Concept Design of a System Architecture for a Manufacturing Cyber-physical Digital Twin System

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Abstract - **This paper discussed a concept design of a system architecture for a manufacturing cyber-physical digital twin system. It firstly described the overall concept of the system architecture consisting of various sub-modules. These sub-modules include digital twin dashboards, digital twin E-scheduler, digital twin wireless modular tracking, and digital twin simulation. In addition, it highlighted the schema of the digital twin database module design which enables the switching between a production database and a simulation database. Some prototyping work of the sub-systems are introduced individually. A complete proof of the concept prototype is being developed to demonstrate the complete features and functionalities of the entire manufacturing cyber-physical digital twin system.**

Keywords – **Industry 4.0, Cyber-physical Digital Twin, Electronics Manufacturing, Digital Twin Simulation**

I. INTRODUCTION

It has been observed a rapid growing trend of Industry 4.0 related research and development worldwide since the first definition of Industry 4.0 was published in 2011 at the Hannover Messe trade fair [1]. The German government supported this idea and announced in 2014 that Industrie 4.0 would be an integral part of their "High-Tech Strategy 2020 for Germany" initiative. Following that, several other initiatives have been announced by different governments and industrial leaders, such as "Industrial Internet of Things", "Factories of the Future" and etc. [2].

Most Industry 4.0 initiatives emphasize applications in manufacturing industry, especially those incorporating Cyber Physical System (CPS) into the next generation of manufacturing systems. Such a category of applications is often referred to as Cyber-Physical Production System (CPPS) [3]. With the disruption of the pandemic of COVID-19, most industries including manufacturing companies are eagerly considering and planning to move towards the direction of Industry 4.0 due to the imperative of operating production remotely and remain operations sustainable. Just like eLearning has been pervasive and entrenched during the pandemic worldwide, online manufacturing operations, remote monitoring and maintenance etc. are urgently demanded by the manufacturing industry.

A core concept of CPPS is cyber-physical digital twin, a system that integrates cyberspace digital models with the physical manufacturing processes and resources. Cyber-physical digital twin only took off in recent years with the advancement of ICT technologies, and as sensors and IT infrastructure have become more cost-effective and reliable. Cyber-physical digital twin system is one of Gartner's Top 10 strategic technology trends for 2018 [4].

As it is infeasible to use a live physical production environment for extensive experiments and interventions, a dedicated and economical alternative is to establish cyberspace models acting as the testing environment for engineering studies and explorations. However, for being a truthful and trustable replicate of the physical production environment, the cyberspace models need to capture the overall physical production settings.

One of the challenges of constructing a manufacturing cyber-physical digital twin lies in the integration of both physical world and cyberspace models. It requires iterative communication and synchronization over between the cyberspace models and physical world. No mature and standard tools are available yet to handle such intensive interactions between the two worlds and among many sub-systems within the entire system.

Another challenge in developing next-generation manufacturing cyber-physical digital twin system is that it requires overwhelmed data involved in the system to be managed robustly, securely, accurately, and timely, with intuitive visibility. Visualization of processes and data together with virtual models in cyberspace allow the achievement of thorough insights concerning the manufacturing operation processes.

This paper aims to propose a concept design of a system architecture for a manufacturing cyber physical digital twin system. A well-designed system architecture is critical in the subsequent implementation of the entire system with various sub-modules. The rest of the paper is organized as below: Section II reviews related work and section III describes the proposed system architecture. Section IV goes through the various sub-modules, and Section V concludes the paper.

II. LITERATURE REVIEW

An ideal manufacturing system under the scheme of CPPS aims to transform the traditional discrete manufacturing to be an entirely seamlessly integrated entity with all machines and devices tightly connected by real-time communication and interaction with each other. This enables the discrete manufacturing resources to work closely in order to be operated in an autonomous and intelligent manner [5, 6]. The ultimate goal of CPPS is to enable the entire manufacturing system to be adaptive, self-

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corrective, and reactive with minimum human interventions. New technologies being involved in CPPS include CPS, IIoT, Big Data, Data Mining and Real-Time Simulation, etc. [7, 8, 9].

As a core engine of CPPS, the cyber-physical digital twin is bridging the gap between cyberspace and physical world, so that a digital model can simulate, validate, and analyze the physical world systems based on near real-time data. Besides, the analytical data and results of digital models can be fed back to help the physical world systems better respond to the changes or make better decisions to optimize the business values [10].

In a cyber-physical digital twin, virtual models are developed in cyberspace to mirror their corresponding physical objects' behaviors in the real world. While the assets of the physical operations need to be digitized and networked in order to communicate with the cyberspace models with all the data involved [11].

As detailed in [12], a cyber-physical digital twin is a concept of having a separate simulated entity of an operation model to provide a digital footprint of the business' operational processes, essentially creating a digital factory environment, and ultimately, improving performance and efficiency in the long run. A cyber-physical digital twin can be applied in a wide variety of contexts and serves various objectives at the facility level, shop floor level, and product level [13].

According to [14], in a cyber-physical digital twin, it is critical for manufacturing digital systems to interact with virtual models and physical assets in the real-world environment. A cyber-physical digital twin can be regarded as a revolutionary breakthrough from the traditional simulation modelling to experimental digital twins. An example of the application of the digital twin technology to workshop manufacturing can be found in [15], which aimed to improve the intelligence, foreseeability, and initiative of the plant.

Since the manufacturing cyber-physical digital twin system is still relatively new in both academic research and practical implementations, this paper is to propose a concept design and system architecture of a manufacturing cyber-physical digital twin system. Section III will explain the concept of system architecture design.

III. SYSTEM ARCHITECTURE DESIGN

This research further developed the authors' previous work on the design of a cyber-physical digital twin for an SMT line manufacturing [16]. With more studies and surveys on system requirements, more detailed system constraints have been taken into considerations for the system architecture design and potential integration with the existing manufacturing systems.

A few new modules have been added into the system architecture, including a digital twin wireless modular tracking sub-system at operation layer, a digital twin dashboards module at visualization layer, and a digital twin E-scheduler sub-system at the intelligence layer. In addition, a digital twin simulation module plays an important role in both the visualization layer and the intelligence layer.

With the new system architecture design of the manufacturing cyber-physical digital twin system, it aims to overcome some limitations of current manufacturing systems, such as the lack of visibility and decision-making capabilities. The new system architecture is expected to enable an integrated and synchronized process monitoring with accurate and timely data visibility and visualization, and also decision making supports.

Fig.1 depicts the envisioned new system architecture. As it is integrated into an existing manufacturing system, the proposed cyber-physical digital twin system must interface with the existing ERP, MES, and SCADA systems. For instance, customer work orders would be imported from the ERP (Enterprise Resource Planning) to the digital twin E-scheduler module. E-scheduler then generates viable production schedules by assigning the customer work orders to production lines and acquiring production resources to support the processing of allocated customer work orders.

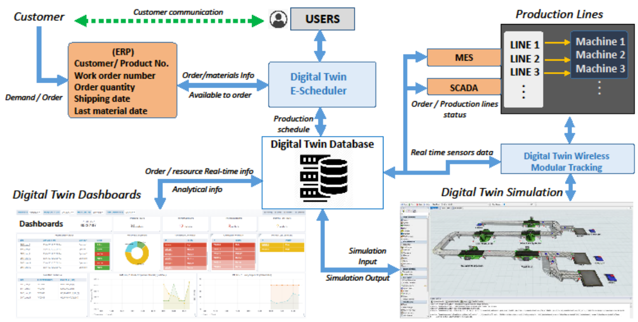

Fig.1 System architecture of the cyber physical digital twin system

The new system architecture consists of a few newly added modules, which are briefly described below, and more information is provided in the next section.

- Digital twin dashboards module
  - A basic requirement of designing the digital twin dashboard module is to allow swiftly switching between information panels of the actual physical production lines and information panels of the cyberspace simulation models. Another key consideration is the need to ensure that the data gathered and displayed from the various modules must be synchronized to ensure integrity, accuracy, timeliness, consistency, and harmony.
- Digital twin database module
  - There are several databases with different sub-modules. All sorts of data in the respective databases must be associated with each other avoiding any conflicts as all of the different modules being working concurrently. For the digital twin database design and implementation are directly connected with the design of the digital twin dashboards module, where dual databases are adopted and

defined as “Production Database” and “Simulation Database” respectively. It is ensured the segregation between the two databases, because the “Production Database” would be indirectly linked with the existing MES and SCADA databases.

- Digital twin E-scheduler module
  - To automate the production scheduling process by minimizing human interventions and improving scheduling efficiency. It retrieves customer order data from existing ERP system and creates a feasible production schedule based on production lines status and resources availability information with the objective to meet customer order shipment date while minimizing the total production lead time and cost.
- Digital twin wireless modular tracking module
  - It enables data collection at any point and any time in the shop floor at a low cost. A distributed wireless modular tracking system can be deployed across the shop floors and plants to collect all needed data to enhance visibility and visualization. Extensive use of IoT devices is a key enabler of a manufacturing cyber-physical digital twin system. It provides significant enhancement of data availability and timeliness on top of the existing IT systems. It plays an important role as a differentiator from the traditional manufacturing system with the ability of efficient communication between the cyberspace and physical world, and tracking of various data related to customer orders, production resources, materials, and manpower etc.
- Digital twin simulation module
  - A real-time 3D simulation model of physical assets and processes in cyberspace with simulation-based optimization algorithms. It can be connected and synchronized with real-world physical production lines and resources. With the inputs of customer orders and production schedules from E-scheduler, the digital twin simulation module is to conduct experiments and what-if analysis for decision making supports. It will generate the orders-to-promise scenarios with current production lines status and resource availability, and it can also plan ahead for decision supports for the different scenarios with predictive changes, such as customer orders, materials, resources etc.

IV. SYSTEM SUB-MODULES DESIGN AND IMPLEMENTATIONS

This section will provide more details of the sub-modules of the manufacturing cyber-physical digital twin system. Some info on implementation approaches is covered as well. These sub-modules will be introduced in sequence, i.e., the digital twin dashboards module, digital twin database module, digital twin E-scheduler module, digital twin wireless modular tracking module, and digital twin simulation module. All these modules are concocted and integrated to work as a whole.

A. Digital Twin Dashboards Module

The digital twin dashboards module is a subsystem with the aim of achieving the total process and data visibility and visualization. Production lines and resources data, either collected by an MES (Manufacturing Execution System), a SCADA (Supervisory Control and Data Acquisition) system, or the digital twin wireless tracking module, are all consolidated and fed into the digital twin database module, based on which the digital twin dashboards would act as a centralized platform for viewing data across all the modules and the entire system.

Fig.2 shows a more detailed system diagram of the digital twin dashboards to illustrate the information flows from the rest sub-modules into the digital twin dashboards module. It can be seen that there are two duplicated databases, where a simulation database is mirroring the production database, so that any data changes in the simulation database will not affect the robustness of the production database.

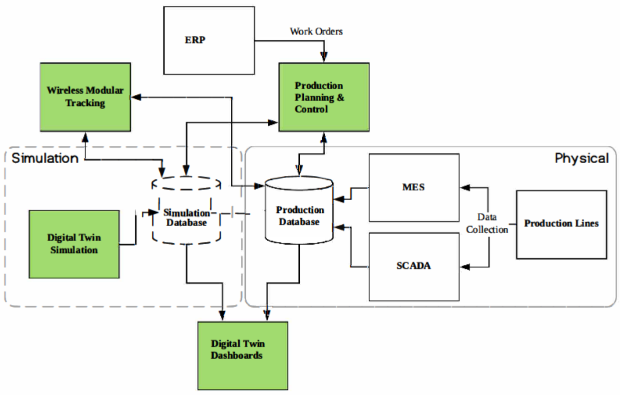

Fig.2 Digital twin dashboards concept design diagram

Grafana® was chosen as the development platform of choice for the digital twin dashboards module. The main reason for this choice is the system maintainability on top of other benefits. It provides a user-friendly web development environment by allowing users to modify panels or customize dashboards according to users' preferences. This allows system users to easily make changes in the future while saving their time and efforts in getting familiar with the web development framework.

B. Digital Twin Database Module

A dual-database structure is adopted for the digital twin database module design, with the two databases share the same database scheme. The “Production Database” would be directly linked with the existing MES and SCADA databases, while the "Simulation Database" has the same database scheme of "Production Database". “Simulation database” is separately managed to support the digital twin simulation module to run in cyberspace to experiment on different scenarios for improving the production schedule, resource allocation and optimizing the overall productivity.

A key consideration of the database schema design is to ensure that all data from the different modules of the cyber-physical digital twin system could be aligned and synchronized for interoperability. As a common database schema is used and shared across the different modules, which are potentially running concurrently, all database table fields defined in the dual databases should be associated with each other in pairs without causing any mismatch or conflict.

To maintain consistency with the other operational systems, Microsoft SQL Server® was chosen as the database management system. Fig.3 shows a partial section of the digital twin database entity relationship diagram mainly showing the tables of Order, Part, Schedule, Line, Backend and ManufacturingTime. The Order and Part information are retrieved from the ERP system, and the Schedule information is obtained from the E-scheduler module. While the rest of the information about Line, Backend, and ManufacturingTime is retrieved from MES and SCADA systems. All these tables are interconnected and formed as part of the digital twin database schema.

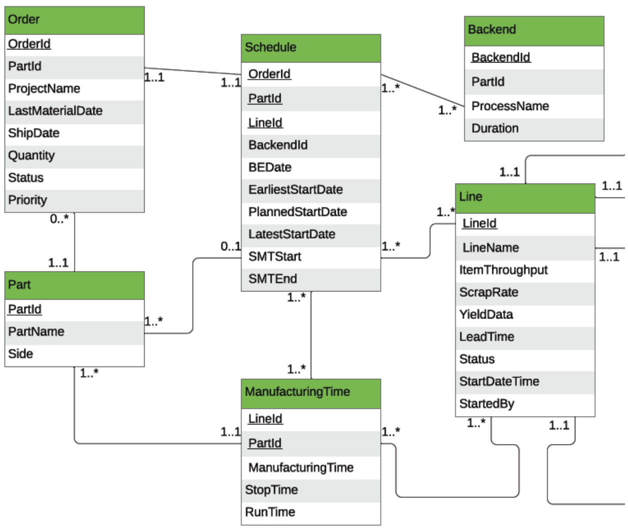

Fig.3 Digital twin database entity relationship diagram (partial)

C. Digital Twin E-Scheduler Module

The functionality of the digital twin E-Scheduler is mainly to take the customer orders information from the ERP system and generate a feasible production schedule based on all the information acquired from physical production lines through MES, SCADA, and wireless modular tracking module. Besides, the generated production schedule can be sent into the digital twin simulation module for further production scheduling optimization. Once the optimal production schedule is confirmed by the user, it is sent back to digital twin database module and production lines for execution.

The presentation of the production schedule is crucial as it needs quickly to provide users with a clear indication of the current processing and upcoming work orders. A Gantt-chart is used to represent the data of scheduled work orders in the digital twin dashboards. The objective is to show the sequence of work orders with assigned production lines and allotted time slots.

D. Digital Twin Wireless Modular Tracking Module

The digital twin wireless modular tracking module provides efficient communication and tracking of various production resources, materials, and manpower. It leverages on the Internet of Things (IoT) network devices to enable data collection at any point in the shop floor. Many wireless technologies can be used to connect these devices to the internet, such as short-range wireless communication, cellular communication, and low power wide area network (LPWAN) communication.

This research selects a market available solution for short-range data collection and communication. The commercial package is featured for supervisory control, data acquisition, and also provides open interfaces for developing IoT applications for collecting data from edge equipment to exchange data with cloud services using MQTT publish and subscribe methods.

For long-distance communication, LoRa® is adopted for sending small data packages over a long distance, operating on a battery, because LoRa is one of the best candidates for long-distance and low power transmissions. As shown in Fig.4, LoRa is a single-hop technology that relays the messages received from LoRa sensor nodes to the central server via gateways. The gateway of the system is taking the data sent from sensor nodes through the LoRa node and transferring back to server database. The sensor types include temperature sensor, humidity sensor, image sensor, infrared sensor, sound sensor, etc.

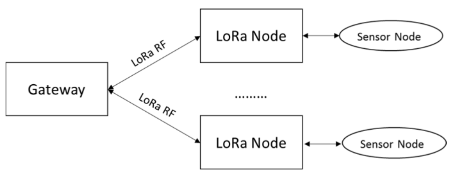

Fig.4 The digital twin modular tracking system using LoRa®

E. Digital Twin Simulation Module

Digital twin simulation module was built as a virtual model and representation of the physical production lines and resources. It is connected and synchronized with the physical world systems in real-time through the Simulation Database and wireless modular tracking systems. With real-time information and data in conjunction with IoT devices, the digital twin simulation module serves as a cyberspace model to mirror the physical production lines and resources. It is used to analyze and diagnose the production processes in real-time operating conditions, and make confident predictions and what-if analysis about future performance to improve productivity and reduce the cost.

The digital twin simulation module is built with FlexSim® as a platform to construct virtual processes and visualization of the production lines and resources, conduct experiments and optimizations. The main features of the digital twin simulation module include:

- Model and visualize the physical production lines and resources into the cyberspace model;
- Communicate with existing manufacturing system through Simulation Database, and collect real-time data from the digital twin modular wireless tracking module about physical machines and processes status;
- Conduct simulation experimentation and optimization with the cyberspace model;
- Provide the simulation and optimization results to system users and other modules, e.g. the digital twin E-scheduler module and the digital twin dashboards module.

V. CONCLUSION

This paper described a concept design of a system architecture for a manufacturing cyber-physical digital twin system. The proposed concept of system architecture integrates various sub-modules tightly to function as a whole. It achieves the requirements such as real-time data gathering from physical machines and processes, connecting with existing manufacturing systems. It provides total visibility and visualization of both cyberspace and physical world production processes and resources. It enables decision making support and simulation optimization using cyberspace models without interrupting the physical production processes.

A cyber-physical digital twin system plays a very important role in Industry 4.0 and CPPS in the manufacturing context. With a carefully designed system architecture, it is expected more real-time intelligent data analytics, machine learning and decision makings can be supported in future to help companies realize their business objectives.

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