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Multi-arm robot teleoperation using mixed reality and digital twin

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Abstract: A user interface for the teleoperation of a multi-arm robotic system is proposed. This leverages mixed reality devices and digital twin simulation for interactive robot manipulation in laboratory tasks. Preliminary testing suggested intuitive operation compared to conventional user interfaces.
Keywords: Mixed Reality, Digital Twin, Teleoperation

1. Introduction

In robot-assisted tasks where direct operation of the robot is impractical, traditional user interfaces such as bimanual master consoles used in surgical systems are effective for robot teleoperation [1]. However, controlling multiple robots by multiple operators in collaborative tasks remains complex and unintuitive with these methods [2]. Prior work on mixed reality (MR) based robot control has largely focused on single-user interfaces [3], task scheduling [4], or general interaction design [5], with few systems supporting real-time, multi-user coordination of multiple robot arms. As reviewed in [6], the integration of MR with collaborative, high-dimensional robot control remains underexplored. This work addresses this gap by introducing an MR user interface for multi-user, multi-arm robotic control in real time through interaction with a digital twin (DT). The system integrates head-mounted display (HMD) Meta Quest 3 (Meta, USA) and virtual-physical synchronization to allow intuitive multi-user multi-robot control. We present preliminary tests of the proposed user interface.


Fig 1: System with four robot arms inside a cage.

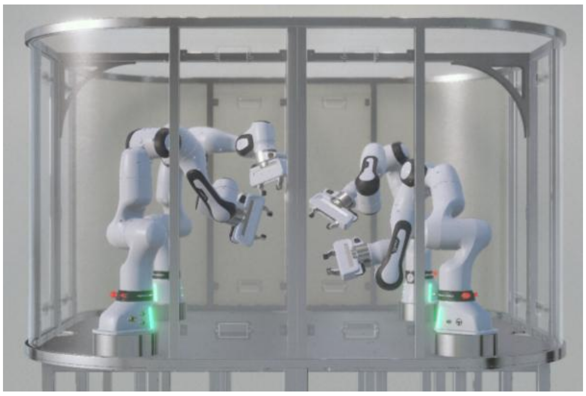
Fig 2: Digital twin replicating the appearance of real system.

2. Materials and methods

2.1 Hardware

A robot system with four Franka Research 3 arms is housed within a 2 m × 2 m × 1.1 m enclosure frame mounted on a fixed base (see Fig. 1). The system is designed for handling lab equipment under sterile conditions. An OptiTrack (NaturalPoint, Inc., USA) system with four cameras tracks both the HMDs, via reflective infrared markers, and the robot system within a unified reference frame.

2.2 Software

The robot arms are controlled using ROS, which handles low-level motion control and execution. A DT of the system is implemented in Unity 3D (see Fig. 2), which serves as a central server for communication between the Meta Quest HMD and the robot controller via UDP. The robot application communicates with the server to update the state of the digital twin and receives the target pose and gripper state upon user interaction in the HMD. Collision avoidance is integrated using the vector field inequalities (VFI) method [7], which incorporates collision

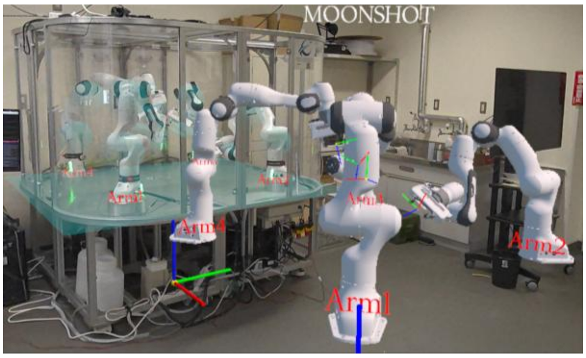

Fig 3: AR overlay on real robots, and MR digital twin.

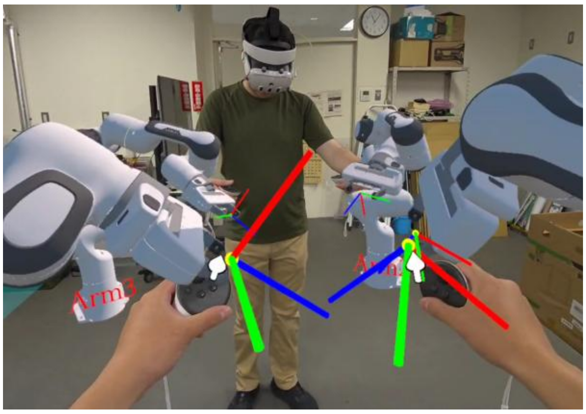

Fig 4. Two users are interacting with the digital twin as seen from one of their HMD.

primitives into the inverse kinematics solver as constraints in an optimization problem. Additional joint limit and velocity constraints are included to ensure safe and smooth operation.

2.3 User Interface

An MR application was developed in Unity 3D for the Meta Quest 3 HMD. The device enables passthrough vision of the real environment with virtual elements overlaid. The MR user interface is used to visualize the digital twin. An AR overlay of the robot collision shapes is rendered on the physical system to visualize the robot constraints (see Fig. 3). The user interacts with the digital twin using the Meta Quest 3 hand-held controllers. To control a robot arm, the user brings their hand close to the robot's end-effector reference frame, presses a thumb trigger button, and moves their hand. The updated target pose is then sent to the robot controller. Using pose data from the OptiTrack system, a unified coordinate reference frame is established, allowing multiple operators to view and interact with the same digital twin in a shared spatial frame (see Fig. 4).

3. Results

The proposed MR and DT-based user interface was tested with a four-arm robotic system, supporting simultaneous control by up to four operators. The system mirrored the physical robots in real time with no noticeable latency. Communication among the HMDs, DT server, and the robot system was fast and reliable. Calibration to a unified coordinate system minimized alignment errors between the physical robots and AR overlays, enabling all users to operate within a shared virtual space.

4. Discussion

The proposed user interface allows intuitive teleoperation, with users free to select and control any robot arm. This contrasts with conventional systems limited to single-operator and two-robots, which is typical in robot-assisted surgery. Use cases include remote manipulation of laboratory equipment, which is relevant for demonstration data collection for training AI models for robot autonomy in wet lab tasks. These initial results highlight the feasibility of the approach and its potential for further development.

5. Conclusion

This study demonstrates the feasibility of MR and DT-based teleoperation for complex robot systems, and opens possibilities for more immersive and accessible robot control tools.

Acknowledgements

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