A Novel Immersive Digital Twin Architecture for Rescue Mission Automated Guided Vehicle with VR Capabilities

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Research question and purpose:

Digital twins are advanced virtual replicas of physical assets capable of mimicking their behavior through bidirectional communication in real-time to improve human understanding of complex systems. This project questions if Virtual Reality (VR) capabilities will take digital twins a step towards easing human interaction by elevating the situational awareness of the user. Here we present a comprehensive framework integrating VR with Dockerized private cloud infrastructure to enhance human interaction with Digital Twins in rescue missions. The system utilizes a Robotic Operating System (ROS) based architecture to integrate robotics applications with VR, incorporating innovative techniques such as proximity heat maps and VR-based hand-gesture controls. The system was tested using a Turtlebot3 robotic kit, demonstrating significant improvements in human interaction and situational awareness.

System's Architecture:

The paper introduces a comprehensive framework for integrating Virtual Reality with a Dockerized private cloud infrastructure for a minimized communication latency between the physical and the digital asset. The architecture consists of three layers:

- Hardware-specific layer: This layer consists of all the physical and digital components each with its ROS master and subcomponents.
- Middleware layer: This layer is responsible for mediating data between the first and third layer where each service introduced in the first layer has a corresponding middleware ROS belonging to the same ROS master.
- Dockerized private cloud layer: This layer hosts services such as AI and real time monitoring to insure minimized latency and efficient communication between both assets.

The overall system is divided into two subsystems: Ubuntu for the interaction with the physical asset, and Windows for the VR development in Unity.

Virtual Reality integration:

In order to integrate VR in our system we opted for the Oculus Quest 2 headset with Unity environment to represent the digital twin. The choice of using Unity is for the flexibility in custom environments and new graphic features and more importantly for its impressive interactive input interfaces such as hand gestures. The integration with ROS is done using the ROS-TCP connector to facilitate real time communication.

The Unity scene of the system is built based on a constructed 2D map on the Ubuntu machine using the Gmapping algorithm for simultaneous localization and mapping. The mesh files were transferred and enhanced with surfaces and colliders in Unity on Windows to create a realistic

3D environment. Additionally, the URDF Importer package facilitates importing the TurtleBot3 OpenMANIPULATOR-AND robot asset into Unity, including its geometry and attributes.

Methods to improve Human Robot Interaction using VR:

To enhance situational awareness of the users we augmented the AGV with several ultrasonic sensors to implement a heat map which adjusts dynamically according to the distance from the surrounding objects. The heat map is integrated on a quad with a shader that changes its color intensity to a darker red once the distance is less than the set threshold.

Given that the traditional actuation method for the arm control using the keyboard is limiting and not very flexible, we have introduced three actuation techniques that are hand gesture based in order to improve the Human Robot Interaction and provide a more immersive experience.

Using the Oculus Quest 2 headset which provides advanced real-time hand tracking and gesture recognition capabilities we were able to implement the following actuation methods:

- Sequential Selection: Allows the user to select and actuate specific joints of the robotic arm using specific hand gestures. Selection is done by switching between joints with thumbs up or down gestures, and actuation is controlled by opening or closing the hand.
- Numerical Selection: Similar to the previous method in actuation, but selection is numerical, based on hand gestures representing numbers, which may streamline the process compared to sequential joint selection.
- Intuitive Selection: Integrates selection and actuation. The user's hand movement is directly mapped to the robotic arm's joints: x-axis movement controls rotation, z-axis movement controls forward/backward motion, y-axis movement controls upward/downward motion, hand orientation adjusts the gripper's direction, and hand gestures control the gripper's opening and closing.

User study and evaluation:

The user studies revealed that our assumptions were correct; the more deeply we implemented the VR feature, the better situational awareness users gained. The results of the survey showed that users performed better and faster in the third method that mixes between selection of the joint and actuating it, compared with their performance in the other methods.

Participants demonstrated clear comprehension of the complex environment surrounding the physical part of the system. Moreover, features implemented in the digital part, such as the proximity heatmap, played a vital role in synchronizing the system's components.

Conclusion and future work:

The immersive nature of VR allowed users to experience realistic scenarios, resulting in a more intuitive understanding of their surroundings and interactions. Overall, the positive outcomes validate the integration of VR as a valuable tool for enhancing situational awareness. Future work will focus on advancing digital twins for rescue missions, incorporating AI for autonomous decision-making, and validating these technologies in real-world scenarios.