Development and Evaluation of an Integrated Tangible, Augmented, and Virtual Reality System for Professional Medical Training

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ABSTRACT

Virtual and augmented reality have become powerful tools in education, providing medical professionals with immersive training environments that enhance procedural confidence and skill acquisition. Traditional training methods often lack of tangible elements, highlighting the need for more dynamic solutions. This project focuses on developing a mixed reality (MR) system for medical training, integrating an embedded system composed of an ESP32, a MPU9250, a touch sensor, and hand tracking via Quest cameras to obtain the position of the objects based on the hand detection provided by the headset. This setup enables real-time tracking of the position and rotation of a 3D printed heart model, enhancing fidelity and embodiment during training. The system was validated through sensor performance analysis and usability tests, demonstrating improved accuracy and responsiveness.

By offering a cost-effective, interactive, and replicable solution, this MR system has the potential to provide a powerful training tool for medical purposes. Future work includes refining tracking algorithms, integrating additional haptic feedback, and more realistic 3D printed objects with animated effects.

INTRODUCTION

The development of Virtual Reality (VR) and Augmented Reality (AR) dates back to the 1950s with its appearance as the first 3D immersive simulator; later in the 1960s the first head-mounted display (HMD) appeared with the Telesphere Mask, which provided stereoscopic 3D images. Later in the 1980s, the first commercial VR systems were developed. [1]. VR creates fully immersive environments through headsets and controllers [2], allowing users to interact with digital objects. In contrast, AR overlays digital elements onto the real world, using Simultaneous Localization and Mapping (SLAM) to detect and enhance physical environments [3].

Mixed Reality (MR) is a recent concept that integrates the physical world with the digital world, allowing the benefits of both VR and AR to merge, involving overlaying and interacting with digital elements within an environment that aligns with the elements, spaces, and barriers present in the physical world, and also allowing an interaction with both digital and physical elements [3].

In medicine, VR and AR have been applied to diagnostics, education, and surgical training, enabling students and professionals to practice procedures in controlled environments. However, research shows inconsistencies in training effectiveness, with challenges in user embodiment [4].

The MeTrA project explores various training modalities for cardiac surgery, including: 3D Printed Hearts, Screen-Based 3D, Augmented Reality (AR) Virtual Reality (VR)

Each modality was evaluated across seven criteria, including startup cost, perceptual fidelity, and interaction possibilities.

A hybrid approach combining these modalities could maximize training benefits, balancing immersion with tactile feedback for more effective medical education.

OBJECTIVES

A. General Objective.

Develop of a medical professional training with mixed/AR experiences and 3D-printed heart components and evaluate its effectiveness.

B. Specific Objectives

- Evaluate and test different ways to establish a connection between existing virtual and augmented reality programs and 3D-printed hearts.
- Make the necessary changes in virtual and augmented reality programs that arise from the connection with 3D printed hearts.
- Compare the progress in the seven indicators when using mixed reality, which integrates the digital environment with physical objects, in comparison to existing training modalities.

METHODOLOGY

The project was developed under the supervision of Gabby Resch at the University of Ontario Tech, in collaboration with researchers from Toronto Metropolitan University, Toronto General Hospital, Georgia Institute of Technology and University of Toronto. It was developed combining virtual and in-person activities.

The MeTrA project design concept is based on three main principles:

1. Access – Evaluates startup cost and development resources for training applications.
2. Representativeness – Focuses on perceptual fidelity, tactile fidelity, and interaction possibilities to ensure accurate training.
3. Customization – Considers adaptable training scenarios and asset handling to optimize learning environments.

For hardware, a comparative testing of ESP32, Arduino Uno, and Raspberry Pi 3 led to the selection of ESP32 for real-time sensor data acquisition. MPU6050 and MPU9250 IMUs were evaluated, but drift issues required further refinement. Meta Quest 2/3 cameras were tested for object tracking. A touch sensor was integrated to enhance physical interaction. MPU9250 transmits quaternions to avoid Gimbal Lock.

Development of software was done in Arduino (ESP32) for data processing and Unity for Mixed Reality (MR). Datatransmission evolved from USB to wireless Bluetooth. Key Unity tools:

- OpenXR Plugin (cross-platform XR).
- Meta XR Interaction SDK (hand/controller input).

Heart models were adapted in Blender, based on the Toronto 3D Heart Atlas. Sensor placement was optimized for accuracy and fit.

Finally, some experts and students assessed MR integration using seven indicators:

- Startup Cost (SC)
- Development Resources (DR)
- Perceptual/Visual Fidelity (PVF)
- Embodied/Tactile Fidelity (ETF)
- Interaction Possibilities (IP)
- Adaptive Training Scenarios (ATS)
- Asset Handling (AH)

Findings highlight the balance between MR immersion and tactile feedback, with limitations in cost and adaptability.

RESULTS

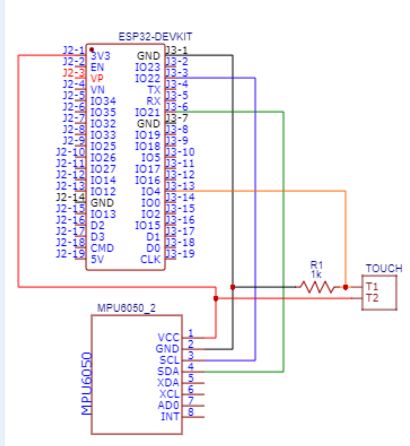

Figure 1. Schematic of the wiring of all the elements used for hardware.

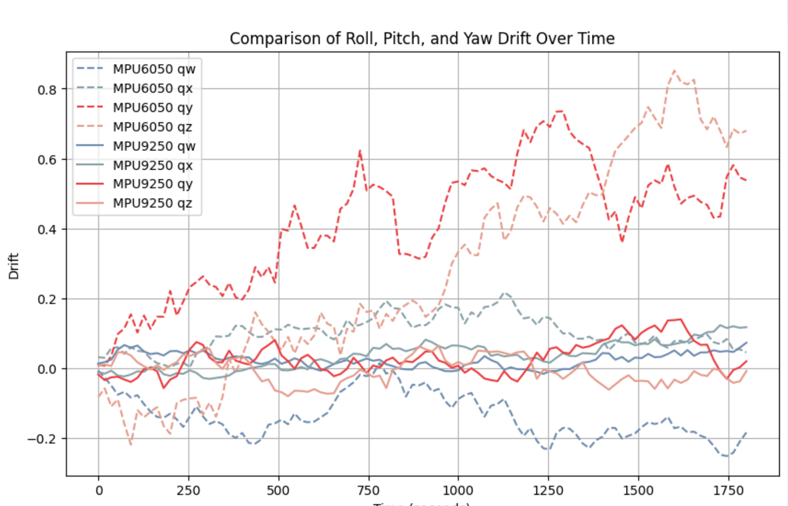

Figure 2. Evaluation of the drift for MPU6050 and MPU9250.

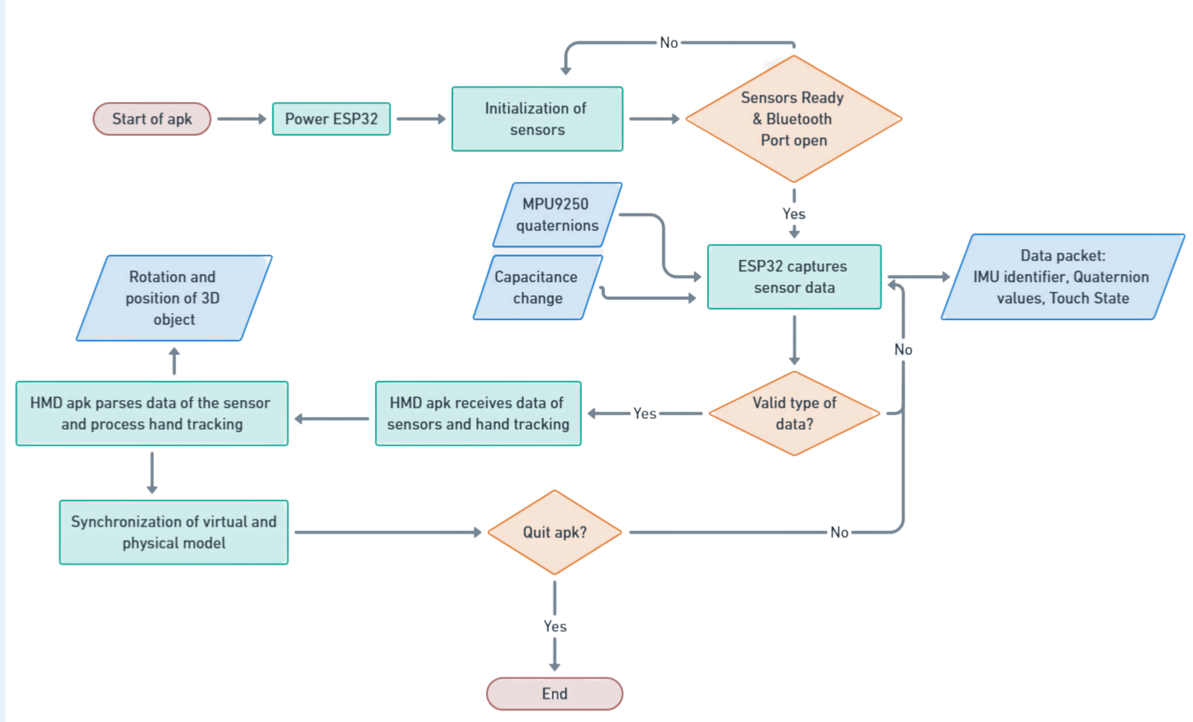

Figure 3. Transmission and interpretation protocol.

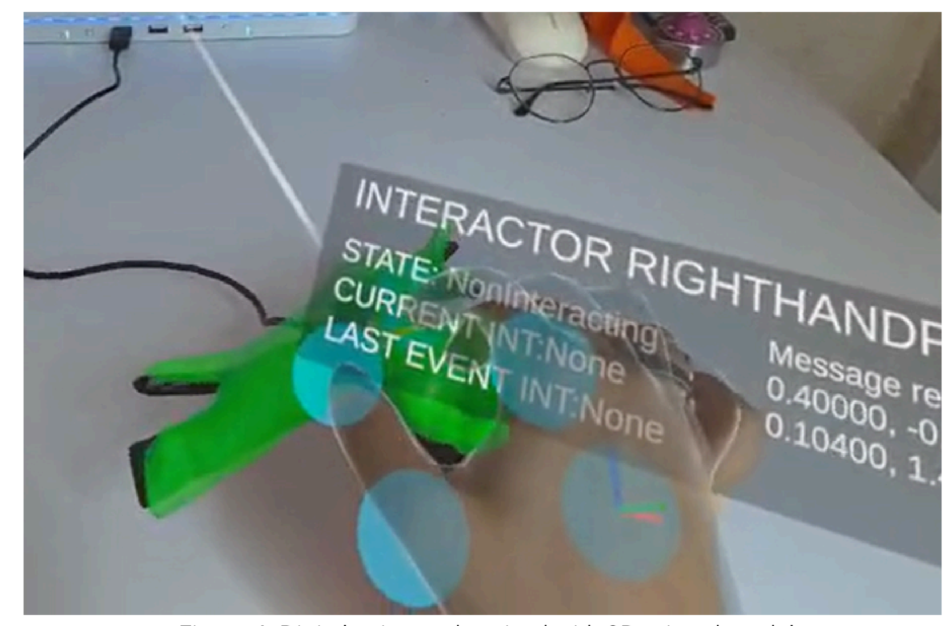

Figure 4. Digital twin synchronized with 3D printed model.

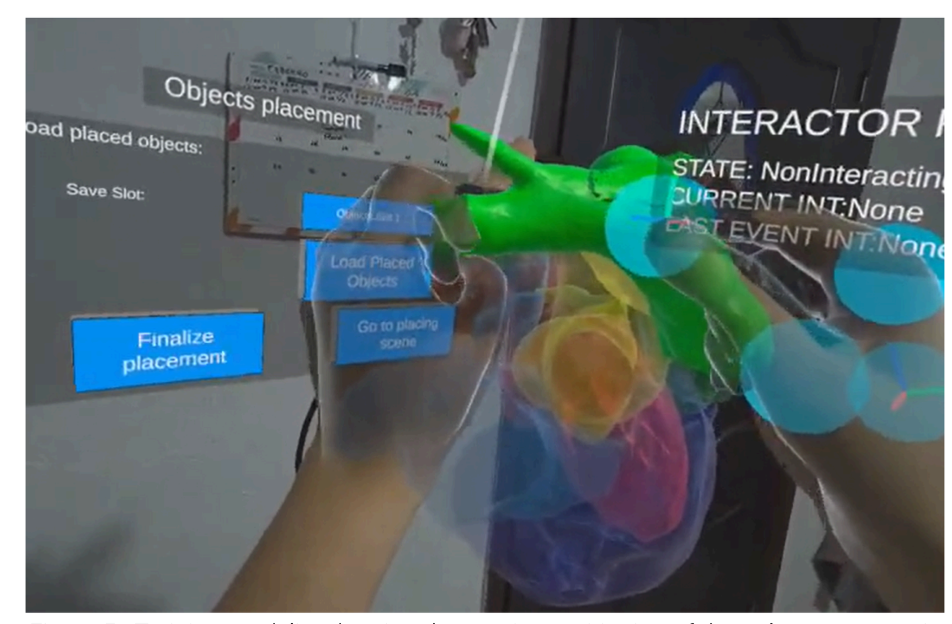

Figure 5. Training modality showing the precise positioning of the pulmonary aorta in the puzzle guide.

DISCUSSION

ESP32 was chosen as the microcontroller due to its integrated wireless communication, low cost, and efficient power consumption, making it ideal for the project's requirements usign SPP (Serial Port Profile) Bluetooth for communication, ensuring reliable data transmission; for rotation tracking, the MPU9250 was preferred due to reduced drift (Fig2.), the hardware was wired as shown in Fig. 1. For position, hand-tracking data combined with a touch sensor provided an effective solution for object positioning.

To 3D printing pieces were modificated as achieving the best proper sensor positioning as represented in Fig. 4.

IMU combined with the hand-tracking data resulted in a precise tracking, making possible the synchronization of the digital twin and the 3D printed model (Fig 5.), allowing us to create an interaction for placing the pieces in a puzzle format as as illustrated in Fig. 6.

We managed to obtain great ratings for the mixed reality Modality in each indicator, being the lowest rate at 3 for DR because of the expertise needed for the development of mixed reality scenarios.

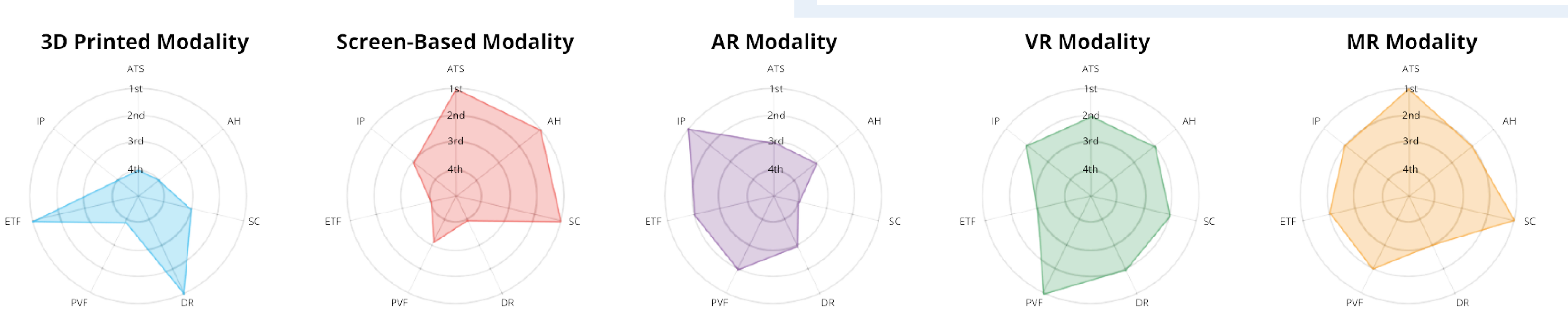

Figure 6. Evaluation of each modality of MeTrA project, including MR

CONCLUSIONS

The integration of wireless motion tracking and touch sensing in an MR environment proves viable for real-time human-computer interaction. Low-latency Bluetooth communication enabled smooth data transfer, while DMP-based quaternion calculations ensured accurate orientation tracking.

Using hand data for object positioning has limitations, as occlusion or poor lighting affects accuracy. Future improvements could include materials that better resemble real objects, animated overlays.

The access to the Quest cameras remains expectant for an improvement of the existing technology to achieve better results in the detection of objects or even using computer vision.

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