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Development of a Mixed Reality Robotics Testing Environment

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Abstract

This work presents the development of a Mixed Reality (MR) robotics framework that integrates real and virtual environments for experimental robotics, education, and visualization. The system combines a motion-capture platform, simulation software, and a ceiling-mounted projector to create a spatially aligned interactive workspace in which physical robots coexist with projected virtual objects. Real-time pose streaming allows the robot's motion to be mirrored within the simulated environment, allowing virtual obstacles, goals, and paths to appear precisely aligned with the physical world. Calibration establishes a coordinate mapping between the motion-capture frame and the projected simulation frame. The system was validated through path planning experiments that included static and dynamic obstacles, demonstrating robust real-time performance and consistent spatial alignment between virtual projections and physical robot behavior. The framework supported multiple STEM outreach events (to over 100 students), demonstrating intuitive visualization of robot navigation. The system provides a calibrated MR foundation for real-time navigation visualization and future multi-robot extensions.

Introduction

Robotics education faces ongoing challenges in helping students bridge the gap between theoretical concepts and real-world robot behavior. Traditional methods often rely on simulation, which offers scalability but lacks physical realism, or on hardware-based experiments, which introduce safety constraints, a complex setup, and limited repeatability. Mixed Reality (MR), a subset of Extended Reality (XR) technologies, combines simulation with the physical embodiment of robots, enabling controlled yet realistic experimentation environments[1]. Previous mixed reality (MR) systems in robotics have employed both wearable displays and projector-based visualization to support navigation and interaction tasks[2]. While these approaches demonstrate the feasibility of MR for robotics, limitations such as device dependence, restricted shared visualization, and a lack of calibrated alignment between virtual cues and physical robot execution reduce their effectiveness for instructional use[3,4]. This motivates the need for MR systems that provide accurate geometric alignment, repeatable behavior, and shared visual context.

MR has also shown substantial promise in educational robotics. Studies demonstrate that MR improves students' understanding of navigation and control by providing safe, repeatable environments that combine virtual and physical interaction[5,6,7]. Additional research highlights significant gains in student motivation, conceptual understanding, and integrative thinking when

AR/MR tools are incorporated into robotics curricula[8,9].

To build on these findings, the present work develops a Mixed Reality robotics testing environment that integrates a high-precision motion capture system, a physics-based simulation environment, a robotics middleware framework, and a ceiling-mounted projector. Motion capture provides millimeter-scale tracking accuracy, which is essential for synchronizing virtual and physical domains[10,11], while the simulation environment provides a widely adopted platform for robotics experimentation[12]. This integration enables the projection of virtual obstacles, goals, and trajectories into the same physical space as the real robot, creating a unified hybrid environment for studying navigation behaviors. This paper is based primarily on a Master's research project and thesis[13]

Background and Related Work

Mixed Reality (MR) blends virtual visualizations with the physical environment. Prior research has shown that MR systems can support student understanding of navigation, control, and robot-environment interaction[5,7,8,9]. These capabilities are particularly valuable in instructional settings where repeated experimentation with physical robots may be constrained by safety, cost, or logistical limitations.

Wearable MR displays have been used to visualize robot state and navigation cues[14,15,16], but are less suitable for shared classroom viewing and multi-observer demonstrations[3].

Projector-based MR systems address several of these limitations by embedding virtual information directly into the shared physical workspace. Previous studies have demonstrated the use of projected navigation paths and interaction cues to support human-robot interaction and swarm robotics research[2,17]. These approaches highlight the value of spatially situated visualization for improving user understanding and enabling collaborative observation in both research and educational contexts.

Prior projector-based MR has demonstrated motion-capture–tracked systems with projected overlays for interactive experimentation[4]. Building on this foundation, the present work develops a projector-based Mixed Reality robotics testing environment that integrates motion capture, simulation, and physical robot execution within a unified framework. By providing geometrically aligned visualization and real-time interaction with a physical robot, the system supports robotics education, classroom demonstrations, and robotics research.

System Overview

The MR system developed consists of four major subsystems: a motion tracking system, a projector, a mixed reality computation and simulation system, and a mobile robot platform. Together, these components enable real-time synchronization between physical robot behavior and virtual environmental elements.

As illustrated in Fig. 1, the motion tracking system provides real-time pose data of the physical robot. These poses are transformed into the simulation coordinate frame by the pose transformation module. The simulation environment generates virtual obstacles, goals, and navigation cues, which are projected into the workspace through the ceiling-mounted projection system. Navigation commands derived from the simulation are then issued to the physical robot through the navigation command interface, enabling coordinated interaction between physical and virtual elements.

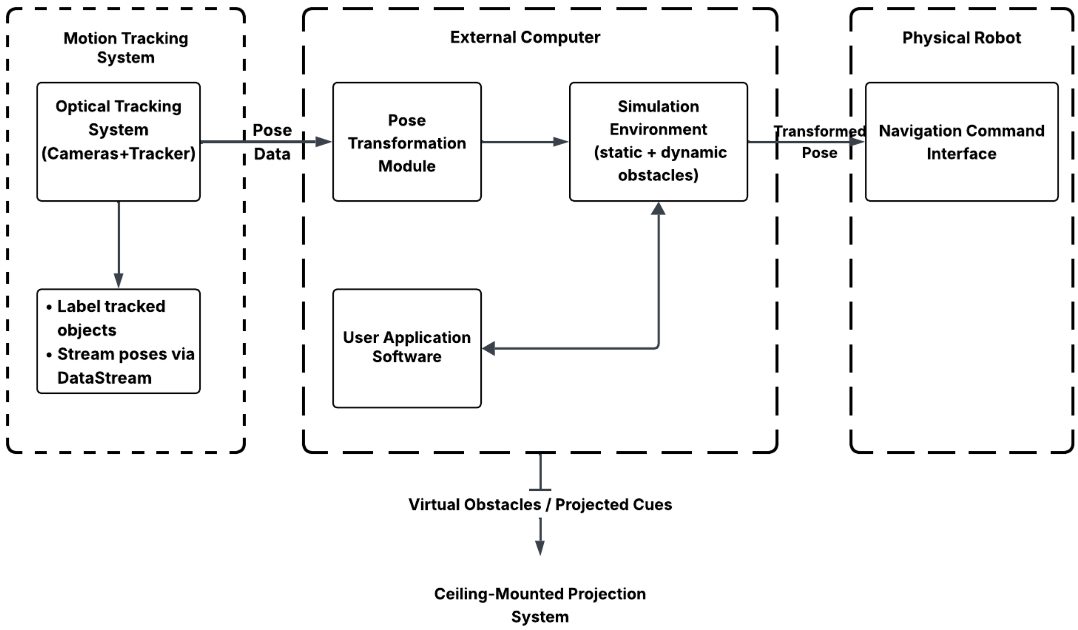

Figure 1: System architecture of the Mixed Reality robotics testing environment.

While Fig. 1 presents the system architecture and data flow, Fig. 2 shows the physical implementation of the mixed-reality workspace. The ceiling-mounted projector overlays virtual obstacles, goals, and trajectories directly onto the floor, allowing the mobile robot to interact with projected elements in real time.

Figure 2: Experimental mixed-reality robotics testbed showing a mobile robot operating within a projected virtual environment.

System Components

Hardware Components

The motion-tracking system uses an optical motion-capture system (Vicon) that provides low-latency millimeter-scale pose tracking for the robot[10,11]. Retro-reflective markers attached to the robot are detected by the cameras, and rigid-body pose data is streamed in real time to the external computer.

A differential-drive mobile robot operates within the tracked workspace and executes navigation commands generated by the mixed-reality framework. A ceiling-mounted high-brightness projector displays virtual obstacles, goals, and navigation cues directly onto the physical floor, enabling shared visualization. Projector-based MR approaches have been shown to support robot navigation visualization and collaborative interaction in both research and educational settings[6,7,8].

Software Components

The system uses ROS 2[18] to coordinate communication between the motion-capture system, the simulation environment, and the robot control interface. Motion-capture data are integrated through the `vrpn_mocap` interface[19], while low-latency message passing is handled by the ROS 2 Data Distribution Service (DDS) layer[20]. A physics-based simulation environment (Gazebo Classic 11) models virtual obstacles and navigation scenarios and provides visualization of planned trajectories[12].

A custom pose-transformation module converts motion-capture coordinates into the simulation frame. This ensures geometric consistency between the physical robot, simulated environment, and projected elements. A lightweight user application allows operators to select goals, configure scenarios, and initiate mixed-reality demonstrations.

Methods

The Mixed Reality Robotics testing environment operates through a calibrated pose-synchronization pipeline that aligns motion capture, simulation, projection, and robot execution in real time.

The alignment between the motion-capture workspace and the simulation environment is achieved using homography-based calibration[21]. This mapping establishes a consistent 2D transformation between floor-plane coordinates measured by the motion-capture system and the projected simulation coordinate frame. For a planar point $\mathbf{p} = [x\ y\ 1]^T$, the projected point $\mathbf{p}'$ is given by

$$\mathbf{p}' \sim \mathbf{H}\mathbf{p}, \quad (1)$$

where $\mathbf{H} \in R^{3\times3}$ is the homography matrix, ensuring that virtual obstacles, goals, and trajectories are geometrically aligned with the robot's physical workspace.

To interface the external tracking system with the robot's onboard navigation stack, a homogeneous rigid-body transformation is used to relate the motion-capture frame to the robot's odometry frame[22]. The transformation is expressed as

$$\mathbf{T} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}^T & 1 \end{bmatrix}, \quad (2)$$

where $\mathbf{R} \in R^{3\times3}$ is a rotation matrix and $\mathbf{t} \in R^3$ is a translation vector. This transformation enables simulation-generated navigation waypoints to be expressed in the robot's local navigation frame for accurate execution.

During execution, real-time pose data from the motion-capture system is used to update the simulated robot state, while navigation commands generated in simulation are transmitted to the physical robot. This closed-loop process enables repeatable mixed-reality experiments.

Educational and Research Applications

The MR testing environment is designed to support both instructional activities and ongoing robotics research by enabling synchronized interaction between physical robots and projected virtual environments.

Educational Application

The mixed-reality system has been used as a demonstration platform for motion planning algorithms, where navigation behaviors are executed and visualized in both simulated and physical settings. During demonstrations, projected virtual obstacles, goals, and planned trajectories are overlaid directly onto the physical workspace, allowing students to observe how algorithmic decisions translate into real robot motion.

Classroom Scenario: Teaching Motion Planning Algorithms

In robotics courses, motion planning algorithms, such as Rapidly-Exploring Random Trees (RRT[23]) and RRT*[24], are often introduced through simulation alone. While students can observe generated paths in software, they may struggle to understand how these trajectories relate to physical robot behavior, path optimality, and collision avoidance in real environments.

Using the mixed-reality system, planned trajectories are projected directly onto the physical workspace alongside the moving robot. This enables students to visually compare multiple algorithms, such as RRT and RRT* solutions, in real time. As shown in Fig. 3 and Fig. 4, the RRT-generated path exhibits irregular branching and suboptimal convergence, whereas the RRT* solution demonstrates improved path quality through rewiring and gradual optimization.

Figure 3: Mixed-reality visualization of a sampling-based motion planning solution projected onto the physical workspace. The blue shapes on the floor represent static virtual obstacles. The green trajectory denotes the planned path generated by the motion planning algorithm, while the red trajectory represents the executed path of the physical Create3 mobile robot.

Figure 4: Comparison of projected planning results in the mixed-reality environment. Static virtual obstacles are shown in blue. The green path indicates the planned trajectory generated by the algorithm, and the red path shows the actual path executed by the Create3 robot in the physical workspace.

By observing both projected trajectories and the robot's physical motion, students gain an intuitive understanding of:

- Differences in path quality between RRT and RRT*
- The effect of rewiring in RRT*
- Convergence behavior and path smoothness
- The relationship between the algorithm output and physical tracking

Additionally, dynamic replanning scenarios can be demonstrated by introducing moving or projected dynamic obstacles in real time. Students can observe how the planner adapts to environmental changes and how these updates affect the robot's motion in the physical workspace. To illustrate this instructional scenario, Fig. 5. presents a real-time replanning demonstration. In Fig. 5(a), the robot follows an initially planned trajectory (green path). In Fig. 5(b), a projected dynamic obstacle intersects the planned path, triggering online replanning. The updated trajectory is immediately projected and executed, allowing students to observe the adaptive behavior of the planner in the physical workspace.

Figure 5: Real-time dynamic replanning demonstration. Static virtual obstacles are shown in blue. The green line represents the initially planned trajectory. The red path corresponds to the executed trajectory of the physical Create3 robot. In (b), a projected dynamic obstacle (labeled in the image) intersects the path, triggering online replanning

From an instructional design perspective, the mixed-reality system aligns with experiential and inquiry-based learning models commonly used in engineering education. By allowing students to observe, predict, and experimentally test algorithmic behavior in a physically grounded environment, the platform supports active learning, visual cognition, and conceptual reinforcement. Rather than passively viewing simulation results, students engage in hypothesis-driven exploration by modifying obstacles, comparing planners, and observing real-time execution outcomes.

These capabilities align with prior findings that mixed-reality robotics environments improve conceptual understanding, engagement, and spatial reasoning in engineering students[3,17,4,5].

Instructional Deployment Example

In a junior-level robotics course, this platform can be integrated into a motion planning lecture module. The learning objective is for students to compare sampling-based algorithms such as RRT and RRT* in terms of path optimality, smoothness, and convergence behavior. The activity format may include (1) simulation in Gazebo, followed by (2) observation of projected trajectories in the mixed-reality workspace, and (3) guided discussion of replanning behavior under dynamic obstacles. Assessment may be conducted through short reflection questions, worksheet-based path analysis, or comparison of algorithm performance metrics observed during the demonstration (e.g., path computation time, robot execution time, and path length).

Broader Educational Use

Beyond motion planning, the system can support instruction in multiple robotics concepts. For example, it can be used to demonstrate sensor fusion for localization by projecting LiDAR point clouds and estimated robot pose directly onto the workspace while comparing against the VICON ground truth. Further, estimation uncertainty estimates can be represented to teach concepts of inconsistent or overconfident estimators. Further, mapping concepts such as loop closure can be visualized spatially. With motion-capture markers placed on humans, advanced concepts human-robot interaction scenarios can be also be explored experientially. The platform can also support instruction in multi-robot coordination algorithms, cooperative control, and swarm robotics by projecting shared virtual goals and interaction regions onto the physical environment. The potential of MR platforms to enrich robotics education is boundless.

Research Application

In addition to instructional use, the system serves as a research platform for studying robot navigation and mixed-reality interaction. The calibrated alignment between motion capture, simulation, and projection enables researchers to evaluate algorithms under controlled yet physically grounded conditions.

The platform is currently being extended for use in a separate research project involving a mobile service robot, where the mixed-reality environment supports algorithm development, visualization, and experimental validation[13]. This ongoing work demonstrates the system's flexibility as a reusable research infrastructure that supports both educational experimentation and applied robotics research. One of our research applications investigates how robots can help reduce fall risk in indoor environments by guiding people away from hazardous floor areas, such as slippery surfaces. Based on previous research on ground slip estimation[25], the MR system was used to project a floor safety map onto the laboratory ground, enabling realistic yet risk-free human–robot interaction experiments. This setup, synchronized with a motion capture system, allowed us to study how robot motion adapts to human positions while subtly influencing human paths away from risky areas in a controlled and reproducible environment.

Results and Summary

The MR robotics testing environment was validated through live demonstrations involving synchronized motion capture, simulation, projection, and physical robot execution. Evaluation focused on observable system behavior and alignment performance during navigation tasks and is shown in Fig.6.

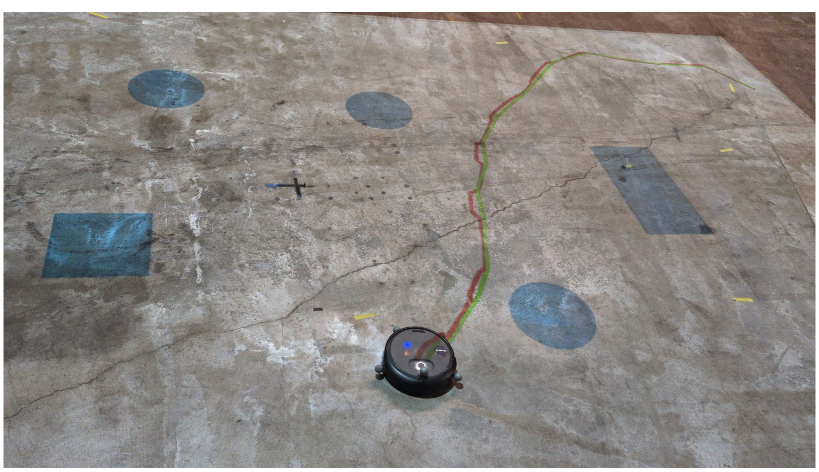

Figure 6: Robot navigation with projected paths and obstacles aligned to the physical workspace during execution.

Across all demonstrations, the physical robot followed planned navigation trajectories while projected virtual obstacles, goals, and paths remained spatially aligned with the robot's motion within the workspace. The projected trajectories accurately reflected the robot's planned and executed paths, allowing deviations and re-planning events to be visually observed in real time.

To enable a fair and consistent comparison across planning algorithms and obstacle configurations, all experiments used the same fixed goal position at $(3, 1)$ in the projected workspace. While the robot's initial pose and the presence of static and dynamic obstacles varied between trials, maintaining a common goal allowed direct evaluation of system behavior, path generation, and re-planning performance under differing conditions. This ensured that observed differences in execution were attributable to planning strategy and environmental changes rather than goal placement.

Alignment performance results are summarized in Table 1, which reports the measured simulated goal positions (Gazebo) and final physical robot positions (Vicon) during static navigation experiments. These results allow comparison between virtual planning outputs and physical execution, demonstrating consistent correspondence between simulation and real-world motion after coordinate transformation.

Table 1: Shows that the physical robot reached positions close to the simulated goal in both RRT and RRT* trials. While the x-coordinates differ in sign due to opposite axis orientation between Gazebo (simulated position) and Vicon (physical position) frames, the relative displacement between simulated and physical positions remains consistent. This indicates stable frame transformation and reliable execution of navigation commands.

Motion Planning Algorithm	**Simulated Goal (m)**			**Physical Result (m)**		
	x	y	z	x	y	z
RRT	2.93	0.96	0.00	-0.428	1.302	0.00
RRT*	3.01	0.90	0.00	-0.400	1.337	0.00

The system further supported dynamic navigation scenarios in which updated paths were generated in response to environmental changes. During these scenarios, projected cues updated consistently with simulation output while the robot continued executing revised commands without interruption. Performance metrics for dynamic re-planning trials are presented in Table 2, demonstrating stable synchronization between simulated and physical execution during dynamic replanning scenarios. An example of real-time re-planning behavior is shown in Fig. 7

Table 2: Demonstrates that similar positional consistency is maintained during dynamic replanning scenarios. The final physical pose remains close to the simulated goal even after obstacle introduction and path updates, indicating that real-time replanning does not significantly degrade synchronization between virtual and physical environments.

Motion Planning Algorithm	**Simulated Goal (m)**			**Physical Result (m)**		
	x	y	z	x	y	z
RRT	3.03	0.98	0.00	-0.434	1.346	0.00

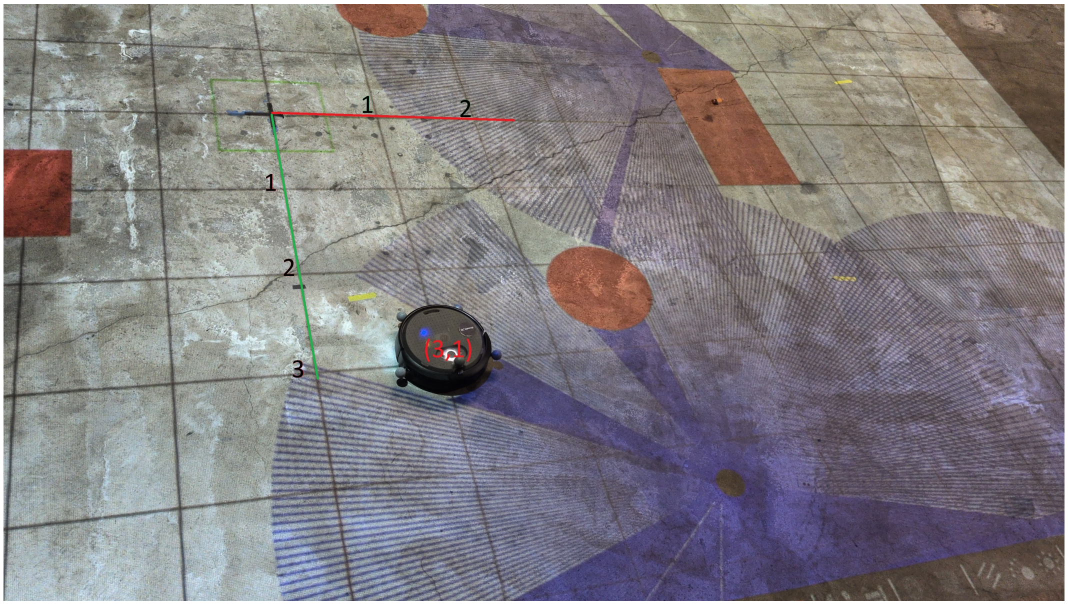

Figure 7: Projection of the Gazebo simulation environment onto the physical workspace. The projected grid represents the Gazebo world frame, red regions denote static virtual obstacles, and the blue radial pattern illustrates the infrared sensing field of the virtual robot. The physical Create3 robot is co-located with its simulated counterpart, demonstrating correct Vicon-to-Gazebo coordinate transformation and spatial alignment between projected simulation and physical robot motion.

Example demonstrations of static and dynamic navigation experiments, including real-time re-planning behavior, are provided in the YouTube playlist[1].

The shared projector-based visualization enabled multiple observers to simultaneously view robot behavior and planning outcomes, supporting both instructional demonstrations and experimental observation. These results demonstrate that the system operates as a stable mixed-reality platform capable of maintaining geometric alignment and real-time interaction between virtual planning outputs and physical robot motion.

Future Work

Future work will focus on extending the mixed reality testing environment to support more complex robotic scenarios and broader experimental evaluation. Planned enhancements include multi-robot coordination and cooperative navigation experiments using the same projector-based visualization and calibration framework. Additional studies will investigate the use of projected visual cues to support real-time drift correction and localization assistance, particularly in GPS-denied environments. The system will also be expanded to evaluate scalability under different robot platforms.

[1] https://www.youtube.com/playlist?list=PL-hqUlE7zZXqCuKznoTQqESw_dY3JztvY

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