Human-Robot Partnership: An Overarching Consideration for Interaction and Collaboration

Jingshuo Yu[1], Qian Chen[1], Samuel A. Prieto[2], and Borja García de Soto[2]

[1]School of Engineering, University of British Columbia, Okanagan Campus, Canada
[2]S.M.A.R.T. Construction Research Group, Division of Engineering, New York University Abu Dhabi (NYUAD), United Arab Emirates
jensonyu@mail.ubc.ca, qian.chen@ubc.ca, samuel.prieto@nyu.edu, garcia.de.soto@nyu.edu

Abstract –

The construction industry is looking at automation and robotization to enhance productivity and reduce the safety risks of various tasks during the construction, operations and maintenance (O&M) phases. In that context, human-robot interaction (HRI) and human-robot collaboration (HRC) are highly relevant. Although those terms are different, there is some misconception, and, in some cases, they have been used interchangeably. To address that, this study clarifies the meanings of each. We collected the existing explanations, reviewed the keywords, and completed a literature review of HRI and HRC applications in construction and O&M, and included definitions for HRI and HRC in the context of construction and O&M needs. Based on the review, we summarized the key elements to differentiate HRI and HRC and promote the concept of human-robot partnership (HRP) as a potential solution to overcome the identified limitations seen from pure HRI and HRC literature, followed by the future directions of HRP applications proposed for construction and O&M activities and needs.

Keywords –

Human-robot Collaboration; Human-robot Interaction; Human-robot Partnership; On-site Construction; Operations & Maintenance; Robotics

1 Introduction

While accounting for 13% of the world's gross domestic production (GDP), the construction industry suffers from low productivity, labor shortage, and high risks [1]. The case is similar for the O&M of buildings and infrastructures, which often costs more than the expenditure of initial construction and contains dangerous tasks (e.g., the maintenance of nuclear power plants and bridges) [2], [3]. As a potential solution for addressing these problems, robots are adopted in construction and O&M fields. However, even though robots for construction and O&M have progressed a lot due to the development of hardware, software, and artificial intelligence, it is still extremely challenging to meet the requirements of full autonomy or no human intervention [4]. The concepts of human-robot interaction (HRI) and human-robot collaboration (HRC) are introduced to make robotics applications in construction and O&M more adaptable to the unstructured and complex working environment [4]. Progress has been made in the intuitive interface for effective communication [5], task allocation to overcome constraints [6], and accurate detection of worker's cognitive load [7]. However, if we go back to the terms HRI and HRC, few researchers defined them and explained why they want to use one or both of them, as the topic of their works. In many scenarios, they were even used interchangeably, which makes it crucial to differentiate the two terms to avoid misuse and confusion. Many applications contain both interaction and collaboration between humans and robots, such as the interaction with collaborative robots [8], [9], [10]. And it is quite difficult to classify many works into HRI or HRC according to existing definitions. For example, according to Liu et al. [11], humans can request robotic assistance by remote control through the proposed brain-computer interface, which not only satisfies the information exchange between human and robot stated in ISO's definition of HRI [12] but also meets the requirement that human and robot work together to achieve the shared goals in the definition of HRC suggested by [13]. This shows the necessity of proposing a term that is feasible for works that concern both HRI and HRC.

To address this gap, in this study, we selected papers related to HRI and HRC applications in construction and O&M by keyword search, filter setting, manual screening, and representative selection, as described in Section 2. Combining the existing explanations, keywords analysis of all relevant publications, and selected papers in Section 2, we offer definitions for HRI and HRC in the scope of construction and O&M, with which the key elements in HRI and HRC applications are analyzed in

Section 3, and HRP is proposed as the combination of HRI and HRC and suggested to be used in future works that concern both HRI and HRP for standardization purposes. Section 4 offers potential future directions, followed by Section 5, which concludes the work with the highlights of our findings.

2 Materials Selection

2.1 Materials Selection

As displayed in Figure 1, we selected papers from the Scopus database with four keywords combinations: "human robot interaction construction", "human robot interaction operation maintenance", "human robot collaboration construction", and "human robot collaboration operation maintenance" with an intention to cover all the HRI and HRC applications in construction and O&M. Then we narrowed down the review scope to journal and conference papers in the last decade. The Scopus database was chosen for being the largest database of peer-reviewed articles. Other indexed databases and books were not selected because they did not provide useful additions [5]. In addition, the subject was limited to engineering, papers published in the last 10 years, and only publications in English were selected. After manual screening, 117 papers were included, of which 8 representative papers [1], [6], [7], [11], [14], [15], [16], [17] that involve the key elements in HRI and HRC applications in construction and O&M were used as the references of the focus review.

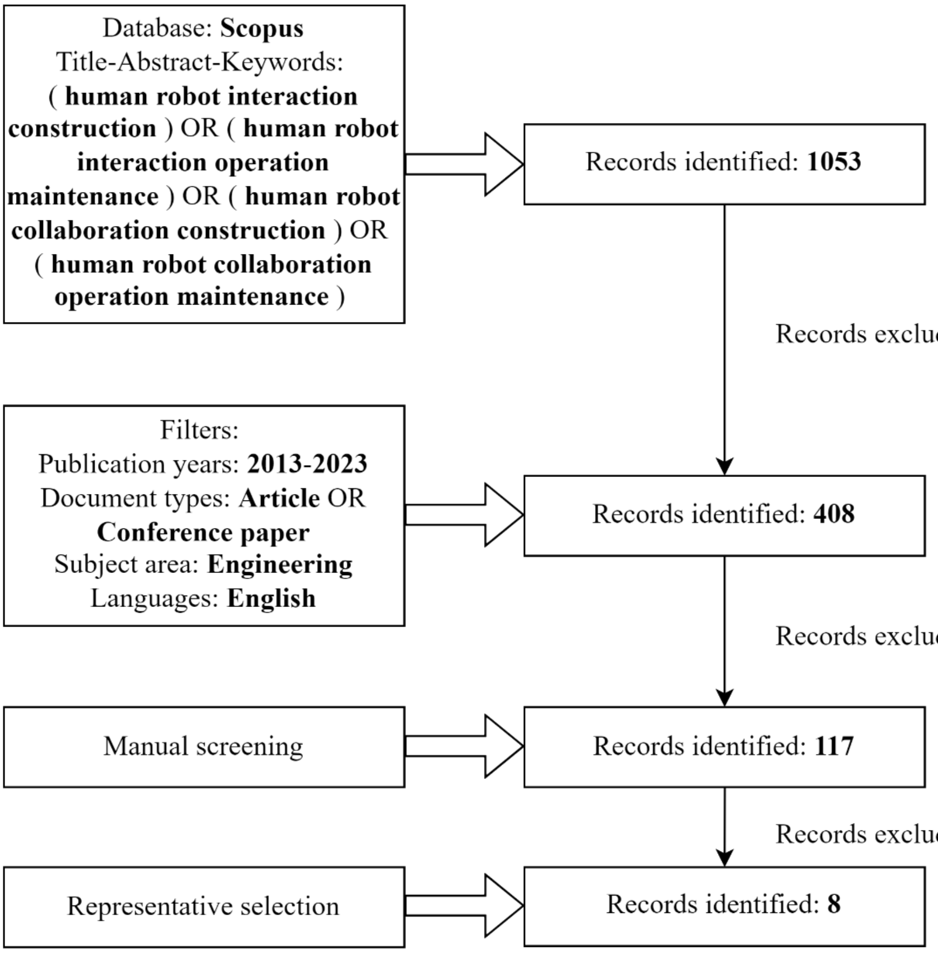

Figure 1. Selection process of relevant literature ([1], [6], [7], [11], [14], [15], [16], [17]) for this study

3 Focus Review

3.1 Key Definitions

To get a definition for HRI and HRC in the scope of construction and O&M, we referred to the existing explanations of the two terms. According to ISO 8373:2021 [12], HRI is the information and action exchange between humans and robots to perform a task by means of a user interface. HRC is described as the study of collaborative processes in human and robot agents working together to achieve shared goals in [13]. Based on that, we searched for HRI (without HRC) and HRC (without HRI) applications in the Scopus database with the keywords combinations "human robot interaction" AND NOT "collaboration" and "human robot collaboration" AND NOT "interaction". A keyword analysis was conducted for the results of the two searches with the open-source software VOSviewer [14]. For both HRI and HRC results, keywords were extracted from the paper title and abstract. The top 20 keywords of HRI and HRC were selected from the items that occurred more than 1700 times for HRI and 250 times for HRC. A list of keywords was obtained after removing overlapping and non-relevant items (e.g., technology, research, and problem) (Table 1). From that, it can be seen that a social robot that interacts and communicates with humans is an important application of HRI. In general, people participate in the process as the user, and the robot functions as the service provider. HRC, however, is mostly used in the context of industrial robots, where the human plays the role of the worker to execute tasks with the robot peer together. Combining the existing explanations, keywords analysis, and literature on HRI and HRC in construction and O&M, we offer the following definitions for HRI and HRC in the scope of construction and O&M:

- HRI is the process in which humans exchange information with robots through a user interface for control or communication, by which they indirectly participate in the tasks.
- HRC is the state in which human workers and robots work together to achieve a certain task.

Based on the above work and definitions, we concluded the key elements of HRI and HRC and proposed human-robot partnership (HRP) as the combination of them in Figure 2, which will be discussed in the following sections in detail.

Table 1. Keywords of HRI and HRC

Type	Keywords
HRI	Social robot, User, Environment, Behaviour, Framework
HRC	Cobot, Industry, Safety, Worker

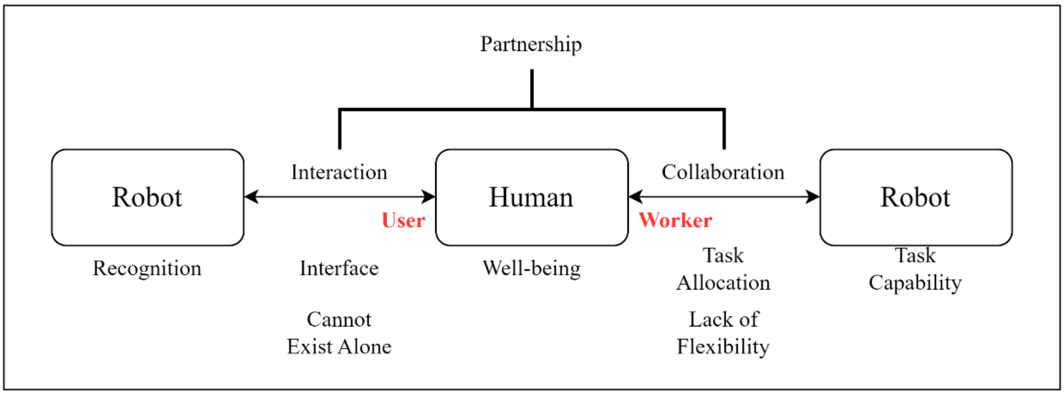

Figure 2. Key elements of HRI and HRC in construction and O&M

3.2 Human

According to the above definitions, HRI and HRC can be distinguished by the role of humans in the process. In HRI, humans are the users of service robots, they do not directly participate in the work, while they function as the workers together with robots in HRC. For both HRI and HRC, in the face of exposure to robots, the key element of humans is their well-being. Besides the potential physical risks like collisions, which can be addressed from the design perspective (e.g., using algorithms to predict workers' movements [17]), human workers may also suffer from cognitive load derived from the lack of confidence and predictability in the robot peers. Towards this end, Liu et al. [7] proposed a brainwave-driven worker-centred framework equipped with a wearable electroencephalograph (EEG) to measure workers' task-related cognitive load, with which robots' behavior can be adjusted accordingly. After a test with 14 subjects who worked with a terrestrial robot under different cognitive loads, the results showed that the robot could adjust its working space with 81.91% accuracy with the help of humans' brain signals.

3.3 Interaction

To enable the information exchange in our definition of HRI, various types of interfaces are used as the interaction bridge between humans and robots. However, the applicable scenarios of many of these interfaces are limited. For example, position and force-based interfaces do not allow human workers to teleoperate the robots in a hands-free manner, which is inconvenient when their hands are occupied. Also, the required headsets of vision-based interfaces (e.g., Virtual Reality, Augmented Reality) may reduce visibility at the actual sites and increase safety risks. Similarly, voice control interface is significantly affected by noise on construction sites. To expand the application scope of robots and better serve human workers, Liu et al. [11] proposed a brain-computer interface (BCI) with hands-free and non-muscular interaction between humans and robots can be achieved. The interface enables users to control robots by transforming users' brain signals from a wearable EEG device into robotic commands with satisfactory accuracy.

In our definition of HRI, humans do not participate in the work directly; instead, they provide task-related information to robots by instructing or communicating with them. Robots are service providers who take the responsibility of completing the tasks physically, following the information from humans and their interpretation of it. To effectively interact with humans, robots must be capable of recognizing the information from humans. To enable robots to capture and interpret the hand gestures of users (construction workers), Wang et al. [14] developed a vision-based framework consisting of three working components: (1) workers detection and tracking, (2) recognition queues formulation and (3) hand gesture recognition. The first component detected the user giving hand gestures and creating their bounding box. With the second component, the region of the user cropped from the original frame was firstly expanded horizontally by 25% to capture more information and avoid errors; then, the extracted frames were compiled to form the hand gesture detection and classification queues for the last component. A hierarchical convolutional neural network (CNN) architecture was applied in the last component to detect and classify the user's hand gestures with 87.0% precision in the implementation.

3.4 Collaboration

To enable humans and robots to work together for a task as described in our definition of HRC, successful HRC applications in construction and O&M must be based on the reasonable task allocation between human workers and robots that takes the requirements of different subtasks and the constraints of both humans and robots into consideration. For example, humans have strong comprehensive analysis ability (lacked by robots), which makes them more suitable for decision-making work, while robots are more efficient in repetitive and labor-intensive work like material and component delivery. To enable the application of human-robot collaboration in building large erectable truss structures in a space station, Zhu et al. [6] decomposed the task process into a certain number of basic actions named *therblig*. Then, hierarchical task analysis was adopted to establish the task model, based on which task allocation was conducted according to the limitations and abilities of humans and robots. Finally, a virtual simulation was applied to verify the feasibility of the proposed method.

For a certain task of construction or O&M, the robots to be adopted should be capable of doing the allocated tasks, which imposes a challenge for the design and programming of robots. For instance, robots should be equipped with enough force capability required by the assigned tasks, should be able to reach all the task locations, should be capable of recognizing the obstacles along the defined path, should be prepared with necessary hand tools, and should be capable of being stopped in an emergency situation. In the work of Gautam et al. [15], a test of a construction robot was conducted for the installation of gypsum board panels, which is identified to be injury-prone from the perspectives of construction professionals. 3D scanning, reverse engineering, and 3D printing are applied to fabricate toll adaptors that enable robots to use human tools and target markings are used to indicate the robots to work at the right location and distance. The results of the experiment in a wooden house construction site showed that gypsum board installation can be achieved by the collaboration of the robot and human worker, and workers can benefit from ergonomics enhanced by collaborative robots.

3.5 Partnership

Based on our definitions of HRI and HRC in the scope of construction and O&M, pure HRI cannot exist alone because the aim of enabling interaction between humans and robots is to offer better collaboration. In other words, information exchange (interaction) alone is just a process as described by the definition in Section 3.1, and it is not meaningful until it realizes the aim of instructing robots to better deliver the task. In this scenario, humans offer instructions, which are followed by robots to guide the physical work, resulting in them working together (collaboration). Without interaction, pure HRC is simply letting humans and robots take the assigned work from task allocation and thus lacks flexibility. In a dynamic and unstructured working environment (like construction sites), a minor change in the task may cause the robot to lose the capability to work, and humans have no access to manipulate or teach the robot to complete the task. Also, the human cannot modify the robot's behavior when an error occurs.

As shown in Figure 3, due to the above drawbacks, actual needs cannot always be fully satisfied (represented by the bland expression on the human's face) by pure HRI or HRC. This representation also shows how the robot is able to interact with the human by asking a question in the HRI, but not in the HRC. A feasible solution to address the issue is combining HRI and HRC to form a novel and flexible relationship between humans and robots that is defined as HRP (represented by a content expression in the human, the interaction part in the robot, and the collaboration in the hands). Actually, many works fit the concept of HRP. For example, Zhou et al. [16] proposed a visual-haptic interface to provide high-fidelity task scenarios and enhance control feedback. Typical physical interactions like weight, texture and inertia are captured with this method. In this work, humans provided instructions by operating an interface and received tactile feedback from the robots performing the physical tasks. However, this form of partnership is relatively low-level as humans still needed to fully control every working process, and robots did not learn how to do the work. Wang et al. [1] improved this using a learning from demonstration (LfD) method that enables humans to flexibly teach robots how to deliver tasks by applying intuitive demonstration. In this method, robots are equipped with basic skill primitives that are required by different construction tasks, such as reaching and nailing. A VR interface is provided to enable human workers to be aware of the on-site status and demonstrate task delivery through the selection of the robot's skill primitives.

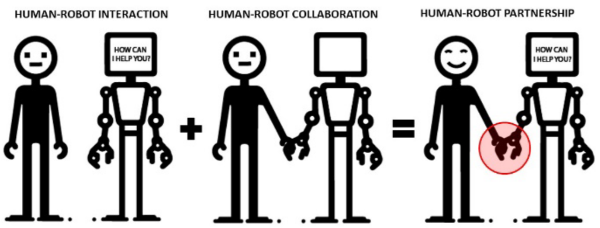

Figure 3. Human-robot interaction, collaboration and partnership

4 Future Directions

4.1 Multi-sensor Fusion of Physiological Signals

With more and more focus imposed on human workers' mental stress during the HRP process, the method for stress measurement has transformed from collecting questionnaires from participants to a more reliable electroencephalogram (EEG) method that captures human brain signals directly. While much work has been done with wearable EEG devices, the concern is that the devices used in the construction field with a small number of electrodes (14-32) may not be capable of collecting reliable EEG signals compared with the 64-256 electrodes used in the clinical field. To address this issue, Liu et al. [15] applied a generative adversarial network to produce high-quality EEG signals. Another potential solution could be to leverage multi-sensor fusion. Besides EEG, there are already various kinds of methods for collecting human physiological signals, such as photoplethysmogram (PPG), electrocardiogram (ECG), and electrooculogram (EOG). By fusing signals from multiple sensors, the uncertainty of data will decrease, and more reliable information will be gained. Thus, we can have a deeper insight into the human worker's mental load.

4.2 Multi-source Data Fusion for HRP-based Predictive Maintenance

For current practices of O&M of buildings and infrastructure assets, robotic applications are mainly devised using vision-based robots for automatic crack detection. However, not all maintenance requirements can be detected with robotic vision, such as the detection of internal cracks in pipes and operating anomalies in building facilities. To achieve early-stage maintenance for these deteriorations and prevent them from further developing into failures, many works have been done in predictive maintenance (PdM) with various sensors. Human expertise [20] can also be fused with sensor data to accommodate the drawbacks of each other, and robots should be capable of multi-source data fusion and anomaly detection to predict the facility's health state in the future. In maintenance activities, given the amount and complexity of maintenance work in modern buildings, it is hard to enable robots to perform tasks by pre-programming them. A feasible solution could be the LfD [1] method mentioned before, which enables humans to teach robot task delivery by intuitive demonstration. In this way, instead of the low-level manual manipulation, humans can conduct high-level experience transferring in the process of HRP-based predictive maintenance, which better leverages the strengths of both humans and robots.

5 Conclusions

This study provided clear definitions of HRI and HRC in the context of construction and O&M applications by reviewing existing definitions, keyword analysis, and a systematic literature review. HRI was defined as the process where humans exchange information with robots through a user interface for control or communication by which they indirectly participate in the tasks. Slightly different is the HRC concept, in which human workers and robots work together to deliver a certain task. The key elements for interaction and collaboration between human users and robots are the interface and task allocation, respectively. For robots, HRI concentrates on their recognition of information from humans, and HRC focuses on their task capability. The crucial point for humans in both processes is the well-being problem. Since HRI cannot exist alone because it serves HRC, and HRC will be rigid and inoperable without HRI, we proposed the relationship defined as HRP to integrate features of HRI and HRC for improved task performance in construction and O&M and suggested to use of HRP in works that concern both HRI and HRC features. Finally, data fusion could be the future direction to innovate HRP research. With multi-sensor fusion of physiological signals (e.g., EEG, PPG, ECG, EOG), more accurate detection of a worker's mental load can be derived to better ensure the human's well-being, a key element for HRP. With multi-source data fusion, human expertise can be included as the guidance of robotic maintenance work, which better leverages human's edge in intellectual work and the robot's ability for physical work.

Acknowledgments

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References

[1] X. Wang, S. Wang, C. C. Menassa, V. R. Kamat, and W. McGee, "Automatic high-level motion sequencing methods for enabling multi-tasking construction robots," *Automation in Construction*, vol. 155, p. 105071, Nov. 2023, doi: 10.1016/j.autcon.2023.105071.

[2] H. Oyediran, P. Ghimire, M. Peavy, K. Kim, and P. Barutha, "Robotics applicability for routine operator tasks in power plant facilities," presented at the 38th International Symposium on Automation and Robotics in Construction, Dubai, UAE, Nov. 2021, doi: 10.22260/ISARC2021/0091.

[3] H.-D. Bui, S. Nguyen, U.-H. Billah, C. Le, A. Tavakkoli, and H. M. La, "Control framework for a hybrid-steel bridge inspection robot," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Las Vegas, NV, USA: IEEE, Oct. 2020, pp. 2585–2591. doi: 10.1109/IROS45743.2020.9340637.

[4] Y. Leng, X. Shi, F. Hiroatsu, A. Kalachev, and D. Wan, "Automated construction for human–robot interaction in wooden buildings: Integrated robotic construction and digital design of iSMART wooden arches," *Journal of Field Robotics*, vol. 40, no. 4, pp. 810–827, Jun. 2023, doi: 10.1002/rob.22154.

[5] M. Zhang, R. Xu, H. Wu, J. Pan, and X. Luo, "Human–robot collaboration for on-site construction," *Automation in Construction*, vol. 150, p. 104812, Jun. 2023, doi: 10.1016/j.autcon.2023.104812.

[6] X. Zhu, C. Wang, M. Chen, S. Li, and J. Wang, "Concept plan and simulation of on-orbit assembly process based on human–robot collaboration for erectable truss structure," in *Man-Machine-Environment System Engineering*, vol. 645, Singapore: Springer Singapore, 2020, pp. 683–691, doi: 10.1007/978-981-15-6978-4_78.

[7] Y. Liu, M. Habibnezhad, and H. Jebelli, "Brainwave-driven human-robot collaboration in construction," *Automation in Construction*, vol. 124, p. 103556, Apr. 2021, doi: 10.1016/j.autcon.2021.103556.

[8] R. R. Galin and R. V. Meshcheryakov, "Human-robot interaction efficiency and human-robot collaboration," in *Robotics: Industry 4.0 Issues & New Intelligent Control Paradigms*, vol. 272, A. G. Kravets, Ed., in Studies in Systems, Decision and Control, vol. 272. , Cham: Springer International Publishing, 2020, pp. 55–63. doi: 10.1007/978-3-030-37841-7_5.

[9] L. G. Christiernin, "How to describe interaction with a collaborative robot," in *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, Vienna Austria: ACM, Mar. 2017, pp. 93–94. doi: 10.1145/3029798.3038325.

[10] J. E. Michaelis, A. Siebert-Evenstone, D. W. Shaffer, and B. Mutlu, "Collaborative or simply uncaged? Understanding human-cobot interactions in automation," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Honolulu HI USA: ACM, Apr. 2020, pp. 1–12. doi: 10.1145/3313831.3376547.

[11] Y. Liu, M. Habibnezhad, and H. Jebelli, "Brain-computer interface for hands-free teleoperation of construction robots," *Automation in Construction*, vol. 123, p. 103523, Mar. 2021, doi: 10.1016/j.autcon.2020.103523.

[12] *Robotics — Vocabulary*, ISO 8373:2021, 2021.

[13] A. Bauer, D. Wollherr, and M. Buss, "Human-robot collaboration: A survey," *Int. J. Human. Robot.*, vol. 05, no. 01, pp. 47–66, Mar. 2008, doi: 10.1142/S0219843608001303.

[14] X. Wang and Z. Zhu, "Vision–based framework for automatic interpretation of construction workers' hand gestures," *Automation in Construction*, vol. 130, p. 103872, Oct. 2021, doi: 10.1016/j.autcon.2021.103872.

[15] M. Gautam, H. Fagerlund, B. Greicevci, F. Christophe, and J. Havula, "Collaborative robotics in construction: A test case on screwing gypsum boards on ceiling," in *2020 5th International Conference on Green Technology and Sustainable Development (GTSD)*, Ho Chi Minh City, Vietnam: IEEE, Nov. 2020, pp. 88–93. doi: 10.1109/GTSD50082.2020.9303061.

[16] T. Zhou, P. Xia, Y. Ye, and J. Du, "Embodied robot teleoperation based on high-fidelity visual-haptic simulator: pipe-fitting example," *J. Constr. Eng. Manage.*, vol. 149, no. 12, p. 04023129, Dec. 2023, doi: 10.1061/JCEMD4.COENG-13916.

[17] J. Cai, A. Du, X. Liang, and S. Li, "Prediction-based path planning for safe and efficient human–robot collaboration in construction via deep reinforcement learning," *J. Comput. Civ. Eng.*, vol. 37, no. 1, p. 04022046, Jan. 2023, doi: 10.1061/(ASCE)CP.1943-5487.0001056.

[18] N. J. Van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping," *Scientometrics*, vol. 84, no. 2, pp. 523–538, Aug. 2010, doi: 10.1007/s11192-009-0146-3.

[19] Y. Liu and H. Jebelli, "Enhanced robotic teleoperation in construction using a GAN-based physiological signal augmentation framework," in *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, vol. 239, S. Walbridge, M. Nik-Bakht, K. T. W. Ng, M. Shome, M. S. Alam, A. El Damatty, and G. Lovegrove, Eds., in Lecture Notes in Civil Engineering, vol. 239. , Singapore: Springer Nature Singapore, 2023, pp. 295–307. doi: 10.1007/978-981-19-0503-2_24.

[20] Z. Liu, N. Meyendorf, and N. Mrad, "The role of data fusion in predictive maintenance using digital twin," presented at the 44th Annual Review of Progress in Quantitative Nondestructive Evaluation, Volume 37, Provo, Utah, USA, 2018, p. 020023. doi: 10.1063/1.5031520.

[21] C.-J. Liang, X. Wang, V. R. Kamat, and C. C. Menassa, "Human–robot collaboration in construction: classification and research trends," *J. Constr. Eng. Manage.*, vol. 147, no. 10, p. 03121006, Oct. 2021, doi: 10.1061/(ASCE)CO.1943-7862.0002154.