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Digitization of Assembly Line for Complex Products – The Digital Nursery of Workpiece Digital Twins

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Abstract: During the last decade the use of digital twins has been spreading to various complex systems, such as assembly lines, and complex products such as aircraft, drones, satellites, vehicles and machinery. This paper discusses the considerations related to the interaction between the assembly-line digital twin and the digital twins of the evolving complex products (workpieces). The paper proposes hierarchical framework including the assembly-line digital twin at the top, that employs the workstation digital twins which are temporarily connected to their current workpiece digital twins. The result is a system that can accurately and efficiently synchronize these simultaneous digital twins. A shared data structure is proposed to facilitate the control and tracking of the assembly progress of each workpiece. This data structure is carried with the workpiece and is shared with the current station digital twin and if necessary the line digital twin.

Keywords: Digital twin, Industry 4.0, Assembly line, Assembly 4.0, Assembly system, smart manufacturing.

1. INTRODUCTION

The emergent use of digital-twins is mostly attributed to the detailed digital representation of an aircraft – that enabled reliable simulation of its characteristics and behavior (e.g, Tuegel et al. 2011; Glaessgen & Stargel, 2012). However, the use of digital twins quickly evolved, to simulate other complex products and systems including manufacturing systems (Zhuang et al.2018; Kritzinger et al. 2018). In recent years the digital-twin has been integrating well with the concepts of "Cyber Physical Systems" (CPS) and "Industry 4.0" (Uhlemann et al. 2017; Leng et al. 2019; Zhang et al. 2019). At the same time, digital-twins have been proposed for simulating and controlling assembly lines and production lines (Chiara et al 2019; Cohen et al. 2019a, 2019b). Nevertheless, so far, the digital-twin literature ignored the case where both production system and products have digital twins. This environment characterizes the assembly of very complex products, such as satellites, submarines, aircrafts, and heavy machinery. However, we claim that the evolution of digital-twins' usage is expected to increase the relevance of this environment. In the long-run, it is expected that usage of digital twin will spread to represent more mundane products such as trucks, buses and cars, and even engines.

This paper focuses on the unique features and requirements when both production system and products have digital twins. The paper discusses where this mode of operation is appropriate and effective, and its advantages for such environments.

The rest of this paper is structured as follows: section 2 briefly reviews the most relevant literature; section 3 introduces the environment where assembled product digital twins is a necessity or an attractive feature. Section 4 presents a framework of digital twins in assembly lines; section 5 develops the main required interactions between the various digital entities. Finally, section 6 concludes the paper.

2. LITERATURE REVIEW

Vachálek et al. (2017) describes the development of a digital twin for a simple industrial production line, and optimized product sequencing and scheduling to save 5.2% of production time. Zhang et al. (2017) proposed digital-twin to improve the design of a production line. Um et al. (2017) proposes a method for digital environment automatic set-up for engineers by using a common data model inspired by the digital twin concept. Sanderson et al. (2018) suggest digital-twin framework for self-organizing assembly and self-adaptive assembly system. Zhuang et al. (2018) offers assembly-line digital-twin for complex products, to be used in four stages of the line's life-cycle: (1) Real-time acquisition and organization of the assembly shop-floor data , (2) Operation of the satellite assembly shop-floor digital twin, (3) Production services for the satellite assembly shop-floor, (4) Feedback operation of the physical assembly shop-floor.

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Karanjkar et al. (2018) showed that usage of digital-twin assisted in reducing energy consumption in assembly of surface mounted technology (SMT) elements onto a printed circuit board (PCB). Sujová et al. (2019) proposes a generic general digital assembly line for assessing flow and utilization, but this digital model is not a digital twin. Gao et al. (2019) uses assembly line to illustrate the efficiency achieved by using a real-time digital twin. Caputo et al. (2019) used digital twin to improve ergonomics in production and assembly workstations. Papanagnou (2020) showed and discussed ways for using digital twins for enhancing performance measurement in assembly lines.

3. DIGITAL-TWINS FOR BOTH PRODUCTION-SYSTEM AND PRODUCTS

Zhuang et al. (2018) deals with the assembly of complex products and presents a digital twin for a satellite assembly-line. However, the origins of digital twins were complex spacecraft. The literature review presented many studies that presented the advantages of a digital-twin of assembly lines. Other papers present the advantage of using a digital twin for modelling the features and behaviour of a product (e.g., Bilberg & Malik, 2019; Tao et al. 2019; Huang et al. 2020). An example of the importance of having a digital twin to a satellite would be instrumental for understanding the reasoning, and the relevance of product digital-twins.

Example:
<u>Digital-twin contribution to a satellite production:</u>
Exact Simulation -based on individual satellite data including individual parts and sub-assemblies
- Simulation of the individual satellite launch
- Simulation of the individual satellite orbiting
- Simulation of the individual satellite operation
- Simulation of unpredictable scenarios (e.g. it by asteroid)

Documentation:
- Documentation of measures & tests for individual parts
- Documentation of production batch and dates for each part
- Documentation of sub-assembly individual components
- Documentation of sub-assembly creation date and tests
- Documentation of maintenance activities

Maintenance
- Detection of quality problems
- Predictive maintenance - failure predictions

Note that the simulation and decision making are individualized and not generic. This means that they are closer to exact replica of the actual behaviour. For example, digital twin of the satellite launch should be able to detect a faulty O-ring (like the O-ring that caused explosion of Challenger) as each part is simulated exactly with its temperatures. While these advantages for a satellite are clear, similar benefits could be relevant to many other assembled products. In particular, digital twin of the main assembly workpieces would be instrumental in real-time documentation of the workpiece status, and inferring the next required assembly operation/s.

The workpiece information is passed to the assembly-line digital twin. Getting the updates from the workpiece, the digital twin of the line prepares itself for the expected work. In most cases it forwards the workpiece to the digital twin of the next workstation. On the other-hand, it can decide on other courses of action: (1) re-work for improving the workpiece quality, (2) reject the workpiece altogether, (3) test the workpiece quality.

From this discussion it could be understood that the proposed assembly line digital twin is an entity that includes modular digital twins of each workstation. The structure of the digital twins is further discussed in section 4.

4. A FRAMEWORK FOR DIGITAL-TWINS IN ASSEMBLY-LINES

The assembly line digital twin is a control system that enables both automated decision-making and decision support for the line operation. As such, it emulates the current state of the line and tracks the work-in-process (WIP) flow. Assembly lines are typically structured as a sequence of workstations, ordered by to the workpiece flow. Once the workpiece arrives at a station, the work in the station is mostly independent of what happens outside of that station. Thus, each station could be naturally modelled as a separate module. Therefore, while the digital twin of the assembly line is an entity by itself, each workstation in the line could also be easily modelled as an entity or an embedded digital twin.

There are three categories of stations along the line: (1) fully automated, (2) semi-automated and (3) manual. Digital twin of a fully automated station is emulating the computerized control over the station's machinery. Digital twin of semi-automated stations, must in addition to emulating machinery behaviour, closely detect the interface between the human operator and machinery. Moreover, for running various scenarios it must simulate the behaviour of human operator. A digital twin of a manual station must specialize in tracking the human operator movements, as well as the workpiece moves. More importantly, the assembly process is the actual evolution of the products, and closely tracking this process is the main purpose of assembly control. Thus, the station digital twin must be in close contact with the workpiece digital twin to track and control the evolving product and the operations it undergoes.

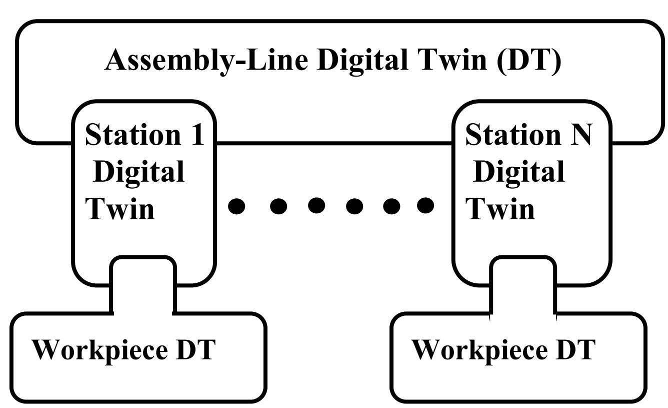


Fig. 1. Main hierarchy of digital twins in the assembly line

Figure 1 schematically depicts the main hierarchy of digital twins in the assembly line. This operation has some similarity to nursery, where the workpieces are analogous to plants in various growth stages, and the stations are analogous to growers (or to gardeners). Eventually, the digital twins of the workpieces will mature and leave the line to the rest of its lifespan.

Upper level control of the assembly line should use the line's digital twin to report the status of various stations (e.g., working time on the current workpiece, or idle time since last workpiece, and a flag for a problem) and buffers between stations. Moreover, statistics should be gathered on the flow characteristics of each station, to allow bottleneck tracking, and estimating maintenance effects whether planned or failure related. More detailed summaries could be attained by collecting information from the stations. The flow of information between the line's digital-twin and the digital twins of the stations is discussed in section 5.

The actual assembly work is done at the station level, and is controlled by the station digital twins. At this level, the work precision and efficiency are of prime importance. As explained in detail in section 5, the individual workpiece data is shared at this stage between the workpiece digital twin and the station digital twin.

5. COMMUNICATION AND INTERACTIONS BETWEEN THE DIGITAL TWINS

This section describes the main interaction and inter-communications between the various digital twins in the proposed framework. As explained above, the assembly workstations are designed to be relatively independent of other stations. If there are dependencies between stations or workpieces, they can be communicated effectively through the assembly-line digital-twin. So, the main two types of interactions and information flow are: (1) the interaction between the digital twin of the assembly-line, and the digital twins of the stations, and (2) the interaction between station digital-twin and workpiece twin. These interactions and communication flows are analysed next.

5.1 Digital Interaction Between Line-and Station Twins

The digital twin of the assembly line, by its definition, should be able to provide current, real-time status profile of all its stations. Therefore, it must hold simultaneous communication channels with all its workstations. This could be achieved by polling, multi-threading, or other techniques. Moreover, to keep the principles of modularization, the line twin is also the only communication channel to and from any station digital twin (except of its communications with the workpieces digital-twins). So inter-station communication and station logistic related communication is performed through the line digital twin. Some generic examples of information items that flow in this Line-Station channel are:

Examples of messages from Station DT to Line DT:
Workpiece arrival (Arrival-time, product-ID, type)
Workpiece departure (Departure time)
Required replenishment of parts/fasteners (part ID, qty.)
Defect (time, product-ID, type, reason, required action)
Missing part/matter (time, product-ID, part num/catalogue)

Examples of messages from Line DT to Station DT
Replenishment on its way (time, part ID, quantity)
Shut-down command (emergency)
Move current workpiece to rework.
Hold the completed workpiece and wait (e.g., in case of downstream jamming).

If a buffer exists between stations the line DT also keep track of each buffer between stations with a list of product IDs (each workpiece is given a unique product ID as it enters the line).

5.2 Digital Interaction Between Station and Workpiece Twins

The main assembly activities are done in the stations. These are the main changes to the workpiece that transform the workpiece into a complete product. In the proposed framework, each workpiece, from its very start, has a digital twin, that caries with it the information of all required parts, materials, and activities for transforming the workpiece into a final product. This includes the bill of materials and detailed assembly activities and precedence relations.

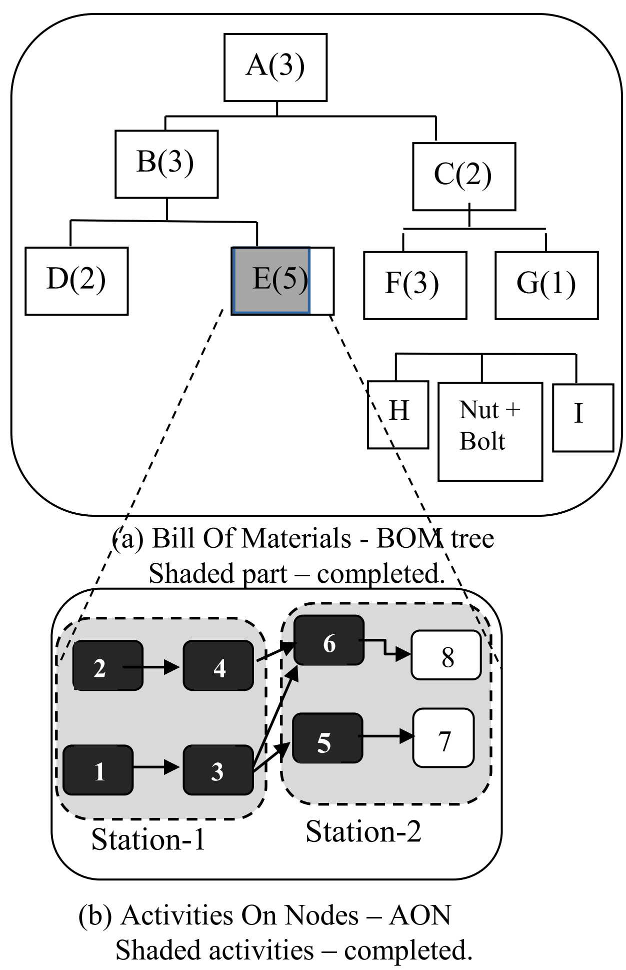
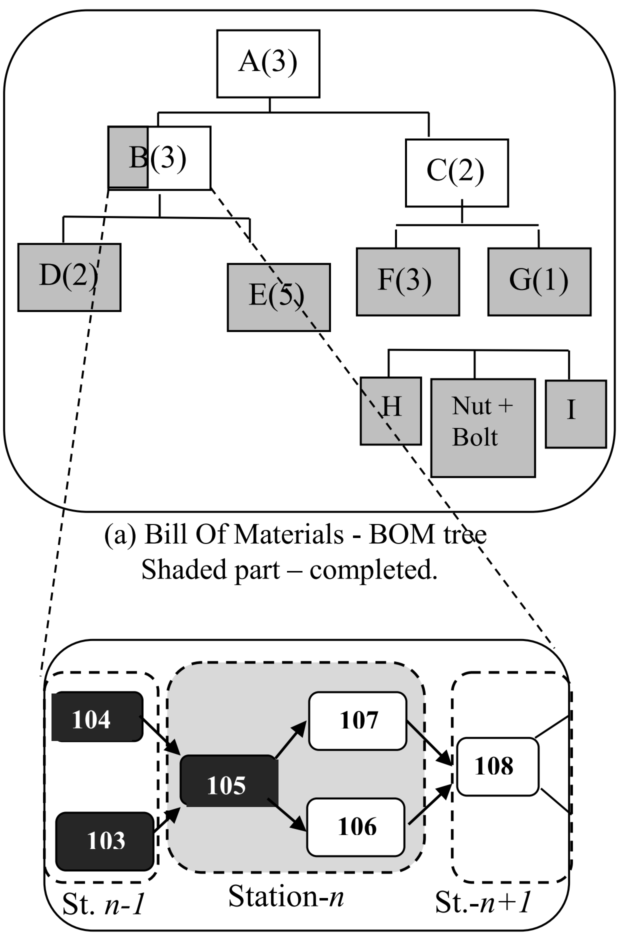


Fig. 2. A schematic example of the proposed information structure and its update process.

As the workpiece progresses through the stations along the line, they perform required activities and mark assemblies as done. This data structure is shared with the current station DT which is responsible for its updates. Figure 2 depicts a schematic example of the proposed shared information structure and its update process.

Figure 2.a depicts a bill of materials tree, where each node is an assembly task made of a small network of activities (Figure 2.b). The networks of activities are divided into work bundles of workstations as depicted in 2.b. during the course of assembly the completed activities are updated and marked as depicted in 2.b. The assembly progress is marked on each product so as depicted in figure 3.



(b) Activities On Nodes – AON
Shaded activities – completed.

Fig. 3. The progress of each workpiece is updated as it goes though the assembly process. Compare to Fig. 2.

Figure 3 shows how easily the status of the assembly is traced and effectively represented. In fact, the status of all WIP in the assembly line is just a profile showing these data structures for each workpiece. So if necessary, this data structure may be shared also with the assembly line DT. This data structure also holds standard parameter values, tolerances, and spaces for measured values for each activity and part. Example of such data is given in Figure 4.

The actual measured values are updated as the product progresses through the assembly line. In such settings, the quality check is easily automated and is immediate. In cases of defects the line DT is immediately informed and can decide on the appropriate action.

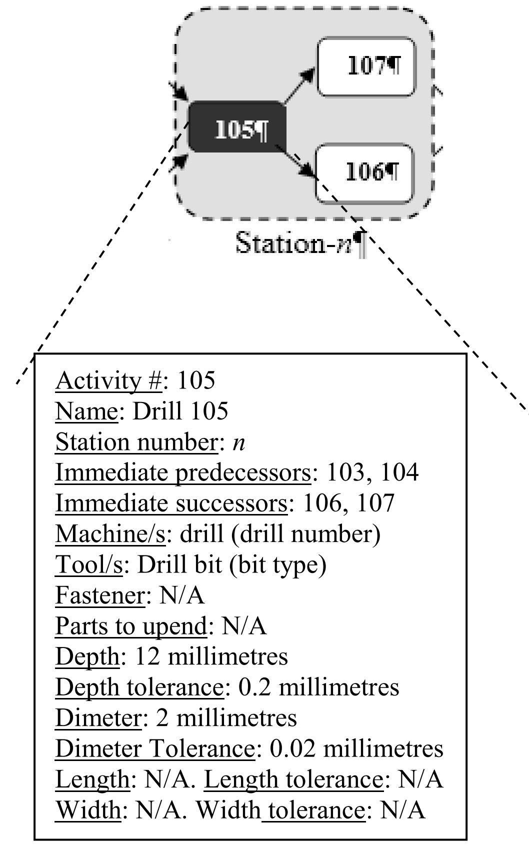


Fig. 4. Example of typical data related to a given activity.

It should be noted though, that workstation DT must emulate the behaviour of machines, tools, and operators. So that the communication with the workpieces is only part of its overall communication. On the other hand, only small portion of the shared data structure of the workpiece DT is relevant to a specific station.

6. CONCLUSION

This paper describes a proposed framework for using digital twins in the assembly line. The main novelty of the paper is modelling an environment of multiple digital twins, each with a specific role and identity. The main digital-twin proposed types are: (1) Assembly line, (2) Workstation, (3) Workpiece.

The proposed framework keeps an intuitive structure: The workpieces' digital twins are based on gradually filled bills of materials and processes. Each station twin adds its specific parts and/or processes the individual BOMs. Finally, the assembly line digital twin is composed of a succession of workstations' digital twins. Another advantage is the easy modularization of the model (for example, it is relatively easy to add or subtract a station or add/subtract a workpiece.)

A special attention is given to the digital twins' interaction and communication. In particular the paper discusses the interaction between: (1) line DT and station DTs this interaction must be done simultaneously, (2) Digital interaction between a station and a workpiece.

A shared data structure is proposed for tracing the assembly progress of each workpiece and for keeping the assembly status at all times.

Future research may advance in several directions: (1) Use this framework in empirical case studies, (2) Improve the modelling framework, (3) Modify the suggested framework to model other manufacturing or production or even service processes.

Finally, the spread of digital twin use is expected to quickly incorporate also complex sub-assemblies such as engines, cooling system, and other sub-systems. Thus, it may well be that the workpiece digital twin, would also be partly composed of the digital twins of complex subassemblies.

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