A Digital Twin Framework for Industry 4.0 Enabling Next-Gen Manufacturing

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***Abstract*—Digital twins offer a framework to support the ever-rising demands in the fast-paced industrial evolution. This technology not only adds to the reliability of industrial processes but also offers an insight in to long-term behaviors and pattern during the aging of the industrial equipment. In this paper, a digital twin framework is presented to replicate the processes of a real production line for product assembly. The proposed work implements a digital/graphical replica of Festo Cyber Physical Factory (CPF) for Industry 4.0 (I4.0). The implemented system allows to schedule orders and specify product configuration which embodies the actions of CPF in digital world. In addition, the paper also presents a viable framework to interlink the physical system with the digital instance to offer extended services and a pathway towards realization of fully functional digital twins.**

Keywords-digital twin; Industry 4.0; cyber physical factory

I. Introduction

The rapid advancements in manufacturing technologies are transforming industry through Industry 4.0, also known as the 4th Industrial Revolution which refers to the integration of information technology and industrial production. Along with the use of innovative technologies and novel data management approaches, this will enable the manufacturers and the supply chain to save time, boost productivity, reduce waste and costs, and respond flexibly and efficiently to consumers' requirements. Industry 4.0 is not only about digitization of manufacturing components and processes, but also about creating smart factories, taking on board Information and Communication Technology (ICT) for evolution in supply chain and production line [1]. Consequently, smart factory relies on several main tightly interconnected concepts, such as: the Cyber Physical System (CPS) [2] designed as a network of interacting elements like embedded computing devices, smart objects, people and physical environments; the Industrial Internet of Things (IIoT) enables the interconnection of smart heterogeneous objects (e.g., sensors actuators, RFID tags, embedded computers and mobile devices) using standard communication protocols, and Big Data captured from the interconnected IoT-based objects, and real-time analysis.

In Industry 4.0, fully automated smart industrial infrastructure relies on low latency feedback networks, high efficiency distributed control systems, fool-proof emergency and safety systems, energy efficient and self-sustaining processes and supportive digital technologies. Automation of processes is an essential attribute of present-day industries. However, with the 4th industrial revolution, notable increase in the complexity of systems is witnessed. Due to the introduction of extremely complex industrial systems, the traditional means of performance evaluation, threat analysis and safety checks result in wastage of time and resources. In addition, some critical and emergency systems cannot be practically evaluated (e.g. oil refinery leakage and fire hazard, submarine underwater pressure failure etc.). Thus, a reliable solution for such systems, which carry all the attributes, processes and software can serve as a reliable debugging and analysis tool.

One important driver of the smart manufacturing paradigm is represented by the Digital Twin technology. Digital twin represents the interconnection and convergence between a physical system and its digital representation created as an entity of its own [3]. Both entities, the physical object and the digital object are fully integrated and can exchange information in both directions. Thus, the digital object could act as a controlling instance of the physical object and vice versa. IoT is used to automatically collect the manufacturing data in real-time while the digital twin along with big data analytics could use the data to predict, estimate and analyze the dynamic changes within the physical object. An optimized solution is then fed back to the physical object that would adapt accordingly [4]. This makes the digital twin technology the focus of the global manufacturing transformation and upgrading as it has the potential to optimize the whole manufacturing process [5].

In this context, this paper proposes a digital twin framework of a real production line, Festo Cyber Physical Factory for Industry 4.0 located at Middlesex University. Additionally, the paper introduces a viable framework for interlinking the physical system with its digital instance in order to offer extended services and advance towards the realization of a fully functional digital twin.

The rest of the paper is structured as follows: Section II introduces the related works carried out in this area, Section III gives an overview of the proposed digital twin framework, Section IV describes the assembly system configuration in details, Section V introduces the digital system for process replication and finally conclusions are drawn in Section VI.

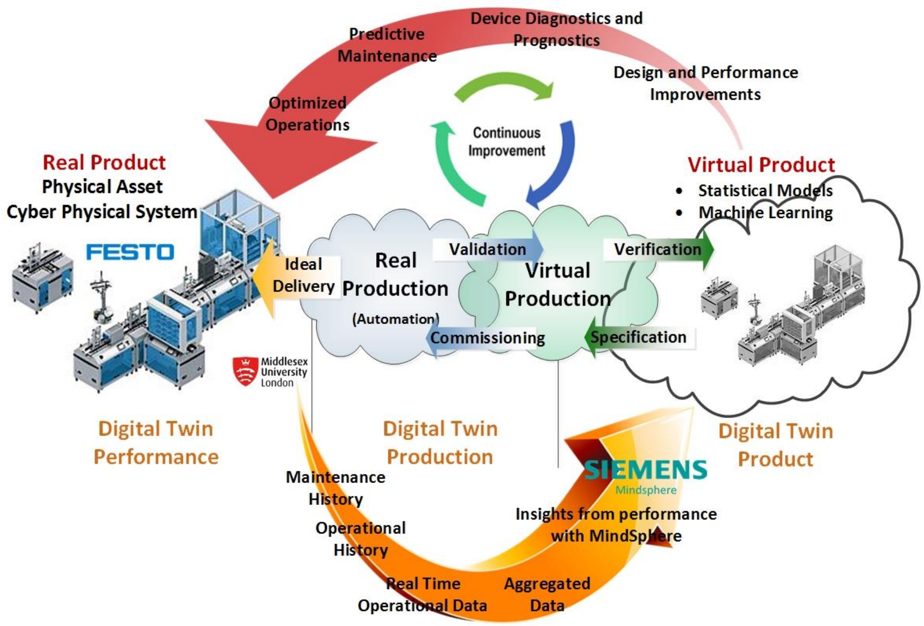

Figure 1. Proposed Digital Twin Framework

II. LITERATURE REVIEW

Industry 4.0 presents a suitable solution for artificial intelligence driven mass production, automation, assembly and processing. The information driven I4.0 framework allows the use of excessive data generated from different systems to make smart decisions. The overall operation of I4.0 can be subdivided into multiple systems including emergency systems, regulatory control, supervisory control, open-loop control, alerting and monitoring systems. Each of these systems can be further distributed into the sensing, communications and actuator blocks which allow the processes to run smoothly and more effectively within industrial systems. The makes the integration of digital twin technology into industrial application a promising solution. Various approaches have focused at integrating digital twin within different stages of a product lifecycle, such as design, production, prognostics, health management, etc [6]. However, the overall aim is to make use of the digital twin technology to make the product production lifecycle more reliable, flexible and predictable. Vachálek et al. in [7] investigated the use of digital twin for continuous optimization of production processes, proactive maintenance, and continuous processing of process data. The authors used the didactic stations made by Festo for a production chain simulating the manufacturing of pneumatic cylinders. The digital model of the production line was created using the Siemens Plant Simulation tool. The results show that by employing digital twin, the material waste could be reduced and the lifetime of the machine could be extended. Brenner et al. [8] investigated the requirements for the integration of the digital twin technology within the Logistics Learning Factory of European School of Business. The aim is to achieve smooth interaction between human, product and machine. Ameri et al. [9] investigated the integration of intelligent maintenance systems within the spare parts supply chain through the digital twin. The aim is to provide lower costs on the supply chain while still delivering higher service level. Uhlemann et al. [10] demonstrated the benefits of automated data acquisition and processing through the use of digital twin technology within a production system. The authors provide a comparison between the use of the digital twin technology and common tools of the process optimization.

III. DIGITAL TWIN FOR FESTO CYBER PHYSICAL FACTORY

Figure 1 illustrates the proposed digital twin framework of the smart cyber physical factory located at Middlesex University. The CPF is supplied by Festo/Siemens and comprises a comprehensive six-station table top unit integrated into two production cells, as well as two bridging stations that enable an Automated Guided Vehicle (AGV) to deliver the logistics/transport between the cells. The aim is to develop the digital counterpart of this Industry 4.0 system to replicate its functionalities, data, communications, feedback, emergency and safety aspects. IoT data is collected at different stages of the product's lifecycle, including product design, manufacturing, distribution, maintenance, etc. This data can contain maintenance history, operational history, real time operational data, etc. Big data analytics is then used to analyze the data for optimized operation, predictive maintenance, device diagnostics and prognostics, design and performance improvements, etc. However, one key challenge

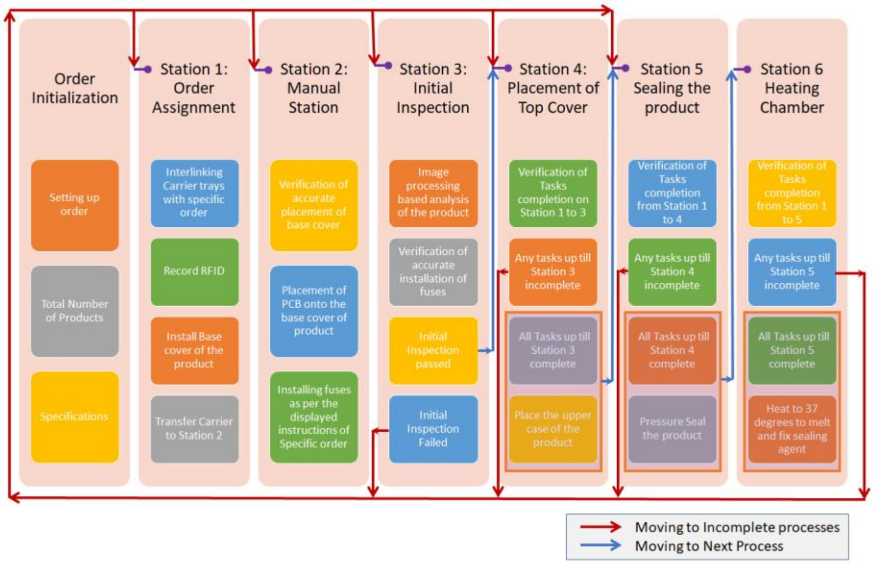

Figure 3. Operation of Festo Cyber Physical Factory for product assembly

is in how to connect the physical space with the digital space to make proper use of the analytical results. This is achieved by integrating the digital twin that could make use of the big data analytics results and inforce an action into the physical system as a real time response for optimized performance and maintenance.

The Festo Cyber Physical Factory represents a product production and assembly line. The sequence of processes for assembly of the product is presented in Fig. 2, whereas details of these processes are presented in Fig. 3. The overall assembly operation from start to completion is divided into six tasks performed at six stations. Figure 3 illustrates a flow diagram with the description of check for process verification and returns of the product to relevant station.
The details of the assembly system and processes are given in the next section.

Figure 2. Festo Cyber Physical Factory product assembly processes

IV. Assembly System Configuration for Industry 4.0

In this work, a digital representation of a sub-section of production and assembly line application is presented. The created digital model of production line uses modular approach to ensure similarities with the physical model. A 2-dimensional (2D) animated environment is developed to give visual representation to the processes.

The product assembly from start to completion is divided in six tasks performed at six stations (S1-S6). After order assignment a carrier tray is reserved for one product until completion. On completion, the carrier tray is assigned to next order. RFID based identification is used to distinguish between multiple carrier trays where each carrier tray can be assigned a different order configuration.

A graphical representation of Station-1 (S1) of a production and assembly line is presented in Fig. 4. As represented in the figure, once a product order is issued, the conveyor belts start rolling and product carrier tray (see Fig. 4 (a)) enters S1 from turn support wheel (see Fig. 4 (b)-①, ②). Once the product enters S1, its entry time is read using capacitive location sensing (see Fig. 4 (b)-③), activated by the passage of product carrier tray over it. Further to this, depending on the order requirements, the carrier tray is stopped using traction-based carrier tray stopper (see Fig. 4 (c)-①). Then, the RFID of the carrier is read using RFID reader (see Fig. 4 (c)-②), which allows to keep track of the processes that have been completed for a specific product. Thus, if a failure in completion of one process occurs, the carrier tray can be returned to pipeline where the completed processes are skipped based on the RFID record and only the incomplete processes will be performed on the product. While the tray stopper is active, the exact location of the tray is evaluated using location sensors depicted in Fig 4. (c)- ③. This allows the product base cover holder (see Fig 4. (d)) to accurately place the base cover on the carrier tray if the carrier tray is empty. This check (whether a carrier tray is empty or not) is performed using IR sensors (see Fig 4. (e)). After the base cover of the product is placed on the carrier tray, the task required from S1 is complete and traction-based carrier tray stopper (see Fig. 4 (c)-①) deactivates to let the carrier tray proceed to station 2 (S2).

The S2 is a manual station where the display units (see Fig. 4 (f)) provide instructions for operator to add Printed Circuit Board (PCB) onto the base cover with a selected combination of fuses. The carrier tray with the PCB is represented in Fig. 5 (a), whereas the top view of the PCB with fuse slots is presented in Fig. 5 (b).

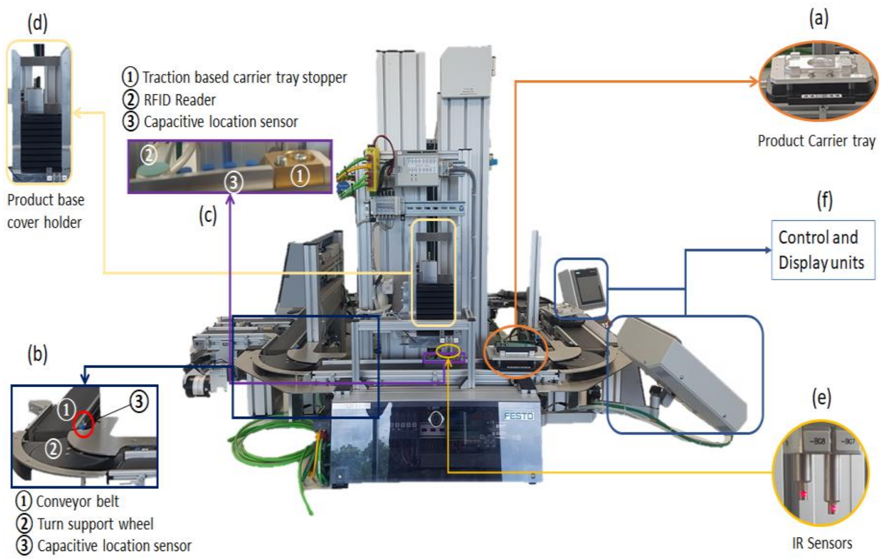

Figure 4. Festo Cyber Physical Factory (Station 1)

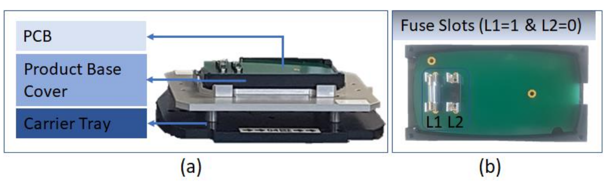

Figure 5. Product Base Carrier Tray (a) Product state after station 2 (b) Top view of PCB with fuse slots

Once the manual operation is complete the specific order (recognized by its RFID code) is moved to the image processing based inspection station (S3), where the fuse configuration on the PCB is verified in accordance with the original order assigned to the carrier tray. If the product's initial inspection passes quality check it is moved to the next station (S4) otherwise it is moved back to Station 1.

If completion check failure occurs at any stage of product assembly, the product is returned to relevant station before proceeding further. The connected system, with sensor readings collected every 6-10ms, and implemented intelligent algorithms allow the return of the product carrier to relevant station for completion of pending/skipped tasks. It is worth mentioning that the return of a particular carrier tray where the two stations are not directly connected (e.g. Station 1 and Station 4) is facilitated by passing through series of stations where each subsequent station will not perform any operation on the product until whole sequence of operations is complete up till the relevant station. Similarly, the stations which already have performed their tasks on a product will also skip the operation. This saves time and resources and improves productivity of the system.

Once the operations until S3 are successfully completed, the carrier tray is moved to Station 4 (S4). S4 performs similar operations as S1, except the difference is that it places top cover of the product on the carrier tray. Since the placement of top cover needs position accuracy, therefore a similar setup like in S1 (as depicted in Fig. 4 (c)) is repeated. The RFID is read, and the product completion status is checked from control units whether it is ready for top lid placement or not (i.e. tasks in S1 to S3 are completed). With capacitive location estimation sensors, the product top cover holder, similar to the one in Fig. 4 (d) places the top cover accurately on the assembled product. After completion of this task, the product is moved to Station 5 which depresses the top lid onto the product. A pre-specified pressure is used to press the top cover of the product. Finally, the product is passed through a heating chamber which heats the product to 37° C to seal it. Once the product is ready, it is removed from the production line and carrier tray moves back to the S1 where it is assigned a new order.

V. DIGITAL SYSTEM FOR PROCESS REPLICATION OF S1-S3

In this work, a station simulator with animated digital motion is developed to give realistic representation of stations S1 to S3. The simulator for stations S1 to S3 is presented in Fig. 6, whereas a multi-step representation of S1 processes is presented in Fig. 7. As represented in Fig. 7, the simulator for S1 depicts assembly line operation using continuous motion animation. Fig. 7 ① represents the physical systems whereas Fig. 7 ②-⑥ represents digital replications of the process where the position of carrier tray changes on conveyor belt after 3, 6, 9, 11 and 14 seconds respectively.

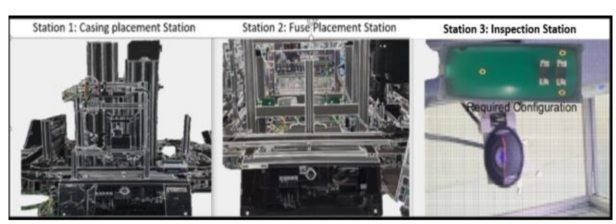

Figure 6. Digital simulator of production line and assembly of CPF

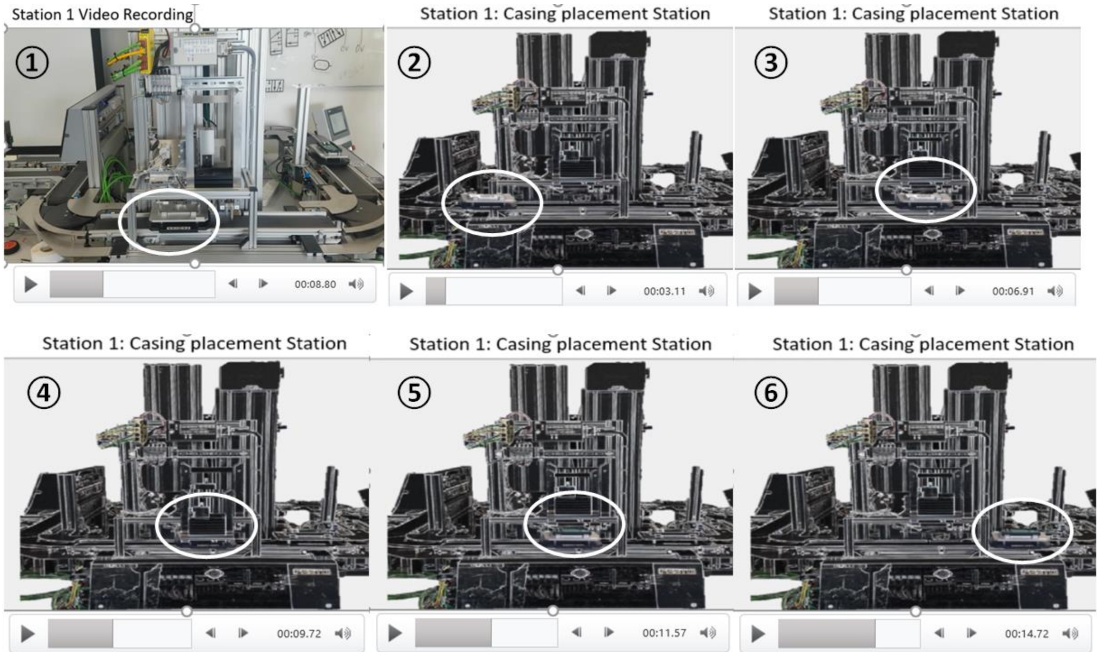

Figure 7. Digital Assembly line simulation with continuous motion animation

The process is represented with continuous motion animations where different blocks within the physical system are animated to present satisfactory visual effects For instance, see Fig. 7 ③, ④ and ⑤. In ③, the empty carrier stops beneath the product base cover holder (see also Fig. 4 (d)). The product base cover holder moves down to place the base cover as represented in ④. Whereas in ⑤ the product base cover holder returns to original position where the carrier tray now contains base cover of the product.

VI. Conclusions

Digital twins emerge as a technology with potential to reshape design, implementation and execution of industrial processes. Digital twin implementation in industries unlocks the possibility of seamless information transfer, digital process replication, system diagnosis, operation stabilization, productivity enhancement, intelligent system development and predictive analysis. The presented digital process replication enables effective representation of assembly line applications in industry 4.0. This digital representation, when coupled with proposed digital twin framework opens new venues of research in similarity learning, virtual analysis, multi-service platform, predictive maintenance, life-long learning and aging.

VII. Acknowledgements

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References

[1] B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee and B. Yin, "Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges," in IEEE Access, vol. 6, pp. 6505-6519, 2018. doi: 10.1109/ACCESS.2017.2783682

[2] J. Jamaludin and J. M. Rohani, "Cyber-Physical System (CPS): State of the Art," 2018 International Conference on Computing, Electronic and Electrical Engineering (ICE Cube), Quetta, 2018, pp. 1-5. doi: 10.1109/ICECUBE.2018.8610996

[3] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, 'Digital Twin in manufacturing: A categorical literature review and classification', IFAC-PapersOnLine, vol. 51, no. 11, pp. 1016–1022, Jan. 2018.

[4] Q. Qi and F. Tao, "Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison," in IEEE Access, vol. 6, pp. 3585-3593, 2018. doi: 10.1109/ACCESS.2018.2793265

[5] J. Liu *et al*., "Dynamic Evaluation Method of Machining Process Planning Based on Digital Twin," in *IEEE Access*, vol. 7, pp. 19312-19323, 2019. doi: 10.1109/ACCESS.2019.2893309

[6] F. Tao, H. Zhang, A. Liu and A. Y. C. Nee, "Digital Twin in Industry: State-of-the-Art," in *IEEE Transactions on Industrial Informatics*, vol. 15, no. 4, pp. 2405-2415, April 2019. doi: 10.1109/TII.2018.2873186

[7] J. Vachálek, L. Bartalský, O. Rovný, D. Šišmišová, M. Morháč and M. Lokšík, "The digital twin of an industrial production line within the industry 4.0 concept," *2017 21st International Conference on Process Control (PC)*, Strbske Pleso, 2017, pp. 258-262. doi: 10.1109/PC.2017.7976223

[8] B. Brenner and V. Hummel, 'Digital Twin as Enabler for an Innovative Digital Shopfloor Management System in the ESB Logistics Learning Factory at Reutlingen - University', Procedia Manufacturing, vol. 9, pp. 198–205, Jan. 2017.

[9] F. Ameri, R. Sabbagh, 'Digital Factories for Capability Modeling and Visualization', IFIP International Conference on Advances in Production Management Systems (APMS), Sep 2016, Iguassu Falls, Brazil. pp.69-78.

[10] T. H.-J. Uhlemann, C. Schock, C. Lehmann, S. Freiberger, and R. Steinhilper, 'The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems', Procedia Manufacturing, vol. 9, pp. 113–120, Jan. 2017.