, and lots of efforts needed for data collection, data cleansing, and best-fit the data before input them into the simulation model. The simulation building process is also very tedious, lots of manual work are needed for converting the process information such as layout, machine parameters and resources data etc. into the format suiting simulation modelling needs. In case of process information changed, the simulation modelling process needs to be repeated again.

In the proposed cyber-physical digital twin system, the visualization is created by modelling the physical assets and collecting real-time data simultaneously from the digitized physical production line and processes. It gives companies a thorough visualization of their production processes and assets throughout the whole product life cycle. Allowing them to better understand the processes involved and improve them on real time manner. So that industrial companies are able to embrace digital twin technologies in monitoring processes and costly assets and maximizing their utilization and useful lives.

As the cyber-physical digital twin is synchronized with the physical counterparts in real-time and sharing data across the company seamlessly, it allows companies to be constantly updated on what is the current status of the production floor without being there physically.

C. Intelligence Layer

On top of the visualization, a digital twin is able to perform real time analytics based on all the real-time data gathered. For example, an intelligent knowledge discovery engine could be developed for data mining of patterns within the data sets. The data sets contain the data captured from the manufacturing system, both historical data and real-time data, as well as other relevant information. The outcomes from the knowledge discovery can hence be applied in future decision makings for production planning and management.

As a brain of the proposed cyber-physical digital twin system for manufacturing, data analytics and decision making modules such as demand forecasting, production planning, inventory planning and logistics planning can be performed on real-time basis.

In addition to the previously mentioned three layers, cybersecurity will be taken into consideration in the overall system design. As a cyber-physical digital twin system is embracing full digitization of manufacturing, there exist also risks in terms of confidentiality, integrity, and availability of manufacturing data. The manufacturing cybersecurity considerations are mainly based on SCADA forensic process models, such as the research suggested in [16], which adapts the traditional IT system forensics investigation process and applies it to SCADA systems.

IV. IMPLEMENTATIONS

This section will discuss the implementation of the proposed cyber-physical digital twin system with an example of a production line. The approach adopted in this research for implementation consists of 4 main steps as shown in Fig.2.

- Data collection refers to the collection of real time information from the physical processes. This can be done using tools such as sensors and other IoTs.
- Process Visualization refers to the viewing of physical assets and processes in cyberspace. This research utilizes FlexSim© and connects it with the SCADA database to acquire real time production data.
- Process analysis refers to the analysis of real time data to generate statistical charts and graphs. These analyses will help to identify issues such as production bottlenecks, breakdown time, etc.
- Process control refers to the controlling of physical machines and processes from digital twin. It allows the controlling of the physical machines and processes autonomously or upon user interaction.

Fig.2 Implementation of the proposed cyber-physical digital twin

Together with an industry partner, a prototype system is constructed and tested in order to validate and proof the concept of the proposed cyber-physical digital twin system architecture.

The prototype is built up based on one of the selected production lines. The production line under study is involved the Surface Mounted Technology (SMT) production line with relevant machines and processes. The SMT production line is split into 7 main processes as shown in Table I and each printed circuit board (PCB) will flow from number 1 to 7.

TABLE I
LIST OF PROCESSES INVOVLED IN PRODUTION LINE

No.	Process	Process Time (seconds)
1	Screen Printing	100
2	Solder Paste Inspection	40
3	Component Placement (Small)	30-45
4	Component Placement (Big)	40
5	Pre-reflow Inspection	50
6	Reflow Soldering	400
7	In-Process Quality Check (IPQC)	45

Apart from the small and big component placement listed in Table I, each of the other main processes in the production line only has 1 machine working on the respective process. The small component placing process is split into 10 physical machines where each one of them is used to place different components onto the PCB. The big component placing process is split into 2 machines operating on the process. The seven processes can be further explained to understand how each process works and issues to be taken into consideration when creating the digital twin of the SMT production line [17].

- Screen Printing: a process where solder paste is printed onto the PCB using an SMT screen printer. The aim of this process is to accurately deposit the correct amount onto each of the pads to be soldered. This is achieved by screen-printing the solder paste through a stencil or foil usually; but also can be applied by jet printing.
- Solder Paste Inspection: to check the accuracy of the solder paste deposits. This process is crucial to the line as an inaccurate solder paste prints will affect the placement of the components; resulting in other defects in later stages and incurring wastage of material and time.
- Component placement: also known as pick-and-place, to place components onto the PCB. There are many different types of component placement machine available but the main aim is to place Surface Mount Components (SMC) onto the PCB as accurately and quickly as possible.
- Pre-reflow inspection: to ensure that all the components are placed correctly before reflow soldering where the components are fixated onto the circuit board. It can be done through an Automatic Optical Inspection (AOI) or human inspection.
- Reflow soldering: to attach the SMC to PCBs by melting the solder paste to form solder joints that hold the SMC firmly in place. It is achieved by preheating the SMC, PCB and solder paste and then melting the solder gradually without causing damage to the SMC and PCB through overheating.
- In-Process Quality Check (IPQC): to check if each SMC is firmly secured onto the PCB before sending it to the testing phase. This is achieved by using an AOI machine to check the solder joint quality. Any PCB that failed the inspection will be sent for rework where the SMC will be removed using various soldering techniques and placed back onto the PCB.

With the implementation of the proposed cyber-physical digital twin system, it helps eliminate the manual information and process data collecting by setting up a centralized database as part of the cyber-physical digital twin system.

The system architecture of the SMT line digital twin consists of three main modules as illustrated in Fig.3, which is corresponding to the proposed cyber-physical digital twin architecture in Section III. The first module is the physical machine and the gathering of real time information, which is represented by a wireless IO module in Fig.3. The second module is the SQL Server that stores the collected data, and the third module is the simulation model to represent the factory processes and assets and serve as a digital twin platform.

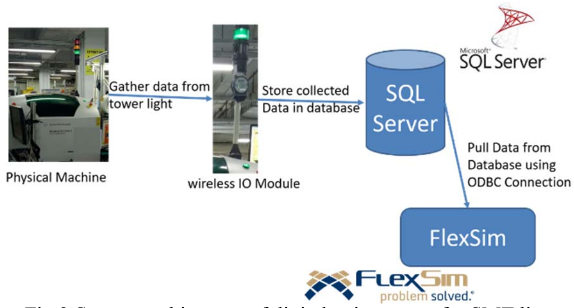

Fig.3 System architecture of digital twin system for SMT line

The details of each module and their implementations can be further explained as below:

- Physical machines are included in the system architecture because one of the objectives of digital twin is to model the real-time status of the physical machines by gathering real time data and feeding into the digital twin. Hence, physical machines that perform the operations of each process need to be included into a cyber-physical digital twin system.
- Gathering real time information through wireless IO modules can be used for older machines. For instance, it is able to capture the status of a physical machine from the tower light attached to it through wireless IO modules if the machine is not equipped with online data collecting networking features.
- Microsoft SQL Server (MSSQL) is used as the database for holding all collected data from the SMT line under study. The objectives of using MSSQL as a centralized database are to ensure consistency in data collecting, data storage and data management.
- FlexSim is used as the main platform to realize visualization of the factory processes, analyze data collected and communicate with the physical machines and processes. Real time data collected and stored in the MSSQL could be retrieved any time for updating the simulation model.

Using simulation in conjunction with IoT devices leading to a cyber-physical digital twin system consisting of both the physical assets or processes and simulation models. So that companies can analyze and diagnose the operation processes in real-time operating conditions.

In summary, the prototype cyber-physical digital twin system was built as a virtual representation of the SMT production line, which is connected and synchronized with the physical production line in real-time. The main features of the cyber-physical digital twin system include:

- Collect real-time data from physical machines and processes;
- Visualize physical processes in the cyber world;
- Analyze processes based on collected data;
- Perform confident predictions and what-if analysis about future performance to improve productivity and reduce the cost.

V. CONCLUSION

This paper described a concept design and implementation of a prototype cyber-physical digital twin system. There are inter-connected three layers in the proposed cyber-physical digital twin system architecture, i.e. operation layer, visualization layer, and intelligence layer. The proposed system design architecture was explained and demonstrated through an implementation for a SMT line to validate and proof the concept.

Future work is planned to further explore the interactions between the physical machine & processes and the digital twin system, which needs more reliable and cautious design. Further work can be done for the intelligence layer with more in-depth data analytics and decision making functions. It is foreseen that advanced real-time intelligence can be explored through the cyber-physical digital twin system to help companies improve their business objectives.

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