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Human–robot collaboration with mixed reality for interactive and safe workspaces

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ABSTRACT

Realizing seamless collaboration between humans and robots in shared workspaces requires advanced systems that can ensure safety and efficiency while considering the inherent unpredictability of human movement. This paper proposes a system that integrates mixed reality (MR) and robotics through a unified coordinate system to facilitate real-time interaction and collaboration. By leveraging a MR interface, human collaborators can visualize and interact with the projected paths of the robotic arms, thereby enhancing both spatial awareness and task coordination. The proposed system adapts the robot's movement path dynamically using the Voronoi diagram algorithm to modify trajectories in response to the detection of a human hand within a predefined caution zone. This mechanism reduces the risk of collisions, which ensures safer collaborative environments. The proposed system's ability to exchange motion information between the operator and the robot supports real-time adjustments and promotes an intuitive and efficient collaborative experience. Our findings suggest that integrating MR technology in human–robot collaboration systems can improve safety protocols and operational fluidity dramatically, thereby representing a significant step forward in the development of safe, efficient, and effective interactive robot systems.

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1. INTRODUCTION

Industrial robots have revolutionized manufacturing processes by offering high precision and efficiency in repetitive tasks within environments that are distinctly isolated from human intervention. Such robots, which are designed for specific functions, e.g., assembling cars in factories, have marked the initial steps toward automated productivity. However, as technology has evolved, the deployment of robots has also been extended beyond industrial settings into human social spaces, e.g., homes, offices, hospitals, shopping malls, and airports. The advancements in artificial intelligence (AI) and machine learning have opened the path for robots to not only interpret human needs and intentions with increased accuracy but also predict them, thus facilitating smoother and more intuitive human-robot collaboration (HRC) [1], [2]. This shift has broadened the scope of robotics and introduced the complex dynamics of human–robot interaction (HRI), which has become an essential field of study [3]. The evolution of robotics enables the adaptation to human emotions, the recognition of social cues, and participation in more complex forms of cooperation. As a result, robots are becoming empathetic companions and collaborators, effectively functioning in various environments. This transition towards intelligent robots unveils new possibilities for personalized assistance, healthcare, education, and companionship, leading towards a truly integrated human-robot ecosystem.

Researchers have focused increasingly on how HRI can be optimized to enhance collaborative efforts, safety, and mutual understanding between humans and robots [4], [5].

The progression from segregated to integrated environments in which humans and robots can coexist and collaborate has necessitated a nuanced and extensive understanding of shared spaces. Such collaborations require more than just physical proximity; they demand exchanges of positional information, recognition of mutual presence, and safe and effective task execution [6], [7]. The complexity of HRC can be categorized into four distinct levels: i) a shared workspace without shared tasks, ii) shared workspace and tasks without physical interaction, iii) shared workspace and tasks with occasional “handing-over” interactions, and iv) shared workspace with direct physical task collaboration [8]. These classifications underscore the increasing need for robots to navigate shared spaces and interpret human intentions and movements to ensure a synergistic relationship that is conducive to both productivity and safety. Furthermore, recent advancements in AI have enabled robots to interpret and predict human intentions and behaviors with increased precision, facilitating natural communication and decision-making mechanisms during interaction processes [9], [10]. This technological integration plays a crucial role in allowing robots to adjust and improve collaboration with human partners in real-time, providing a highly customized user experience.

Historically, the HRC concept has been explored through teleoperation, where human operators control robots remotely, particularly in scenarios deemed too hazardous for direct human involvement. This method has played a pivotal role in various fields and operations, e.g., disaster recovery, where robots can traverse through dangerous terrain under human guidance. The advent of virtual reality and augmented reality (AR) technologies have further bridged the gap, enabling more intuitive remote control of robots by providing operators with a immersive visual representation of the robot’s environment [11]. In addition, other technologies, e.g., simultaneous localization and mapping, coupled with sensory inputs from devices, e.g., light detection and ranging or depth sensors, have enabled the creation of dynamic three-dimensional (3D) maps, which has facilitated precise control over robotic actions in virtualized real-world settings [12]. Among the scope of technologies to enhance HRC, AR is particularly transformative because it provides a real-time overlay of virtual information onto the physical world, and this convergence of digital and physical realities has improved the spatial awareness and interactive capabilities between humans and robots considerably [13], [14]. The real-time computational power of AI further enriches this interaction by predicting and visualizing the robot’s movement paths, which allows human collaborators to adapt their actions effectively, thereby ensuring harmonious and efficient collaborative processes [15].

The application of AR technology in the manufacturing sector is revolutionizing production line efficiency and worker safety [16]. For example, through AR, employees can visualize the operational status of complex machinery in real-time or follow maintenance procedures step by step. This is particularly effective in reducing time and costs associated with training new employees. Additionally, equipment adjustment guides utilizing AR minimize errors in processes requiring precision work and facilitate collaboration in the product design and prototype review process by overlaying virtual models onto the real environment, thereby shortening the development cycle [17], [18]. Thus, AR supports decision-making and enhances worker interactions at various stages in manufacturing, opening up new possibilities beyond traditional manufacturing methods.

Existing technologies operate by prioritizing human safety, allowing robots to avoid contact with workers by predicting human movements. However, while advancements in AI enable robots to anticipate human actions, humans cannot predict robot movements. This paper proposes a study to facilitate HRC by integrating mixed reality (MR) technology with the Microsoft HoloLens 2 device. Through MR, humans can visualize the robot’s movement path, allowing them to avoid disrupting the robot’s tasks. Traditional human safety-centered collaboration systems prioritize human safety, which may decrease robotic task efficiency. In contrast, a human-robot interaction (HRI) system that emphasizes mutual collaboration enables both safety and operational efficiency by minimizing interference between human and robot movements. Additionally, the system anticipates spatial dynamics in a shared environment and dynamically adjusts the robot’s trajectory based on human activity to mitigate potential collisions and coordinate tasks. By bridging the gap between human intent and robot actions through MR, this study aims to promote safer, more intuitive, and productive HRC, marking a significant step forward in the HRI field.

In section 2, this paper examines the use of MR technology, specifically through Microsoft HoloLens 2, to enable advanced collaboration between humans and robots, highlighting the integration of virtual and physical worlds for enhanced interaction. Section 3 focuses on the implementation and evaluation of the proposed MR-based system, showcasing its potential to improve safety, efficiency, and intuitive communication in HRC. Section 4 the conclusion underscores the significant impact of integrating MR with robotics on the future of collaborative tasks, emphasizing the need for further research on path planning and collision avoidance to expand the technology’s applicability and responsiveness in dynamic environments.

2. MIXED REALITY SYSTEM

MR bridges the gap between the real and virtual worlds by creating environments where physical and digital elements coexist and interact in real time. AR, a subset of MR, enhances the user's perception by overlaying virtual information onto their real-world view, which can be achieved using various devices, including desktop computers, handheld tablets, and head-mounted displays e.g., the Google Glass and Microsoft HoloLens devices [19]. These technologies analyze the physical environment to place virtual objects accurately, thereby enriching numerous applications in various fields, e.g., education, design, healthcare, entertainment, and robotic collaboration [20], [21].

As mentioned previously, AR enriches the user's perception by overlaying additional information on the objects or locations they observe; however, MR extends these capabilities by integrating virtual information with changes in the physical world [22]. This integration has applications across various sectors, e.g., education, design, healthcare, entertainment, and robotics collaboration research [23], [24]. The essence of MR lies in its ability to merge the physical and virtual worlds seamlessly, thereby facilitating real-time information exchange, which ensures that virtual data overlay and interact with the physical environment, thereby creating a unified experience where users perceive a blended reality. MR technology enables the projection of virtual information onto real objects, which allows users to visualize and predict robot movements accurately, thereby enhancing safety and collaboration in robotics [25]. Using MR displays and hand interfaces, users can specify a robot's destination and trajectory to avoid obstacles, which ensures efficient task execution while avoiding collisions [26].

As shown in Figure 1, the proposed system integrates an MR system, a robot control system, and a network server. The application of HoloLens 2 and network server system developed were implemented utilizing the unity game engine. Unity game engine serves as a powerful development platform offering complex 3D environment construction and real-time data processing capabilities, essential for realizing advanced interactions such as user hand position recognition. This allowed developers to more easily implement high levels of interaction within the MR environment and real-time network communications.

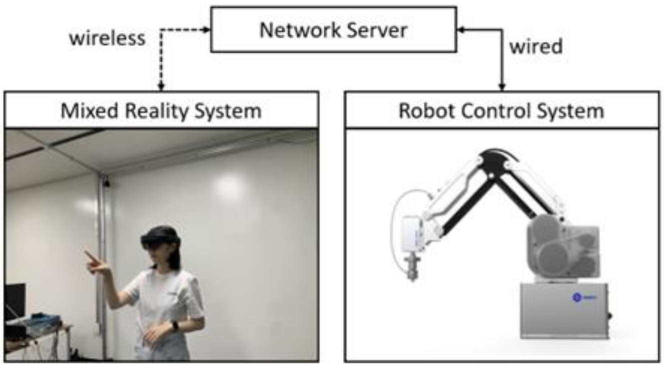

Figure 1. Structure of the MR collaboration system

Here, the HoloLens 2 is central to the MR system. The HoloLens 2 is a sophisticated MR device that seamlessly integrates a CPU, GPU, headphones, and a network module for comprehensive functionality. The HoloLens 2 also uses a depth sensor to map the observed environment and create MR space based on a spatial coordinate system, which allows the HoloLens 2 to track the user's hand movements and recognize gestures accurately, thereby realizing intuitive command execution.

Two key elements exist in the physical environment, i.e., the robotic arm and the human hand. The trajectory of the robotic arm is represented in the physical environment. The HoloLens 2 and both hands tracked by HoloLens 2 exist in the MR environment. To realize effective integration of the physical and virtual environments, the HoloLens 2 (worn by the operator) functions as a pivotal interface. This configuration involves aligning the HoloLens 2's coordinate system with that of the robot's to facilitate effective spatial synchronization, as shown in Figure 2. This alignment is crucial to ensure that movements in the physical space are mirrored accurately and interacted with in the MR environment, which enables precise control and collaboration between the human operators and robotic systems.

The robotic arm operates in the physical world coordinate system, denoted C_{PW}, and the HoloLens 2 employs its distinct virtual coordinate system C_H positions of the human hands, as tracked by the HoloLens 2, are represented in this virtual coordinate system C_H. To prevent collisions between the robotic arm and the operator's hands, their positions must be reconciled within a unified coordinate system, which necessitates the definition of a mixed world coordinate system C_{MW} (denoted where the HoloLens 2 anchor function aligns the MR environment with the anchor's physical coordinates). Following an environmental scan with the HoloLens 2, the user manually sets the anchor's position and orientation to ensure that the virtual and physical coordinate systems are aligned through a calibration process. This integration allows the proposed MR collaboration system to convert and interpret the HoloLens 2 device's positional data in the context of the mixed world coordinate system. Communication between the HoloLens 2 and the robot control computer is critical to coordinate movements and ensure safety. The position data of the use's hands (captured by the HoloLens 2) are transmitted to the robot control computer, which then returns the robot's planned movement path to the MR interface. This interactive process allows the user to monitor and adjust to the robot's trajectory visually in real time, thereby preventing potential collisions.

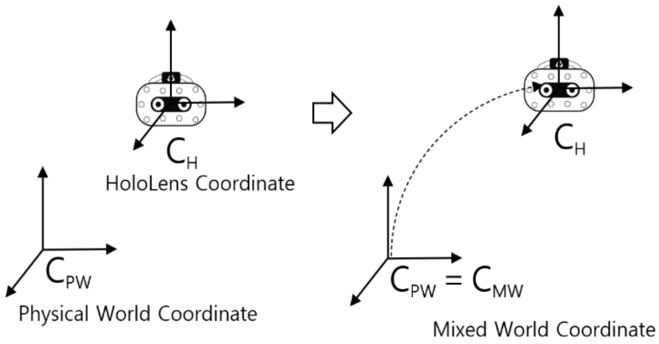

Figure 2. Coordination of the MR collaboration system

The network server manages and stores the positional data of the user's hands in the MR system and the current and projected movements of the robotic arm's gripper. This server implements web-based HTTP communication to ensure seamless integration across the systems. Using the "UnityWebRequest.Post()" function, the hand position data from the HoloLens are uploaded periodically to the network server. Similarly, the robot control system regularly updates the server with the robotic arm's location and intended path. When the robotic arm's ID is specified in a "UnityWebRequest.Get()" request to the network server, the server responds with the relevant position and 3D spatial data, which is then conveyed to the HoloLens 2. This mechanism allows the robot control system to adjust its operations based on the user's hand positions, enhancing collaborative safety and efficiency. Data exchange between the server and the systems is facilitated using JSON format, enabling straightforward parsing and utilization of numerical data for both the MR and robot control systems.

3. HUMAN–ROBOT COLLABORATION

The 3D collaboration system integrates the HoloLens 2 with the robotic mechanisms in a defined space. Using the HoloLens 2, users can control the robot's actions in the operational environment. The proposed system employs inverse kinematics to calculate the robot arm's joint angles, which allows it to move to predetermined positions. The movement trajectory of the robot arm, including the sequence by which the gripper accesses these positions, is calculated and then visualized on the HoloLens 2, thereby addressing safety concerns inherent in real-time collaboration systems. When a potential collision is detected, which is indicated by the hand position recognized by HoloLens 2, the system recalculates the robot's path dynamically to ensure task continuation without incident.

In a shared environment where humans and robots coexist, the inherent variability in human movement means that individuals cannot replicate the precise movements or timing of a robot. Thus, the robots must adapt to the unpredictable nature of human motion to ensure safe collaborations. Robots are equipped with sensors that can be used to track and anticipate human movements; however, it is difficult for humans to predict the robot's actions. AR technology addresses this issue by integrating and visualizing both the robot's actual movement and its projected trajectory, which necessitates the real-time exchange of physical and virtual information to align the robot's position and operational environment with the virtual environment's coordinate system. Thus, the movement path of the robot arm is transmitted and visualized in real time, which enables the human operator to verify the amalgamation of the physical robot and its trajectory through the HoloLens 2, as shown in Figure 3.

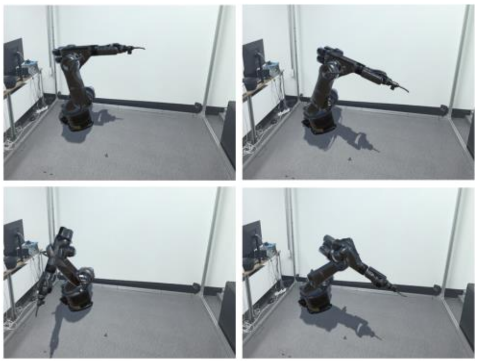

Figure 3. Augmented robot visualization in MR environment

The HoloLens 2 recognizes the position of the user's hand in the virtual environment's coordinate system, and when this information is relayed to the robot system, robot control system promptly recalculates the spatial path of robot arm to ensure safety by adjusting the spatial path to avoid collisions with humans or halt operations as required. A robotic system designed for human collaboration is detailed with a structure diagram in Figure 4. This system allows an the operator to sequentially establish the robot arm's destination and operation mode tailored to for specific tasks. Initially, the system assesses if whether the robot arm's intended position falls within its operational capacity, which is followed by the calculation of the calculating the required necessary movement trajectory. The operational range of the robot arm is predefined by its technical specifications, and a reachability test module evaluates if whether the operator's commands can be executed within this range in (1). Utilizing the HoloLens 2, the operators can visually confirm that their the designated target positions lie within the robot arm's capabilities. Commands that fit within the operational space are deemed executable, while and commands that are beyond the operational space are considered unfeasible. This process ensures that tasks are assigned based on the practical reachability and movement potential of the robot arm, which optimizes efficiency and feasibility in collaborative human–robot scenarios.

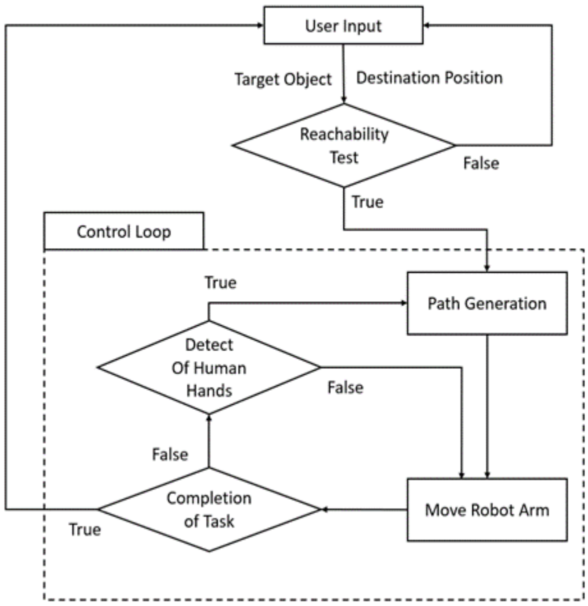

Figure 4. Robot arm operation

$$Reachability\ Test = \begin{cases} True & (P(Robot)_{Start}, P(Robot)_{End}) \in workspace \\ False & otherwise \end{cases} \quad (1)$$

If the reachability test is successful, the robot control system forwards the command to the robot arm; otherwise, the robot control system prompts the operator to adjust the operation. Based on the operator's instructions, the system devises a movement path for the robot arm, which is then activated to follow this designated path. Note that the path generation process utilizes inverse kinematics to calculate the route from the starting point to the targeted location. In addition, in the robot control system, entering a work loop triggers the robotic arm to execute the specified task repetitively.

However, when operating in a shared space with humans, the human body can intersect the robot's path in various situations. Thus, to realize sufficient safety, if a person is detected within the operational pathway, the robot arm either halts or recalculates its trajectory based on the person's location and the proximity to the robot's moving parts. Movement commands are issued to the robot arm, and the AR system monitors the position of the user's hands. If the operator's hand enter a potentially hazardous area along the robot arm's path, the system either stops the arm's movement or generates an alternative route to avoid contact. The robot system then either completes the task as instructed or repeats the process as required, thereby ensuring both task efficiency and safety.

The path regeneration method utilizes the Voronoi diagram algorithm to modify the trajectory. Typically, humans use both arms for tasks; thus, the directions of the arms are represented as vectors. The new path is then recalculated on a plane perpendicular to the arm's direction. Here, the Voronoi diagram algorithm is applied with five key points, i.e., the starting point, the endpoint, the intersection point with the human arm, and two boundary points representing the limits of the robot's movement perpendicular to the initial path. As shown in Figure 5, this process generates a new path along the diagram's boundary. When two potential paths emerge, the path more distant from the human arm is selected to ensure safety and efficiency.

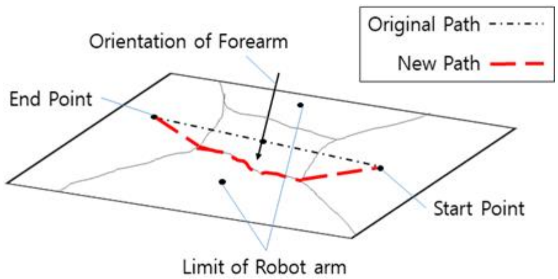

Figure 5. Dynamic spatial path generation using Voronoi diagram algorithm

4. CONCLUSION

This paper has introduced a human–robot collaboration system that integrates MR technology to address safety challenges in HRI. The proposed system enhances collaboration by enabling users to visualize the robot's trajectory, thereby allowing the users to predict the robot's movements and coordinate their actions in a shared space. Integrating MR technology with advanced path planning algorithms represents a significant step forward in the field of HRC. This improves both safety and efficiency, and it opens up new possibilities for collaborative tasks that were previously too risky or complex. These results suggest that combining MR with real-time path adjustment algorithms can significantly contribute to enhancing the intuitiveness and safety of HRI.

Previous studies have focused on ensuring the safety of human-centered HRI by using sensors installed on robots to detect human movements, thus enabling safe collaboration. This study goes beyond that scope by emphasizing a bidirectional HRI that allows users to view the robot's movements and anticipated trajectory, facilitating real-time adjustments to the robot's path to enhance efficiency while ensuring human safety. This system has the advantage of recognizing human hand movements in real time and dynamically adjusting the path, thereby enhancing safety while maintaining operational efficiency.

Future research will focus on further improving the responsiveness and accuracy of the proposed system and enhancing collaboration stability and efficiency through the use of more sophisticated path planning and collision avoidance algorithms. The primary objective of this study is to establish an integrated environment where humans and robots can collaborate harmoniously, thereby presenting potential applications across various fields, such as personalized assistance, healthcare, and education. This study provides a foundation for advancing the collaborative relationship between humans and robots, serving as a basis for future research on real-time decision-making and behavior prediction technologies.

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REFERENCES

[1] A. Borboni, K. V. V. Reddy, I. Elamvazuthi, M. S. AL-Quraishi, E. Natarajan, and S. S. A. Ali, “The expanding role of artificial intelligence in collaborative robots for industrial applications: a systematic review of recent works,” *Machines*, vol. 11, no. 1, p. 111, 2023, doi: 10.3390/machines11010111.

[2] W. Wang, Y. Chen, R. Li, and Y. Jia, “Learning and comfort in human–robot interaction: A review,” *Applied Sciences*, vol. 9, no. 23, 5152, 2019, doi: 10.3390/app9235152.

[3] N. Robinson, B. Tidd, D. Campbell, D. Kulić, and P. Corke, “Robotic vision for human-robot interaction and collaboration: A survey and systematic review,” *ACM Transactions on Human-Robot Interaction*, vol. 12, no. 1, pp. 1-66, 2023, doi: 10.1145/3570731.

[4] T. Kanda and H. Ishiguro, “Human-Robot Interaction in Social Robotics,” CRC Press, 2017.

[5] T. Fong, I. Nourbakhsh, and K. Dautenhahn, “A survey of socially interactive robots,” *Robotics and Autonomous Systems*, vol. 42, no. 3-4, pp. 143-166, 2003, doi: 10.1016/S0921-8890(02)00372-X.

[6] A. Bauer, D. Wollherr, and M. Buss, “Human-robot collaboration: a survey,” *International Journal of Humanoid Robotics*, vol. 05, no. 1, pp. 47-66, 2008, doi: 10.1142/S0219843608001303.

[7] S. Hopko, J. Wang, and R. Mehta, “Human factors considerations and metrics in shared space human-robot collaboration: A systematic review,” *Frontiers in Robotics and AI*, vol. 9, p. 799522, 2022, doi: 10.3389/frobt.2022.799522.

[8] M. Bdiwi, M. Pfeifer, and A. Sterzing, “A new strategy for ensuring human safety during various levels of interaction with industrial robots,” *CIRP Annals*, vol. 66, no. 1, pp. 453-456, 2017, doi: 10.1016/j.cirp.2017.04.009.

[9] F. Semeraro, A. Griffiths, and A. Cangelosi, “Human–robot collaboration and machine learning: A systematic review of recent research,” *Robotics and Computer-Integrated Manufacturing*, vol. 79, p. 102432, 2023, doi: 10.1016/j.rcim.2022.102432.

[10] P. Amaral, F. Silva, and V. Santos, “Recognition of Grasping Patterns Using Deep Learning for Human–Robot Collaboration,” *Sensors*, vol. 23, no. 21, 8989. 2023, doi: 10.3390/s23218989

[11] P. Milgram, S. Zhai, D. Drascic, and J. Grodski, “Applications of augmented reality for human-robot communication,” in *Proceedings of 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '93)*, Jul. 1993, pp. 1467-1472, doi: 10.1109/IROS.1993.583833.

[12] P. Wang, J. Xiao, H. Lu, H. Zhang, R. Yan, and S. Hong, “A novel human-robot interaction system based on 3D mapping and virtual reality,” in *2017 Chinese Automation Congress (CAC)*, Oct. 2017, pp. 5888-5894, doi: 10.1109/CAC.2017.8243836.

[13] T. Williams, D. Szafir, T. Chakraborti, and H. B. Amor, “Virtual, augmented, and mixed reality for human-robot interaction,” in *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, Mar. 2018, pp. 403-404, doi: 10.1145/3173386.3173561.

[14] D. Szafir, “Mediating human-robot interactions with virtual, augmented, and mixed reality,” in *Virtual, Augmented and Mixed Reality. Applications and Case Studies: 11th International Conference, VAMR*, 2019, pp. 124-149, doi: 10.1007/978-3-030-21565-1_9.

[15] C. Hutton, N. Sohre, B. Davis, S. Guy, and E. S. Rosenberg, “An augmented reality motion planning interface for robotics,” in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2019, pp. 1313-1314, Mar. 2019, doi: 10.1109/VR.2019.8798010.

[16] G. D. Voinea, F. Gîrbacia, M. Duguleană, R. G. Boboc, and C. Gheorghe, “Mapping the emergent trends in industrial augmented reality,” *Electronics*, vol. 12, no. 7, p. 1719, 2023, doi: 10.3390/electronics12071719.

[17] G. D. M. Costa, M. R. Petry, and A. P. Moreira, “Augmented reality for human–robot collaboration and cooperation in industrial applications: A systematic literature review,” *Sensors*, vol. 22, no. 7, p. 2725, 2022, doi: 10.3390/s22072725.

[18] M. D. Mura and G. Dini, “Augmented reality in assembly systems: state of the art and future perspectives,” *Smart Technologies for Precision Assembly: 9th IFIP WG 5.5 International Precision Assembly Seminar*, 2020, pp. 3-22, doi: 10.1007/978-3-030-72632-4_.

[19] A. Coppens, “Merging real and virtual worlds: An analysis of the state of the art and practical evaluation of Microsoft Hololens,” *arXiv preprint*, 2017, doi: 10.48550/arXiv.1706.08096.

[20] B. Bach, R. Sicat, H. Pfister, and A. Quigley, “Drawing into the AR-CANVAS: designing embedded visualizations for augmented reality,” *Workshop on Immersive Analytics, IEEE Vis*, vol. 4, Nov. 2016.

[21] X. Wang, S. K. Ong, and A. Y. C. Nee, “A comprehensive survey of augmented reality assembly research,” *Advances in Manufacturing*, vol. 4, no. 1, pp. 1-22, 2016, doi: 10.1007/s40436-015-0131-4.

[22] B. Arnaldi, P. Guitton, and G. Moreau, “Virtual Reality and Augmented Reality: Myths and Realities,” John Wiley & Sons, 2018.

[23] W. Hönig, C. Milanes, L. Scaria, T. Phan, M. Bolas, and N. Ayanian, “Mixed reality for robotics,” *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 5382-5387, doi: 10.1109/IROS.2015.7354138.

[24] E. Peters *et al*., “Design for collaboration in mixed reality: technical challenges and solutions,” *2016 8th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES*), 2016, pp. 1-7, doi: 10.1109/VS-GAMES.2016.7590343.

[25] F. Ghiringhelli, J. Guzzi, G. A. Di Caro, V. Caglioti, L. M. Gambardella, and A. Giusti, “Interactive augmented reality for understanding and analyzing multi-robot systems, in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sep. 2014, pp. 1195-1201, doi: 10.1109/IROS.2014.6942709.

[26] F. Leutert, C. Herrmann, and K. Schilling, “A spatial augmented reality system for intuitive display of robotic data,” in *2013 8th ACM/IEEE International Conference on Human-Robot Interaction*, Mar. 2013, pp. 179-180, doi: 10.1109/HRI.2013.6483560.

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