Digital Twin and Manufacturing Simulation Integrated Platform embedded in cyber-physical system

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Abstract. Simulation on manufacturing process of production line is essential to reduce the cost and time of production line layout design. Traditional simulation methods either have low fidelity or depend on actual equipment and external tools. Digital Twin is a core element in Industry 4.0 and is viewed as the next generation of simulation. However, applying Digital Twin to simulate manufacturing process is inadequately researched. To simulate and assess the manufacturing process of production lines in advance, this paper proposes Digital Twin and Manufacturing Simulation Integrated Platform (DTMSIP) embedded in Cyber-Physical System (CPS). Powered by the Plug-and-Play CPS, DTMSIP can serve the function of both monitoring and simulation, where fidelity is ensured by precise mapping of Digital Twin. After DTMSIP is established for a reconfigurable production line, DTMSIP as a simulation method is validated on a reconfiguration evaluation problem in this paper.

1. Introduction

Reconfigurable Manufacturing System (RMS) is empowered to rapidly adjust production capacity and functionality within a part family to meet the changed needs in market [1]. A RMS’s configuration can facilitate or impede its productivity and needs to be designed and optimized [2]. Recently, digital simulation methods are introduced into the designing process of configuration of RMS [3-6], overcoming the problems of traditional design methods that newly designed configuration cannot prove effective until reconfiguration is already done. However, fidelity of these simulation methods cannot be guaranteed because no accurate mapping is established on virtual models. Cyber-Physical Systems and Digital Twin can be introduced to help enhance simulation fidelity.

Cyber-Physical Systems (CPS) are defined as new generation of systems which integrate computational and physical capabilities to establish interaction between cyber world and physical world [7]. In CPS, the standardized service interfaces and the property of Plug-and-Play transform traditional factories into modular and flexible setup, allowing dynamic rearrangement for any purposes [8]. Modularity is among the core characteristics of CPS that enables CPS to be flexibly changed and reconfigured in response to market change [9]. Thus, CPS provides new possibilities to help build simulation platform for RMS. Moreover, with unified data interfaces, additional services and applications can be added to the CPS and extend the boundaries of manufacturing systems. Among these, Digital Twin plays a decisive role in CPS and represents the prerequisite for the development of CPS [10].
Proposed in 2003 by Michael Grieves [11], Digital Twin has aroused significant attention for its potential to shape future manufacturing. Digital Twin contains three main parts: physical products, virtual products and the connections of information that ties physical and virtual products together. At its first invention, Digital Twin was limited to be applied on Product Lifecycle Management (PLM). After the enhancement of enabling information technology, Digital Twin is now extended to be the virtual and synchronized representation of manufacturing elements such as products, personnel, equipment and process. Current researches on Digital Twin focuses mostly on product operation and maintenance while research on manufacturing is inadequate [12]. Thus, Digital Twin related research is still in an early stage [13] and its full capacity is yet to be explored [14]. Nevertheless, because of its ability to extend simulation to full life cycle of products, and because of the trend of CPS application, Digital Twin is viewed as the next wave in model, simulation and optimization [8, 14, 15].

2. Related work
Applying Digital Twin-based simulation method on production processes attracts great interest recently. Zhang et al. [16] set up a simulation platform that has real physical properties (e.g., gravity, friction, speed, impact and inertia) and perform distributed semi-physical simulation (based on secondary development on database and 3D engine) on it to evaluate the performance of designed production line. In Digital Twin-based Virtual Factory proposed by Yildiz et al. [17], Virtual Factory uses data generated in real systems and simulation systems to analyse the performance of production systems. Ding et al. [18] proposes Digital Twin-based Cyber-Physical Production System where simulation is performed in Digital Twin based on knowledge in database. All of these methods achieve good results. However, these simulation methods are dependent on actual device or external simulation systems, which does not fulfill the potential of Digital Twin.

In this paper, it is made possible to perform production process simulation completely inside Digital Twin by enabling virtual devices in Digital Twin to fully emulate actual devices, communicating with manufacturing control system. This novel manufacturing simulation method is validated with the construction and usage on a reconfigurable production line.

Tao and Zhang [19] proposed Digital Twin Shop-floor (DTS), seeing Digital Twin as a method of achieving the convergence between physical and virtual spaces. In DTS framework, Physical Shop-floor includes objectively existing entities. Cyber Shop-floor consists of models built to evolve with Physical Shop-floor, both interacting with Shop-floor Service System. This framework is adopted in this paper to base our proposed simulation method on.

3. Digital Twin and Manufacturing Simulation Integrated Platform
Digital Twin is based on accurate mapping between physical and virtual entities, and is driven by real data acquired by sensors. Therefore, Digital Twin's potential on simulation is foreseen. Embedded in CPS, Digital Twin can gain access to heterogeneous multi-source data and further use it to drive 3D virtual devices. Because virtual equipment in Digital Twin can be arbitrarily duplicated and replaced without limitation of hours, room, cost, etc., Digital Twin is able to simulate whole production processes which are unable to carry out in physical world. Within this preview of manufacturing, bottleneck can be identified, effectiveness of production line can be assessed in advance. Based on this idea, Digital Twin and Manufacturing Simulation Integrated Platform (DTMSIP) is proposed. Figure 1 illustrates DTMSIP architecture and its role in a CPS.
Figure 1. Digital Twin and Manufacturing Simulation Integrated Platform.

3.1. CPS Bus
Shop-floor data sent from device to software, from software to device, from software to software flows into and is transmitted by CPS Bus. Direct transmission between each component in CPS is not permitted. This constraint compels all data to be reachable by Digital Twin.

3.2. Physical shop-floor
The decoupled machines are connected with CPS Bus and driven by corresponding proxy software. The machine’s unawareness of surrounding machines contributes to hardware's ability of Plug-and-Play and rapid reconfiguration.

3.3. Shop-Floor Service System (SSS)
SSS controls the behaviour of Physical Shop-floor. Manufacturing Execution Server (MEServer) carries out the function of order handling, process control and production scheduling. Monitor Server transfers runtime data to any monitoring app, including Digital Twin.

3.4. DTMSIP also Cyber Shop-Floor
DTMSIP can serve the purposes of both production monitoring and manufacturing simulation, along with the ability to seamlessly switch between these two modes.

In Monitoring Mode, DTMSIP receives data produced by equipment and service through CPS bus, and use it to drive the virtual equipment inside DTMSIP. The one-direction and low-latency data flow ensures an accurate mapping from Physical Shop-floor to Cyber Shop-floor. After establish this procedure, knowledge can be accumulated in order to enhance the real-time performance of data
driving, the accuracy of mapping, the recurring fidelity of physical process. As a consequence, the Degree of Cyber-Physical Fusion is enhanced.

In simulation mode, whole production process simulation can be done offline. With high-fidelity physics environment, with behaviour and constraints set, virtual equipment in 3D environment can emulate real equipment in physical world. Every virtual machine can not only run independently as real machine would behave, but also form into the whole production line. More importantly, these virtual machines are endowed with the ability to communicate with SSS, that is, to send query to SSS and receive command made by SSS, using it to display the behaviour of 3D models. Thus, production process in Physical Shop-floor can be fully simulated by DTMSIP with no need of any actual devices. No physical asset involved, though, fidelity of this type of simulation method is ensured by Degree of Fusion from Monitoring Mode.

After manufacturing simulation is realized, efficiency assessment of production line configuration design is attainable, according to which designed configuration can be iteratively verified and optimized in a full virtual setting. When this procedure is done, the optimized configuration designed result can be applied to Physical Shop-floor. And this is how Cyber Shop-floor and Physical Shop-floor evolve with each other.

By comparison with other proposed simulation methods, DTMSIP has considerable advantages:
- DTMSIP serves the function of both monitoring and simulation. In actual production, DTMSIP can monitor the process; in need of production line reconfiguration, DTMSIP can simulate production process of arbitrary RMS configuration.
- Degree of Fusion in Monitoring Mode guarantees Simulation Fidelity.
- In simulation, virtual equipment substitutes for real equipment, communicating with and actuating command from SSS. Therefore, the performance of SSS can be improved as well.
- DTMSIP is other than simply a standalone simulation method. Instead, it is a key functioning component in Digital Twin Shop-floor.

4. Using DTMSIP to analyse production line configuration

4.1. Overview of studied reconfigurable production line
The production line is formed with any number of identical base (Figure 2) with different module installed on each. Four conveyor belts run in four directions, driving trays, with material loaded on, from one base to another. On each base, there are three workstations where assembly process is executed on trays. Path switch is controlled to shift path for tray to move to different adjacent base.

All the bases are in control of MEServer developed for this line. MEServer, as SSS, is where production line configuration is analysed. It handles orders received from customers, distributes orders to vacant trays, commands modules to actuate working steps, and controls the path switches to guide trays onto their optimized path.

Figure 2. The universal base forming up the reconfigurable production line.
4.2. Problem description
Configurations of this production line refers to the placement and orientation of each base. Two configurations of this production and the assembly steps and averaged step time of a certain product are shown in Figure 3. For this product, Configuration I provides two module F in parallel for tray to choose, reducing block due to the longest step time of F. Configuration I is how physical equipment is placed. Configuration II uses one module F less, causing no parallel module existing.

When market need for the product is dropped, this production line can be scaled down by removing the parallel module F to other lines, shifting to Configuration II. But managers want to know how much production capacity will drop before the reconfiguration. Therefore, this section aims to evaluate how much the parallel module F influences production time through simulation provided by DTMSIP.

![Figure 3. Two configurations to be assessed by simulation.](image)

4.3. Construction of DTMSIP
Unreal Engine 4 (UE4) is a free and open-source game engine developed by Epic Games. Its real-time rendering performance, reliable physics system, various developing framework win UE4 great popularity among game, film and architecture industry. Compared with other 3D creation platform, UE4 provides more encapsulation and inheritance, which suit the construction of RMS Digital Twin well. UE4 is adopted to construct DTMSIP for above production line.

Zhang et al. [7] proposed a five-dimensional (Geometry, Physics, Capabilities, Behaviour, Rules) model-driven framework of Reconfigurable Digital Twin manufacturing systems. This framework can be adopted to guide the construction of Digital Twin. Therefore, DTMSIP construction process is introduced in these five dimensions respectively.

**Geometry.** Precise 3D models can be attained by converting equipment design models from AutoCAD or SolidWorks into engine-ready models using Digital Content Creation (DCC) tools such
as Cinema 4D, 3ds Max, Maya, etc. Once models of bases and modules are set, the configuration should be generated according to simulation requirement and stay the same as configuration analysed in MEServer.

**Physics.** Physics refers to real mass and force, and resulted velocity and acceleration. Physics is crucial to Digital Twin of production line because by Physics is how spontaneous yet natural movement occurs. Collision in UE attached to objects represents the boundary of physics interaction with other objects. With original-shaped Collision set, gravity enabled, and material with friction assigned, the conveyor belt is ready to drive trays along.

**Capability.** It is necessary that different function modules installed on Physical Shop-floor's bases are mapped into Digital Twin. Different modules impose different processes on product's manufacturing and this is realized by function encapsulation and polymorphism in UE4.

**Behaviour.** If something happens in Physical Shop-floor, it is supposed to happen in Digital Twin. This behaviour mapping is achieved through discrete event frames transmitted to Digital Twin. Each element in DTMSIP is a listener to specific events originated from whether sensors or SSS. When events are triggered, subsequent behaviour predefined by programming is driven by received structured data in frames.

**Rule.** To obtain more precise mapping, rule is to be formulated additionally when mapping data transition ceases. For example, time-out mechanism can increase mapping robustness in case of material tracking failure.

Development with UE4 is based on C++ and Blueprint. Blueprint is a visual scripting system using a node-based interface to create runtime elements within UE4. As stated above, the Blueprint of the base is shown in Figure 4.

![Figure 4. The UE4 blueprint of reconfigurable production line base.](image)

**4.4. Simulation of production process using DTMSIP**

First, monitoring procedure is followed when physical production line (Configuration I) fulfills five orders of customized product, recording production time of each order and the whole production. Then, simulation is carried out on Configuration I and Configuration II. Production time is put into contrast in Table 1.
Table 1. Monitoring and Simulation on a production process: production time contrast.

|                  | Monitoring on Configuration I | Simulation on Configuration I | Simulation on Configuration II |
|------------------|-------------------------------|------------------------------|-------------------------------|
| Runtime          |                               |                              |                               |
| Screenshot       |                               |                              |                               |
| Total time (5 orders) | 537 s                      | 502 s                        | 542 s                        |
| Average order time | 320 s                      | 335 s                        | 358 s                        |

4.5. Results and discussion

As presented in Table 1, DTMSIP simulated production time on Configuration I is close to real production time with errors of 6.5% on total time and 4.7% on order time. Also, simulation result shows that scaling down from Configuration I to Configuration II will increase total production time and order time by 8.0% and 6.9%, respectively.

The error of simulation on Configuration I is mainly caused by variant module execution time, while process time in simulation is set the average step time for each module. To be specific, because this production line assembles products with customized part, time of execution and reset varies among different part ordered. This error can be eliminated with data acquired from inside PLC of module actuators. With mapping and behaviour imitation of actuator established, time can be no longer constant for each module in simulation. It can be seen that simulation fidelity depends on the extensive data acquisition of Physical Shop-floor, which is a great challenge for DTMSIP to be accurate.

The result of simulation on Configuration I and Configuration II is as expected: removing parallel module causes bottleneck and increases production time. This quantitative analysis can offer valuable information in a rapid and convenient manner before the reconfiguration.

5. Conclusions

This paper proposes DTMSIP both as a simulation method and a key component in CPS. Within flexible CPS, DTMSIP brings Digital Twin’ properties of precise mapping, Cyber-Physical Fusion into full play by introducing Digital Twin to simulation. For one, traditional factory simulation software provides manufacturing preview whose fidelity is hard to estimate. For the other, recently proposed Digital Twin-based simulation method can ensure fidelity but has a heavy dependence on physical assets or external simulation tools. Simulation method proposed in this paper overcomes these two weaknesses. Using UE4, DTMSIP is built for a reconfigurable production line. Through Monitoring and Simulation done to a production process, DTMSIP as a simulation method is validated. This simulation method can preview and assess the efficiency of any configuration of RMS. As data is collected in any possible configuration, more data-driven research should be done on these materials. Future work is focused on how to proceed with these statistics to optimize RMS and to establish a systematic RMS optimization methodology based on proposed simulation method.

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