Exploring Multimodal Blended Environments for Medical Training and Simulation

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ABSTRACT

Designing and developing a training system requires a structured approach that encompasses the product lifecycle, from initial analysis of how the system is to be used through system development, verification, fielding, maintenance, and disposal. Much time has been devoted to researching the constraints, benefits, cost, and maintenance of different types of haptics technologies used in medical training devices. In parallel with haptics, a considerably larger body of work has been done in the research and development of Extended Reality (XR) displays including tethered and untethered video and see-through head mounted displays. To explore the use of haptics to enhance augmented reality medical training for the U.S. Army's Combat Capabilities Development Command Soldier Center, the team created an environment that optimizes the most critical requirements, even at the expense of less critical requirements.

The team evaluated the key requirement parameters and thresholds, as well as the research objective and trade space to develop a Care Under Fire (CUF) training capability that immerses a trainee with defending an enemy attack, moving an injured soldier into concealment, applying a hasty tourniquet and a nasopharyngeal airway (NPA) to the casualty. Post-training evaluations and after-action review (including combat metrics, time to treatment, efficacy of treatment, etc.) can be provided to the trainee, trainer, and third-party observers. These features are enhanced with both first-person and third-person XR displays that function as "windows" into the virtual and physical environment. Communication between commercial, off-the-shelf products and custom embedded microprocessors allow for a rich range of capabilities within a robust and multimodal training environment. This paper describes the design, development, and trade-offs of an integrated, XR system that makes use of blended environments with virtual and physical interactions, as well as aural and haptic feedback.

ABOUT THE AUTHORS

Dr. Darin Hughes has worked in the simulation field for over 20 years as a research faculty member at UCF's Institute for Simulation and Training, an assistant professor at Rollins College, a high school teacher at Lake Highland Preparatory School, and currently as the lead software engineer at SIMETRI. He holds bachelor's degrees in English Literature from the University of Florida and Information Technology from the University of Central Florida where he also obtained and M.S. and a PhD in Modeling and Simulation. Research interests include medical simulation, auditory simulation, digital puppetry, and mixed, augmented, and virtual realities.

Dr. Bill Pike is a Science and Technology Manager with the US Army DEVCOM Soldier Center Simulation & Training Technology Center in Orlando, where he leads a variety of research efforts focused on training solutions to save lives on the battlefield. He earned his doctorate in Modeling and Simulation from the University of Central Florida, where he also holds master's degrees in both Computer Engineering and Modeling and Simulation. In his 36-year civil service career, Dr. Pike has worked for the Air Force, Navy, and Army. He has authored or co-authored over 40 papers, book chapters, articles, and presentations. Dr. Pike is also a Navy Reservist, holding the rank of Captain (O6). He is the National Director of the Naval Sea Systems Command's Surge Maintenance program, the largest community within the NAVSEA Reserve program with over 1100 enlisted Sailors and officers.

Ed Stadler is a systems engineer and SIMETRI's Chief Engineer with 32 years of experience in the simulation and training industry. He has served as technical lead and chief engineer for complex simulation and training programs over the past 17 years and has extensive experience in the full life cycle development and production of simulation

systems and products. Ed received his Bachelor of Science in Electrical Engineering from the University of Central Florida.

Liam O'Neill is a recent graduate from the Full Sail University Game Development program where he earned a bachelor's degree in Computer Science. He has been with SIMETRI, Inc. for just over a year now, starting as an intern and is now a software engineer.

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INTRODUCTION

This paper discusses the design and development of the Multi Modal Medical Training System (M3TS) as part of a multi-phase project to address Care Under Fire (CUF) scenarios in Tactical Combat Casualty Care (TCCC). TCCC has a formal, approved Program of Instruction (POI). Government and industry organizations provide training to Combat Medics (68W), Special Forces medics (18D), and infantry soldiers buddy care as stand-alone training, as well as integrated medical training in Live, Virtual, and Constructive (LVC) exercises (Butler et al., 1996). Though significant medical simulation technology exists, to date, no formal Program of Record (POR) has combined TCCC, LVC, Augmented Reality/Virtual Reality/Extended Reality (AR/VR/XR), human patient simulators (HPS), and haptic devices into a single approach with a clear path to Synthetic Training Environment (STE) integration. Existing approaches to inserting haptics into AR/VR combat medicine have focused on altering and/or unnecessarily complicating the training use case to allow for the inclusion of ill-suited haptics such as gloves with vibration or simulated force. The system described in this paper aims to create a new, innovative approach to fill this gap with training methods that yield proficiency over familiarization.

High physical fidelity training systems can provide improved training transfer by immersing the trainee in realistic situations and environments, but this can come at a high cost. Moreover, from a STE perspective, the introduction of HPSs in the training environment still leaves gaps in training because a clear interface for the medical training scenarios and the byte/bit level communications between the two has not yet been established. Progress in this area has been slow since most medical procedures are not typically performed in active combat environments. Rather, there is a small subset of combat medical tasks known as CUF that need to be trained in the STE. These CUF medical tasks include returning fire and taking cover, checking for breathing and pulse, applying a hasty tourniquet, and moving the casualty to a more secure position where Tactical Field Care (TFC) can be performed. Integrating the medical training into STE requires creating new interfaces between both training environments; the medical environment will be receiving externally generated queues to include incoming weapons fire and non-medical instruments such as a medic's M4 rifle.

The Army has recognized that air superiority and quick access to Forward Surgical Hospitals (FSH) will no longer be the norm. Instead, Combat Medics and Combat Lifesavers will need to perform Prolonged Field Care (PFC), which involves caring for wounded Soldiers for up to several days in austere and often hostile environments. As a result, TFC may often be interrupted by periods of enemy fire, thereby temporarily blurring the lines between combat, CUF, and TFC. These are ideal targets for future STE training efforts and for possible training and mission rehearsal scenarios using the Army's Integrated Visual Augmentation System (IVAS).

Utilizing the M3TS approach, traditional high-cost systems can be replaced with targeted visuals and haptics to supplement lower cost HPS and PTT systems. Incorporating additional physical devices through use of actual devices or facsimiles of real devices is a key development effort. Several key medical procedures and devices associated with CUF, TCCC, and PFC training scenarios are explored to further the haptics insertion in medical training. AR/VR techniques are used to provide an immersive environment, enemy and friendly combatants, blood, 3D auditory cues, auditory haptics, and environmental sounds. Lessons learned from the evaluation of optical pass-though and video pass-through head-mounted XR displays are discussed as well as future steps.

BACKGROUND

During the first phase of work, a basic proof of concept was completed using the optical pass-through, Microsoft HoloLens 2 head-mounted display, a Sensoryx tracking system, and microcontrollers with WIFI capability to communicate data from embedded devices. The CUF scenario for this phase involved the following virtual objects: an overturned Humvee, an enemy combatant, a barricade, and blood, as well as physical objects: a manikin with an injured leg, an instrumented tourniquet, and an instrumented M4 air rifle. The trainee's objectives are to 1) engage hostile threats, 2) move the injured soldier to cover, and 3) apply a hasty tourniquet.

All virtual objects were rendered to the HoloLens using the Universal Windows Platform and Unity 3D. Once deployed to the HoloLens, the simulation could run on the embedded Snapdragon computer without tethering or otherwise interfacing with an external computer. Using Sensoryx's tracking system, a virtual blood pool would form at the point of injury on the manikin and the air rifle's aim could be calibrated with the virtual objects. Shots were registered using an embedded processor connected to a button behind the trigger. This data was then communicated to the HoloLens over a WIFI network. The tracking and trigger data allow the simulation to create a vector for any shots fired which were used to determine if the trainee successfully hit the enemy combatant. The instrumented tourniquet contained a pressure sensor underneath the windlass that passed values to an embedded processor which, in turn, communicated that data via WIFI to the HoloLens. The data allowed the simulation to determine if the trainee had successfully tightened the tourniquet thus spotting the virtual bleeding and bringing the simulation to a conclusion. Audio cues were delivered through the built-in speakers on the HoloLens.

Usability Study and Knowledge Solicitation Findings

The Phase I Usability Study conclusions pointed toward three general improvements: the realism of the weapon; the realism of the scenario through exploring other available VR/AR/XR headsets, the accuracy of the tracking systems and the realism of the audio cues. The Knowledge Elicitation results concluded the following scene improvements: adding friendly entities to help in gaining fire superiority, adding the ability to check the patient for pulse and breathing, moving the wounded soldier from cover to concealment, and continuing to provide aid (including airway management) while in concealment.

The Phase I VR HoloLens II Headset limitations included a narrow field of view, unrealistic and poorly rendered audio, augmented objects that move inadvertently due to loss of tracking and occlusion mapping, occlusion by real objects, and inadvertent Main Menu pop ups with hand movements. To make the scenario more realistic and enable the ability to gain fire superiority and render aid to the wounded soldier, it was suggested that friendly and enemy combatants be added to the scenario with enemy combatants engaging both the user and the friendly entities. The user's weapon should be upgraded to a high-end airsoft rifle with the correct overall weight and weight distribution to accurately model the M4. Controls should be added to allow the user to locate an enemy, look at them through the scope and fire with correct shots impacting the virtual entity.

Figure 1. Object Drifting and Occlusion Issues in Phase One.

The initial virtual environment developed was a Middle Eastern market street, allowing the user to render aid to the injured soldier and apply a hasty tourniquet while firing back at the engaging enemies and taking cover behind a concrete street barrier. To continue the progression of Care Under Fire, it was recommended that the environment include open building spaces to allowing a secured space to bring the injured soldier to continue care. Recommendations were also made for the incorporation of additional treatments, such as a nasopharyngeal airway (NPA) and physical cues such as pulse and respiration. Additionally, it was suggested that these treatments and cues have two-way communication to a physiology model to improve realism and accuracy.

Evaluating XR Display Systems

The major advantages of the HoloLens 2 are its low-profile, untethered design, and the ability to see the real world with your own eyes. However, these advantages also create limitations for certain kinds of simulations. The processing power in the HoloLens' Snapdragon computer does not allow for complex 3D graphics and scenes had to be simplified to the most basic, essential components. Even with a slimmed down graphics profile, the simulation would push the limits of the HoloLens causing the battery life to be very short (e.g., less than an hour) and the headset to become uncomfortably hot. To compensate for the short battery life, it often became necessary to attach a large USB battery pack to the headset, thus negating some of the advantages of a low-profile, untethered design. Furthermore, the HoloLens performs poorly in bright light, rendering the holograms invisible. To compensate for this, the light levels were often reduced thus making it more difficult to see the real world, and negating some of the advantages of seeing through your own eyes. The HoloLens seems better suited for augmented environments with basic overlays and not useful (or capable) for rendering immersive, graphic-heavy scenes.

With these considerations in mind, it was determined that a video-pass through device capable of leveraging the processing and graphical power of a modern gaming computer would be better suited for this application. The Varjo XR-3 was evaluated as an all-in-one, off the shelf option. However, due to pricing, licensing, and limited community support, this option was not considered viable. Instead, a hybrid approach was devised that would leverage the support of the VR gaming community by modifying an HTC Vive Pro 2 with StereoLab's Mini ZED stereo camera and UltraLeap's hand-tracking device. This combination provides comparable features to the Varjo XR-3 at a much lower price point with no licensing fees and a large, active development community. It should be noted, that as of the time of this writing, HTC has released an all-in-one XR headset, the Vive Elite XR. SIMETRI is currently working to integrate the new headset.

Figure 2. HTC Vive Pro 2 Hybrid XR headset with ZED cameras and UltraLeap

THE MULTIMODAL BLENDED ENVIRONMENT

Figure 3 illustrates the software and hardware infrastructure of the hybrid XR platform. Unity 3D functions as the graphics and runtime engine connecting the various software components including plugins for the ZED cameras, STEAM VR, VIVE, and UltraLeap. A Windows Native BLE plugin was created by the team to interface with the embedded microcontrollers (e.g., an instrumented tourniquet and head). This configuration allows for tracking of up to 64 individual items. Currently, the headset, the weapon, the manikin, and the third-person camera are positionally and orientationally tracked.

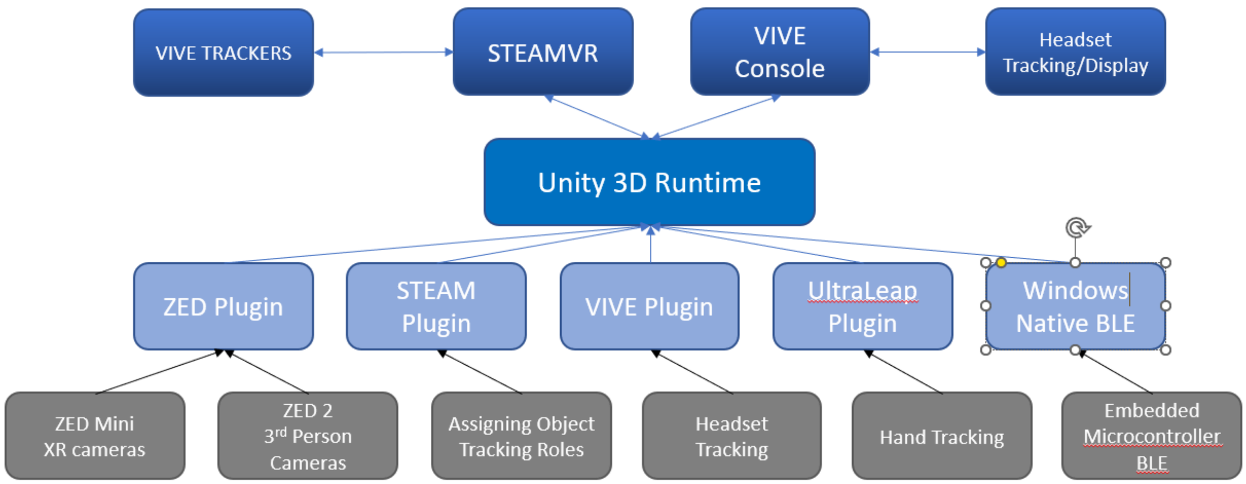

Figure 3. Hybrid XR Software and Hardware Infrastructure

Chromakey-based Occlusion

To further address some of the shortcomings from the first phase of M3TS, it would be necessary to come up with a practical and relatively simple solution to the occlusion of virtual objects. While real-time spatial mapping has progressed considerably, it has not reached the maturity and stability needed for immersive, complicated, and dynamic experiences such as those required for a CUF scenario (Darwish, M., Kamel, S., Assem, A., 2023). Chromakey-based occlusion is a simple and proven way to handle virtual and real objects in a shared scene with far less processing requirements and jitteriness than spatial mapping (Rauschnabel, A., et al., 2022).

To leverage the advantages of chromakey occlusion, an XR chromakey stage was designed and developed that included 3D audio and haptic audio (e.g., a transducer attached to the stage floor), lighting rigs, and tracking beacons. Collectively, the Vive beacons, positioned in each upper corner, provide unobstructed positional data of all XR sensors in the room in real time. A dynamic, third person XR camera was freely installed in the studio projecting to a large external monitor to assist in demonstrations and usability studies. Magnetic linings sewn into the curtain fabric allows for a seamless wall enclosure entryway into the stage.

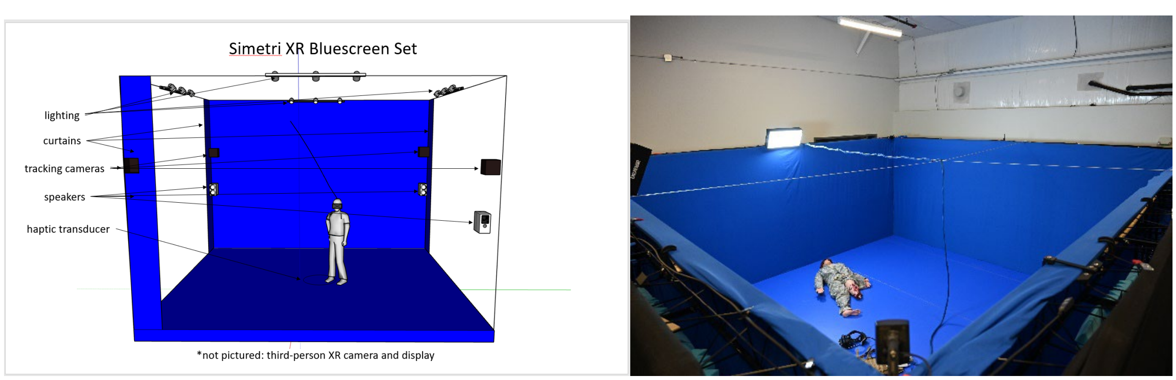

Figure 4. XR Chromakey Stage Design and Implementation

Weapon Development

A market study was conducted to find a realistic weapon platform that would provide the look and feel of a M4 rifle. Based on outcomes from the usability study done during Phase 1, it was determined that the plastic airsoft rifle was too light, felt unrealistic, and did not provide haptic feedback or recoil. Several high-end airsoft rifles were evaluated, and it was determined that the KWA RONIN T10 RM4 rifle has the correct overall weight and weight distribution to accurately model the M4. An electric force-feedback system within the rifle simulates the effects of recoil. This model is also used by the Department of Homeland Security and US Border Control for training.

Figure 5. M4 Replica Air Rifle

A custom 3D printed bracket was fabricated to attach the Vive Tracker 3.0 on top of a red dot sight that reduces vibration to maintain accurate tracking. The positioning of the tracker on the rifle provides a clear line of sight and an unobstructed view for the user when aiming. Figure 6 shows the custom bracket as well as the trigger module.

Figure 6. Trigger System and Red Dot Sights with Custom Mounted Tracker

Feedback from the rifle while firing is communicated to the Vive Tracker 3.0 by way of a trigger housing mounted switch. The switch is connected to a custom connector and interfaces with the pins on the Vive Tracker 3.0 and then sent to Windows over BLE.

Object Tracking

The Vive Tracker 3.0 was used in combination with the Vive Lighthouse camera system. These are off-the-shelf products with a large support structure and active community involvement. Integrating this tracking system within a Unity application enables access to developer plugins and a host of technology integrations. The trackers are lightweight, relatively low in profile, and easily mounted to objects such as a weapon, a manikin, and a 3rd person XR camera.

Figure 7. Vive Tracker 3.0

Physiology Integration

After evaluating the currently available physiology simulators, the Pulse Physiology Engine plugin for Unity was chosen as it is well documented and has an event-based system that allows for easy integration.

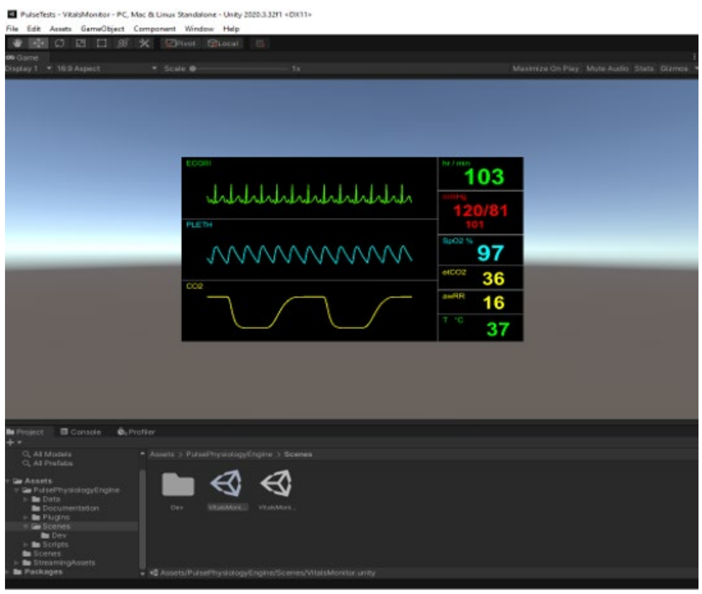

Figure 8. Pulse Physiology Plugin for Unity

During the integration of the physiology engine to the M3TS simulation, both hemorrhaging and airway obstruction physiology changes were added. Pressure data from the Smart Tourniquet[1] is used by Pulse to determine how much blood the patient is losing. If the tourniquet is fully applied, the blood loss will stop. If the tourniquet is partially applied, the blood loss will slow. If the tourniquet is not applied, blood loss will continue until the patient dies of cardiovascular collapse. The pulse data and rate of blood loss is displayed in the third person XR view, allowing observers to see the patient's vitals. A first-person view of the physiology vitals was also added as an option on the patient through a pop-up menu triggered by a hand gesture, as detailed in the following section.

Hand Tracking and Menu Systems

A menu system was added to the simulation using hand tracking. Hand position is used to inform the simulation when the user has their palm facing upwards, enabling the menu system. Since the Phase I Usability Study concluded that inadvertent menu popups disrupted the training, the Phase II menu items were created by SIMETRI and can be controlled to eliminate inadvertent display of items with the ability to tweak the sensitivity with which they appear.

[1] The modified, pressure-limited tourniquet referred to throughout this document is the subject of a patent application before the United States Patent and Trademark Office (USPTO), filed by SIMETRI, Inc.

Figure 9. Hand Tracking and Gesture Recognition using UltraLeap plugin for Unity

Debugging options were added to allow the developers to activate a virtual laser sight on the weapon for testing accuracy, the ability to view the Pulse Physiology Engine output in the first-person simulation, tourniquet calibration, and video recording settings.

Design of Nasopharyngeal Airway Trainer

The Training Needs Analysis conducted at the beginning of the phase concluded that a nasopharyngeal airway was a procedure that would be common to perform in the next phase of CUF. Designs for devices to integrate in the scenario include a head form with restricted airway. An airway restriction attachment piece was 3D printed with IR diode sensors included to detect the nasal trumpet progress through nasal passage. Figure 10 displays the initial head form, 3D printed attachment, and the airway.

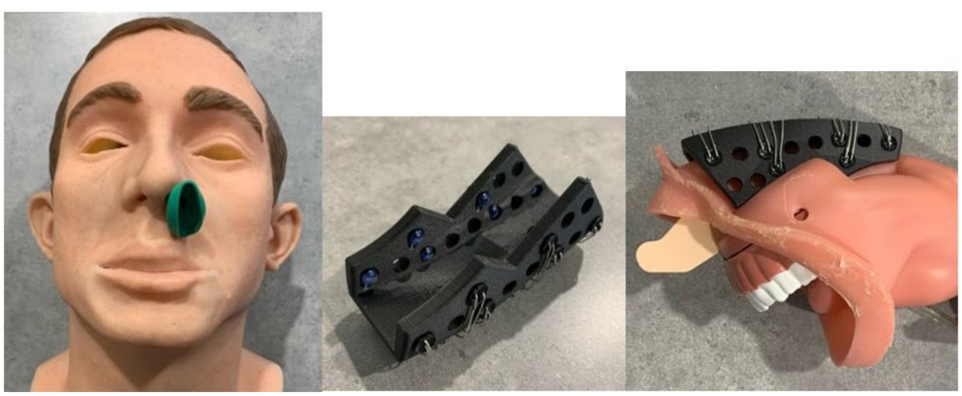

Figure 10. Designing an Instrumented Head

Following the drafting phase for the nasal passage assembly, the mount design underwent a process of rapid prototyping to shroud the anatomical profile from the nasal cavity to the trachea. Initial research of the sensory detection concluded infrared LED emitters and receiver pairs were a better option than contact or inductive sensors. These IR sensors provide a discretely distributed position detection of the nasal trumpet along the airway. Prototype circuit design and testing reliably demonstrated successful signal output from a microcontroller through serial communication.

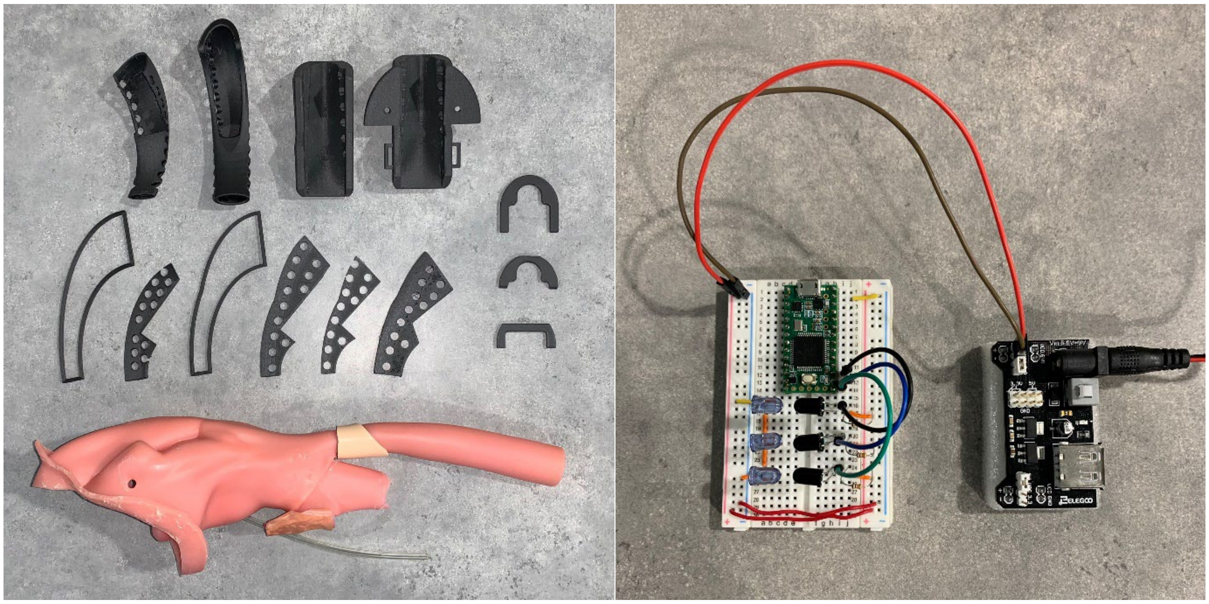

Figure 11. Nasal Passageway and Embedded Electronics Prototyping.

Improvements to the internal structure of the Standalone NPA Head resulted in the decoupling of the functional sensor arrays from the structural housing. Utilizing modular design on the trainer allows for quicker and cheaper design iteration without compromising on functionality. Additionally, reductions in the NPA passageway size limits the availability for false negative sensor errors, improving reliability in digital output. Further internal coordination has resulted in a definite aesthetic shape overlaying the engineered design.

The current iteration features a bust of a female solider and can communicate over BLE to the M3TS simulation as well as app-based individual task trainers as discussed in the following section (figure 12).

Figure 12. Female Bust for NPA training

Mobile Applications

Two Android apps were developed to provide performance-assessment feedback and an easy, portable demonstration for the standalone Smart Tourniquet and NPA Training Devices. The Pulse Physiology Engine was successfully ported to the Android platform and Arduino code was written for the recognition of light sensor data to determine the depth of the nasal trumpet. Bluetooth Low Energy (BLE) communication was implemented on the Android devices and microcontrollers. Heart rate data is also being sent to the NPA microcontroller using the values from the physiology engine.

Linear interpolation was used to smooth virtual animations for the nasal trumpet between the data from the six light sensors embedded in the SIMETRI female manikin head to improve the look and feel of the application. The applications and associated training devices held up well for hundreds of demonstrations across four days. Figure 13 depicts the mobile applications developed for the tourniquet and NPA.

Figure 13. Mobile Apps for Individual Task Training

The Full XR Simulation

The previously discussed modalities and components can be blended into an immersive CUF simulation as depicted in Figure 14. In this figure, we see a human user defending against an enemy attack along with a virtual soldier and a physical manikin of an injured patient. The image was captured from the 3rd person camera that is displayed on a large monitor outside of the XR Chromakey Stage allowing for any number of viewers to see both the real and virtual components during the simulation. The Pulse Physiology Engine can be seen running in the bottom right of the screen.

Figure 14. XR CUF Simulation from a 3rd Person XR View

Figure 15 shows the first-person perspective of the user engaging enemy combatants. The first-person view is also made available on a large screen monitor outside the XR Chromakey Stage.

Figure 15. XR CUF Simulation from a 1st Person Perspective

CONCLUSIONS

The Multi Modal Medical Training System (M3TS) includes a Care Under Fire scenario using a chromakey studio with 3D sound, modified video pass through mixed reality headset, modified simulation M4 rifle, instrumented tourniquet, modified medical manikin with a wounded leg, a developed human head with embedded sensors, tracking of each component, and an integrated physiology system. This developed technology provides the user with a care under fire scenario requiring them to fire back at the enemy, render aid to the wounded soldier, apply a hasty tourniquet, move the wounded soldier to a safer location, and continue aid which includes inserting a nasopharyngeal airway (NPA). Each entity is tracked, and the sensors on the training system provide input for the virtual blood flow to stop when the tourniquet has been applied properly. The sensors also provide input to the integrated physiology engine when the tourniquet has been applied and NPA has been inserted properly. This patient and physiology data can be transferred to the Synthetic Training Environment (STE) over generic Remote Procedure Calls (gRPC) that are already in place within the simulation infrastructure.

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