Building Digital Twins of Cyber Physical Systems With Metaverse for Industry 5.0 and Beyond

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The digital twin has recently emerged as a virtual representation, that enables a real-time digital counterpart of a process or a physical object. Further, as the investments in Industry 5.0 are growing rapidly, their primary focus is to enhance the interactions between cyber-physical systems (CPS) and humans, for which outstanding contribution is expected through the metaverse. It enables humans to immerse into a high-dimensional 3-D virtual world, tackles the interactions among the CPS, and explore their status, which is found to be promising through the digital clones of CPS. This work presents the service-oriented digital twin architecture in conjunction with metaverse-enabled platforms with recommendations for ambitious interactions with the CPS for Industry 5.0 scenarios and beyond. They account for revolutionary changes in modern industries, supported through the Internet of Everything (IoE), VR/AR gadgets, and extended reality (XR) as prominent technology enablers.

The digital twin provides a digital representation of the real-world objects (e.g., processes, entities, systems, etc.). Such digital representation could be synchronized with real-world objects or processes based on the demand and applications. Nowadays, given the capabilities of sensors that relay information in addition to the two-way object interactions through the Industrial Internet of Things (IIoT), the digital twin paradigm can serve as a synchronization enabler of the digital space with the physical world (or vice versa). Here, changes in the physical world are synchronously reflected on the twin digital representation, whereas the feedback and responses are communicated in the other direction.

Most smart industries have partnered with 3-D real-time content developers like Unity to establish road maps toward building new metaverse platforms. Such platforms would transform the smart factories into virtual metafactories that enable them to test cases in the metaverse. Leading automobile production plants have started using digital twins to collaborate with their global team of experts through real-time 3-D virtual spaces. It primarily assists the industries in revalorizing the planning and production processes with the adaptive response toward efficient workflows.

Moreover, the progressive updates and learning allow the digital twin to deliver the real time (synchronous) position, status, and condition of the physical processes/assets. This integration of the virtual/digital and physical worlds ensures efficient monitoring of assets, failure anticipation, and optimization plan development. The digital twin technology primarily combines IoT, AI, software analytics, and network graphs to replicate physical twins (i.e., processes or assets).[1]

Although the digital twin technology has attained significant attention as an emerging paradigm in recent years, prominent challenges remain to be addressed. Such challenges include, but are not limited to, digital twin integration with metaverse-supported frameworks, digital cloning in smart industries, and virtual interactions with digital clones. This article discusses the current standing of digital twin technology in relevance to cyber-physical systems (CPS) with metaverse for industry 5.0 and beyond. A model of a

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Digital Object Identifier 10.1109/MITP.2022.3225064
Date of current version 11 January 2023.

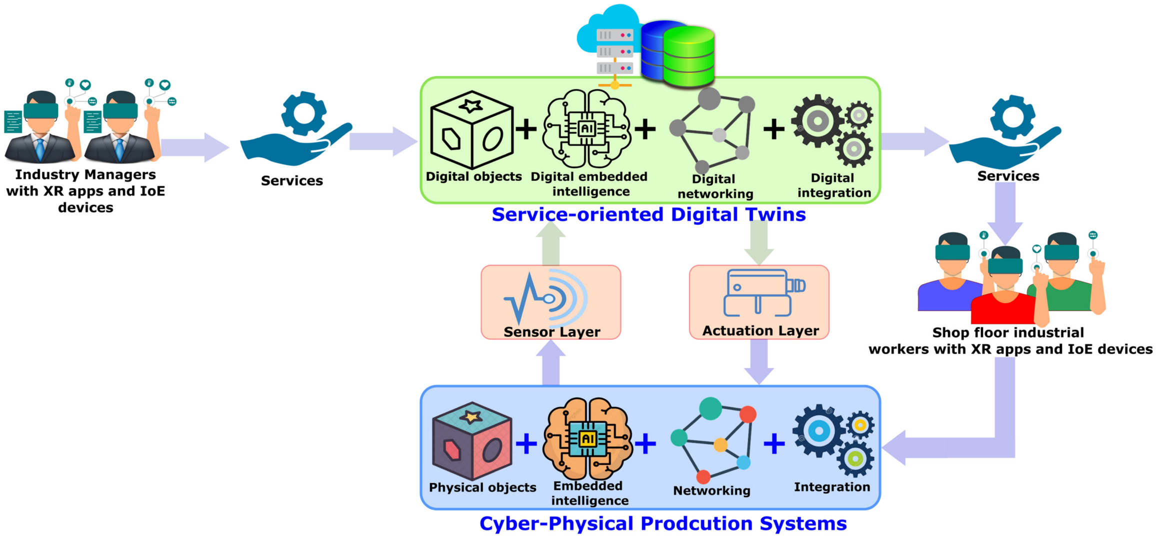

FIGURE 1. Metaverse-based service-oriented digital-twin model for Industry 5.0.

metaverse-enabled service-oriented digital twin for industry 5.0 is also presented as shown in Figure 1.

DIGITAL TWINS: AN OVERVIEW

Nowadays, Industry 5.0 can accomplish a dramatic technological transformation by linking the physical world to the digital space. Indeed, digital twin technology plays a substantial role in boosting this convergence. Further, such technology permits global industries to establish digital copies of their processes, products, and assets in order to optimize maintenance and performance. For instance, in the smart automobile industry, this technology can be deployed to develop digital copies of vehicles and replicate the physical processes of production.[2]

Therefore, digital twin technology provides a virtual representation of digital replicas/copies of products, processes, people, devices, and systems. Instances of components that can be replicated through digital twin technology include, but are not limited to, airplane engines and vehicles.[3] If a car manufacturing company creates a virtual representation of a vehicle's model, this digital copy (i.e., replica) represents the physical vehicle's digital twin. Likewise, if the company develops a digital (i.e., virtual) representation of the vehicle's model manufacturing process, the replicated or digital process represents a digital twin of the physical process. The digital twin may also be expressed as a virtual (digital) profile of a physical thing or process's current and past state, providing the elements and dynamics of how smart devices function.

Characteristics

The digital twin technology integrates the following primary characteristics:

- *Connectivity:* Like physical assets to their virtual counterparts by binding sensors to physical things. The attached sensors improve interconnectivity between the physical and digital worlds, enable data collection from the physical assets, and permit the transfer of collected data to the user's end.[1]
- *Homogenization:* Creating a virtual (digital) representation of the physical thing using the sensors' data. Homogenization further enables sensor data to be decoupled from the physical artifacts.[4]
- *Digital traces:* Representing traces left after developing a digital twin. Traces are employed by system operators during the diagnosis phase upon system failure occurrence.[5]
- *Re-programmability:* Reprogramming the replicated (copy) physical asset to allow for creating new versions of the initial asset.[6]
- *Modularity:* Allowing industries to distinguish areas requiring enhancements, improving the customization of digital manufacturing modules.[7]

Applications

The following are the primary industries of digital twin technology:

- *Manufacturing:* Manufacturers can use digital twins to replicate physical processes. This enhances the virtual-physical interaction of objects and helps address errors/problems in the physical process by assessing the digital twin's trace.

- *Automotive industry:* Companies can develop digital twins of their vehicles to showcase how actual (physical) vehicles function. Using digital twins, they can further explore new features to enhance the real vehicle's model performance.
- *Logistics and supply chain:* Using digital twins, companies can virtualize packages prior to actual packaging, leading to packaging error reductions, efficient material feasibility assessment, feasible networks of logistics, and reliable warehouse layouts.
- *Urban planning:* Professionals can use digital twins in the planning of smart cities and modeling related data for urban cities. This can further improve the digitization of related tasks such as urban project operation, maintenance, and construction by integrating the developed project with its corresponding digital replica, leading to optimal performance.[8]
- *Healthcare:* Health practitioners can develop personalized models to enhance medical care by using the digital twin of patients or organs to practice critical procedures (instead of using real patients).

CPS AND METAVERSE IN SMART INDUSTRIES

The technological stack of digital twins adds value to the industrial metaverse for Industry 5.0 and beyond from the perspective of extended reality, and IIoT being metamorphosed into IoE. It comprises exclusive platforms for managing and analyzing data and developing apps, as well as deployments of AI and autonomous technology for experiencing immersiveness interactions. To experience the metaverse in Industry 5.0-based scenarios, smartphones and other handheld devices could assist in experiencing the capabilities of real-time digital twins, with dedicated tools and applications that integrate 3D models with real-world data.

Evolution of CPS Reference Architectures for Smart Industries

The state-of-the-art and industry-standard CPS architecture are crucial in comprehending the characteristics of the industrial landscape as emerging components for Industry 5.0. The main issue with traditional CPS architectures is that they do not take into account vertical and horizontal diversification with human, physical, and cyber components. Here, we elaborate on the evolution of CPS architectures toward digital cloning technology.

- *3C architecture:* The 3C CPS architecture enables to meet the objectives of smart industries by integrating computation, communication, and control as core components.[9] These components in 3C CPS are essential for smart industries for integrating human, physical, and cyber components.
- *5C architecture:* The 5C CPS architecture involves smart connection, conversion, cyber, cognition, and configuration levels.[10] It combines the sensors and actuators in the production environment and supports intelligent decision-making through cognitive modules and enriched levels of automation.
- *Self-adaptive architecture:* The self-adaptive CPS is capable of operating in uncertain and dynamic conditions. This class of architectures is deployed with adaptation logic, which learns from the environment during the run-time and adapts to handle adverse conditions and uncertainties.[11]
- *Fog computing:* Fog gateways enable quick evaluation compared to conventional cloud servers because they can process more samples successfully under heavy load. Industrial CPS based on the fog computing paradigm is capable of embedding predictive models with the smart machinery.[12]
- *Reference Architecture Model:* With the standardization of the International Electrotechnical Commission, the reference architecture model of Industry 4.0 (RAMI 4.0) was commissioned to adapt with earlier standards and to mature information and communication sharing strategies in smart industries.[13] Further, it also enables interoperability among different technologies that connect the business processes with the vendors and customers.
- *Industrial Internet Reference Architecture:* Considering the automation of industrial processes from the computing, control, and networking perspective, the adoption of Industrial Internet Reference Architecture (IIRA) plays a key role.[14] Particularly, the cascaded model of the reference architecture initiates robust and reliable integration of IIoT and CPS.[15]

The aforementioned CPS architectures pave the way toward establishing a crucial learning platform, that could be used as a blueprint for digital twin

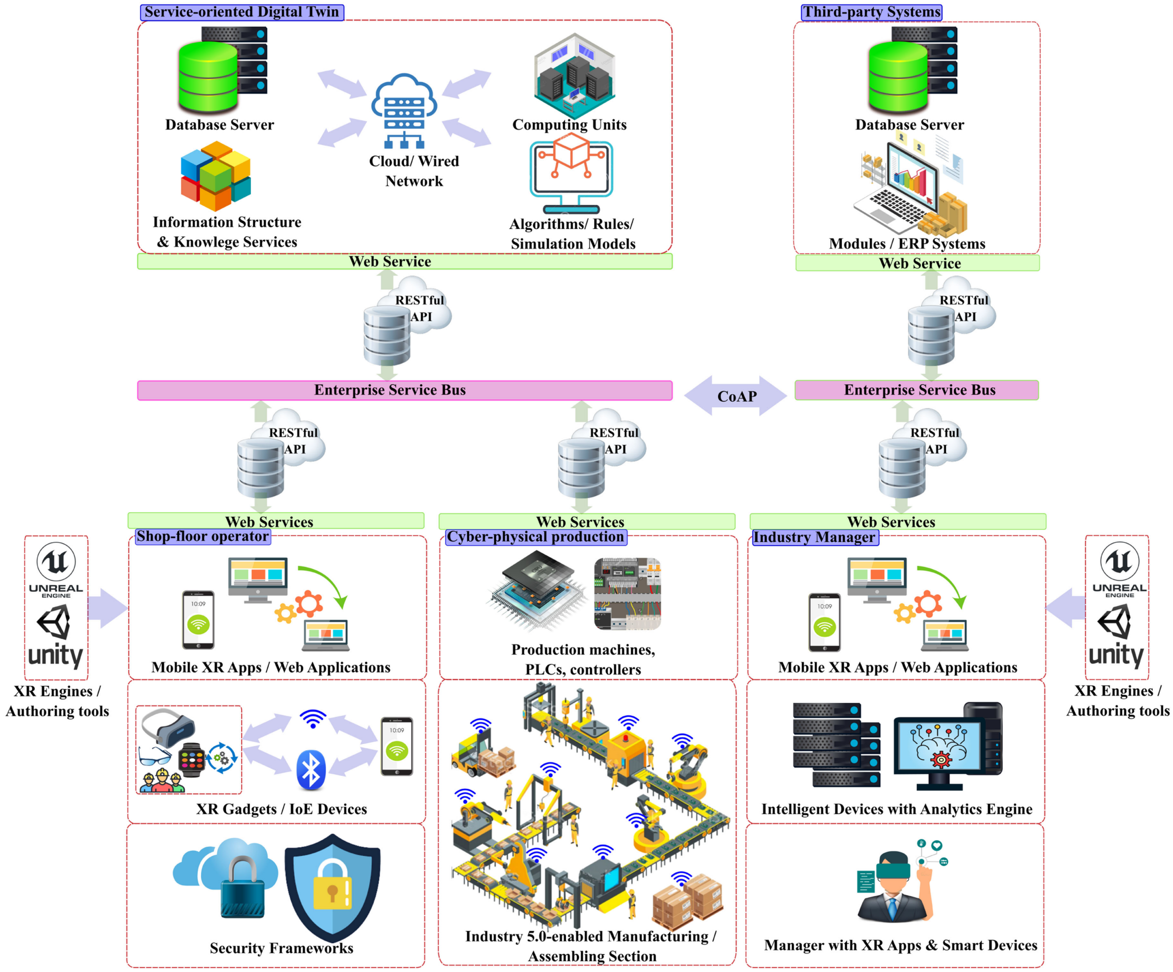

FIGURE 2. The architecture of metaverse-enabled service-oriented digital-twin Industry 5.0 application.

models integrated with metaverse in industries engaged in smart manufacturing.

Metaverse Era for Industry 5.0

Integration of metaverse-enabled platforms for immersive remote monitoring and control of smart industrial applications could be challenging. By developing appropriate VR/AR gadgets, XR apps, and IoE systems, and through the adaptation of virtual platforms, it is possible to embrace the growth of the Industry 5.0 setting in an effective way. Figure 2 shows the architecture of the metaverse-enabled service-oriented digital twin for Industry 5.0 applications, driven by XR engines and authoring tools for supporting the XR application interfaces.

An industrial metaverse can include detailed digital twin models equivalent to full real-world objects. IIoT-derived data and the rendered 3-D digital model could serve as a link between the digital and physical worlds. The significance of establishing seamless connectivity among the smart machines in the industries in the future will be crucial. Recent advancements in 5G and 6G communication services can accommodate devices and provide immersive experiences with high bandwidth and low latency. The merging of digital and physical object interactions gives credibility to the concept of a metaverse as a viable future reality.[16] Digital twins have become a fundamental requirement for the realization of CPS. They are closely correlated, and analysis of their role in smart industries is normally perceived from multidimensional perspectives.

For the smart manufacturing systems in Industry 5.0 and beyond, deploying metaverse could initiate new manufacturing frameworks, remote control/monitor/troubleshooting, and training of new workforces through an interactive simulation. This provisions immersive experience in the configuration layers of CPS by considering the digital twins of the workspace.

RECOMMENDATIONS FOR INDUSTRY 5.0 & BEYOND

We have articulated the following recommendations to assist the industrial managers and shop floor workers in the smart industries in getting customized to adopt and adapt common virtual immersive platforms for provisioning optimized manufacturing, assembly, and supply chain solutions.

Recommendation #1: Explore for Best-Fit VR/AR Gadgets, XR Apps, and IoE Devices

Inspect the metaverse platforms and their associated technologies that provide industrial managers and shop floor workers with flexible remote access solutions for monitoring and control. Efficient usage of appropriate VR/AR gadgets, IoE systems, and immersive XR apps provides convenient, economic, and cost-effective solutions. With the analysis of considerable tradeoffs in the selection criteria, concrete metaverse-enabled frameworks could be established. For instance, accessibility, and cost factors are involved in deploying smart gadgets, for ensuring technical feasibility, convenient remote access, and immersive user experience. Based on the Industry 5.0 application and the convenience of using the metaverse-enabled platforms, digital cloning of smart machines could be comfortably used by the stakeholders.

Recommendation #2: Embrace the Supporting Technologies as Building Blocks of Industry 5.0

Integrating digital twin technology with real-world data-related technologies will enable the creation of advanced simulation programs that could anticipate how processes and products should perform. Such programs must integrate IIoT, IoE, software analytics, and artificial intelligence to improve Industry 5.0 output.

Given the advancements of artificial intelligence (e.g., machine learning) and supporting Big Data technologies, the virtual models (digital twin replica of processes) can be rendered a staple in modern engineering, enhancing performance and driving innovation in Industry 5.0. In brief, embracing such technological advances could enable the enhancement of strategic technology trends in Industry 5.0, thwarting the costly physical object-based failures, sophisticated testing of products and processes, and efficient predictive and monitoring capabilities of supply chain systems.

Recommendation #3: Setup Immersive Framework for Remote Analysis and Control

Initiating the development of the metaverse and digital twin-enabled solutions as a training platform for the industrial authorities even despite flaws in the setup helps in testing the system and obtaining feedback. Based on the feedback, the system could be optimized, and the experimentation could be repeated. At the initial stage of the testing, since a digital platform or a clone of the machines is used, the wear and tear of the smart industrial machines and gadgets are safeguarded. Further, based on the learning from the digital simulation platforms, testing could be done on the physical industrial machines in the Industry 5.0 settings.

Furthermore, as mentioned in the aforementioned discussion on the choice of supporting tools and gadgets, the feedback from the digitally cloned machines also suggests other best-fit alternatives. For instance, claiming other solutions might facilitate better monitoring and control of the machines by sacrificing other parameters on virtual access. In terms of provisioning more immersiveness with the operations of the machines in the Industry 5.0 scenario, it is recommended to evaluate the possibility of collaborating with the experts and trainers from remote locations.

Recommendation #4: Establish Social Interactions Among the Workforce, Supply Chain, and Consumers

Strongly and immersively connected industrial managers with the workgroups, supply chain system, and consumers psychologically reduce their stresses and dedicated responsibilities toward continuously monitoring the flow of activities. It helps the stakeholders establish concrete social interactions, be completely fulfilled with the services, and learn and adapt to the changes more effectively. Further, they also assist in providing secured means of remote manufacturing supported through intrusion detection, network traffic analysis, and anomaly detection.[9]

Moreover, such interactions supported through the metaverse platforms enhance social bonding and create more responsible workers and citizens. With the feedback from the digital cloning platforms, the workforce could learn from mistakes, feel free to adapt, and employ their imagination, creativity, and cognitive skills to solve the existing challenges in the Industry 5.0 platforms.

OPEN CHALLENGES

Although digital twins have attained much attention in recent years, there are few challenges to be discussed, particularly in its integration with metaverse-enabled frameworks. Digital cloning achieved through digital twins has solved numerous issues related to cyber-physical systems in smart industries. However, immersive virtual interactions with the digital clones and remote access for monitoring and controlling those CPS in smart industries are still in infancy.

It is crucial to estimate the shortcomings and limits of the digital twins and accessibility constraints through the XR apps and IoE devices. For instance, it must not hinder the authorized industrial experts from gaining access to the functionalities of the digital clone irrespective of their present location. Indeed, in the current industrial settings, the authorities will have access to the smart machines through the trustworthy network that was laid through robust security policies. However, using metaverse-enabled solutions implies that such smart industries must implement and enforce immersive virtual remote access policies to deploy secure, interactive training, monitoring, and controlling of the smart machines.

Furthermore, assessment of the feedback from the digital clones of industrial equipment and machinery is also raising concerns, especially for the workforce focused on other priorities. Automated data logging, analytics through artificial intelligence, and cloud solutions enabled through metaverse could be apt for remote monitoring and assessment of the feedback from the digital twins of CPS.

Further, as the CPS deployed in the Industry 5.0 scenario is scalable to the demands and requirements of the customers, the issues related to privacy and security could also be considered. Even though the blockchain solutions are the core integral building blocks of metaverse platforms, their scalability concerns need to be considered with appropriate AI and cloud-based solutions. Further, due to the shared data among the digital clones and smart machines, privacy threats do occur, where such scenarios need to be satisfied with the centralized solutions. Perfect tradeoffs are recommended over the decisions on decentralized and centralized solutions for imparting privacy and security.

These technological advances enable a paradigm shift in Industry 5.0, with potential ethical, technical, and security challenges. This substantial shift requires new design paradigms along with new global privacy and security standardizations and regulations.[17] Standardizations are expected to be elaborated on shared values between software, hardware, and rules, while the economic aspect is driven by the maintenance, development, and demand.

Last but not least, to thwart the nondesirable consequences in XR systems improved by autonomous and intelligent systems (A/IS), communities should proactively seek standards and deploy approaches that may improve innovation, access, and governance to ensure human well-being. Currently, there are no remarkable efforts at open governance, standards, and interoperability.[18] The metaverse proponents primarily aim to capture a future market instead of establishing a new shared space without any single owner. Besides, integrated XR-awareness frameworks (within a social consensus) cocreated by manufacturers and policymakers are also needed for end-users and technology developers.

CONCLUSION

A sophisticated means of precise monitoring and control of CPS in smart industries are mandated in the Industry 5.0 framework. The consideration of digital twins during the design phases enables comfortable learning of the operations CPS in industries and supports experimentation with dynamic changes in the systems. Metaverse-enabled solutions are most important for remote industrial managers and workforce groups to utilize the digitally cloned CPS models for investigations. As a result, the metaverse will become a significant platform for Industry 5.0 operations and beyond to plan activities, manufacturing, assembling, supply chain, marketing, and other relationships with stakeholders in an effort to enhance the business. Its role in assisting virtual teams in gaining access or control over the digital clones of CPS is also being considered as a means of promoting, networking, and trading both physical and virtual goods. Technological support through IoE devices, XR apps, and VR/AR headsets fosters a responsible solution to incorporate the metaverse solution among the operating team and consumers. They allow the smart industries to conduct innovative alterations in the digital clones for new product development and embrace novel marketing strategies for their products.

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