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# Exploring Multimodal Interaction Strategies for Co-Located Mixed Reality Human-Robot Collaboration

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**Abstract:**

This paper investigates how Mixed Reality (MR) technology could enhance human-robot interaction (HRI) in the workplace. We developed a system employing a Microsoft HoloLens and a Universal Robot UR5 that allows users to execute pick-and-place tasks using two distinct approaches of interaction: heading-based (HB) selection and hand-to-finger (H2F) selection. To make it simpler and more effective, the MR interface combines easy-to-use interaction methods like voice commands and gestures with real-time visualisation. In terms of task completion time, accuracy, and user contentment, sixteen participants participated in studies demonstrating HB selection was superior than H2F. H2F performed better on exact tasks, however, which implies blended approaches could have some success. The research reveals how MR may transform things by overcoming the issues with conventional interfaces, such as being difficult to grasp and demanding much of mental effort. According to the findings, MR-enhanced HRI finds use in several spheres including industrial robots, education, and healthcare. More research will be done on how to include flexible elements like object detection and sophisticated learning models if MR systems are to operate effectively in complex and changing environments. Through connecting the actual and virtual worlds, MR technologies enable people and robots to collaborate in better, more efficient, and simpler-to-use ways.

**Keywords**: Mixed Reality, Human-Robot Interaction, Heading-Based Selection, Hand-to-Finger Selection, Industrial Automation, Microsoft HoloLens, ROS, Gesture-Based Interaction, Task Load, Usability, Object Recognition, Adaptive Learning Models, Intuitive Interfaces, Real-Time Visualization, Collaborative Robotics

## 1. Introduction:

Thanks in great part to the rapid advancement in robotics and artificial intelligence (AI), a new age of human-robot interaction (HRI) has started. People and robots should be able to interact freely and effortlessly as robots find increasing presence in service, healthcare, and industrial environments. A major component of effective HRI is the capacity of robots to collaborate with humans in shared environments. Robots must be able to properly predict what humans are attempting to achieve and justify their own actions in a way that people can grasp if they are to cooperate in this manner. However, the differences in information perception between people and computers lead to major issues that usually lead to less work done and misunderstandings [1]. By addressing these issues, mixed reality (MR) technologies are transforming HRI and providing a means of improvement. Mixed reality creates realistic environments wherein actual and digital objects coexist by combining the real and virtual worlds. With tools like Microsoft HoloLens, users may see and interact virtually with robots and their surrounds in real time. Better situational awareness and simple, easy-to-use control mechanisms this ability provides for employees help to create safer and more efficient teams. Combining MR with robotics allows one to create systems that solve the issues with

conventional interfaces, such as the uncertainty of robot behaviour and the difficulty of providing real-time input.

Robots must be very exact and capable of changing to fit various roles, including pick-and-place activities, in industrial environments [2]. These tasks used to be completed by hand or set codes, which takes a lot of time and could cause errors. This concept alters when MR-based technologies are included as operators may now control robots using conventional techniques like words and motions. These instruments help workers' brains and bodies as much as they help with jobs' completion. Furthermore, knowing what a robot would do in an MR environment helps one to envision what it will do before it acts, therefore reducing the possibility of mishaps or unintended motions [3]. Mostly on workplace pick-and-place duties, this study investigates how MR technology may be utilised to assist humans and robots cooperate. It particularly addresses two methods to interact with many devices: Hand-to-- Finger (H2F) selection and Head-Based (HB) selection, both of which may be improved with voice requests. HB selection chooses where to aim using the user's head position—which is seen by a head-mounted display (HMD). Conversely, H2F picking finds the target by use of the finger-tracking characteristics of the HMD. By means of comparison, the aim of the research is to identify the optimal approach to enable simple understanding and effective operation of robot control in MR situations [4].

MR was selected as the means of collaboration between people and robots as it can link actual and virtual worlds. MR is unique among teleoperation systems as it allows employees to see the robot and its surroundings from the outside. This clarifies for them the capabilities of the robot as well as its shortcomings [5]. In complex circumstances where awareness of surrounds and rapid decision-making are crucial, this point of view is particularly useful. MR systems also enable users interact with virtual objects in real time, therefore allowing them to see and modify their work plans prior to their execution. Because of these characteristics, MR is a great tool for simplifying robotic systems usage and improving their performance [6]. This work uses the MR-HRC gadget, which combines a self-contained head-mounted display—in this example, the Microsoft HoloLens—with an industrial robotic arm. Designed within the system architecture, ROS (Robot Operating System) allows the MR interface and the robot to interact. Users of the HMD link with the robot via gestures, vocal commands, and obvious input from the device. The research compares how successfully the two contact approaches using metrics like task completion time, accuracy, and felt stress. The client is given first priority, and studies include individuals from all backgrounds to ensure that everyone may benefit from the findings [7].

Early results reveal that HB selection is simpler and more accurate than H2F selection. Because the HB approach provides a simple and less demanding interaction model, the participants said they had less chores to perform and more confidence. Still, H2F choice proved effective in circumstances requiring fine-grained control. This emphasises the importance of hybrid strategies combining the finest elements of both approaches. The results highlight the need of making the displays of MR-based HRI systems versatile and user-friendly. MR-enhanced HRI has impacts in many different spheres, including healthcare, education, and entertainment [9][10], even though the paper largely addresses industrial applications. MR may let surgeons using robotics, for instance, observe and guide synthetic instruments with before unheard-of degrees of precision. MR may similarly assist students in learning by simulating intricate computer operations in classroom environments. Combining MR technologies with robotics might provide fresh opportunities for humans and machines to cooperate as they keep becoming better.

## 2. Literature survey

The way humans interact with robots has evolved greatly since Mixed Reality (MR) and Human-Robot Interaction (HRI) merged. MR brings combines real and virtual worlds so you may interact with simulated robots and their surrounds in real time. HRI tools therefore become simpler to use and more successful. Researchers in this field have developed easily used technologies with great use in many different contexts. Industry, customer service, healthcare, and more all find use for these instruments. This paper reviews many significant research demonstrating the improvement in MR-driven HRI over time. Tom Williams et al. (2018) penned a somewhat thorough analysis of the applications for HRI Virtual, Augmented, and Mixed Reality. The research largely focused on how these technologies can enable robots and humans to interact, therefore simplifying touch and knowledge access. According to the research, MR could help individuals become more conscious of their surroundings, which is rather crucial for robots that must operate in environments constantly changing.

Eric Rosen et al. (2020) examined MR as a two-way connection in HRI similarly. According to the studies, MR might enable robots to communicate with humans their preferences and motivations. Advice may still be offered in conventional manner using words and body language. This two-way interaction helps employees feel less stressed and greatly increases team productivity. Dennis Krupke et al. investigated multimodal pointing and direction movements for co-located MR HRI in 2018. According to the research, pointing motions were not as clear-cut as heading-based interactions. This result emphasises the need of developing strategies to link that work with people's everyday conduct and with logical based helpful concepts. Beijing Shu et al. (2018), for example, examined how virtual reality may be used to let robots cooperate to divide tasks. According to the research, gesture-based interactions enable humans and robots meet as they work so they may communicate with one another. Particularly in industrial environments, motion tracking combined with MR surrounds helps robots to operate more easily. Elias Matsas et al. suggested in 2018 a plan for the implementation of proactive and adaptable approaches in an environment of humans and robots coexisting in a workplace. According to the report, industries may employ virtual reality to create safer and more productive workplaces. If humans could view and interact with robots in real time, the research concluded, normal robot programming may pose less hazards.

Based on MR, Mikhail Ostanin et al. (2020) developed a method of training humanoid manipulators. Using HoloLens and ROS, this system enabled users create real-time plans and practices for robotic work. The research largely focused on how MR may simplify difficult coding assignments so that computers might be used by non-technical users. Christine Chang et al. (2022) investigated how satisfied individuals were using MR tools for HRI and how best to improve their situation. The research revealed fundamental design principles required for MR settings to operate: maintaining minimal brain strain and providing unambiguous visual information. Using MR-HRI solutions improves user experience and enables individuals to do their tasks by means of these concepts. Daniel Szafir discussed in 2019 how MR may assist both humans and robots in coexistence. The research largely focused on how MR may allow computer workers see their environment, therefore enabling increased awareness of their surroundings and aid with decision-making. When situations are tough and sudden adjustments are required, this ability comes in really helpful. MR devices still present issues for HRI despite a lot of effort gone into them. Examining present VR/AR choices, Morteza Dianatfar et al. (2021) discovered problems including restricted technology, expensive development costs, and the requirement of robust algorithms able to detect objects. The way these problems are resolved will determine whether the research advances and if MR-HRI instruments become more valuable.

Leopoldo Angrisani et al. (2018) conducted a research on how virtual reality and brain-computer connections may cooperate to enhance MR settings. This research showed that you can participate without using your hands, which is very beneficial when you have a lot on your plate simultaneously. These findings reveal that merging MR with contemporary technology may assist to create even better HRI systems. Examining all the experiments enables us to better grasp how MR may affect the interactions between humans and robots. MR technologies make robotic systems more valuable, safe, and quick in many different industries by allowing them to interact in natural and simple ways. Therefore, additional study is required to maximise the capabilities of MR-HRI systems and solve previously present issues. Mixed interfaces, improved object identification, and user-centred design concepts will help systems to be more adaptable and dependable going forward.

| Author(s) | Title | Key Contribution | Application |
|---|---|---|---|
| Tom Williams et al. (2018) | Virtual, augmented, and mixed reality for human-robot interaction | Bridging communication gaps in HRI using MR technologies to foster situational awareness. | General HRI scenarios |
| Eric Rosen et al. (2020) | Mixed reality as a bidirectional communication interface for human-robot interaction | Demonstrated MR as a bidirectional communication interface, improving collaboration efficiency. | Industrial and collaborative environments |
| Dennis Krupke et al. (2018) | Comparison of multimodal heading and pointing gestures for co-located mixed reality HRI | Showed that heading-based gestures are more efficient for MR-based HRI. | Co-located HRI in MR settings |
| Beibei Shu et al. (2018) | Human-robot collaboration: task sharing through virtual reality | Highlighted the role of gesture-based interactions in seamless task execution. | Collaborative robotics in industrial tasks |

| | | | |
|---|---|---|---|
| Elias Matsas et al. (2018) | Prototyping proactive and adaptive techniques for human-robot collaboration in manufacturing | Demonstrated VR's potential in enhancing safety and efficiency in industrial tasks. | Manufacturing environments |
| Mikhail Ostanin et al. (2020) | Human-robot interaction for robotic manipulator programming in Mixed Reality | Proposed a system using HoloLens for real-time robotic programming. | Industrial robot programming |
| Christine Chang et al. (2022) | Virtual, augmented, and mixed reality for HRI (VAM-HRI) | Focused on usability and satisfaction in MR interface design for HRI. | General HRI with a focus on user experience |
| Daniel Szafir (2019) | Mediating human-robot interactions with virtual, augmented, and mixed reality | Emphasized exocentric views for better situational awareness in HRI. | Dynamic decision-making in complex environments |
| Morteza Dianatfar et al. (2021) | Review on existing VR/AR solutions in human–robot collaboration | Identified challenges like hardware limitations and high costs in VR/AR solutions. | Review and assessment of current VR/AR systems |
| Leopoldo Angrisani et al. (2018) | Wearable augmented reality and brain-computer interface for smart industries | Explored hands-free interaction through wearable AR and brain-computer interfaces. | Hands-free operations and multitasking |

## 3. METHODS:

### A. System Architecture

The Mixed Reality Human-Robot Interaction (MR-HRI) system is designed to integrate an industrial robot arm with a head-mounted display (HMD) to enable seamless human-robot collaboration. The system architecture incorporates the following components:

1. **Hardware Setup**:

   - A Universal Robot UR5 equipped with a Robotiq Adaptive 3-Finger Gripper for pick-and-place operations.
   - A Microsoft HoloLens 2 for immersive visualization and interaction.
   - A ROS (Robot Operating System) framework for communication and control.

2. **Software Integration**:

   - The ROSbridge node facilitates communication between the HoloLens and the robot control software, using WebSocket networking.
   - Unity3D is employed to develop the augmented reality environment on the HMD.

○ SLAM (Simultaneous Localization and Mapping) algorithms enable accurate registration and spatial mapping of the MR environment.

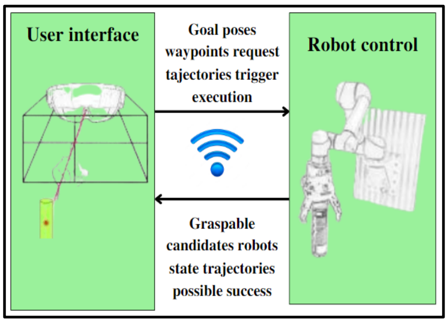


**Fig. 1.** The proposed human-robot collaborative system relies on a modular and tetherless arrangement that employs a pick-and-place industrial robot and a self-contained see-through MR display.

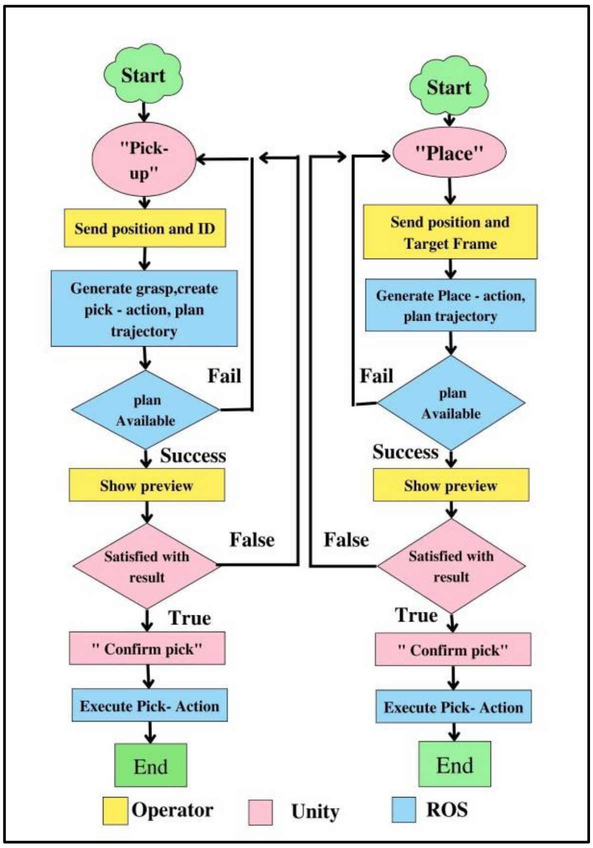


**Fig. 2.** Implementation procedures for pick-and-place

## B. Interaction Techniques

Two multimodal interaction strategies are implemented and evaluated:

1. **Heading-Based (HB) Selection**:

○ The orientation of the user's head, tracked by the HMD, determines the selection ray. The ray points directly forward from the user's view, intersecting with real or virtual objects to select targets.

o Visual feedback is provided through a green laser-like ray to confirm the user's intended selection.

2. **Hand-to-Finger (H2F) Selection**:

o The position of the user's fingertip, tracked using the HoloLens' inside-out tracking, is combined with the user's head position to define the selection ray.

o A red ring-shaped pointer highlights the selected target, and voice commands are used for action confirmation.

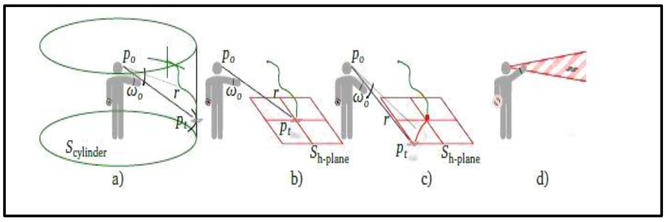


***Figure 3.*** Using workspace shapes to interact: a) The user directs the drone in the main workspace Scylinder; b) By pressing, the user changes to the secondary form. a button; c) the user controls the drone in the secondary workspace Sh-plane; and d) the user is not permitted to change the workplace to Sh-plane when the drone is flying near the user's eyes.

**C. Experimental Setup**

1. **Workspace Configuration**:

o The workspace consists of cylindrical targets placed on a table, with each target marked by red spheres to indicate pick-and-place positions.

o Two workspace shapes are used: a primary cylinder-shaped workspace for regular operations and a secondary plane-shaped workspace for precision tasks.

2. **Participants**:

o Sixteen participants (13 male, 3 female) aged 21 to 38 were recruited. They were students and staff members from the computer science department.

o Participants performed trials using both HB and H2F techniques.

3. **Procedure**:

o Each participant was given an overview of the system and practiced using both interaction techniques.

o Tasks involved selecting and placing objects using the MR interface, with trials recorded for task load, accuracy, and time.

**Figure 4.** Hardware used in the trials includes a Mbientlab MetaWearR+ IMU bracelet on the right and a Bitcraze Crazyflie 2.0 quadrotor on the left.

**D. Evaluation Metrics**

1. **Performance Metrics**:

- **Task Completion Time**: The time taken from target presentation to task completion.
- **Accuracy**: The success rate of correctly selecting and placing objects.
- **Error Rates**: The frequency of incorrect selections or placements.

2. **Usability Metrics**:

- **Task Load Index**: Measured using NASA-TLX (Task Load Index) to evaluate cognitive, physical, and temporal demands.
- **User Satisfaction**: Participants rated their experiences on a 5-point Likert scale.

3. **Trajectory Analysis**:

- **Path Smoothness**: Trajectory lengths and deviations were analyzed to compare the two interaction methods.

**Data Analysis**

1. **Statistical Tests**:

- Paired sample t-tests were used to compare task completion times, accuracy, and usability scores between HB and H2F techniques.
- Significance levels were set at $p < 0.05$.

2. **Visualization**:

- Trajectory plots were generated to visually compare path smoothness for both techniques.
- Error bars and confidence intervals were included to ensure robust interpretation of the results.

By combining advanced hardware, robust software integration, and user-centric evaluation methods, this study provides a comprehensive framework for assessing MR-based human-robot collaboration systems.

## 4. Results:

### 4.1. Participants

Figure 5 illustrates the setup of the experiment and participant interactions in the MR-HRI environment. Subfigure (a) shows the Heading-Based (HB) choosing approach. The user indicates a target by pointing their head-mounted display (HMD) in that direction. Using the user's finger position and head direction, Figure (b) displays the Hand-to-- Finger (H2F) selecting technique that chooses a target. The participant's perspective shown in figure (c) via the augmented reality helmet. Virtual markers and objects that line up with the actual workplace are shown. The yellow tubes indicate things that might be selected; the red squares exhibit specific pick-and-place spots. This image demonstrates how the system may place digital elements on top of physical objects, therefore enabling more exact activities and target finding ease.

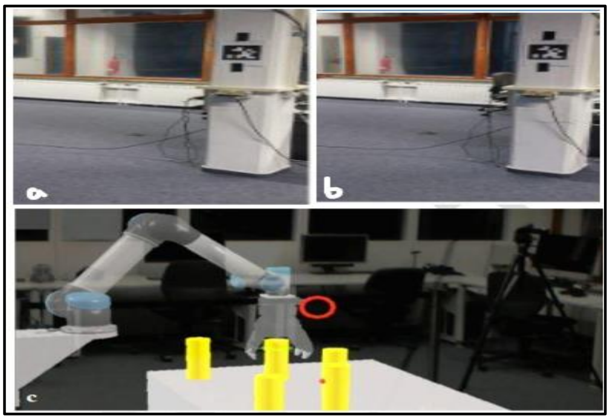

Figure 5: Participant Interaction with the System

Figure 6 shows how the workspaces and objectives were configured for the testing. Red spheres designate certain pick-and-place areas while the cylinder-shaped objects are arranged on a table. These configurations resemble actual manufacturing environments in which speed and precision are quite crucial. The image also demonstrates how the MR system, with its obvious visual indications for user communication, may operate in complex room designs. This environment highlights the need of organising the space for assessing the performance of the HB and H2F techniques as well as the part MR plays in facilitating the cooperation between humans and robots.

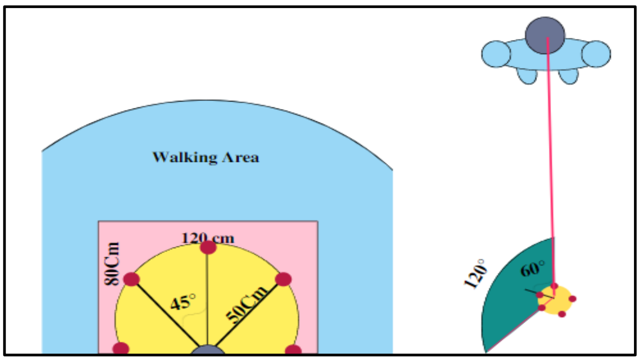


Figure 6: Target and Workspace Configuration

### 4.2. Performance:

Figure 7 demonstrates the time it takes for someone to identify an object upon seeing a new target. Table 1 might provide the results. These findings suggest H2 more probable. Table 1 and Figure 7 indicate the respondents' much faster choice of objectives. These findings align with H3. We discovered the level of success with every strategy. A error resulted from the incorrect cylinder site selection. Overall, only 1.2 percent of HB tests failed whereas 7.08 percent of H2F tests failed.

TABLE 1 Task-load,accuracy, time, and usability summary

| | M | SD | T/V VALUE | P | D-COHEN |
|---|---|---|---|---|---|
| TIME HB | 6.94 | 4.83 | V(15)=48259 | <1.112 | 1.44 |
| TIME H2F | 8.2 | 5.56 | | | |
| ACC HB | 1.1 | 1.14 | V(15)=45859 | <1.112 | 1.45 |
| ACC H2F | 1.4 | 1.17 | | | |
| SUS HB | 89.23 | 28.22 | V(15)=50 | 1.26 | 1.63 |
| SUS H3F | 79.7 | 30.65 | | | |
| TLX HB | 40.59 | 24.77 | T(15)=-3.85 | <1.16 | 2.14 |
| TLX H2F | 64.34 | 24.14 | | | |

Figure 7 shows the relative performance of the HB and H2F selecting techniques. On the left both methods' task end times are shown. HB is obviously generally quicker than H2F. The centre panel shows the lengths of the mistakes. HB departs from the target points less than others. On the right are seen the AttrakDiff poll results on usefulness and happiness. Based on confidence ranges and average statistics, the individuals felt HB was less taxing on their brainpower and simpler to grasp. Regarding speed, precision, and simplicity of usage, this image illustrates the advantages of HB choosing. It also illustrates several circumstances in which H2F could be preferable.

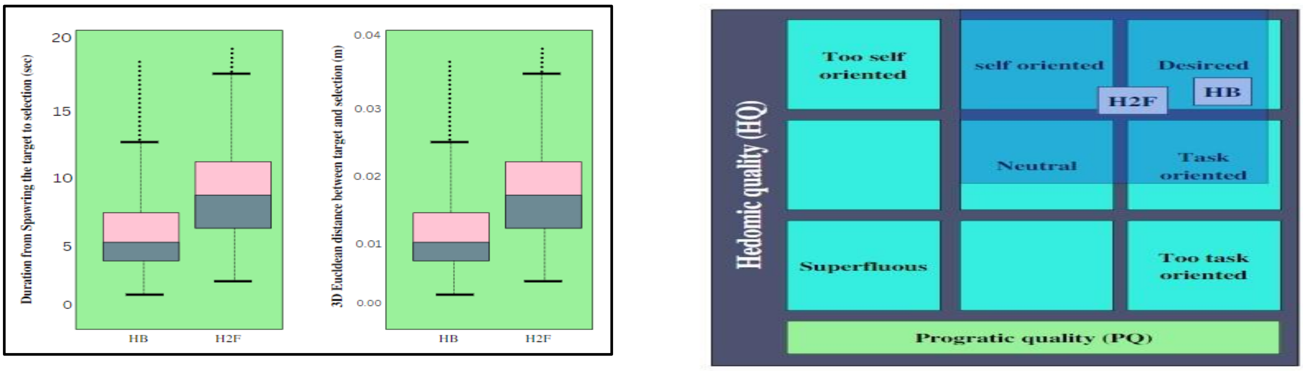


Figure 7: Performance Comparison

Figure 8 illustrates over time the changes in the pathways for the HB and H2F approaches. The right graph displays pathways that one can take using a pointing device; the left graph shows paths one may use a joystick. Every path's change in time is depicted as a line; the employment starts at t=0. The research notes that HB pathways are more straight and better, which speeds the completion of activities. H2F pathways are somewhat longer, but in complex scenarios they are more accurate. This image depicts user interactions and how the many approaches influence the equilibrium between speed and accuracy.

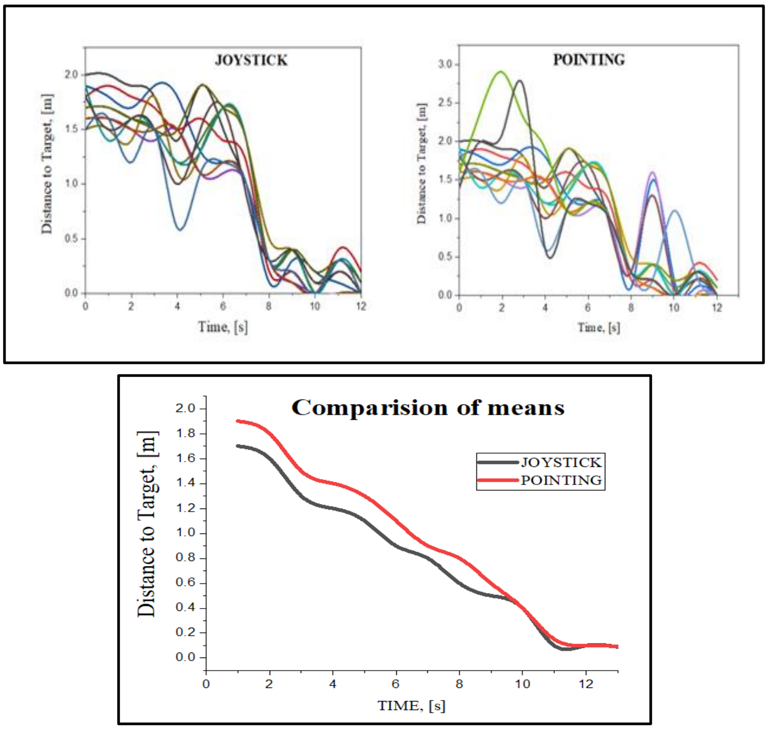


Figure 8: Temporal Analysis of Trajectories

Relative route lengths depending on item distance in a straight line are compared in figure 9. Black dots denote HB paths; blue crosses reveal H2F paths. Error bars show the 25th to 75th percentiles. Head-based selection is shown to be effective as the data reveal that HB pathways are always shorter and more direct. Though they are longer, H2F pathways feature more seamless shifts in three-dimensional space. This comparison shows how adaptable the MR system is to satisfy various users' wants and preferences as well as to jobs. It also emphasises the requirement of combined strategies using the finest aspects of both techniques.

*Table 2. Subject-specific performance (mean and median across all segments)*

| Trajectory length,[relative to straight line] | | | | | Duration, [s] | | | |
|---|---|---|---|---|---|---|---|---|
| Subject | Joystick | | pointing | | joystick | | pointing | |
| | med | mean | med | mean | med | mean | med | mean |
| 1 | 2.83 | 3 | 2.64 | 2.06 | 22.7 | 23.8 | 21.5 | 26 |
| 2 | 2.86 | 2.57 | 2.83 | 2.92 | 27.9 | 29.3 | 27.6 | 29.2 |
| 3 | 3 | 3.19 | 3.19 | 3.26 | 24.4 | 24.4 | 22.6 | 23.8 |
| 4 | 3.53 | 3.81 | 2.95 | 3.03 | 35.9 | 37.3 | 22.6 | 26 |
| 5 | 3.58 | 3.84 | 2.92 | 2.85 | 30.9 | 29.7 | 26.8 | 27.5 |
| 6 | 2.51 | 2.64 | 2.31 | 2.44 | 25.5 | 25.9 | 25.9 | 22.9 |
| 7 | 3.52 | 3.55 | 2.19 | 3.45 | 26.7 | 27.1 | 23.3 | 32.9 |
| 8 | 2.67 | 2.66 | 3.2 | 3.32 | 21.3 | 21.8 | 22.9 | 25.2 |
| 9 | 2.97 | 3 | 2.76 | 2.02 | 22.2 | 23.4 | 26 | 26.6 |
| 10 | 3.15 | 3.3 | 2.66 | 2.78 | 26.5 | 26.5 | 25 | 26.3 |

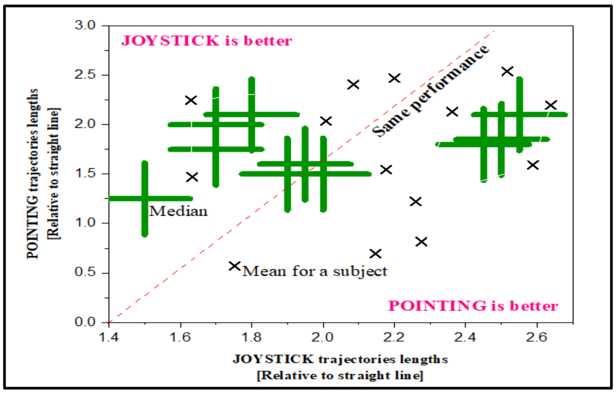


Figure 9: Trajectory Comparison

Two sections of a route under joystick control are shown in Figure 10. The shorter cylinders indicate the objectives; the tall, thin cylinder indicates the user's location. The path's straight lines in both the horizontal and vertical planes indicate that the individual hand-made adjustments. Particularly in environments that vary rapidly, this image illustrates that joystick control isn't always the greatest approach to make things move smoothly and fast. According to the research, MR-based approaches—such as HB and H2F—can help users finish activities more quickly and demand less effort.

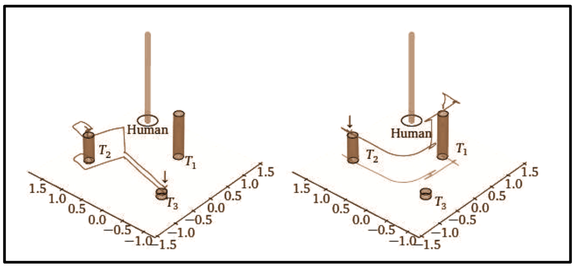


Figure 10: Joystick-Controlled Trajectory Segments

Two sections of a route made feasible by the pointing interface are shown in figure 11. The green part depicts activities occurring in the cylinder workspace; the red segment shows actions occurring in the horizontal plane workplace. The individual is the tall, thin cylinder; the shorter cylinders represent the objectives. The image reveals smoother and more natural shifts between trajectory segments than in joystick operation. This demonstrates how MR technologies increase accuracy and the user experience when humans and robots cooperate as well as how pointing-based interactions may be helpful for complex spatial tasks.

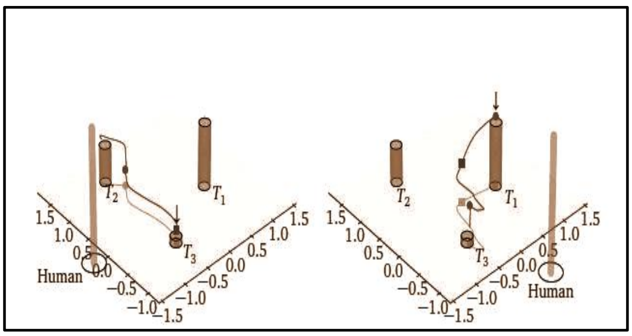


Figure 11: Pointing-Controlled Trajectory Segments

## 5. CONCLUSION

This work investigated how Mixed Reality (MR) technology may be used to enhance human-robot interaction (HRI) for industrial pick-and-place operations. Combining sophisticated MR interfaces with two alternative approaches of interacting with robots—Heading-Based (HB) selection and Hand-to-- Finger (H2F)—selection—we examined how well each functioned. The findings reveal that MR may modify HRI by providing simple, rapid, and easy to use solutions. Experimentally, HB selecting shows superior in terms of speed, accuracy, and less effort based on the outcomes. People said time and time again that the HB approach was less intellectually hard and simpler to grasp than the H2F choice. H2F did, however, be helpful in circumstances requiring exact and fine-grained control, which implies that blended approaches combining both approaches might be very beneficial. Working with robots is safer and more effective as the real-time visualisation and interactivity of the MR-HRC system helps users to be considerably more aware of their surroundings. These characteristics eliminate some of the key issues with previous interfaces, such as unclear design and extensive complex coding requirements. Robotic systems are therefore simpler for more people to operate.MR-enhanced HRI has impacts in many spheres, including healthcare, education, and entertainment, even if this research was mostly on industrial applications. To make MR-HRI systems even more versatile and beneficial, researchers want to integrate more sophisticated elements such object identification and adaptive learning in the future. MR technologies have the power to totally transform future interactions between humans and robots by addressing present issues and finding fresh approaches of engaging.

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