Comprehensive Application Analysis of Digital Twin System in Human Robot Collaboration

Qiyi Xie *

Department of Electrical and Electronic Engineering, Xiamen University Malaysia, Sepang, Selangor, 43900, Malaysia

* Corresponding Author Email: EEE2109300@xmu.edu.my

Abstract. Twin Systems (DTs) on Human-Robot Collaboration (HRC) within the context of Industry 5.0, drawing insights from 18 selected studies. It highlights three primary applications of DTs in HRC: optimizing production workflows through real-time simulation and analysis for efficiency enhancement, leveraging real-time data for dynamic task allocation to increase system flexibility, and improving worker safety by intelligently managing robot movements based on safety distance monitoring. In order to serve as a reference for upcoming researchers, this study provides an overview of recent research accomplishments in the primary applications of digital twin systems in HRC. This research explores Digital Twin Systems (DTs) in Human-Robot Collaboration (HRC) in Industry 5.0 in detail, emphasizing how they might improve productivity, adaptability, and safety. Furthermore, while examining the potential paths for digital twin evolution, the study's findings provide insightful information for upcoming investigations and applications pertaining to human-robot cooperation. This paper emphasizes how crucial DTs are to the development of intelligent, effective, and safe industrial processes.

Keywords: Human-Robot Collaboration (HRC), Industry 5.0, Digital Twin Systems (DTs).

1. Introduction

As a continuation and advancement of Industry 4.0, Industry 5.0 has recently placed a strong emphasis on human-centric, resilient, and sustainable directions [1], with a particular emphasis on human-robot collaboration (HRC). Within this framework, the utilization of digital twin systems has emerged as a critical technology propelling industrial advancement. Three main categories can be used to describe the implementation of digital twin technology in HRC: improving worker safety, increasing flexibility, and enhancing efficiency.

Increasing Efficiency: Digital twins make it possible to simulate and analyze industrial processes in real time, which makes it possible to forecast and optimize production workflows. Robots and automated systems can better cooperate with human workers by adjusting their operations in real-time based on their anticipation of human behavior. This method improves manufacturing efficiency, streamlines workflow, and decreases downtime [2].

Enhancing flexibility in HRC systems means the ability to intelligently reassign tasks and balance human-robot task distribution upon changes in work objectives. For instance, Zhu et al. [3] proposed the integration of the nondominated sorting genetic algorithm-II into a DTs-based HRC system for dynamic reconstruction optimization. This integration significantly increases the system's flexibility in the face of task changes, showcasing an advanced approach to managing workflow adjustments within the HRC framework effectively.

Enhancing Worker Safety: By monitoring whether a safe distance is kept between people and machinery, digital twins can simulate human-machine interaction situations to identify safety concerns and respond appropriately [4]. Within HRC, Digital Twins (DTs) provide real-time monitoring and analysis of robotic behavior and the work environment to assist prevent accidents and ensure worker safety.

Future predictions indicate that the use of digital twins in HRC will grow in scope and depth as technology advances. They can improve worker safety as well as production flexibility and efficiency, creating a more intelligent and humane work environment. Thus, the realization of Industry 5.0's

ambition depends on the study and use of digital twin technologies. In order to serve as a reference for upcoming researchers, this study provides an overview of recent research accomplishments in the primary applications of digital twin systems in HRC. Furthermore, while examining the potential paths for digital twin evolution, the study's findings provide insightful information for upcoming investigations and applications pertaining to human-robot cooperation.

2. Research Background

2.1. Human Robot Collaboration (HRC)

Human-Robot Collaboration (HRC) is kind of system that involves humans and robots working together in shared environments to complete tasks, with research spanning manufacturing, agriculture, and other industries. The research goals of HRC differ by industry.

In agriculture, recent HRC research aims to expand application scenarios and enhance system performance. For instance, [5] demonstrated that integrating HRC in avocado harvesting increased production efficiency by 15% and total yield by 23% compared to traditional human-only methods. [6] developed a robot-assisted solution using transfer learning to identify tomato ripeness, improving harvesting efficiency. Additionally, [7] applies digital twin technology to plan operational paths in tea oil tree ditching tasks.

HRC research in assembly is mostly concerned with improving safety and efficiency. In order to increase production efficiency, study [8], for instance, presented a framework for HRC in high mix manufacturing applications, assigning simple tasks to robots and difficult, complex tasks to humans. A risk perception module that combines with a hidden semi-Markov model was described in [9]. This allows the robot to automatically modify its motions according to the speed at which the human operator assembles the parts, enhancing safety without sacrificing efficiency.

2.2. Digital Twin System (DTs) in Human Robot Collaboration (HRC)

DTs is a system that usually makes use of a large number of sensors to collect the activity and condition of the target object or target system in the real world, and then DTs would display them in a virtual system. Moreover, based on historical data, it can also use big data and machine learning technology to provide operators with forecasting performance and possible problems of the object or system. As mentioned in the paper [10], the essence of natural interaction necessitates mutual perception among robots, humans, and the environment. DTs has extensive sensor networks to sense and represent the state of the real world, thus, it has become the quintessential tool for facilitating real-time interactive control and sensory perception of production resources. Furthermore, operators can now interact with robots through the virtual system of DTs, and with the integration of Internet of Things (IoT) technology, machines in the real world will perform the operations as instructed. This seamless interaction between the virtual and physical domains enables precise control and execution of tasks, enhancing operational efficiency and reducing errors in real-world applications.

3. Comprehensive Application Analysis

3.1. Enhancing Efficiency

One of the most widespread applications of Digital Twin Systems (DTs) in Human-Robot Collaboration (HRC) is enhancing system efficiency. DTs leverage a large number of sensors to digitize real-world data, enabling the integration of algorithms, AI technologies or others for system analysis, thereby simplifying operation, optimizing HRC workflows and etc. Additionally, DTs can predict potential conflicts and bottlenecks, alerting human operators to make adjustments or interventions in advance, ensuring the smooth progression of workflows. This capability to predict and optimize in real-time significantly improves overall efficiency and productivity in HRC environments.

For instance, Li et al. has created and tested a unique human-in-the-loop controlled multi-robot collaborative manufacturing system. First, the digital twins of industrial robots are mapped to their physical counterparts using DT technology. Next, for visualization, Augmented Reality (AR) technology is used. This improves operational efficiency since human operators may remotely operate several robots in the multi-robot collaborative manufacturing system [11]. Ye et al. [12] have implemented DTs into Human-Robot Collaboration (HRC) systems, improving the construction industry's efficiency and adaptability in the assembly of intricate architectural buildings. The integration makes it possible to update architectural geometric models in real time. Furthermore, it permits constant changes to the appropriate robotic commands by integrating real-time detection of human operator activities. The construction industry's assembly process has been greatly improved by this novel use of real-time optimization with DTs in HRC, which solves the drawbacks of rigidity in fully automated systems and inefficiency in completely manual operations.

Moreover, Zhang. and Lv. et al. [13] have proposed a novel Flexible Scheduling Method for Human-Machine Collaborative Workshops. This method leverages DTs to monitor and predict the status of complex machinery and employing Reinforcement Learning (RL) for dynamic adjustments in the production line when detect or predict there is machine failure or environmental disturbance. Thus, the influence caused by machine failure or environmental disturbance can be minimized and the efficiency can be enhanced. Furthermore, Htet and Koomsap [14] make DTs designed a collaborative multi-robot assembly system. The human operators can supervise and train the robots virtually. When new orders come, they can determine the assembly sequences soon without interrupting the operation of the multi-robot assembly system. Thus, the downtime for setting up the assembly line can be reduced, and the efficiency would improve. Liu et al. [15] proposed a new Digital Twin-driven HRC assembly system. This system conducts assembly planning and testing for the next task in advance based on function blocks within the DTs and adapts robot control based on Human-centric assembly. It then presents this to human operators through AR technology for convenient and timely updates and modifications, ultimately leading to a reliable and effective solution that significantly enhances efficiency. Liu et al. [16] developed a human-centric collaborative assembly system (HCAS) for the Large-scale Space Deployable Mechanism (LSDM) of spacecraft. This system includes an assembly quality Digital Twin (DT) that introduces a co-robot to simulate microgravity and uses Augmented Reality (AR) technology to guide operators in real-time adjustments of process parameters. This reduces the frequency of rework and improves assembly efficiency and quality.

3.2. Improving Worker Safety

In HRC (Human-Robot Collaboration) environments, human workers share workspaces with robots. Traditional manufacturing robots are designed to operate in fixed, predetermined patterns and are not capable of automatically adjusting their operating modes based on human behavior, often leading to injuries among human workers. Consequently, with the widespread of HRC in recent years, to ensure human workers' safety within HRC systems has become one of the hot topics.

Yi et al. [17] have applied the new method for developing a human-robot collaborative assembly system proposed in the paper to the digital twin domain. Based on this, a high-precision human key point recognition and localization system based on depth cameras was developed. By comparing human key points with robot key points obtained through the mapping of robot calibration in DTs, a collision warning module was implemented, ensuring the efficient and safe completion of human-robot collaborative assembly tasks. Zhang et al. [18] suggested adding a DTs-based workplace monitoring system to HRC system. This monitoring system employs a body-tracking camera and laser scanners to measure an operator's distance from dangerous regions and their posture, thereby regulating the robot's speed and movement to protect the human operator. Moreover, Choi et al. [19] proposed a novel mixed reality system for the safety in HRC integrated with deep learning and DTs. This system can calculate the safety distance using 3D offset method (data from two deep camera in the working area) and provide human operators with task assistance via MR glasses. To enable self-

governing robot control systems and guarantee the safety of the HRC system, Wang et al. [20] presented a revolutionary Digital Twin architecture with deep learning capabilities that can identify and categorize human and robot actions. Within the framework, the author designed a quicker region-based convolutional neural network (CNN)-based fully supervised detector for quick recognition and classification. In addition, the authors designed a different semi-supervised detector with improved data solving capabilities based on this one.

3.3. Others

Another popular topic of research is enhancing the flexibility of HRC. Such studies often relate to methods of improving system efficiency. As mentioned in the Enhancing Efficiency part, reference [12] mentioned that Zhang et al. used Digital Twins (DTs) to continuously update the digital models of the building under construction. This process generates new robot commands on the fly, addressing the rigidity of traditional construction robot workflows. And as mentioned in reference [14], human operators can virtually train on a multi-robot assembly system using the DTs proposed by Htet and Koomsap. This enables the rapid implementation of assembly systems for custom medium-sized products with significant variations in small batch production. Moreover, to improve the flexibility of human-robot collaboration (HRC), Zhang et al. [21] developed an advanced intelligent deployment technique. For community-based process optimization, this method makes use of a hierarchical reinforcement learning algorithm powered by Digital Twins. HRC systems' flexibility is greatly increased by this intelligent modification based on production content and load intensity. Berti et al. [22] proposed a real-time monitoring and dynamic scheduling architecture for a DTs-based HRC system, capable of detecting staff conditions by analyzing individual features. When poor staff conditions or imbalanced workloads are detected, the DTs system suggests rescheduling of the jobs to optimize workload distribution and enhance operational efficiency. Thus, the flexibility of the HRC system would be enhanced.

In addition to research aimed at enhancing production efficiency, improving human operator safety and enhancing the flexibility of HRC, attempting to optimize the interaction between humans and machines became a hot topic in recent years as well. Liu et al. [23] have proposed a novel random forest-based depth estimator to optimize the gesture recognition process. The estimator, by integrating Digital Twins (DTs) during gesture recognition, can supplement the additional spatial information, thereby simplifying the design of gesture interaction systems and avoiding communication mismatches. Baratta et al. [24] integrated an emotion recognition system based on multimodal analysis into the DTs-based HRC system. It effectively detects negative emotions in human operators. When negative emotions are detected in human operators, the DTs adjust work assignments, temporarily assigning fewer tasks to the operators to allow them to recover, thereby increasing the system's flexibility.

There was other topic research in recent years. For example, Zhong et al. [25] proposed a framework for a Human Digital Twin (HDT) model that processes multimodal human body data using the bidirectional long short-term memory and convolutional neural network (BiLSTM-CNN), thereby enhancing the performance of human motion recognition. Si et al. [26] proposed an immersive teleoperation interface that combines Digital Twins (DTs) and Virtual Reality (VR) technologies, providing human operators with a remote-control system equipped with visual and haptic feedback. Moreover, to address the impact of unpredictable events on HRC systems, Ma et al. [27] proposed a factor–event–act mechanism that comprehensively analyzes dynamic events and their impacts within DTs. This approach also employs a genetic algorithm-based allocation algorithm for timely response, effectively managing and mitigating the effects of unforeseen circumstances on the system's operations. In addition to these, Lee et al. [28] proposed a visually based automated/semi-automated teleoperation framework to tackle the challenges of teaching and controlling collaborative robots (cobots). This innovative framework utilizes models of human and cobot digital twins to enhance the teaching and control processes. Initially, human body recognition and skeletal model inference are achieved through a convolutional encoder-decoder. This skeletal data then teaches the

developed human digital twin model. Following pose mapping, the developed robot digital twin model controls the actual cobot. This method effectively bridges the gap between human operators and cobots, facilitating more intuitive and efficient interactions by directly translating human movements into robot actions.

4. Analysis and Future Challenge

DTs-based HRC systems require rapid processing of large data volumes for real-time synchronization. A significant portion of recent papers in related fields proposes integrating AI technologies into DTs systems for data processing. For instance, papers integrate hierarchical reinforcement learning, image processing algorithms, and deep learning for RGB camera data. They also mention using a random forest-based depth estimator for gesture recognition and genetic algorithms for task allocation. The current variety of algorithms applied is limited, indicating a trend towards employing more diverse algorithms in future DTs-based HRC systems, such as metaheuristic algorithms for spatial computations. The exploration of new applications for novel algorithms or existing algorithms in new contexts would likely become a hot topic.

Additionally, there were many studies incorporate AR, VR, or MR for visualization operations in recent years. AR technology is used to display mechanical states in front of operators, with additional haptic feedback provided for an optimized remote-control experience. AR/MR technologies are mentioned for offering real-time task assistance to human operators, enhancing work accuracy and efficiency. These technologies enable the visualization of DTs data, allowing human operators to quickly understand the status of the HRC system and facilitate easier remote control. Thus, this will also be one of the future hot topics, where the combination of VR/AR+DTs+AI technologies could predict and visualize future events, making it highly suitable for immersive training and simulation environments for operators. This approach can rapidly enhance their understanding of and interaction with robots, thereby improving production efficiency.

5. Conclusions

This research explores Digital Twin Systems (DTs) in Human-Robot Collaboration (HRC) in Industry 5.0 in detail, emphasizing how they might improve productivity, adaptability, and safety. It highlights the optimization of DTs in HRC and the advantages of combining AI techniques, AR/VR for data processing and immersive training by compiling results from eighteen papers. It emphasizes how crucial DTs are to the development of intelligent, effective, and safe industrial processes and suggests future research avenues centered on fusing novel technologies and a variety of algorithms to enhance HRC's capabilities and functions.

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