Digital twin-enabled human-robot collaborative teaming towards sustainable and healthy built environments

Weisheng Lu [a], Junjie Chen [a, □], Yonglin Fu [a], Yipeng Pan [a], Frank Ato Ghansah [a] [a]

Department of Real Estate and Construction, The University of Hong Kong, Pokfulam Road, Hong Kong, China

This is the pre-print version of the paper:

Lu, W., Chen, J., Fu, Y., Pan Y., & Ghansah F.A. (2023). Digital Twin-Enabled HumanRobot Collaborative Teaming Towards Sustainable and Healthy Built Environments.
Journal of Cleaner Production, 137412. Doi: 10.1016/j.jclepro.2023.137412

The final version of this paper is available at: https://doi.org/10.1016/j.jclepro.2023.137412.

Abstract

To achieve the collective societal good for all, development of sustainable and healthy built environments (SHBE) is highly advocated. Part of the pathway to such SHBE is the engagement of robots to manage the ever-complex facilities for tasks such as inspection and disinfection. However, despite the increasing advancements of robot intelligence, it is still "mission impossible" for robots to undertake, independently, such open-ended problems as facility management, calling for a need to "team up" the robots with humans. Leveraging digital twin's ability to capture real-time data and inform decision-making via dynamic simulation, this study aims to develop a human-robot teaming framework for facility management to achieve sustainability and healthiness in the built environments. A digital twinenabled prototype system is developed based on the framework. Case studies showed that the framework can safely and efficiently incorporate robotics into facility management tasks (e.g., patrolling, inspection, and cleaning) by allowing humans to plan, oversee, manage, and cooperate with robot operations via the digital twin bi-directional mechanism. The study lays out a high-level framework, under which purposeful efforts can be made to unlock digital twin's full potential in collaborating humans and robots in facility management towards SHBE.

Keywords: Sustainability; Green building; Human–robot teaming; Human–robot interaction; Digital twin.

---

* Corresponding author.
E-mail address: chenjj10@hku.hk.

1 Introduction

Given the immense importance of buildings in maintaining all walks of life, transforming existing built environments to a sustainable and healthy one will bring tremendous benefits to achieve the collective societal good. A critical step to develop such sustainable and healthy built environments (SHBE) is to properly manage and maintain those have been built. Facility management (FM) is a multi-disciplinary profession aimed at ensuring functionality of the built environment by integrating people, place, process and technology [1]. With the growing complexity of modern facilities (e.g., hospitals, shopping malls, and stadiums), the importance of FM cannot be over-emphasized [2][3]. The development of smart technologies, especially information and communication technologies (ICT), provides promising tools to manage the ever-more complex facilities. Buckman et al. [4] foresees the rapidly accumulated information will turn existing buildings into smart ones that can prepare for and adapt to changes over all timescales. Xu et al. [2] proposes cognitive FM for active intelligent management of facilities, which has three key characteristics including perception, learning, and action. Despite the different naming, these new tools and concepts can be broadly referred to as "smart FM".

Part of smart FM is the increasing use of robots in built facilities. The introduction of robotics to the built environment can be traced back to the 1960s, when Joe Engelberger asserted that the use of robotics should go beyond manufacturing plants to social scenarios for service tasks such as health care, inspection, and FM [5,6]. This vision has not become a reality until very recently, as advancements in cybernetics and artificial intelligence have made it possible to deploy, at scale, autonomous robots in the built environment [5]. Nowadays, it is not uncommon to encounter robots taking up mundane and repetitive FM tasks traditionally done by humans in daily life, from toy-like floor cleaning robots in household environments [7] to disinfection robots in large shopping malls [8]. However, having been designed to operate in relatively structured environments, existing FM robots are far from autonomous and perfect. From time to time, cases of malfunctioning robots are reported [9], especially in open, dynamic environments with uncertainties. As captured by Max Frisch in his novel, *Homo Faber*, "The machine has no feelings, it feels no fear and no hope ... it operates according to the pure logic of probability".

This deficiency in dealing with uncertainty gives rise to a need for robots to "team up" with human counterparts to accomplish shared goals and get the best out of both as intelligent agents [10]. In human–robot teaming (HRT), robotic precision complements human flexibility and vice versa, enabling more efficient delivery of task targets than either party could achieve alone [11]. Collaboration in a team of humans and robots can be flexible, for example, involving the use of remote control with two parties in different environments [12], or side-by-side cooperation in the same workspace [13]. HRT usually involves a fleet of robots and human peers. This flexible collaboration mode and multi-agent nature of HRT make it suitable for exploratory tasks in open and dynamic environments [14] and, specifically, FM tasks in a built environment.

Despite this promise, existing HRT in FM tends to be ad-hoc, piecemeal, and sporadic [5]. Floor cleaning robots, for example, are usually operated by a FM worker onsite through an onboard pendant that activates functionalities such as mapping, navigating, and floor cleaning. No systematic framework is available to monitor and manage the robots consistently, and FM personnel at different managerial levels are not coordinated. This creates several limitations: (a) failure to monitor the real-time operational status of the robots from a holistic perspective, leading to delayed response to possible robot malfunctions; (b) inability to collectively consider information from all robots to dynamically plan FM task allocation (e.g., work areas allocated to different cleaning robots); and (c) lack of an effective human–robot interface to intuitively inform humans of the intentions of the robots, making teamwork less efficient and increasing accident potential.

Digital twin (DT) technologies have the potential to improve collaboration between humans and robots in FM. While there have been many different understandings of DT, it is commonly believed that a DT is a virtual replica of a physical entity (e.g., a product, process, system) that can exert influence on the physical counterpart by predictive analytics and simulation based on real-time collected data [15,16]. This study adopts this prevalent definition, and believes the bi-directional communication mechanism and dynamic simulation capability of DT can benefit HRT in FM from various aspects. First, the DT can collect and aggregate real-time robot information, allowing 24-7 monitoring by FM staff to ensure proper functioning of the robots and timely countermeasures in the event of anomaly. Second, the DT can provide human experts with powerful analytics and simulation tools to plan FM tasks holistically with optimized workload assigned to robotic agents. Thirdly, an intuitive and interactive humanrobot interface enabled by the DT will assist humans better understand or predict robots' intentions, and vice versa.

The aim of this research is to explore the DT potential for collaborative HRT in FM tasks, with the ultimate goal of achieving sustainability and healthiness in the built environments. A constructive research approach is adopted, which involves understanding HRT problems in FM, development of a DT-enabled framework for collaborative HRT, and evaluation of the framework via prototyping. The remainder of this paper is organized as follows. Section 2 reviews the related works on FM robotics, HRT in built environments, and DT for HRT. The research methodology is elaborated in Section 3, which is followed by framework development in Section 4 and prototyping in Section 5. Major findings and insights from the prototyping are discussed in Section 6, and Section 7 concludes by summarizing the contributions and pointing out future research directions.

2 Related works

As summarized in Table 1, this section reviews major scholarly works in related fields. It is found that even though many research has adopted robotics in FM, the level of HRT in this area is relatively low compared with other areas, in particular the manufacturing and assembly industry.

2.1 Robotics in the built environments

Driven by the rapid development of robotics and related smart technologies, the applications of robots in FM have gained momentum. The robotization of FM has multiple advantages in terms of versatility, wide coverage, high efficiency and maintainability [17]. Many FM tasks/scenarios can benefit from the use of robots. The use of robotics in cleaning and disinfection, for instance, increased dramatically during the COVID-19 pandemic [18]. Guettari et al. [8] developed a robot equipped with Ultraviolet-C lights for disinfection in massgathering facilities such as hospitals, airlines, and public transit, while Bock et al. [19] designed a semiautomatic service robot for skyscraper façade cleaning. Hu et al. [20] proposed an adaptive robotic framework to disinfect areas of potential contamination. Beyond the "hard" technologies, researchers have also tried to understand the "soft" social implications of cleaning robots. Forlizzi [7] found that the adoption of automation had allowed for multitasking, while Gutmann et al. [21] revealed that the use of a cleaning robot saves at least one hour of time per week for their household users.

Another important use of robotics in FM is inspection and safety surveillance. The built facilities, especially large public facilities, usually occupy large areas that are too laborious to inspect, and can involve dangerous places (e.g., high-rise façade) for humans to access [22]. As such, their inspection and surveillance using traditional manual methods has become very challenging. Robots have been used to replace (or partially replace) humans for facility inspection [23]. Oyediran et al. [24] designed an autonomous robot-based system for gaugechecking in power plant facilities. Chen et al. [25] proposed to use an unmanned aerial vehicle (UAV) to detect and reconstruct defects occurring to the façade of old buildings. For sewer pipe inspection, Cheng and Wang [26] applied deep learning to process closed-circuit television images captured by wheel robots. Lattanzi and Miller [27] found the growing use of infrastructure inspection robots has provided unprecedented platforms to deploy nondestructive inspection technologies.

Nonetheless, full automation of FM tasks is difficult to achieve given the complicated and dynamic nature of the built environment [5]. Where FM tasks cannot be independently undertaken by robotic agents, the involvement of human experts is needed.

2.2 HRT in the built environments

There is no consensus on a formal definition of HRT [10] but it is widely accepted that it differs from human–robot collaboration (HRC) [28], which studies how humans and robots work simultaneously in a shared space for a shared goal. While HRT involves the accomplishment of a shared goal through joint efforts, it does not require humans and robots to share space.

HRT has been advocated in urban search and rescue (SaR) [14] as a means of counteracting the open and complex environments in such scenarios through flexible interactions between humans and robots (remote control, or close collaboration). Since the application of HRT in 9/11 rescue activities [29], rescue robotics has become an important line of human–robot interaction research [30]. Nourbakhsh et al. [14] established an urban SaR framework via which first responders can remotely control a team of rovers to explore the disaster site for survivors. Goodrich et al. [31] explored the impact of human factors when engaging UAVs in SaR. They found that while HRT can fit into existing SaR information models, the organization of the HRT roles depends strongly on specific situational factors. Chen et al. [32] developed a simulator in the "Gazebo+ROS" environment to train first responders on how to effectively cooperate with aerial SaR robots.

Compared with the aforementioned areas, limited attention has been paid to HRT in FM. AlSabbag et al. [33] proposed a human–machine collaborative inspection system to coordinate human inspectors with a robotic data collection platform via a mixed reality interface. Zhou et al. [34] developed an intuitive robot teleoperation method via a deep learning reconstructed scene in virtual reality. Despite these research efforts, existing HRT falls short of coordinating FM personnel at different managerial levels with the robotic agents. In addition, it is usually difficult to gather information about the state of the robot and the environment [35] so that humans can proactively and effectively oversee, monitor, manage, and intervene in (if necessary) FM task implementation.

2.3 Digital twins for HRT

Originating from space exploration in last century, the concept of a DT was formally introduced by Grieves in 2002 [15]. Since then, the concept has been applied in a wide range of areas [36,37]. Due to its ability to capture real-time data and inform decision-making via dynamic multi-scale and multi-physics simulation, the potential of DT in HRT has been documented in many scholarly works. Elbasheer et al. [11] have conducted a comprehensive review of DT critical design considerations for human–robot systems, identifying a series of beneficial roles that a DT can play, e.g., monitoring and online diagnosis of robotic agents, robot behavior forecasting, and autonomous system control. Adopting the DT concept, Reardon et al. [38] developed a set of prototypes that integrate augmented reality (AR) with smart robots to enable effective HRT in field environments. Kramberger et al. [39] investigated the use of DT in closing the loop between design and robotic assembly of timber structures in a human–robot collaboration setup. The manufacturing and assembly industry has been actively exploring DT for HRC. Sun et al. [40] noticed an absence of perception and cognitive capability in existing HRC, and developed a DT-driven human–robot collaborative product assemblycommissioning framework. Kousi et al. [41,42] studied the implications of DT to existing assembly industry, and developed frameworks to guide the design and reconfiguration of adaptive HRC in such scenarios.

In the architecture, engineering, construction and operation sector, the exploration of DT for HRT is still in its initial stage [11]. Recognizing the unique challenges posed by the unstructured and fragmented nature of construction environments, Wang et al. [43] proposed an interactive and immersive process-level DT system. The system can facilitate collaborative human–robot construction works through task visualization, supervision, planning and execution. Liang et al. [44] reported the development of a system to bridge a physical robot with its virtual representation in simulated environments using a DT, empowering humans to better plan robotic construction works. Fukushima et al. [45] presented a DT-enabled system to support, manage, monitor, and validate autonomous mobile robots. However, existing DTenabled HRT studies have mainly focused on the construction stage. As FM has its unique characteristics in terms of space and task nature, a new DT-enabled HRT framework oriented to FM is needed.

Table 1. A brief summary of related works in the areas of HRT.

No.	Works	Areas [1]	Task	Use DT?	HRT level [1]
1	Guettari et al. [8]	FM	Disinfection	N	Initialization
2	Bock et al. [19]		Façade cleaning	N	Initialization
3	Forlizzi [7] and Gutmann et al. [21]		Floor cleaning	N	Initialization
4	Chen et al. [25]		Inspection	N	Teleoperation
5	Cheng and Wang [26]		Inspection	N	Teleoperation
6	Nourbakhsh et al. [14]	SaR	Survivor searching	N	Supervisory control
7	Chen et al. [32]		Training	N	Supervisory control
8	Zhou et al. [34]	Construction	Pipe installation	N	Teleoperation
9	Kramberger et al. [39]		Timber structure assembly	Y	Collaborative
10	Wang et al. [43]		Drywall installation	Y	Collaborative
11	Sun et al. [40]	MaA	Product assemblycommissioning	Y	Collaborative
12	Kousi et al. [41,42]		Automotive assembly	Y	Collaborative

[1] Application areas of the works: FM (Facility Management), SaR (Search and Rescue), MaA (Manufacturing and Assembly);

[2] Adapted from Goodrich and Schultz [46]. Initialization, teleoperation, supervisory control and collaborative represent the least level of HRT to the highest level.

3 Research method

As shown in Fig. 1, the research design follows a typical constructive research approach (CRA). CRA produces innovative artefacts such as models, algorithms, and information systems aimed at solving real-world problems, as well as contributing to the theory of the relevant disciplines [47]. CRA involves three steps as follows.

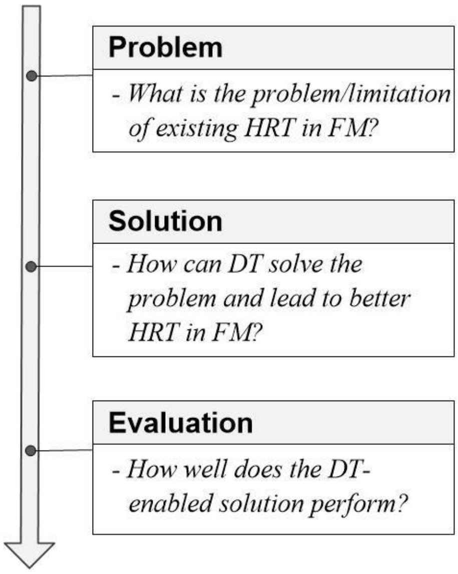

Fig. 1. The research design adopted.

(1) Problem identification. Based on the research team's engagement with professionals from the FM sector [48], the problem of humans and robots working effectively together is one of both practical and theoretical significance. A major problem of existing FM practice is the lack of a systematic framework to coordinate human FM personnel and robots in a consistent and collaborative manner. This could either lead to underuse of the robotic or human resources, or raise potential safety concerns because of insufficient communication between the two parties [9]. Given the criticality of FM, achieving systematic and collaborative HRT would have enormous economic and societal implications. In addition, as previous HRT research focuses mainly on the area of SaR, the research in FM will derive new theoretical insights beyond its original field.

(2) Solution development. Based on a deep understanding of the HRT problem in FM, a solution is devised. Co-operative teamwork should be adopted to involve both practitioners and researchers [47]. Following this teamwork model, a multi-disciplinary team is assembled, comprising university researchers in real estate and construction, robotics engineers, and real estate managers. An iterative development process is followed, during which the researchers and robotics engineers first come up with an initial DT-enabled framework, which is then forwarded to estate managers for their comments to refine the framework. The process goes on until a technically feasible and practical solution is reached. The iterative process will result in a solution that is tailormade to solve the problem of HRT in FM. The most distinct innovation of the solution is

the central role of DT in coordinating robots and human staff in the FM administrative hierarchy. It is expected, via the solution, the existing sporadic human-robot interaction in FM will be turned into a coherent teaming.

(3) Evaluation. Once a solution is available, it should be implemented to evaluate its performance and potential theoretical contributions. For evaluation purposes, a set of prototypes based on the DT-enabled HRT framework are built. The prototypes are tested and evaluated in terms of their functionalities and effectiveness in facilitating collaboration among humans and robots in FM tasks. The evaluation will focus on validating the prototypes' efficacy in filling major gaps of existing sporadic HRT, e.g., poor situational awareness, insufficient multi-party coordination among different FM staff, and lack of tools in guiding safe HRC in a shared space.

4 Developing the DT-enabled HRT framework

4.1 Conceptual model: A shift from sporadic interaction to collaborative teaming

The schematic diagram in Fig. 2(a) depicts how humans and robots are teamed up in existing FM practice. It can be observed that there are missing links (control flow, information flow, or both) between humans and humans (i.e., managers and engineers) and humans and robots, indicating that the interactions among FM teams are somehow random. Because no centralized system is available to coordinate people with the robotic agents, it is difficult to unleash the full potential of robotics in accomplishing FM tasks. Even worse, in the event of malfunction, the robots might not receive timely assistance as the missing information flows prevent them from directly communicating with their human teammates.

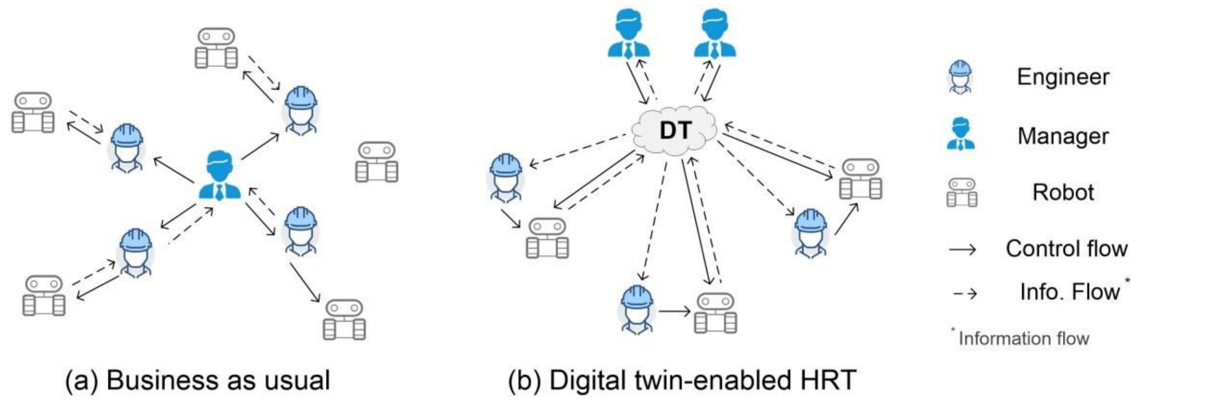

Fig. 2. Schematic diagrams showing how FM robots are teamed up with their human peers (a) in existing practice, and (b) in a DT-enabled model.

The sporadic human–robot interaction that currently exists should shift to a collaborative HRT model as described by Fig. 2(b). In this conceptual model, DTs of FM robots will be created and serve as a central hub where information on robot operating conditions will be aggregated from all agents and can be disseminated to human FM staff at various levels (managers, engineers, workers, etc.) on demand and in real time. Via this centralized model, all participants in the human–robot teams can be connected based on the DT. The benefits are multi-fold. First, as human facility managers/engineers can easily access any robot's information anytime and anywhere via the DT, they are less likely to be unaware of malfunctioned robots. Second, facility managers or other mid-/high-level FM staff can simultaneously monitor or even control multiple robots remotely, greatly eliminating time and distance barriers. In addition, the model allows mid-/high-level FM staff to directly oversee and manage the robots, flattening the existing hierarchical FM structure and shortening the decision chain. Last but not least, by aggregating state information (e.g., position, task progress, and remaining battery) of all the robotic agents, an optimal FM plan and task allocation scheme can be developed. The proposed DT-enabled HRT model for FM coincides with Tao's proposition to treat DT as a "transit station of all things" in industrial manufacturing [49].

4.2 The developed DT-enabled framework for collaborative HRT in FM

In order to overcome the challenges of existing approaches, this study proposed an DT-enabled framework to enhance HRT for FM. The framework was developed by combinatory considerations of typical DT structures [50,51] and the practical requirements of HRT in FM. As shown in Fig. 3, the framework comprises a DT of the FM robots and DT-enabled FM business. The former is a prerequisite for the latter, and the latter is the purpose of the former. The framework can be further divided into six layers, as explained below.

(1) Physical layer

In the physical layer are the various FM robots. They can include ground robots that navigate the facility floor to perform cleaning and disinfection tasks, aerial robots that undertake facility inspection tasks, and robot arms that are used for maintenance jobs. Forming the physical part of the DT, the fleet of FM robots are sources of robot operating information on one hand, and executers of FM tasks on the other.

(2) Middleware layer

The middleware layer connects the physical part with the virtual part. It is essentially a combination of sensors and actuators. The sensors (e.g., gyroscope, thermometer, accelerometer, encoder) collect data of the robot states (positions, payload, level of battery, etc.), and then update them to the virtual layer. The actuators (e.g., electric motor, piezoelectric actuator), on the other hand, receive feedback signals from the virtual layer, and then adjust motor output to control the robot motions. There are two types of feedback signals. The first type is automatically generated by the robotic digital replica in the virtual layer. The second type is initiated by human FM staff in the user layer to enable remote control when the agents cannot independently deal with external uncertainties.

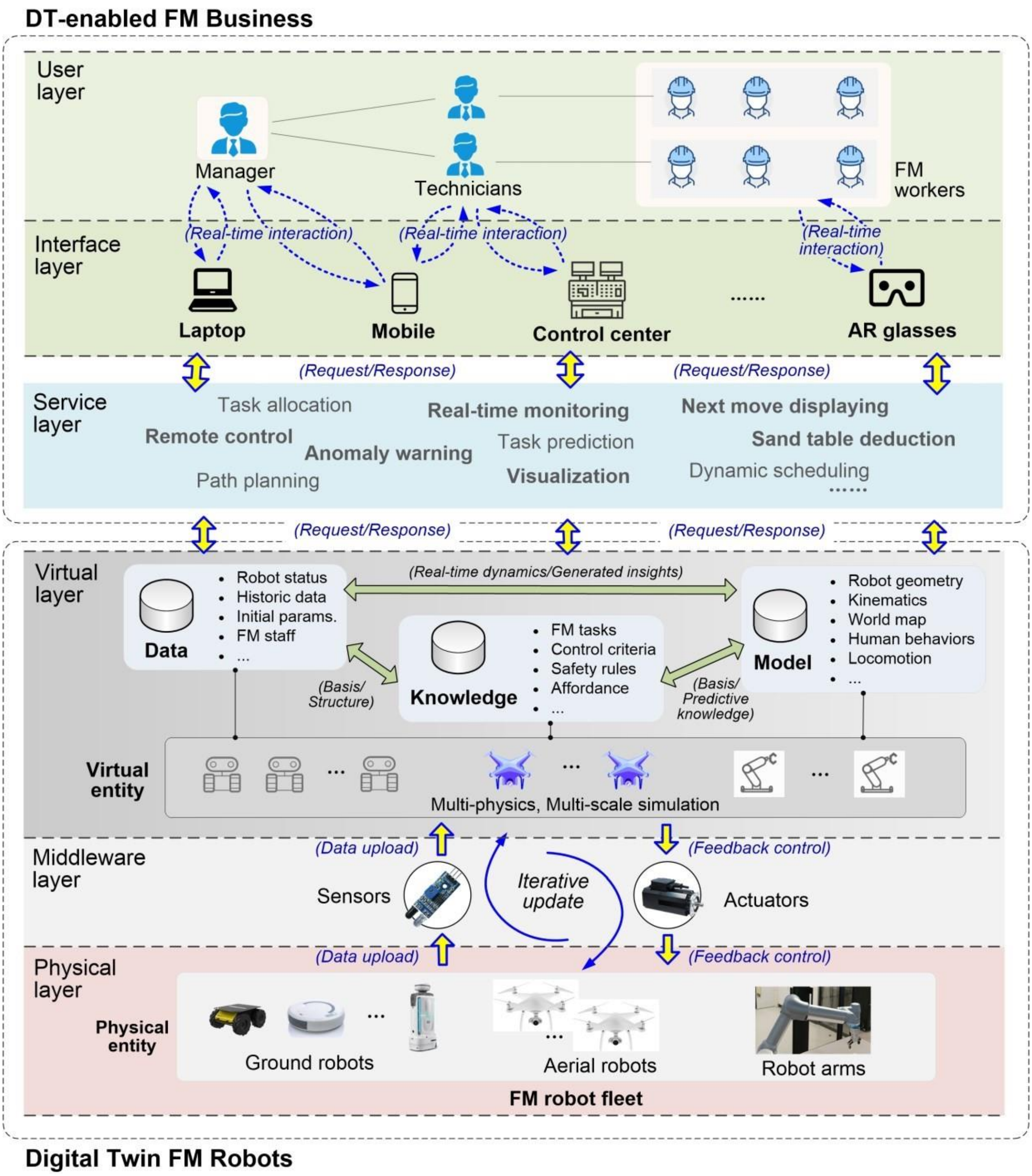

Fig. 3. The developed DT-enabled framework for HRT in FM.

(3) Virtual layer

The virtual layer is a digital replica of the physical FM robots. It mirrors the various physics systems of the physical entities at different levels of granularity regarding three aspects, i.e., data, knowledge, and model. Comprising unorganized facts and figures in primitive formats, data is a fundamental element in the DT of FM robots because it is the carrier of information for the bi-directional communication between the physical and virtual space. A database in the virtual layer records data of various types, including, *inter alia*, the robot states (position, speed, overload, etc.), historical data of past FM events, system initial parameters, and information of the FM staff.

Knowledge plays a critical role in predictive analytics, adaptive control, enabling autonomy, and simulating the FM robots. For example, knowledge about FM tasks (e.g., breakdown workflow) and affordance (action possibilities offered to an agent [52]) is needed in order to plan the FM schedule and allow the robots to independently undertake FM tasks. Another example is warnings for unsafe or malfunctioned robot behaviors. Knowledge about control criteria and safety rules (e.g., upper limit of moving speed) is required to enable judgements as whether the robots are operating within allowed safety ranges. To facilitate interoperability and reusability, techniques such as web ontology language (OWL) is suggested to formalize the knowledge in standard manner.

A model is a mathematical or conceptual representation of a system of ideas, events or processes. To enable the DT's simulation capability, a comprehensive modeling of the physical robotic systems and their dynamics with the human counterparts is indispensable. A first step is to model the geometry of the robots. A geometric model not only has its own uses such as visualization, but is also a precondition for other simulation applications such as clearance analysis. For motion simulation, kinematics and locomotion modeling are prerequisites. An important part of the model also lies the world map that can be either converted from a building information model (BIM), or dynamically created as the robot navigates and perceives the environment. Also, as the FM robots may directly collaborate with human workers in a shared space, a human behavior model will help the robots better parse and even predict their coworkers' motions, leading to safer cooperation.

The data, knowledge and model complement each other and form a coherent system. The data serves as basis on which new knowledge can be elicited, while knowledge provides a structure for how the data should be organized. Knowledge and data will feed the multi-physics scientific model with robot states and other basic information in different time scales, allowing dynamic simulations in FM scenarios. The other way around, the model-based simulation will derive insights and predictive knowledge that will be stored in the database and knowledge base, respectively.

(4) Service layer

The physical, middleware, and virtual layers constitute a DT of the FM robots, based on which FM business is enabled. Directly connecting to the virtual layer is the service layer, an encapsulation of functionalities and services oriented to the FM business and an application of the data–knowledge–model system in the virtual layer. The series of HRT FM services that can be enabled by the DT include:

- Real-time monitoring: Based on the bi-directional mechanism of DT, the processes of all FM tasks implemented by the robots can be visualized and monitored in real time.
- Remote control: When necessary, human experts can intervene and operate the robot remotely.
- Task prediction/Next move visualization: As the task implementation sequences are formalized in the knowledge base, the next move of the robots can be predicted and displayed to FM staff. This is particularly useful for FM tasks (e.g., table wiping) that need direct collaboration among humans and robots in the same space.
- Task allocation: With the robot status, FM task knowledge, affordance, and locomotion model aggregated in the virtual layer, it is possible to come up with an optimal (or quasioptimal) task allocation plan among the robots.
- Anomaly warning: The robot condition is automatically compared with safety threshold. If this threshold is exceeded, a warning can be issued for timely human assistance.
- Sand table deduction: Using the multi-physics models offered by the DT, users can simulate and compare outcomes of different robotic FM plans under different scenarios, which will assist managers in task planning.

(5) Interface layer

The interface layer allows users to access the functionalities provided by the service layer. An array of smart devices can be used, ranging from mobile devices such as laptop and smart phone, to a stationary setup such as a control center, and to emerging AR glasses. Mobile devices allow FM personnel to remotely oversee robot task implementation at any place and any time Internet is available. A control center is similar to the big room in construction management, acting as the central hub for deploying, monitoring, controlling, and managing the FM robots. Large dashboard screens can be set up to display FM, and consoles with joysticks can be installed to remotely control the robots. AR glasses can be used by FM workers, helping them better collaborate with their robotic counterparts.

(6) User layer

In the user layer are human FM staff at different hierarchical levels who are teamed up with the robots in various ways, with different interface devices to support their work. For highlevel managers, their main responsibility is to ensure overall FM performance and oversee the implementation process when necessary. Thus, these managers can access the system using laptops and mobile phones and, in event of anomaly, receive warning messages via phone. Mid-level staff (e.g., technicians) are directly in charge of assigning robotic agents for specific FM tasks, monitoring the FM process, and taking over by remote control when necessary. To assist their work, mobile phone and the control center are the suggested interface. FM workers are those dispatched onsite. They will be equipped with the AR glasses, which displays robot operating information (e.g., battery level, and next move) to help them plan/adjust their actions (e.g., charging the robots).

5 Prototyping and testing

This section aims to demonstrate the effectiveness of the DT-enabled framework in facilitating collaboration among human–robot teams in FM. A prototype system is developed based on key concepts of the framework, and then applied in two typical FM task scenarios (i.e., facility inspection and table disinfection).

5.1 System architecture design

The system prototype adopts a “cloud/edge” architecture to accommodate the centralized HRT model depicted by Fig. 2(b). As shown in Fig. 4, the system consists of a cloud-based server cluster (CBSC), a remote control and monitoring module (RCMM), and an onsite task collaboration module (OTCM). The CBSC is where the DT and its enabling services are deployed, acting as the central hub to handle or respond to data requests (e.g., to retrieve/update robot states, or to issue a control instruction) from the other two modules. The RCMM is designed to team up high-/mid-level FM staff with the robotic agents via supervisory control. The RCMM adopts a Web-based system as the human–robot interface. It allows human experts to conveniently access the system via personal computers, smart phones, or dashboard in a control center. The OTCM sets out to enable FM workers to better co-work with their robotic counterparts by equipping the them with hands-free AR devices (e.g., the HoloLens AR glasses).

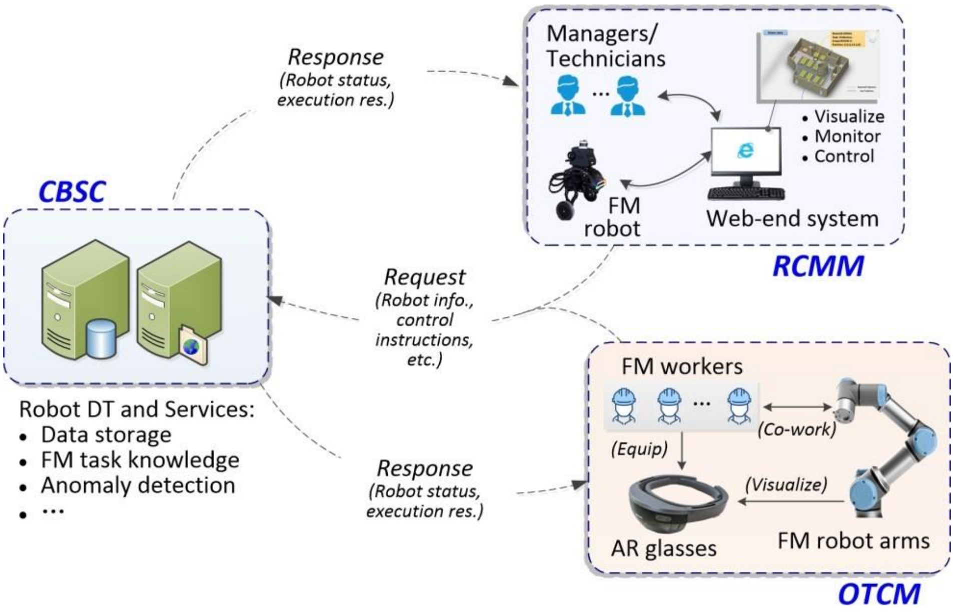

Fig. 4. Architecture of the system prototype.

5.2 System prototype development

Technical details of the prototype development process are introduced in this subsection.

(1) CBSC

The CBSC is hosted on the cloud service instance "ECS.n4" provided by Alibaba Cloud. The server instance has an Ubuntu 20.04 64-bit operating system, a one-core CPU, and a 2GB RAM memory. From a business logic perspective, the CBSC consists of a database server, an application server, and a web server. Node.js is used to build a scalable network application on the CBSC. Fig. 5 shows snapshots of the data, knowledge and model in the database server. To be more specific, information of the robot states, initial parameters, FM staff, and other structured data is stored in a MySQL relational database (see Fig. 5 (a)). There are five tables in the database, including (a) the "Room-Info" table that stores information of functional spaces in a facility, (b) the "Robot-Info" table that stores basic information of the FM robots, (c) the "Robot-Opt-Data" that records the robot operating status (e.g., coordinates, velocity, acceleration, and joint angles), (d) the "Staff-Info" table that saves FM staff information, and (e) the "Model-Info" table that stores file path to 3D representations of the FM robots. The tables are inter-referenced via primary and foreign keys, which are basic components in relational database theory to indicate association among entities. The "Robot-Info" table plays a central role. It is linked to information of storing places ("Room-Info") and model representations ("Model-Info") of the FM robots via key "space_id" and "model_id", respectively; on the other hand, information of operating status of the robots and staff that have assigned the robots can also be indexed via the key "rob_code" and "staff_id" in "Robot-Info" table.

Formalized FM knowledge in terms of task implementation procedure, control criteria and safety rules is first created using Protégé, and then converted into an RDF (Resource Description Framework) format. The Knowledge base in RDF format is hosted on the database server, which can be queried, accessed, and updated by SPARQL. Fig. 5 (b) shows part of the built knowledge base that describes the break-down workflow of typical FM tasks. Another important part of the database is the models, which in the prototype include the geometric models of the environment and the robotic agent. The models are stored in a file-base format, as presented in Fig. 5 (c).

The application server encapsulates a series of system functionalities that can be accessed remotely by the RCMM and OTCM. For example, in order to receive real-time operating status of the robots, a function is written in Node.js to listen to any data incoming event. The anomaly detection and warning functionalities are also realized by Node.js, which compares current robot operating status with the control criteria and safety rule in the knowledge base, and automatically issues a warning to corresponding parties when anomalies are detected. As for the Web server, the Node.js NPM http-server is used to launch the web system, allowing users to access the provided services from a web browser.

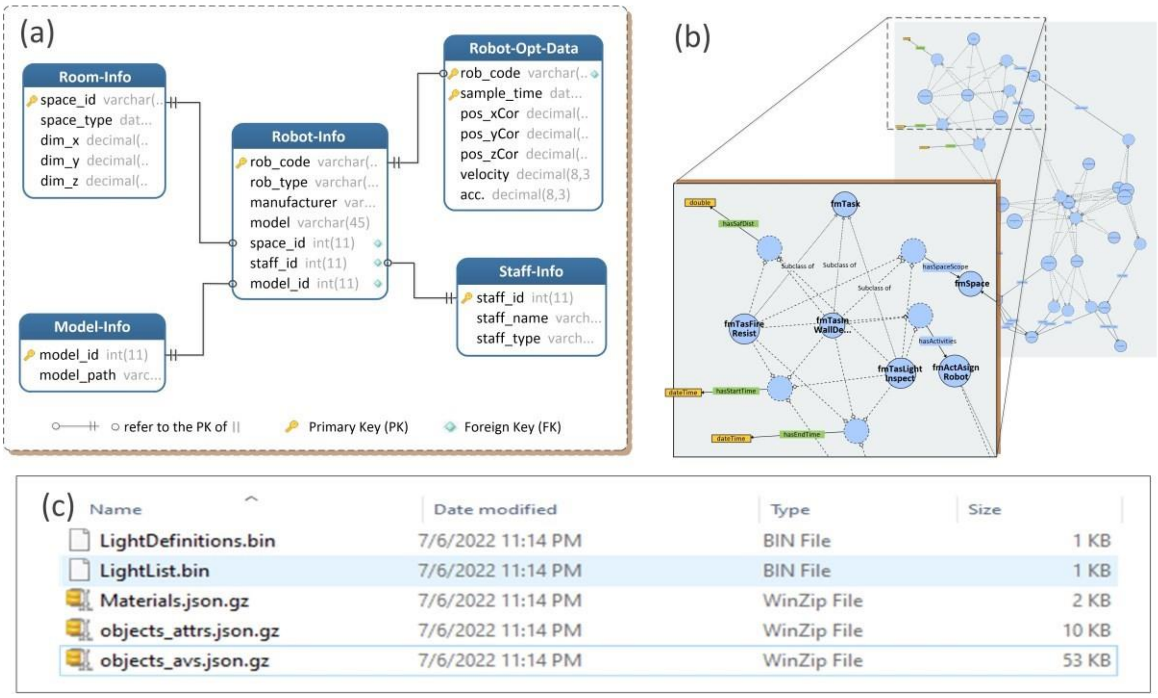

Fig. 5. Database server composition: (a) Entity relationship diagram of the database; (b) Graph representation of the knowledge base; (c) Models stored on the database server as separate files.

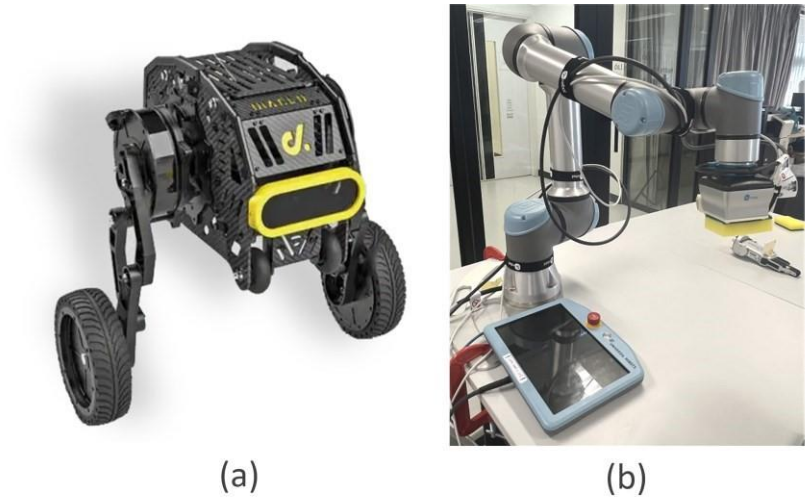

Fig. 6. Robotic hardware used in the system prototype: (a) Direct Drive Diablo [53]; (b) UR5e collaborative robot arms [54].

(2) RCMM

The development of RCMM can be introduced from hardware (FM robot) and software (web-end system) aspects. The robot hardware is a Direct Drive Diablo, as shown in Fig. 6 (a) and comprising a wheel-legged moving base and a SLAM (simultaneous localization and mapping) sense device. There are four cameras on the SLAM sense device, which will capture video streams for inspection purposes. The research team uses a 128-line lidar to get a more intensive point cloud. The robot system is built on ROS. Distributed communication is utilized for function coordination of each component. The web-end system is developed using HTML, JavaScript, CSS, and Ajax. The communication between the robot and the web is based on HTTP. To intuitively visualize the robot, a lightweight BIM model of the facility is integrated and displayed on the Web using Autodesk Forge Viewer. A 3D virtual representation of the robotic agent is created using Three.js.

(3) OTCM

The proposed OTCM integrates AR glasses and a UR5e robot arm (see Fig. 6 (b)) through ROS (version Noetic) as the middleware. Hololens2, a Microsoft AR headset, is used to create an AR interface based on Unity (version 2021.3.7f1). The AR-based virtual robot described by Unified Robot Description Format (URDF) is connected to the corresponding real robot through the middleware, which is responsible for communication between AR and real robot, trajectory planning, and robot control.

OTCM provides a mechanism for intention recognition and communication between humans and robots. Via the AR glasses, the following functionalities are provided:

a) Next move prediction. Based on the break-down process of FM tasks provided by the knowledge base, the next move and moving trajectory of the robots can be planned and predicted;

b) Next move visualization. The predicted robot motion and trajectory will be sent to the virtual robot in Unity. The Unity, as a subscriber, accepts the next-move information in JSON format by C# from the middleware, and then drives the virtual robot to adapt its joint angles ahead of the real robot's movement. It is in this way that the next move of the real robot is visualized to the users in the AR environment;

c) Task coordination. With the robot movements predicted and visualized, the collaboration between FM robots and workers can be effectively coordinated. For example, with proper visual cues (text and 3D model) fed in AR glasses, the workers can easily understand the intentions of their robotic counterparts, and plan their works accordingly.

5.3 Prototype application and evaluation

The performance of the developed prototype is evaluated in two FM task scenarios.

5.3.1 Scenario #1: Facility inspection using the RCMM

The first scenario simulates facility inspection tasks that are widely implemented in FM. An open office space in Pingshan district, Shenzhen, China is used as a testbed. As shown in Fig. 7, the office occupies an area of around 22.6 m × 18.5 m. When a robot is assigned to inspect the office, it is required to navigate the office, and record a video of the environment as it moves. The video is processed afterwards, e.g., by artificial intelligence, to identify defects in the office.

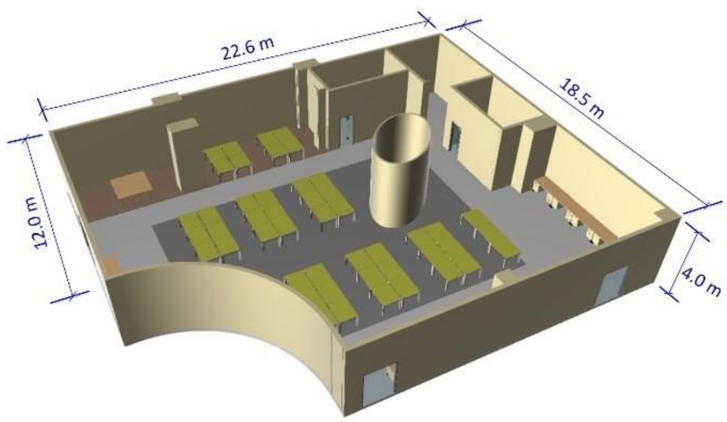

Fig. 7. Diagram showing specifications of the facility to inspect by the robot.

Fig. 8 (a) shows a Web interface of the developed RCMM, which is consisted of four parts, i.e., the main viewport, the main menu, the plan view, and the robot camera view. The main viewport is a 3D viewer displaying the virtual representations of the facility and the FM robots. A DT of the physical robot (i.e., the Direct Drive Diablo) is shown in the main viewport, which mirrors real-time states of the real robot. The robot trajectory is visualized in the viewport. Based on the physics model and the planned path, the next movements of the robots are predicted, and displayed to inform human experts. The main menu is where human operators access functionalities of the RCMM. For example, by clicking the “Task” button, a new panel will pop up, where the human expert (usually a technician who mans the control center) can allocate FM tasks to different robots. The task allocation service at the CBSC will consider all the available robots and their capabilities to suggest an optimal task allocation scheme. Clicking the “Monitor” button will activate the monitoring function as shown in the current main viewport in Fig. 8 (a), whereas the “Control” button will activate remote control mode, allowing users to designate in which direction the robot will navigate by clicking target point in the viewport. On the top-right corner of the interface is the plan view showing the robot trajectory from the top down. Right below the plan view is an area where the realtime camera view of the robot is streamed.

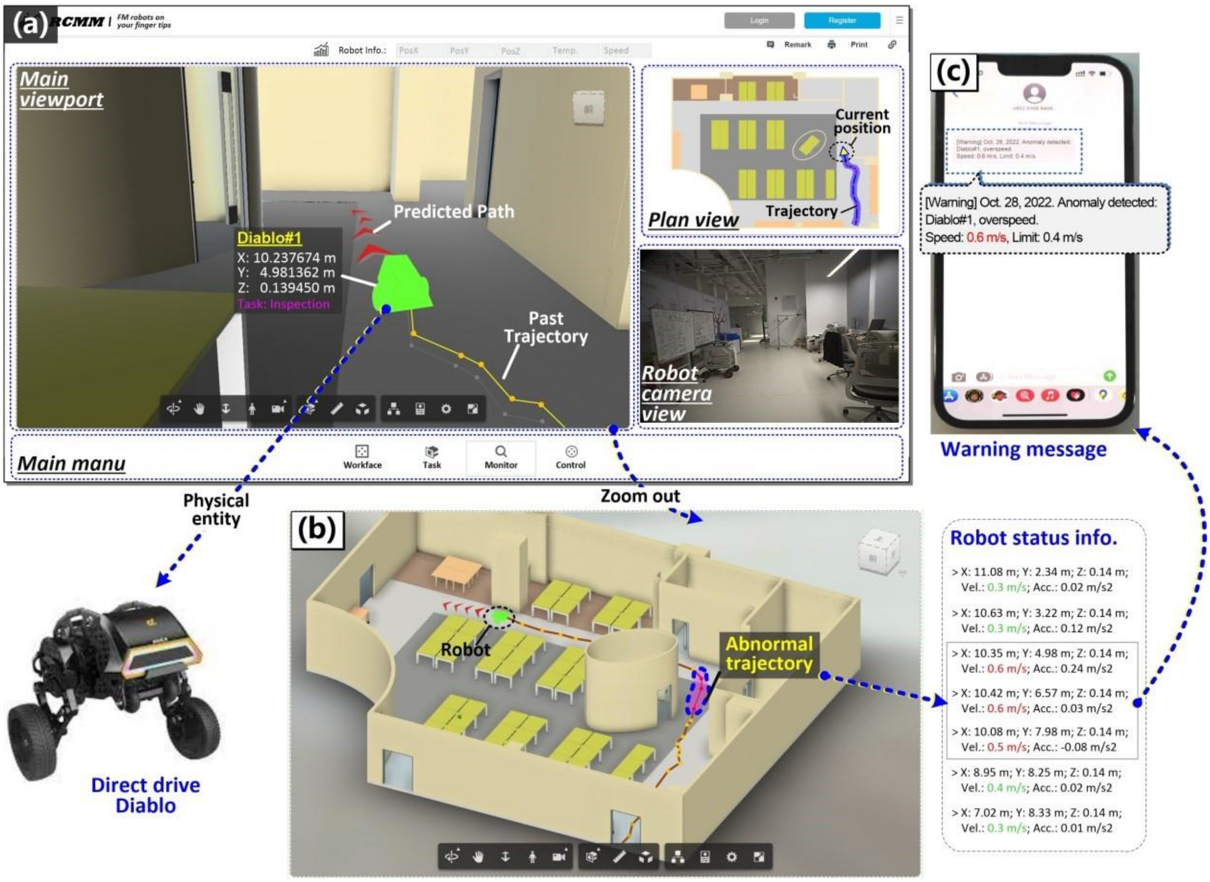

Fig. 8. Implementation results of the RCMM: (a) Web interface of the module; (b) Zoom-out showing the moving trajectory of the inspection robots; (c) Warning message received on mobile phone about abnormal robot operation, e.g., overspeed.

Via the RCMM, a close and collaborative teaming of FM robots and humans is formed. In the experiment on Oct. 27, 2022, the FM technician assigned a robot with ID “Diablo#1” to execute the task of inspecting the entire office. The technician sat in front of the computer to monitor the whole process as the robot navigated the environment to implement the inspection task. Because the robot operating information throughout the process is recorded and visualized by the DT, the human experts do not have to worry about not being informed in a timely manner if the robot goes out of control. Fig. 8 (b) shows a bird-eye view of the inspection process. It is noticed the robot once went overspeed when it was about to take a left turn, as indicated by the trajectory highlighted in purple in Fig. 8(b). This overspeed anomaly was recorded and issued as a warning message to the mobile phone of the FM manager, as shown by Fig. 8 (c). The manager then contacted the FM technician to check the causes of the warning. The warning was actually a false alarm induced by an overheated motor. After the motor cooled, the warning ceased.

Scenario #1 demonstrates efficacy of the DT-enabled framework in addressing some problems of HRT in FM. a) Improved situational awareness. Via the real-time robot information twined to the system, all authorized human FM staff were able to monitor conditions of the robots through a Web-based portal. Compared with existing approach that can only access robot operating information via pendants attached onboard, this significantly improved humans’ situational awareness toward the FM robots. b) Enhanced coordination across managerial hierarchy. The framework has been successful in coordinating FM staff at different level, e.g., the technician that monitored the robots via Web, and the manager that received warning messages via mobile phone, which has led to a more responsive mechanism to manage potential risks (e.g., to rapidly detect and repair a malfunctioned robot).

5.3.2 Scenario #2: Collaborative table disinfection using the OTCM

As shown in Fig. 9, the second scenario simulates a table disinfection task where a human worker needs to co-operate with a robot arm. The purpose of this case study is to demonstrate the predictive and visualization capability of the framework in coordinating the two parties. The task is broken down into two parts undertaken by human and robot, respectively. First, the human worker sprays detergent onto the table; second, the robot arm with a sponge attached wipes the table. In this human–robot collaboration task, the human worker should have a clear understanding of the robot’s intention (e.g., its next move) so as to ensure a safe and effective collaboration. This can be realized by the developed OTCM, which was designed to enhance the HRT communication for onsite FM tasks.

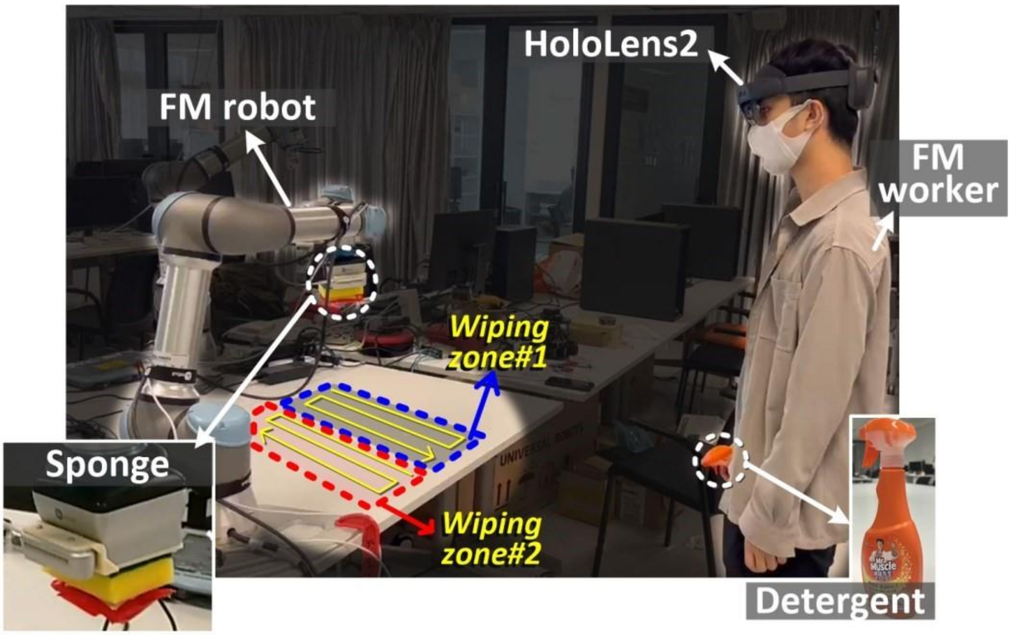

Fig. 9. Setup of the table disinfection task in Scenario #2.

There are two wiping zones (WZ) on the table, i.e., WZ#1 and WZ#2. During the process, it is critical for the FM worker to spray the detergent using the correct timing. Fig. 10 shows results of applying OTCM in task scenario #2. In each frame, the image in the first row represents a third-person view, whereas the one in the second row shows the view captured by the AR glasses.

As shown by Frame#1 in Fig. 10, the human worker first sprayed detergent onto the table in WZ#1. Afterwards, the robot was activated to wipe the table by navigating its attached sponge across areas that have been sprayed (see Frame#2 and #3 of Fig. 10). The worker stood by and oversaw the process through the AR glasses as the robot arm executed the wiping operation. In the AR glasses, a robot DT is displayed to visualize the next move and moving direction of the robot arm. With the information provided, the FM worker can intuit his robot peer's intention so as to avoid potential collision. After the robot finished wiping WZ#1, it returned to its initial pose and a reminder was shown in the AR glasses so that the worker would spray detergent in the next region at the designated time (see Frame#4 of Fig. 10). Getting the message that the robot would pause for some time, the worker understood it was his turn to spray the detergent in WP#2. After spraying, the wiping was executed by the robot arm again to disinfect the region, as shown in Frame#5 and #6 of Fig. 10.

From the experiment, it can be seen that the OTCM, which is enabled by DT, can predict the robot's movement and convey it unambiguously and intuitively to the co-worker. Compared with business as usual where humans and robots work in a shared space but have no effective means to communicate with each other, the presented approach has lowered the risks of potential collision caused by misinterpretation of each other's intentions. With the approach, trust can be built between robots and humans, leading to a more efficient and productive collaboration. The results demonstrated a safe and efficient human-robot teaming for the shared task of table disinfection.

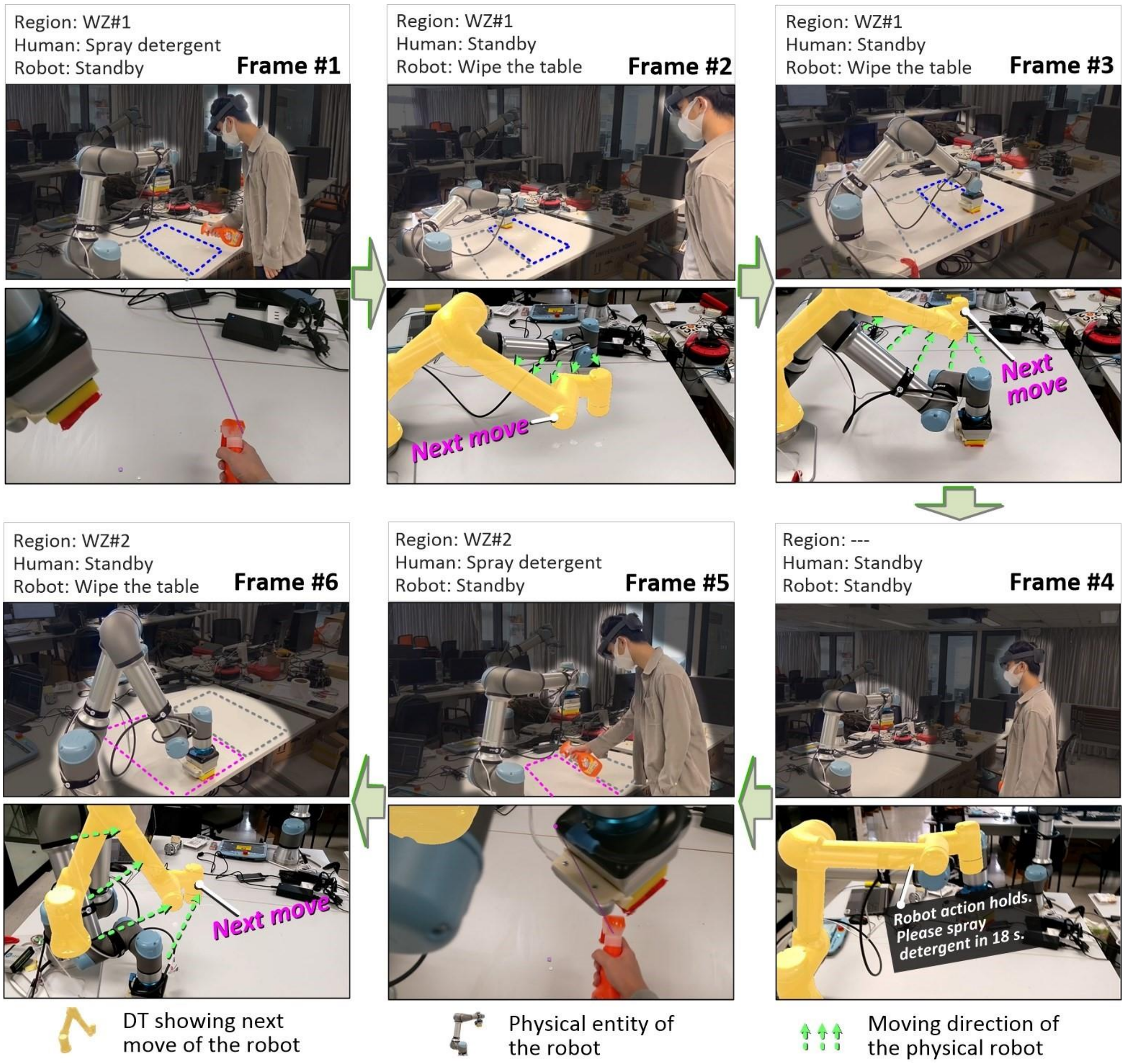

Fig. 10. Implementation results of OTCM, which predicts and visualizes robot movements to guide the human co-worker (Note: the top and bottom row in each frame represent the thirdperson and the HoloLens view, respectively).

6 Discussion

Although the idea of service robots in built environments has existed for decades [5,6], it is not until recent years that the use of robotics for FM has become prevalent. The growing adoption of robots in human-inhabited environments poses a new challenge regarding how teams of humans and robots can work collaboratively to accomplish FM together. The present study provides a high-level framework to potentially solve the challenge by applying DT.

The prototyping and testing reveal important findings in terms of the adoption and generalization of the framework. First, the benefits of DT serving as a central hub of both information and control flow are demonstrated. Existing teaming of humans and robots in FM is in a sporadic and distributed manner, which leads to waste of resources because of insufficient coordination. Our centralized framework can effectively trace all the robotic resources and link them with human staff at different managerial levels, thus ensuring resources are utilized at their full capacity. This has been shown by Scenario #1 where malfunctioning robots were timely identified and FM staff of different roles are automatically notified. Second, by integrating DT's predictive capability and suitable user interface, the proposed framework is able to safely and productively coordinate human workers with FM robots for a shared task in a shared space. This is evident in Scenario #2, where visual cues (e.g., robot next move predicted by DT) were fed to the workers via AR in the right time to guide their behaviors. Thirdly, although the prototyping has not exhausted all FM services/tasks, it validates core principles (DT, multi-party collaboration, predictive analytics, visualization, etc.) of the proposed framework. Building upon it, the framework is scalable to more FM tasks for collaborative HRT in more realistic settings.

Despite the promise shown by the prototyping, it also uncovers two aspects of limitations. On the one hand, more realistic modelling of the robots and their interactive dynamics with human peers and environments should be incorporated to enable simulation at different scales. The case studies only include geometric models (for both the robots and facilities), knowledge of the FM tasks, and hard-coded rules, *inter alia*. They are sufficient for certain applications such as moving trajectory prediction and anomaly warning, but might fall short of achieving other functionalities like defect detection, human behavior prediction, and anomaly diagnosis. An example is manual identification of the root-cause of the overspeed warning in Scenario #1. Should the robot internal operating mechanisms and relevant diagnosis knowledge be modeled and included, the DT might be able to automatically diagnose the cause of the anomaly.

On the other hand, computation latency did not emerge as a major problem since the system responded instantly. However, this might only be valid in less computation-demanding scenarios. In running computation-intensive tasks (e.g., machine learning models to predict human behaviors), the required processing time will need to be considered. Another factor influencing the time performance is the physical distance over which the information is communicated. For example, if a robot needs to be remote controlled by a human from a different region (e.g., cross-city or even cross-country), the signal transmission may cost a delay that cannot be tolerated in time-sensitive tasks, e.g., emergency maintenance. Further research is needed to investigate how the aforementioned factors affect latency and to develop possible counter measures (e.g., use of high-performance computers and 5G).

7 Conclusion

To adapt to the increasing use of robotics for FM in social environments, a new framework is needed for coordinating teams of humans and robots. This research endeavors to establish one such framework, which adopts DT as a central communication hub to enable collaborative rather than sporadic human–robot interaction in FM. The framework is comprised of six layers, from the bottom up: the physical layer, middleware layer, virtual layer, service layer, interface layer, and user layer. According to the DT-enabled framework, a prototype system consisting of a cloud-based server cluster, a remote control and monitoring module, and an onsite task collaboration module is developed. The developed prototype was tested with two typical FM task scenarios. It is found that the system can effectively coordinate FM personnel at different managerial levels (managers, technicians, and FM workers) with the robotic agents.

The contribution is three-fold. First, a novel DT-enabled framework is proposed to provide a high-level architecture to facilitate collaboration between humans and robots in FM task implementation. In the framework, DT serves as a central hub to aggregate and process information about resources (humans and robots), and disseminate control instructions based on the processing results. All available robotic agents and their working environments can be considered as a whole, enabling multi-scale and multi-physics simulations. Because the FM robots are all closely overseen, predicted and controlled, the human–robot teaming is significantly improved. Secondly, by focusing on FM scenarios, the research contributes to the general theory of HRT. Existing studies on HRT mainly relate to urban SaR. As built facilities significantly differ from the collapsed ones in the SaR scenarios (indoor versus outdoor, flat floor versus rough terrain, etc.), the use case of FM presents an ideal testbed to examine how HRT can extend beyond its original field. Last but not least, the developed DTenabled collaborative HRT framework provides another example of social-technical systems. FM robots, as a disruptive technology, affect every aspect of FM practice and the humans involved. The proposed framework harmonizes the social sphere (humans and organization) and the technology sphere (robots, DT), paving the way for safe and productive deployment of robots in built environments.

Future research is suggested to further develop the framework. First, as the study only intends to provide a high-level framework for HRT in FM, many components in the framework remain open for future exploration. For example, simulation of the DT relies on a diverse set of physics models. It is imperative for future research to explore and establish such scientific models as human behavior, interaction, and environments, which will serve as the core reasoning capability of the DT-enabled framework. Secondly, the research only considers human FM personnel and the FM robots. However, modern buildings are usually equipped with complex smart systems for elevator control, temperature and ventilation, fire alarming, etc. The framework should be integrated with these existing smart systems to facilitate interoperability and enable more value-added applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] K. Roper, R. Payant, The facility management handbook, Amacom, 2014.

[2] J. Xu, W. Lu, F. Xue, K. Chen, 'Cognitive facility management': Definition, system architecture, and example scenario, Automation in Construction 107 (2019) 102922. https://doi.org/10.1016/j.autcon.2019.102922.

[3] B. Atkin, A. Brooks, Total facility management, (2021).

[4] A.H. Buckman, M. Mayfield, S. B.M. Beck, What is a Smart Building?, Smart and Sustainable Built Environment 3 (2) (2014) pp. 92-109. 10.1108/SASBE-01-2014-0003.

[5] T. Bock, T. Linner, W. Ikeda, Exoskeleton and humanoid robotic technology in construction and built environment, The future of humanoid robots-research and applications (2012) pp. 111-144.

[6] J.F. Englberger, Robotics in Service, MIT Press, Massachussets, 1989.

[7] J. Forlizzi, How robotic products become social products: an ethnographic study of cleaning in the home, 2007 2nd ACM/IEEE International Conference on Human-Robot Interaction (HRI), IEEE, 2007, pp. 129-136.

[8] M. Guettari, I. Gharbi, S. Hamza, UVC disinfection robot, Environmental Science and Pollution Research 28 (30) (2021) pp. 40394-40399. 10.1007/s11356-020-11184-2.

[9] A.F. Winfield, K. Winkle, H. Webb, U. Lyngs, M. Jirotka, C. Macrae, Robot accident investigation: a case study in responsible robotics, Software engineering for robotics, Springer, 2021, pp. 165-187.

[10] L. Mingyue Ma, T. Fong, M.J. Micire, Y.K. Kim, K. Feigh, Human-robot teaming: Concepts and components for design, Field and service robotics, Springer, 2018, pp. 649-663.

[11] M. Elbasheer, F. Longo, G. Mirabelli, L. Nicoletti, A. Padovano, V. Solina, Shaping the role of the digital twins for human-robot dyad: Connotations, scenarios, and future perspectives, IET Collaborative Intelligent Manufacturing n/a (n/a) (2022). https://doi.org/10.1049/cim2.12066.

[12] R. Parasuraman, M. Barnes, K. Cosenzo, S. Mulgund, Adaptive automation for human-robot teaming in future command and control systems, Army research lab aberdeen proving ground md human research and engineering …, 2007.

[13] T. Iqbal, L.D. Riek, Human-robot teaming: Approaches from joint action and dynamical systems, Humanoid robotics: A reference (2019) pp. 2293-2312.

[14] I. Nourbakhsh, K. Sycara, M. Koes, M. Yong, M. Lewis, S. Burion, Human-Robot Teaming for Search and Rescue, Pervasive Computing, IEEE 4 (2005) pp. 72-79. 10.1109/MPRV.2005.13.

[15] M. Grieves, J. Vickers, Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems, Transdisciplinary perspectives on complex systems, Springer, 2017, pp. 85-113.

[16] D. Andronas, G. Kokotinis, S. Makris, On modelling and handling of flexible materials: A review on Digital Twins and planning systems, Procedia CIRP 97 (2021) pp. 447-452. https://doi.org/10.1016/j.procir.2020.08.005.

[17] J. López, D. Pérez, E. Paz, A. Santana, WatchBot: A building maintenance and surveillance system based on autonomous robots, Robotics and Autonomous Systems 61 (12) (2013) pp. 1559-1571.

[18] Z. Zeng, P.-J. Chen, A.A. Lew, From high-touch to high-tech: COVID-19 drives robotics adoption, Tourism geographies 22 (3) (2020) pp. 724-734.

[19] T. Bock, A. Bulgakow, S. Ashida, Façade Cleaning Robot, Advances in Building Technology:(ABT 2002) (2002) 339.

[20] D. Hu, H. Zhong, S. Li, J. Tan, Q. He, Segmenting areas of potential contamination for adaptive robotic disinfection in built environments, BUILDING AND ENVIRONMENT 184 (2020) 107226. https://doi.org/10.1016/j.buildenv.2020.107226.

[21] J.-S. Gutmann, K. Culp, M.E. Munich, P. Pirjanian, The social impact of a systematic floor cleaner, 2012 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO), IEEE, 2012, pp. 50-53.

[22] D. Liu, J. Chen, D. Hu, Z. Zhang, Dynamic BIM-augmented UAV safety inspection for water diversion project, Computers in Industry 108 (2019) pp. 163-177. https://doi.org/10.1016/j.compind.2019.03.004.

[23] M. Ben-Ari, F. Mondada, Robots and Their Applications, in: M. Ben-Ari, F. Mondada (Eds.), Elements of Robotics, Springer International Publishing, Cham, 2018, pp. 1-20.

[24] H. Oyediran, P. Ghimire, M. Peavy, K. Kim, P. Barutha, Robotics Applicability for Routine Operator Tasks in Power Plant Facilities, ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, Vol. 38, IAARC Publications, 2021, pp. 677-682.

[25] J. Chen, W. Lu, J. Lou, Automatic concrete defect detection and reconstruction by aligning aerial images onto semantic-rich building information model, Computer-Aided Civil and Infrastructure Engineering published online (2022). https://doi.org/10.1111/mice.12928.

[26] J.C.P. Cheng, M. Wang, Automated detection of sewer pipe defects in closed-circuit television images using deep learning techniques, Automation in Construction 95 (2018) pp. 155-171. https://doi.org/10.1016/j.autcon.2018.08.006.

[27] D. Lattanzi, G. Miller, Review of Robotic Infrastructure Inspection Systems, Journal of Infrastructure Systems 23 (3) (2017) 16. 10.1061/(asce)is.1943-555x.0000353.

[28] I. Aaltonen, T. Salmi, I. Marstio, Refining levels of collaboration to support the design and evaluation of human-robot interaction in the manufacturing industry, Procedia CIRP 72 (2018) pp. 93-98. https://doi.org/10.1016/j.procir.2018.03.214.

[29] J. Casper, R.R. Murphy, Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center, IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics) 33 (3) (2003) pp. 367-385.

[30] R.R. Murphy, Human-robot interaction in rescue robotics, IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 34 (2) (2004) pp. 138-153. 10.1109/TSMCC.2004.826267.

[31] M.A. Goodrich, J.L. Cooper, J.A. Adams, C. Humphrey, R. Zeeman, B.G. Buss, Using a Mini-UAV to Support Wilderness Search and Rescue: Practices for Human-Robot Teaming, 2007 IEEE International Workshop on Safety, Security and Rescue Robotics, 2007, pp. 1-6.

[32] J. Chen, S. Li, D. Liu, X. Li, AiRobSim: Simulating a Multisensor Aerial Robot for Urban Search and Rescue Operation and Training, Sensors 20 (18) (2020) 5223.

[33] Z.A. Al-Sabbag, C.M. Yeum, S. Narasimhan, Enabling human–machine collaboration in infrastructure

inspections through mixed reality, Advanced Engineering Informatics 53 (2022) 101709.

[34] T. Zhou, Q. Zhu, J. Du, Intuitive robot teleoperation for civil engineering operations with virtual reality and deep learning scene reconstruction, Advanced Engineering Informatics 46 (2020) 101170. https://doi.org/10.1016/j.aei.2020.101170.

[35] J.L. Burke, R.R. Murphy, M.D. Coovert, D.L. Riddle, Moonlight in Miami: Field Study of HumanRobot Interaction in the Context of an Urban Search and Rescue Disaster Response Training Exercise, Human–Computer Interaction 19 (1-2) (2004) pp. 85-116. 10.1080/07370024.2004.9667341.

[36] P. Aivaliotis, K. Georgoulias, Z. Arkouli, S. Makris, Methodology for enabling Digital Twin using advanced physics-based modelling in predictive maintenance, Procedia CIRP 81 (2019) pp. 417-422. https://doi.org/10.1016/j.procir.2019.03.072.

[37] D. Mourtzis, V. Zogopoulos, E. Vlachou, Augmented Reality Application to Support Remote Maintenance as a Service in the Robotics Industry, Procedia CIRP 63 (2017) pp. 46-51. https://doi.org/10.1016/j.procir.2017.03.154.

[38] C. Reardon, K. Lee, J.G. Rogers, J. Fink, Augmented Reality for Human-Robot Teaming in Field Environments, in: J.Y.C. Chen, G. Fragomeni (Eds.),Virtual, Augmented and Mixed Reality. Applications and Case Studies, Springer International Publishing, Cham, 2019, pp. 79-92.

[39] A. Kramberger, A. Kunic, I. Iturrate, C. Sloth, R. Naboni, C. Schlette, Robotic Assembly of Timber Structures in a Human-Robot Collaboration Setup, Frontiers in Robotics and AI 8 (2022). 10.3389/frobt.2021.768038.

[40] X. Sun, R. Zhang, S. Liu, Q. Lv, J. Bao, J. Li, A digital twin-driven human–robot collaborative assembly-commissioning method for complex products, The International Journal of Advanced Manufacturing Technology 118 (9) (2022) pp. 3389-3402. 10.1007/s00170-021-08211-y.

[41] N. Kousi, C. Gkournelos, S. Aivaliotis, K. Lotsaris, A.C. Bavelos, P. Baris, G. Michalos, S. Makris, Digital Twin for Designing and Reconfiguring Human–Robot Collaborative Assembly Lines, Applied Sciences 11 (10) (2021) 4620.

[42] N. Kousi, C. Gkournelos, S. Aivaliotis, C. Giannoulis, G. Michalos, S. Makris, Digital twin for adaptation of robots' behavior in flexible robotic assembly lines, Procedia Manufacturing 28 (2019) pp. 121-126. https://doi.org/10.1016/j.promfg.2018.12.020.

[43] X. Wang, C.-J. Liang, C.C. Menassa, V.R. Kamat, Interactive and Immersive Process-Level Digital Twin for Collaborative Human-Robot Construction Work, Journal of Computing in Civil Engineering 35 (6) (2021) 04021023. doi:10.1061/(ASCE)CP.1943-5487.0000988.

[44] C.-J. Liang, W. McGee, C.C. Menassa, V.R. Kamat, Real-time state synchronization between physical construction robots and process-level digital twins, Construction Robotics 6 (1) (2022) pp. 57-73. 10.1007/s41693-022-00068-1.

[45] Y. Fukushima, Y. Asai, S. Aoki, T. Yonezawa, N. Kawaguchi, DigiMobot: Digital Twin for HumanRobot Collaboration in Indoor Environments, 2021 IEEE Intelligent Vehicles Symposium (IV), 2021, pp. 55-62.

[46] M.A. Goodrich, A.C. Schultz, Human–robot interaction: a survey, Foundations and Trends® in Human–Computer Interaction 1 (3) (2008) pp. 203-275.

[47] L. Lehtiranta, J.-M. Junnonen, S. Kärnä, L. Pekuri, The constructive research approach: Problem

solving for complex projects, Designs, methods and practices for research of project management (2015) pp. 95-106.

[48] J. Chen, W. Lu, Y. Fu, Z. Dong, Automated facility inspection using robotics and BIM: A knowledgedriven approach, Advanced Engineering Informatics 55 (2023) 101838. https://doi.org/10.1016/j.aei.2022.101838.

[49] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, F. Sui, Digital twin-driven product design, manufacturing and service with big data, The International Journal of Advanced Manufacturing Technology 94 (9) (2018) pp. 3563-3576. 10.1007/s00170-017-0233-1.

[50] F. Tao, H. Zhang, A. Liu, A.Y. Nee, Digital twin in industry: State-of-the-art, IEEE Transactions on industrial informatics 15 (4) (2018) pp. 2405-2415.

[51] F. Tao, Q. Qi, Make more digital twins, Nature, 2019.

[52] E. Şahin, M. Cakmak, M.R. Doğar, E. Uğur, G. Üçoluk, To afford or not to afford: A new formalization of affordances toward affordance-based robot control, ADAPTIVE BEHAVIOR 15 (4) (2007) pp. 447472.

[53] Direct Drive Diablo Robot, 2023, https://shop.directdrive.com/ (Accessed Jan. 1 2023).

[54] UNIVERSAL ROBOT UR5e: A flexible and lightweight robotic arm, 2023, https://www.universal-robots.com/products/ur5-robot/ (Accessed Jan. 1 2023).