Immersive Platform for VR-Driven Robotics with a Cloud Framework

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(a) Hardware Setup (b) Demonstration Scene

Figure 1: **Hardware Setup:** (a) VR omnidirectional treadmill (Omnideck), (b) AlienGo Quadruped Robot.
Demonstration Scene: - (a) Unity scene view, (b) VR user view, (c) user-robot representation in the virtual environment, (d) geo-tagged screenshot, (e) real-time camera stream from the robot displayed in VR.

Abstract

The ability to remotely navigate and interact with physical environments through Virtual Reality (VR) and robotics is vital for advancing teleoperation frameworks. This demo showcases a novel framework integrating VR, a Quadruped Robot, and a Dockerized Private Cloud for seamless, low-latency interaction between VR systems and robotic agents. Using a VR omnidirectional treadmill synchronized with the robot, operators navigate a high-fidelity digital twin of the physical environment. Real-time video streams and dynamic scene updates enhance situational awareness and ensure consistency between virtual and physical environments. This framework supports applications in teleoperation, remote inspection, and collaboration with future enhancements aimed at multi-user and multi-robot systems, autonomous agents, and improved scalability.

1 Introduction

In a large-scale manufacturing facility, a critical incident—such as equipment malfunction, structural damage, or hazardous material exposure—can compromise operational safety and make the affected zone unsafe for immediate human intervention [7]. Currently, industrial facilities are equipped with Automated Guided Vehicles (AGVs), which can be repurposed for emergency response [6]. When incidents occur, a centralized AGV coordination platform can activate emergency protocols, allowing remote operators to instantly connect to available AGVs for real-time visual access to the environment via onboard cameras and sensors. Operators can remotely navigate AGVs through the affected area, collecting critical visual and environmental data. To streamline the process, the system allows operators to capture and flag key visual data points via screenshots. These images are automatically transmitted to a parallel analysis platform, where safety and operations experts can perform detailed assessments without being overwhelmed by continuous video streams. This division of labor enables remote operators to focus on maneuvering AGVs and identifying areas of interest, while experts conduct in-depth analysis on the flagged data. This paper introduces a novel framework leveraging AGVs, VR, and a Dockerized Private Cloud for enhanced situational awareness and analysis in critical factory environments. The proposed system consists of two integrated components: a centralized platform connecting multiple AGVs with remote operators and a Point of Interest (POI) interface for expert evaluation. This framework aims to reduce response time, enhance situational visibility, and support synchronized operations between field observation and expert analysis.

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2 Hardware and Software

The proposed system integrates hardware components, including a VR omnidirectional treadmill and a Quadruped Robot, with software solutions to synchronize interactions between virtual and physical environments. The following subsections detail the core components and their integration.

2.1 Compositional Simulation Interconnect

The system leverages a Dockerized Private Cloud for seamless communication and synchronization between components, as shown in Figure 2. The choice of this architecture is based on the following key considerations:
Generic Interface: Building a comprehensive digital twin requires the integration of sensing, computing, and actuating modules. The simulation interconnect, through its generic interface, enables this

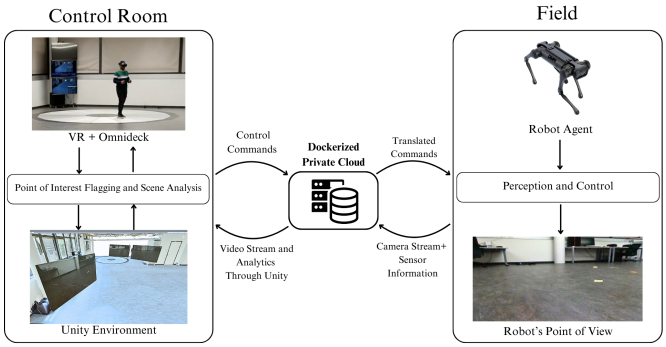


Figure 2: **System Overview -** Interactive operations via Unity environment showing the map and robotic agent's perspective, enabling synchronized remote control and inspection.

via a ROS-based three-layered architecture:
(a) Hardware Specific Layer: It is a ROS-based layer consisting of independent ROS nodes for sensory data collection and actuation. Each node carries a specific functionality to ensure modularity, fault tolerance, and scalability. These nodes are mirrored to allow a smooth transition from digital representation to physical implementation.
(b) Middleware Layer: This layer acts as an abstraction between the hardware-specific nodes and the web server hosted on the dockerized private cloud, marshaling the data to meet the needs of the exposed endpoints.
(c) Dockerized Private Cloud: This layer acts as the focal point between different systems hooked to the private cloud. It also hosts multiple containerized services, mitigating heavy compute from power and compute-constrained edge devices.
Low Latency: This architecture offers reduced latency compared to public cloud providers. Experiments in [1] show that a local cloud is 5.5 times faster for transmitting 128-byte data. Utilizing local infrastructure ensures minimal data transmission latency, crucial for keeping the physical and digital worlds synchronized.
Enhanced Security: Hosting the digital twin on-premise reduces the risks of cyberattacks, breaches, and unauthorized access.

2.2 VR Omnidirectional Treadmill

The Omnideck treadmill[1](Figure 1a-a) enables users to navigate hazardous environments by simulating natural walking in VR. Its movements are translated into commands for controlling robots in the physical environment. Powered by Unity[2], the VR experience uses a high-fidelity digital twin created with Matterport[3] LiDAR-scanned data, ensuring an exact replication of the physical lab/factory layout.

2.3 Robot Control and Software Integration

The Aliengo Quadruped Robot (Figure 1a-b) navigates hazardous areas while streaming real-time visual data to the VR headset. User movements on the Omnideck treadmill control the robot's locomotion, ensuring precise alignment between the operator's virtual and physical positions. Unity manages the digital twin environment and input synchronization, while a Dockerized Private Cloud ensures low-latency communication and real-time positional accuracy.

3 Use Case: Remote Inspection

The proposed system is demonstrated through a critical use case of remote inspection in an industrial manufacturing facility [4]. Using a VR headset and the Omnideck treadmill, the operator remotely controls the Aliengo Quadruped Robot while navigating a high-fidelity digital twin synchronized with the physical facility. The operator's VR movements are mirrored by the robot in real-time [5]. A demo video is available on YouTube[4].

The robot's onboard cameras stream real-time video to the VR headset, providing an immersive first-person perspective [3]. This allows the operator to inspect the virtual environment for hazards or anomalies, such as misplaced objects or structural damages. As shown in Figure 1b-(c–e), the operator captures a geotagged screenshot from the robot's camera feed upon detecting an anomaly, seamlessly integrated into the digital twin for precise documentation.

Flagged points of interest (POIs) are sent to a centralized platform for expert review and corrective action recommendations. This use case demonstrates the system's ability to address industrial challenges through synchronized virtual and physical environments, showcasing its potential for scalable deployment in industrial, emergency, and exploratory scenarios.

4 Conclusion and Future Work

This demo presented a framework integrating VR technology, AGVs, and a Dockerized Private Cloud to address remote teleoperation and inspection challenges. A VR omnidirectional treadmill synchronized with AGVs enables seamless interaction between virtual and physical environments. Containerization with tools like K3S ensures reproducibility, ease of deployment, and efficient resource management. Real-time video streams and dynamic digital twin updates enhance situational awareness and geotagging.

Future work includes developing a multi-agent system with diverse robots, such as drones, ground robots, and quadrupeds, to improve flexibility in complex environments. Adding multi-view scene analysis would allow operators to visualize different perspectives simultaneously, enhancing situational awareness and decision-making. Advanced sensors like thermal imaging and LiDAR can further enrich hazard detection and environmental mapping [2].

This framework offers significant potential for advancing remote teleoperation, multi-robot coordination, and digital twin optimization. It supports scalable teleoperation systems, shared control strategies, and synthetic data generation for training and evaluation. Expanding to include multi-user collaboration and automation opens new opportunities for industrial operations, emergency response, and exploratory missions.

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