Mixed Reality Based Teleoperation System For Prefabricated Building Assembly

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Abstract -

In response to the challenges in the assembly process of prefabricated buildings and the pursuit of sustainable construction, this paper proposes an industrial robot arm teleoperation method based on mixed reality (MR) technology. Traditional assembly processes that rely on manual installation face challenges such as operator safety issues, and high energy consumption. Our proposed method utilizes MR technology to achieve immersive and remote control and uses Optimal Resolved Acceleration (ORA) and Resolved Acceleration Control (RAC) to complement the shortcomings of Resolved-Rate Motion Controller (RRMC) by introducing compliance control to enhance environmental adaptability and telemanipulation accuracy. The aluminum profile assembly and precision testing experiments have shown the feasibility and accuracy of this method. The MR teleoperation framework allows for compliance control, and despite some noise, the robotic arm exhibits good accuracy. Future work will focus on expanding task complexity, improving system accuracy, integrating intelligent functions, and exploring scalability for large-scale construction projects.

Keywords -

Mixed Reality; Teleoperation; Robotic arm; Prefabricated Building; Sustainable Construction

1 Introduction

In recent years, with the increasing global industry attention to sustainability, integrating low-carbon and environmental practices into the construction industry has become a focus. For example, the European Union continuously updates its Building Energy Efficiency Directive, requiring building projects to standardize carbon emission management from design to construction to operation and maintenance, and transform them into environmentally friendly projects. Industry and market demand are also driving the construction industry to transition towards low-carbon operations.

Prefabricated construction refers to transferring a large amount of on-site work from traditional construction methods to factories, where building components and accessories (such as floor slabs, wall panels, stairs, balconies, etc.) are processed and manufactured, transported to the construction site, and assembled and installed on site through reliable connection methods. Compared to traditional buildings, buildings using prefabricated components can reduce greenhouse gas emissions by 8.06%. In addition, using alternative green concrete materials in the prefabrication process of prefabricated buildings can reduce the total greenhouse gas emissions by 2.83-12.05% [1]. Xiang [2] also pointed out that the construction industry has caused a significant amount of carbon emissions worldwide. The adoption of prefabricated buildings has reduced the industry's environmental pressure. The comparison between prefabrication methods (such as assembly) and traditional in-situ casting methods shows that in all categories of influence, prefabrication methods have greater environmental advantages than traditional methods [3].

Although prefabricated structures have many advantages compared to traditional construction techniques, there are still many disadvantages in the assembly process. Due to differences in operational proficiency and on-site conditions, prefabricated buildings often and energy. In order to solve the above problems, this article proposes a teleoperation method for industrial robot arms based on mixed reality technology, which is used for assembly work in prefabricated buildings. This method enables us to detect hand displacement and angle deflection through MR devices while wearing them, and accurately control the robot arm to make responsive actions to complete assembly work. Compared to using cranes and manual assembly methods. This method can complete assembly work more accurately and quickly while maintaining low carbon emissions. In order to solve the challenge of realizing slosh-free assembly in the assembly process of prefabricated buildings and improve the efficiency and accuracy of the assembly work and the computational efficiency of the slosh-free assembly trajectory under the condition of real-time feedback, ORA and RAC with compliance control algorithm is proposed. This algorithm introduced the compliance matrix into the existing motion controller to make the robot arm perform the assembly task more smoothly and naturally[4]. Ensure that the robot arm can not only meet the accuracy of assembly without shaking in the condition of human-computer interaction, but also reduce the vibration and impact caused by rigid movement, further improving the response ability to external forces. This method supports remote assembly by experienced workers, avoiding the cost increase and additional carbon emissions associated with personnel mobility. In addition, it can replace operators in some extremely dangerous situations and still accurately and effectively complete assembly work, ensuring the safety of construction personnel.

This article mainly consists of six parts: we begin by discussing introduction, followed by related work of this study. The methodology for implementing the article will be presented in the third section. The experimental verification of the technology and the analysis of the results are presented in the fourth and fifth parts, respectively. The final section includes a summary of this study and plans for future research work.

2 Related work

The integration of mixed reality (MR) technology enriches and enhances collaborative experiences by seamlessly merging digital and physical elements. For instance, MR systems empower operators to engage with both digital and physical environments, thereby reducing redundant hardware and maximizing workspace efficiency [5]. MR technology amalgamates the strengths of AR and VR, augmenting user immersion and facilitating interaction with holographic physical devices within the real environment. This enables humans to remotely operate robotic arms, significantly mitigating the environmental footprint associated with substantial human resource deployment. Moreover, immersive systems diminish the necessity for construction industry operators to travel, consequently reducing the carbon footprint linked to transportation. Case in point, the Australian company GRAINTECH has implemented Microsoft's HoloLens mixed reality technology to enhance remote assistance and collaboration, reportedly slashing travel expenses and carbon emissions by 68% [6]. This showcases the potential of MR technology in reducing the need for physical travel and lowering the carbon footprint. The MR remote control method can also prevent humans from working in extremely dangerous situations, improving worker safety and work efficiency [7].

MR remote-controlled robots have achieved considerable success in assembly tasks. Takahashi [8]proposed a virtual reality-based robot teaching interface, offering a user-friendly environment where novice operators can effortlessly instruct robots. Robots in the workplace replicate the actions of operators within a virtual workspace to perform assembly tasks. Jarecki and Lee [9] introduced a mixed reality (MR) user interface (UI)-based system device that supports the remote operation of mobile robotic arms. Their findings suggest that MR-based UIs may be perceived as more intuitive by operators compared to conventional control interfaces. Zhang et al. [10] integrated collaborative robots with mixed reality technology to achieve human-machine collaborative assembly, enhancing assembly efficiency and presenting a novel and viable assembly model for the intelligent collaborative assembly of large-scale and complex spatial products.

In the operation scenario of an industrial assembly line, the robot arm must be able to accurately control its motion trajectory and speed. Although the current research on gesture-based building robot control has been relatively abundant. However, in this dynamic environment, it is difficult to ensure that the assembly slosh-free when moving rapidly due to inertia. Humans need special skills to perform tasks efficiently without shaking. Therefore, how to balance the agility of the robot arm and the maneuverability in slosh-free, and improve the assembly accuracy and efficiency is an important challenge. We can improve the agility of the robot system by designing advanced control methods, so that the robot arm can achieve superhuman slosh-free motion. In addition, in the case of real-time feedback, the calculation of slosh-free trajectory requires a lot of computational resources, so the design of an efficient optimized solver is also crucial. To solve these problems, this paper proposes a solution based on conformance control algorithm ORA (Optimization trajectory algorithm) and RAC (real-time adjustment algorithm). The algorithm is improved on the basis of ORA and RAC, and the compliance matrix is introduced to ensure the high precision and efficiency of the robot arm during assembly. The tolerance of the robot arm to the rigid external force is enhanced, so that the worker's operation is safer and smoother. This approach greatly facilitates remote assembly by experienced workers, significantly reducing safety risks and the additional carbon emissions associated with too many workers.

3 Methodology

The methodology integrates Mixed Reality (MR) technology with advanced motion control algorithms to enhance robotic arm manipulation. It employs Transmission Control Protocol/Internet Protocol (TCP/IP) [11] for Unity [12]and xArm 6 communication [13], ensuring synchronized movements. Data transmission aligns position and rotation data, minimizing operational gaps. The system was first introduced by the Resolved-Rate Motion Controller (RRMC), improved with the Optimal Resolved Acceleration (ORA) algorithm for precision control in the context of assembly, and finally combined with compliance control for adaptability. The framework (as shown

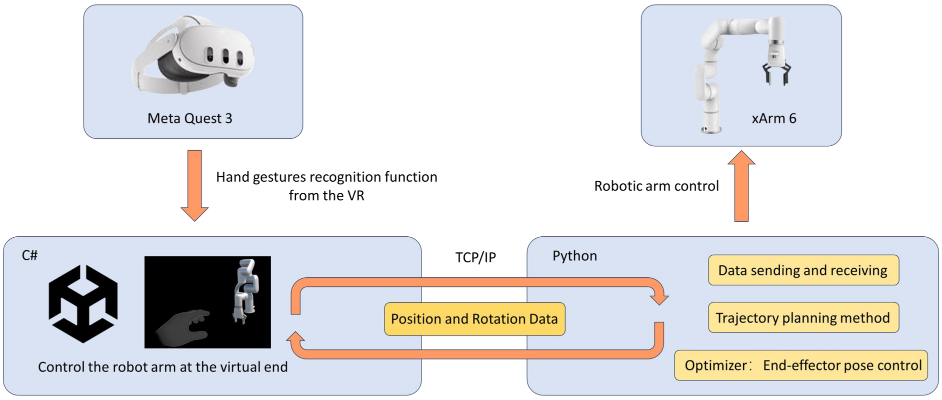


Figure 1. The workflow of the communication between Unity and xArm-6

in Figure 1) aims to improve assembly accuracy and efficiency while maintaining low carbon emissions, in line with sustainable building goals.

3.1 TCP/IP Connection

As depicted in Figure 1, the TCP/IP connection method was used in this study primarily to fulfil the communication function between Unity based on C # and xArm 6. Python implemented both the sending and receiving of control information, as well as the optimization functions of xArm 6. The objective was to transmit the data of hand recognition coordinates and attitude angles (position x, y, z, and rotation x, y, z) data provided by Meta Quest 3's SDK function in the VR headset and Unity scene to the xArm 6, with which a control connection had already been established, through the specified IP address and port, thus achieving the control of the real end (xArm 6) by the virtual end (Unity and VR). Meanwhile, the target angles of each link of the robotic arm could also be reversely transmitted to Unity through the PyCharm end to control the movement of the virtual xArm 6 model, thus realizing the control of the virtual end by the real end.

3.2 Data Transmission

The hand gesture recognition technology (i.e. pinch interaction) in VR equipment captures the spatial coordinates of the five fingers and the palm's center point. The palm's center point data is used to map the end-effector of the robotic arm, enabling precise control of its position and rotation. The pinching distance (spatial separation between fingertips) is directly mapped to the gripper aperture, where a smaller distance corresponds to a narrower gripper closure, providing intuitive control.

In the data transfer module, a calibration coefficient of 1000 is applied to position data in Python to align Unity's meter (m) units with Python's millimeter (mm) units. This ensures that the actual displacement values remain aligned between the two systems. For large industrial robotic arms, this coefficient can be adjusted to handle tasks like automobile assembly, where precise positioning of large components is required. The robotic arm's motion is controlled using coordinate and attitude rotation differences between consecutive frames, enabling accurate trajectory tracking based on real-time hand position and orientation changes.

3.3 Manipulator motion control and trajectory optimization

3.3.1 Resolved-Rate Motion Controller (RRMC)

For attitude control at the end of a robotic arm, we first introduce Resolved-Rate Motion Controller (RRMC) [14]. This is a closed-loop attitude controller that is applied directly to the robotic arm as a first-order differential equation to generate the motion trajectory of the end-effector with velocity-level commands.

$$\mathbf{T} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1a}$$

$$\rho(\mathbf{T}) = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{1b}$$

$$\tau(\mathbf{T}) = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} \tag{1c}$$

where $\rho(\mathbf{T}) \in \mathbb{R}^3$ constitutes the rotation component, $\tau(\mathbf{T}) \in \mathbb{R}^3$ constitutes the translation component.

The translation and rotation of the end effector with respect to the difference between the current attitude and the desired attitude is represented by the error vector e:

$$e = \frac{\tau\left({}^0T_{e^U}\right) - \tau\left({}^0T_{e^R}\right)}{\alpha\left(\rho\left({}^0T_{e^U}\right)\rho\left({}^0T_{e^R}\right)^T\right)} \in \mathbb{R}^6 \tag{2}$$

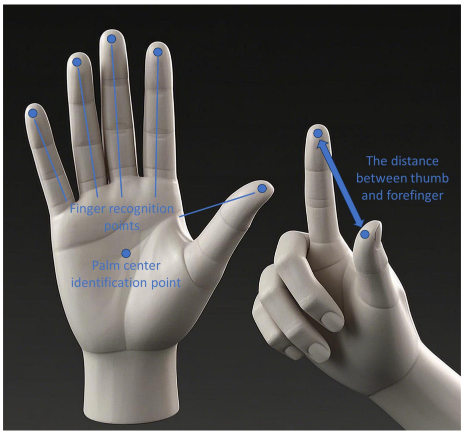


Figure 2. Hand gesture recognition points for the teleoperation

where ${}^0T_{e^R}$ is the end effect pose in the base frame, ${}^0T_{e^U}$ is the desired end effect pose in the base frame. $\alpha(\cdot)$: **SO**(Special Orthogonal Group) $\in \mathbb{R}^3$ turns rotation matrix into an equivalent Euler vector.The Euler vector specifies the rotation axis and rotation angle.

The v in the RRMC equation is determined by the error e, when $v = ke$ and k is the proportional gain term. We limit v to some value v_m by modifying the magnitude of the proportional gain term k until the error e drops below some value e_m:

$$v = \begin{cases} k_e \frac{v_m}{||k_e||} & \text{if } ||k_e|| > v_m \\ k_e & \text{if } v_m \geq ||k_e|| > ||e||_m \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

The RRMC ensures that the error decreases at the same rate until the speed gradually decreases to a smooth stopping of the arm.

3.3.2 Optimal Resolved Acceleration (ORA) with Resolved Acceleration Control (RAC)

RRMC relies more on the computation of Jacobi matrices and pseudo-inverses to deal with external forces and constraints indirectly through pliability matrices and avoids dealing directly with constraints arising in the system, leading to controller degradation. To solve this problem, we introduce quadratic programming techniques to achieve the desired results. Quadratic programming (QP) can transform the RRMC into an optimization problem and quickly generate the optimal control strategy in a short time. As a general optimization algorithm, it can provide additional functions directly in the formulation of RRMC and show good results when dealing with equality, inequality and cost constraints. Therefore, QP applied to the control of a robotic arm is a quadratic planning process that includes the physical constraints of the whole system, and does not encounter the problem of generating very high control speeds due to the presence of non-square and rank-loss Jacobi matrices.

In addition, RRMC, as a first-order differential equation, generates motion trajectories only at the velocity-level command. Precise positioning and trajectory tracking of the robotic arm is achieved by accurately controlling the acceleration in response to rapidly changing task demands and environmental conditions. For the required accuracy in the context of assembled buildings, we can introduce Optimal Resolved Acceleration (ORA) for optimization. ORA is primarily concerned with optimizing the acceleration of the robot, and is usually formulated through a quadratic programming problem with formulas that contain the cost terms for acceleration and velocity, as well as velocity and acceleration constraints in the task space. At the acceleration-level command, optimal joint accelerations and velocities are found by minimizing the cost functions of acceleration and velocity.

We use the resolved acceleration control (RAC) method, which maps the acceleration command $u_a(t)$ in the task space to the joint space [15]:

$$u_j(t) = [q(t),\ \dot{q(t)}, \ddot{q(t)}] \tag{4}$$

By direct application of second-order differential equations at the acceleration-level command, an optimal control problem under constraints is solved in each iteration to ensure the feasibility of the joint configurations. For an intial joint space configuration $u_j(t) = [q(t),\ \dot{q(t)}, \ddot{q(t)}]$, in each iteration of the QP solution, acceleration command $\ddot{x_d}$ and kinematics contraints of robotic arm can be showed:

$$\min_{q,\dot{q},\ddot{q},\delta} [q, \dot{q}, \ddot{q}, \delta] P [q, \dot{q}, \ddot{q}, \delta]^T \tag{5a}$$

Contraints:

$$q = q_0 + \dot{q_0}\Delta t \tag{1}$$

$$\dot{q} = \dot{q_0} + \ddot{q}\Delta t \tag{2}$$

$$\ddot{x_d} + \delta = J_0\ddot{q} + \dot{q_0} \bigotimes H_0\dot{q_0} \tag{5b}$$

where $P \in \mathbb{R}^{27\times 27}$, Δt is time-step, $J_0 = J(q_0)$, $H_0 = H(q_0)$.

The introduction of slack variables $\delta \in \mathbb{R}^6$ to the task-space controller in the minimization of the acceleration command $\ddot{x_d}$, when the variables include $q, \dot{q}, \ddot{q}, \delta$, ensures that the optimal control problem is reachable to an optimal solution. The slack variable δ is in the cost function and is activated only if the acceleration command u_a does not satisfy the kinematic constraints. For ease of understanding and computation, we rewrite the objective function:

$$\min V(\ddot{q}) = \ddot{q}^T P \ddot{q} + \dot{q}^T Q \dot{q} \tag{6a}$$

Constraints:

$$\ddot{x_d} = J(q)\ddot{q} + \dot{J(q)}\dot{q} \quad (6b)$$

$$\dot{x_d} = J(q)\dot{q} \quad (6c)$$

where $\dot{x_d}, \ddot{x_d}$ are desired mission space velocity and acceleration.

Both P and Q are positive definite matrices used to weight the cost of joint acceleration and velocity.

For the first part of the optimization objective of the objective function $\ddot{q}^T P\ddot{q}$, minimizing joint acceleration $\ddot{q}$ and controlling acceleration amplitude.

For the second part of the optimization objective of the objective function $\dot{q}^T Q\dot{q}$, minimizing joint velocity $\dot{q}$ and controlling velocity smooth.

3.3.3 Compliance Control and Environmental Adaptability

Since we need to meet accuracy not only in the context of assembly-type building installation, but also in applications where humans collaborate with robotic arms, or operate in uncertain environments, we introduced suppleness control to robotic arm operation to avoid collisions and injuries.

In order to enhance the compliance, a compliance matrix S is introduced into the objective function $V(\ddot{q})$. This compliance matrix S, weighs the relationship between joint acceleration $\ddot{q}$ and end-actuator acceleration $\ddot{x_d}$ while enhancing the collaborative capability of the robotic arm. The objective function $V(\ddot{q})$ can be modified as:

$$\min V(\ddot{q}) = \ddot{q}^T P\ddot{q} + \dot{q}^T Q\dot{q} + (\ddot{x} - \ddot{x_d})^T S(\ddot{x} - \ddot{x_d}) \quad (7a)$$

Constraints:

$$\ddot{x_d} = J(q)\ddot{q} + \dot{J(q)}\dot{q} \quad (7b)$$

$$\dot{x_d} = J(q)\dot{q} \quad (7c)$$

where $\dot{x_d}, \ddot{x_d}$ are desired mission space velocity and acceleration. For the compliance matrix S, which reflects the weight of the system on the end-effector acceleration error. S as a symmetric positive definite matrix for tuning the sensitivity of the system to different directional pliability:

$$S = \text{diag}(\lambda_x, \lambda_y, \lambda_z) \quad (8)$$

where $\lambda_x, \lambda_y, \lambda_z$ denote the weights on the acceleration errors in Cartesian space for the three directions, respectively. When $\lambda_x, \lambda_y, \lambda_z$ is small, the system is less sensitive to errors and exhibits a higher degree of suppleness; conversely, it exhibits rigidity.

In human-robot collaboration, the compliance matrix S can be dynamically adjusted to enhance the compliance and adaptability of the robotic arm according to environmental demands. The compliance matrix S can also be combined with an impedance control strategy to further improve the responsiveness of the robotic arm to external forces.

3.4 Apparatus

3.4.1 Manipulator

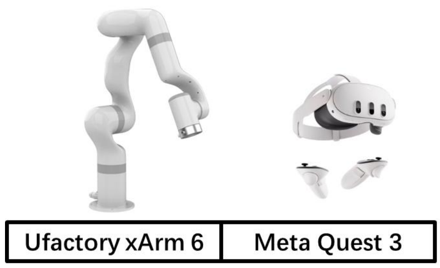


Figure 3. Hardware required for the teleoperation

In order to verify the feasibility of our approach to this control, we chose a robotic arm of the xArm 6 model from Ufactory as shown in Figure 3 . It has high load and accuracy, with a maximum load of 5kg and repeatability of ±0.1mm. xArm-Python-SDK provides a complete Python interface, which makes it easy for researchers to quickly get started and perform new algorithms. Compared with other industrial robots, xArm 6 is less expensive and more cost-effective. Therefore, this approach was used to validate the feasibility of the control method proposed in the paper.

3.4.2 Teleoperator

Meta Quest 3 (Figure 3) supports 6 Degree of Freedom (DoF) tracking function with excellent motion tracking performance. It is capable of accurately capturing the user's movements with an average latency of only 12 milliseconds, which enables natural and smooth interactions, allowing us to manipulate the virtual objects and carry out experimental simulations in a more precise way, improving the accuracy and efficiency of scientific research.

4 Experiment

The experimental section provides a detailed introduction to two key experiments: aluminum profile assembly based on MR teleoperation framework and robot arm trajectory accuracy testing. The aluminum profile assembly experiment demonstrated the effectiveness of the remote control framework in controlling the construction of assembly tasks for the robotic arm. The trajectory accuracy test of the robot arm evaluates its accuracy by comparing its trajectory with the trajectory of the hand. The results indicate that although there are some errors in the accuracy of the robotic arm trajectory, the overall control accuracy

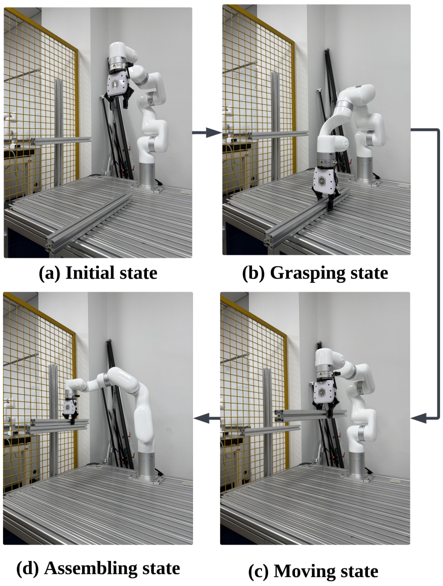


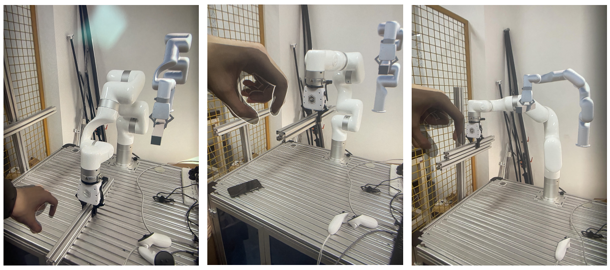
Figure 4. The teleoperation of assembling aluminum profiles. Subfigure (a) represents the initial position of the robotic arm, at which point there is no movement of the robotic arm. (b) illustrates that robotic arm received instructions to clamp the aluminum profile. Subfigure (c) shows arm moves according to the trajectory of the hand. And (d) presents the state that robotic arm completes the assembly process.

is considerably high. Both experiments emphasize the potential of remote operating systems in sustainable building practices.

4.1 Aluminum Profile Assembly

To explore whether a robotic arm can replace human labor to perform various assembly tasks, it is necessary to test its flexibility. When the robotic arm is operated using the MR telecontrol frame, it is tested whether the robotic arm can assemble the components as flexibly as the traditional assembly method. For this purpose, a small experiment was designed to use the MR device to manipulate the robotic arm to pick up aluminum profiles on the workbench and place them on a shelf built from aluminum profiles. The experimental process is shown in the Figure 4 .

The key to this experiment is to observe whether the robot arm can complete the task quickly and flexibly. If the robotic arm is able to complete the task successfully, then the framework is feasible and the assembly task will not be affected by remote control or MR interaction. This manipulation method can be further tested to manipulate larger industrial robotic arms to accomplish some assembly tasks.



(a) (b) (c)

Figure 5. Movement of the manipulator and hand during the assembly process: (a) The robotic arm is controlled via hand interaction using MR-based gesture recognition to clamp aluminum profiles. (b) The robotic arm follows the trajectory of the hand interaction to move to the designated location. (c) Completion of the assembly task by the robotic arm.

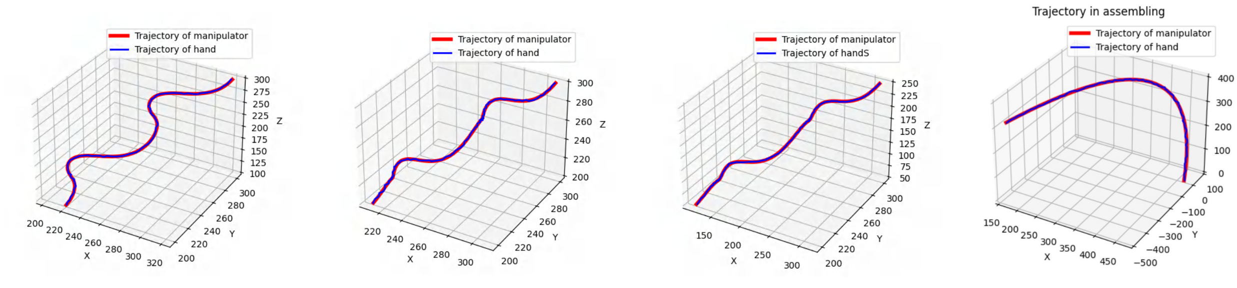
4.2 Accuracy test

Another measure of teleoperation of robotic arms to replace humans in completing assembly work is accuracy, as robots need to fully follow the operator's hand movements to complete task responses. The higher the precision, the higher the success rate of the robot arm in completing assembly work. In this experiment, MR equipment will be used to detect three different human-demonstrated paths (experiment ***a***, ***b*** and ***c*** shown in Figure 5). In experiments, the operator's hand will operate the robotic arm within a reasonable range to draw different trajectories. Then observe whether the trajectory generated by the robot arm is consistent with the trajectory of the hand. The degree of overlap between two trajectories is the precision of control.

5 Result and Analysis

5.1 Result of Aluminum Profile Assembly

As shown in the Figure 5 , the operator finally controlled the robotic arm to successfully complete the assembly work of the aluminum profile. This indicates that the MR teleoperation framework can flexibly control robot arms to complete simple assembly tasks. In addition, setting aside various physical controllers, the control method of directly detecting the position and state of the hand is also more convenient for operators to understand its control mode. We extracted 200 points from the hand trajectory and robotic arm trajectory of each group of experiments, and then calculated the offsets of adjacent two points on the X, Y, and Z axes in turn. Then, the distance threshold is set, and the offset error between the trajectory of the manipulator and the trajectory of the hand is smaller than the threshold, which Indicates that the two trajectories are aligned In this study, the distance threshold was set



(a) (b) (c) (d)

Figure 6. Trajectory comparison of human-demonstrated paths and robotic manipulator replication under various conditions. Subfigures (a), (b), and (c) illustrate three distinct trajectories demonstrated by hand movements using MR-based remote control of a robotic manipulator. The trajectories executed by the manipulator (red lines) are compared against the original human-demonstrated trajectories (blue lines) to evaluate precision and alignment accuracy. (d) presents the trajectory comparison during an assembly task, where the manipulator replicates the trajectory of grasping aluminum profiles.

at 0.5mm. The experimental results also show that the remote control scheme has a delay of less than 400 ms, and the main reason for the delay is the network delay, and the coincidence between the hand trajectory and the robot arm trajectory reaches 96%. However, the assembly work in the experiment was too simple and unitary, so more experiments are needed to explore whether the robotic arm controlled by the scheme can help workers complete the assembly work in high-risk or extreme environments.

5.2 Result of Accuracy test

As can be seen in the Figure 6 , the trajectory of the robotic arm essentially coincides with the trajectory of the hand. The table 1 also shows the overlap of the two trajectories in each set of experiments.The higher overlap among the three groups indicates that the robot arm has a certain degree of accuracy. In Experiment ***a***, the overlap between the two trajectories reached 97%, and in Experiments ***b*** and ***c***, the overlap between the two trajectories also reached 92% and 94%, respectively. This means that the manipulator can use this control method for more precise control. From the figure, it can be seen that there is some noise in the hand trajectory, which may be introduced by the MR device when detecting the position and posture of the hand. However, after optimizing the motion control algorithm of the robot arm, the trajectory of the arm became smoother. This indicates that using this control framework, the robot arm also has a certain degree of noise resistance, which can avoid shaking caused by noise.

6 Conclusion and Future work

In this study, we propose an industrial robot arm teleoperation method based on mixed reality technology for assembly work in prefabricated buildings. Through the integration of TCP connection, data transmission and advanced motion control algorithm, xArm 6 robot arm and Meta Quest 3 are used to carry out the feasibility analysis of this control method, and the aluminum profile assembly experiment and accuracy test are carried out.

Experiments	Accuracy
a	97%
b	92%
c	94%
Trajectory in assembling	96%

Table 1. Accuracy of manipulator

The experimental results show that the MR teleoperation frame can effectively and flexibly control the robot arm to complete simple assembly tasks. This direct detection of the position and status of the hand control mode, for the operator to understand and operate the system provides convenience. However, current assembly tasks do not fully demonstrate the complexity of assembly tasks, so further experiments are needed to explore the full potential of robotic arms in supporting and assisting humans with difficult assembly tasks.

In the accuracy test, the robotic arm has a certain accuracy, and its trajectory is very consistent with the trajectory of the hand. Although there is some noise in the hand trajectory, which may be introduced by the MR Device during the hand position and attitude detection process, the motion control algorithm optimization of the robot arm effectively smooths its trajectory. This shows that the control frame makes the manipulator have the ability to resist noise and avoid jitter.

Future work will focus on several key areas. Firstly, our goal is to increase the complexity and diversity of assembly tasks to more comprehensively evaluate whether robotic arms have the potential to help humans in assembly tasks. This will involve testing a wider range of building components and assembly scenarios. Secondly, in order to improve the accuracy and efficiency of assembly work, efforts will be made to enhance the accuracy and stability of the system. This will require further optimization of motion control algorithms and calibration of MR devices to minimize errors and noise. Finally, we plan to explore the integration of more intelligent features, such as real-time obstacle detection and avoidance, to improve the safety and reliability of robotic arms in building environments [16].

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