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Digital Twin Technology for Real-Time Monitoring and Control in Smart Manufacturing

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Abstract

The future trajectory of manufacturing will include the profound inclusion of the internet, communication, and cognition within industrial applications, driven by ongoing advancements in science and engineering. The increasing sophistication of technological innovations, including the Internet of Things (IoT), massive data sets, and cloud computing (CC), has led to the development and utilization of a promising technology - Digital Twin (DT). Presently, investigations on DT have yielded several ideas and results that have been implemented across various domains. This study introduced a Digital Twin Technology for Real-Time Monitoring and Control in Smart Manufacturing (DT-MC-SM). The DT is an important technology that allows for actualizing the potential of SM and Industry 4.0 to enhance the functioning of manufacturing processes. Fuelled by collecting and examining substantial information from linked virtual and physical environments, DTs are real-time digital representations of physical operations, procedures, or items that facilitate the assessment and enhancement of corporate performance. This research presents an innovative DT framework for continuous surveillance and assessment of extensive SM systems. An SM flow-shop implementation is shown to demonstrate the efficacy of the suggested technique.

Keywords: Digital Twin, Smart Manufacturing, Monitor, Control, Industry 4.0, Virtual Environment, Physical Environment.

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Introduction

Grieves introduced the Mirrored Spaced Model (MSM) in 2004, which serves as an illustration of the mathematical structure of the DT. This notion comprises a digital representation of a physical entity and an interconnection between the two (Grieves, 2005). In 2012, NASA introduced the special idea of DT and implemented it for the wellness monitoring and safeguarding of potential aircraft. A prototype has been developed in a digital environment. Sensors were used to attain full coordination with the aircraft's actual condition, and past information was examined to evaluate repair needs (Tao et al., 2018). The expansion of industrial IoT has rendered DT technology very important. The DT is not confined to aircraft; it also encompasses manufacturing design, industrial design, DT shop flooring, manufacturing process effectiveness, the Industrial IoT benchmark structure, prognostic and wellness administration, and intelligent cities. Consequently, DTs possess more significance and scope, progressively transitioning from theory to practice.

A DT is a virtual representation of a tangible object, constructed digitally, that utilizes data to emulate the behavior of the genuine thing within its surroundings. It facilitates the response and interchange of physical objects via proactive opinions, data integration and evaluation, and recurrent decision refinement for optimum control, safety surveillance, and data analytics (Li et al., 2022). A universal definition of DT remains elusive due to technological advancement and the proliferation of its uses. A primary cause is the variety of focal regions across numerous fields. Authors in (Semeraro et al., 2021) provide a synopsis of this study. They delineate the concept of DT into five elements: the capacity for simulation throughout a good's development process, the coordination of the online system with tangible resources, the combination of real-time information, the behavioral predicting of the physical environment, and the services rendered by the digital system.

As a layered multi-physical, multiple scales, stochastic simulation of a complicated production system, the DT necessitates a multidimensional, interdisciplinary, and multi-integrated approach for its categorization and analysis (Ma et al., 2022). Various phases of digital transformation exhibit distinct features, and comprehension of digital transformation is inextricably linked to particular objects, applications, and requirements. As previously stated, the center of attention must vary across various topic areas. Consequently, the following is a DT taxonomy based on many comprehension dimensions. Building upon the aforementioned description of DT, the following categorization categorizes DT based on its function in usage, involving modeling, virtual-real connection, model construction, and data analysis.

Upon reviewing several articles, it can be determined that the primary function of DT in implementations is as a simulation and design tool. In contrast, its role as a virtual-real connectivity technique involving information processing is comparatively less significant. This methodology is detailed in (Kritzinger et al., 2018), where authors categorize DT into three divisions: digital framework, digital shading, and DT (Fig. 1). A digital framework signifies that changes in the condition of the real thing do not directly influence the digital organization, and conversely. A digital shadow refers to a situation where a modification in the condition of a physical item results in a corresponding alteration in the state of a digital entity. Still, the reverse is not true (Newrzella et al., 2021). DT signifies that a modification in the condition of the physical item immediately induces a modification in the condition of the digital item, and conversely. Figure 1 illustrates the data flow charts for the three elements.

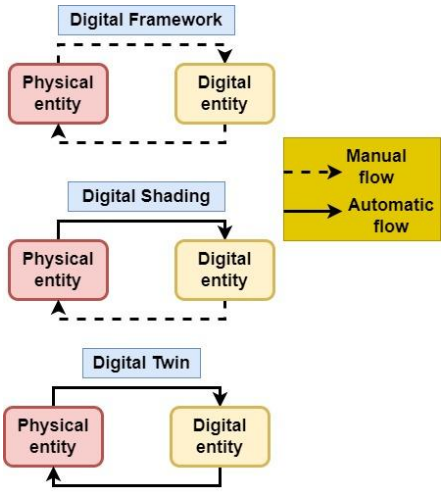


Fig. 1: Information flow in (a) Digital framework (b) Digital shading (c) DT

Nonetheless, achieving precise alignment between actual elements and computer models is challenging. Consequently, the aforementioned data cycling and updates must correspond to the system's scale to facilitate the regular upgrades and iterations of the DT. For instance, a municipal system that gathers and analyzes data within days needs daily coordination between actual things and virtual versions.

DT-MC-SM Methodology

The suggested DT framework equips the Software-based MC (SbMC) architecture with the capacity to develop components of a comprehensive perspective of the SM system for various applications (e.g., MC, abnormality prediction, real-time effectiveness, etc.). The DT technology offers real-time simulation of the MC system across several tiers of the ISA-95 protocol. Various categories of models are included in the DT architecture. Methods are constructed at the machine and network phases, considering ongoing, independent, and hybrid characteristics at every tier. They integrate physics-based and driven information to enhance evaluation.

The design of the DT system primarily comprises a DT pooling and a DT administrator. The DT pooling contains samples of several DT kinds linked by a Distribute Pledge (dis-ple) architecture. The DT administrator oversees the DT goal by orchestrating the startup of the DT pooling, facilitating dis-ple communication among DT situations, managing application inquiries via the API Handler, and managing interactions with the choice creator.

A. DT Repository

As previously stated, DTs are virtual representations of tangible items, resources, operations, and systems categorized as DT categories. A DT module may be constructed repeatedly and distributed on the DT infrastructure as DT examples. The machinery asset DT category may include several instances of machine resource DT, each linked to an individual machine inside an SM system. Within the framework of SbMC, the DT cases serve as foundational components that allow an SbMC user to tailor the functionalities of the DT framework according to the requirements of the SM platform. The collection of DT examples implemented on the DT platform is termed DT pooling.

Every DT entity comprises a computational framework, an information agent, and a communication operator.

1) Computational framework: The computational framework is the foundation of a DT experience. An arbitrary participation, such as one founded on physics, delineates the functioning of a physical entity or operation. Test results can be utilized to verify and perpetually refine the model, enhancing the practicality and worth of the digital depiction. This data encompasses information produced by the plant via the information agent or other DT cases via the message controller.
2) Information Agent: Every DT example has an information agent that links it to the information sources. It enables a DT implementation to get current and past information using an established protocol. This interface permits the inclusion of any plant-specific information source from information products and services if required.
3) Communication operator: DT examples and the DT management are linked by a dis-ple architecture inside the DT pooling. A DT instance may operate independently or collaboratively, depending on the objective, wherein its operation might rely on data produced by other DT to get the desired outcome. Each DT example has a communication operator to manage messages published and subscribed from other DT implementations.

B. DT Administrator

The DT administrator orchestrates the necessary exchanges among the DT examples and other SbMC elements, namely the SbMC programs and the choice maker. The responsibilities of the DT administrator are addressing data transfer queries between DT cases (via the dis-ple architecture) and other SbMC elements, accessing the current state of devices, and starting simulation activities. The DT administrator consists of (a) a DT importer, (b) a DT manager, and (c) a simulation administrator.

1) DT Importer: an operator of the DT framework may tailor the framework by designing and establishing a collection of DT cases that offer a specified set of functionalities for the MC-SM system. Clients may flexibly import or delete a DT version from the DT database using the DT importer. Furthermore, the DT category, with its functionalities and information constraints (subjects for dis-ple), is associated with the DT organizer during the importation and initialization of a DT entity.
2) DT Manager: The DT manager serves as the access interface to the DT during execution. It manages data exchange between the DTs and the inquiries generated by the SbMC programs and decision-makers. Based on the nature of the inquiries, the DT manager assigns the relevant jobs and information to the appropriate DTs.

A communication agent manages the dis-ple data transfer among the DT clients. A DT disseminates information whenever it ascertains that a modification is necessary. A DT can sign up with the communication provider to receive a collection of data disseminated by other DTs. Consequently, the customer of DT is certain to receive notifications and acquire the most recent data anytime there is a revision from a distributor DT. Upon the importation of a new DT, the DT coordinator supplies the most recent data for its subscribed subjects when the new DT has been verified and initiated.

3) Simulation Administrator: alongside real-time simulation functionalities, many DT categories provide simulation features that enable the respective DT examples to forecast the future behavior of the equipment and system. Utilizing technology like Effective Mock-up Interaction (EMI) enables the execution of simulations across numerous DT versions. This functionality is advantageous for verifying alterations in production plans, forecasting SM performance, and assessing various plant designs, among other applications. A simulation manager is used inside the DT framework to oversee the simulation jobs required by SbMC services or those making the decisions. Upon obtaining a simulation inquiry, the simulation administrator analyzes the query and allocates it to the appropriate DT entities. The simulation administrator then collects the results and provides them to the inquirer.

Conclusion

This research presented Digital Twin Technology for Real-Time Monitoring and Control in Smart Manufacturing (DT-MC-SM). The DT is a crucial technology that enables the realization of the capabilities of Smart production and Industry 4.0 to improve production operations. Driven by the aggregation and analysis of extensive data from interconnected virtual and physical realms, DTs are real-time digital representations of physical activities, processes, or objects that enable the evaluation and improvement of organizational performance. This study introduces a novel digital twin architecture for ongoing monitoring and evaluation of large-scale social media networks. An SM flow implementation is shown to illustrate the effectiveness of the proposed method.

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