Digital Twinning: Integrating AI-ML and Big Data Analytics for Virtual Representation

The paradigm shift in manufacturing that Industry 4.0 brings forth with new advanced technologies and the rapid growth of sensing and controlling technologies enable further visualization and optimization that can contribute to achieving improved decision-making in manufacturing. A significant new capability is the ability to construct a Digital Twin that connects the physical and virtual space. Digital twin is a virtual replica of a physical product by using artificial intelligence and machine learning techniques and big data analytics. It will be the innovation backbone of the future delivering virtual representation of the products and systems in the real world. It is a physics-based representation of the product/system, capable of simulating its behavior and use in real-time. As a result, the product/system can be tested in different environments and on the actual tasks that it's designed for. It allows us to understand how a product would perform before we have to build it. The digital twins can be inspected and modified when necessary, and stakeholders can get involved in the development process at an earlier stage. The rapid development iterations that the digital twin enables will results in fewer prototypes, reduced costs, and faster lead-time. For example, digital twin of an electric car not only displays form, but also analyzes functions from battery charge to thermal condition in the motor and engine, and data from sensors and beyond. Digital twin continuously evolves throughout the life-cycle of the product/system with the flow data, user experience feedback and new input. This data can also be used to develop the product further. This is greatly influencing development, production, and operation in the era of industry 4.0 and beyond. Today proliferation of IoT sensors, faster computing power, and capturing data locally has grown exponentially and is enabling the further development of integrated system model with the digital Twin. The digital twin market is predicted to share over 90 billion dollars by 2025, which is segmented based on application, manufacturing process planning, product design and both software/hardware. This technology shall be implemented in the developed countries where rapid adaptation of IoT enabled technology by medium and large-scale enterprises is already in place, and by the advent of digital twin, the operational performance will be improved. Being able to see it before we built it has been a long-time aspiration for the manufacturing industries. The technology of digital twin is now making this a reality. In development, a product's behavior can be simulated and tested long before a physical prototype has been built. This special section aims to solicit original research and practical contributions, which advance the digital twin computing architecture, technologies, and applications.

After a strict peer-review progress, nine papers are included in this special session. We will review them in the following context.

Digital twins are to play a crucial role to support and enhance industrial manufacturing processes. In order to build a common narrative about digital twins, an elaborated structure of digital twins, namely, spiral DT-framework, was presented by Khan et al. [1]. In this proposed DT framework, it is composed of six dimensions such as physical product, virtual product, performance data, optimization utility, spiral ring, and dynamicity. Digital twins collect a huge volume of data from all phases of the product life cycle, therefore, the security and reliability of the data management has become a main concern. A blockchain technology rather than cloud or fog was addressed in [1] for a secure and reliable management of the data in digital twins. The proposed blockchain, namely twin-chain, aimed to be quantum resilient and offer immediate transaction confirmation. A case study was addressed for a deployment of the twin-chain for manufacturing of robot surgical machines.

To enhance smart manufacturing relying on a better integration of cyber and physical space, it is of interest to realize a real-time recognition for multiple objects with different positions and various sizes and then express them virtually in digital twins. In the work authored by Zhou *et al.* [2], an intelligent small object detection framework for digital twins was developed, where equipment, product, and operator were regarded as three basic environmental parameters in digital twins to inspect dynamic properties and real-time changes from physical manufacturing space to virtual space. A hybrid neural network model was built to ameliorate feature extraction and further profit the detection of static small objects. An efficient learning algorithm was addressed for multi-type small object detection hinged on feature integration and fusion from both shallow and deep layers, to facilitate the modelling, monitoring and optimization of the whole smart manufacturing process in digital-twins system. The effectiveness of the proposed approaches was demonstrated in case studies and using comparisons.

Automotive cyber-physical systems are safety-critical systems, which need to be checked and tested rigorously under a variety of physical conditions. Moreover, automotive industries have a globally competitive market, and the conventional development process suffers from the challenges such as long development cycle, poor scalability, and low test integrity. In order to improve the development efficiency, in the paper by Xie *et al.* [3], a digital twinning based adaptive development environment was presented for automotive cyber-physical systems. By developing an integrated digital twinning clone flow, each physical entity cloned a resulting digital twin.

By establishing a smart digital twinning board, digital twins and their physical counterparts were interacted closely. A case study with an automotive body control system was carried out to demonstrate the effectiveness of the proposed design framework. It was concluded that the addressed development environment was a successful digital twinning solution to automotive cyber-physical system development.

In the work by Zhang *et al*. [4], digital twins and multi-agent learning algorithms were incorporated to establish an efficient vehicular edge computing network. Digital twins can help reveal probable edge service matching among enormous vehicle pairs and decrease the complexity of service management. The learning algorithm enabled the vehicles to achieve their task offloading strategies. Furthermore, a gravity model was developed based on vehicle aggregation scheme in the digital-twin side, and a resulting multi-agent learning algorithm was addressed to optimize edge resource scheduling in physical vehicular networks. The proposed schemes were evaluated on real traffic data sets, which showed the proposed strategies possessed lower costs compared with the benchmarks.

In paper by Xu *et al.* [5], edge computing was used in the digital-twinning empowered internet of vehicles to deliver vehicular services with a high quality of service level, and a service offloading approach was presented using deep reinforcement learning algorithm. Specifically, a multi-user offloading system was modeled in digital-twinning entrusted internet of vehicles by taking response time into account. Deep Q-network, with the advantages of both reinforcement learning and deep learning, was employed in the offloading system to achieve optimal offloading strategy. The experiment studies were conducted using a real-world dataset of roadside unit locations and internet of vehicle service requests, and the effectiveness and adaptability of the proposed service offload approach was demonstrated.

As an encouraging networking archetype, network slicing has appeared to deliver resources adapted for Industry 4.0 and various services in 5G networks. It is noticed that the growing network complexity has brought an immense challenge in network management due to virtualised infrastructure and rigorous quality of service stipulations. In the work by Wang *et al*. [6], digital twinning technology was used to attain an optimal management by generating a virtual representation of slicing enabled networks to replicate its behaviors and predict the dynamic performance. Explicitly, scalable digital twins of network slicing were addressed to seize intertwined relationships among slices and observe the end-to-end metrics of slices under a variety of network environments. A novel graph neural network model was exploited in digital twins to learn insights directly from slicing-enabled networks described by non-Euclidean graph structures. Experimental results demonstrated that the digital twinning techniques can effectively mirror the network behavior and envisage the end-to-end latency under various topologies and varying environments.

Scene graph generation is a digital-twin task, empowering effective machine perception by delivering a virtual graph representation of visual scenes in the real world. In the paper by Yao *et al.* [7], the key challenges in scene graph generation were addressed, and a deep learning based multi-hub driven attention network was proposed, driving information to pass within multiple hub subgroups. As a result, multi-hub driven attention network was able to learn the compact relation-aware features of the visual scenes and estimate their relationships. It was concluded based on experimental results using on real-world datasets, the proposed multi-hub driven attention network can achieve satisfactory performance, particularly in alleviating the imbalance of the predicted relationship classifications.

It is crucially important to make an appropriate site selection for sports facilities in cities, but the challenges lie in the lack of effective and systematic analysis tool. In the work by Zhang *et al.* [8], an interactive visual analysis system using digital twins, called SpoVis, was developed for scheduling sport facilities and site selections. By using SpoVis system, real city data can be visually displayed and analyzed, and corresponding decision-making algorithms can help the decision-makers implement the scheme to locate facilities. The effectiveness of the proposed site-selection models and algorithms was verified by experimental works.

Pepper is the first social humanoid robot in the world which can express body languages and interact with the surrounding environment. In the work by Cascone et al. [9], digital twining technique was used to generate a virtual clone of the Pepper, and the interaction of the digital twin with the replicas of the smart-objects in a smart-home was investigated. Machine learning algorithms were proved to be smoothly moved to/from the digital twin with a notable speed-up and preventing the physical robot from degradation. It was revealed that the virtual duplicate of the Pepper and the smart environment can provide chances for the physical accuracy of the simulation and for the availability of machine Learning instruments adopted for real settings. The case study showed potential applicability of system in health care.

We have reviewed the 9 selected papers of the special session ``Digital Twinning: Integrating AI-ML and Big Data Analytics for Virtual Representation'' which have reflected most recent progress in digital twins and applications. We hope this special session can further stimulate the research and applications in this direction.

The authors have reached an understanding that a great amount of effort is required to reach the fundamentals of Digital Twin, both in time and resources. An interesting research question would be about measuring resources and effort in relation to created value. This would require studying the phenomenon over a long period of time in order to measure resource consumption and then perform a comparison with the created business value.

It would be useful for future research to examine a plug-in solution for Digital Twin, due to the difficulties to generate and collect real-time data from aging machine parks and production systems that currently exist in manufacturing industries.

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