Technology for an Affordable Augmented Reality Fire Support Team Trainer

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ABSTRACT

Marine Fire Support Teams (FiSTs) consist of four or five Marines who direct aircraft, artillery, mortar, and naval fire in support of friendly troops on the ground. Historically, FiST training has been hindered by high costs and a limited availability of range time and associated supporting arms. Augmented reality (AR) is a technology that inserts computer-generated virtual objects in the user's real-world environment. A portion of the Office of Naval Research 3D Warfighter Augmented Reality (3D WAR) program aims to provide Marine FiSTs with the "sets and reps" required to develop and maintain proficiency by prototyping an affordable AR field simulator. The Marine Augmented Reality Team Trainer (MARTT) is made entirely from commercial off-the-shelf (COTS) components and allows Marine FiSTs in a field exercise to train with virtual entities and battlefield effects in their actual environment. Users wear an occlusive head-mounted display (HMD) while a camera inserts the real-world view onto the screen. High-performance computer vision-based tracking algorithms monitor user's position and orientation and, in conjunction with a detailed terrain model, accurately insert virtual objects into the scene. Each FiST member is linked via Wi-Fi or other IP network, giving all users the ability to see the same virtual scene from their own perspective.

In this paper, we will discuss how a previously designed custom AR system has been ported to relatively inexpensive COTS components. The resulting MARTT system maintains performance and allows for affordable experimentation with FiST-scale training. We will discuss the technologies that were designed and developed for this effort, along with the benefits and limitations of exclusively using COTS components. Finally, the paper includes initial reactions from trial use at several Marine Corps locations.

ABOUT THE AUTHORS

Mr. Colin Sullivan is a Software Engineer at Lockheed Martin Rotary and Mission Systems (RMS). He received his B.S. degree in Computer Science from the University of Michigan in 2018 and has worked in augmented reality and training simulations since graduating. Colin is currently one of the principal engineers on the 3D Warfighter Augmented Reality team, developing AR training and tactical systems.

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INTRODUCTION

Over the past fifty years, United States Marine Corps Fire Support Teams (FiSTs) have directed lethal aircraft, artillery, mortar, and naval fire in support of friendly forces on the ground. FiSTs often provide the “best means to exploit tactical opportunities in the offense or defense” by providing “fires to destroy, disrupt, suppress, fix, harass, neutralize, or delay enemy forces” (United States Joint Chiefs of Staff, 2009, p. ix).

While the demand for FiSTs continues to increase, and advances in technology create ever more complex weapon systems, FiST training remains challenging and expensive. Today, high costs and limited availability of range time and associated supporting arms hinders training, resulting in an inability to provide Marines with the hands-on instruction time needed to maintain and improve their skills.

The Office of Naval Research (ONR) 3D Warfighter Augmented Reality (3D WAR) program aims to solve this problem by providing Marine FiSTs with the “sets and reps” required to develop and maintain proficiency through prototyping an affordable augmented reality (AR) field training system. The Marine Augmented Reality Team Trainer (MARTT) is unit-worn and made entirely from commercial off-the-shelf (COTS) components. It allows FiSTs in field exercises to train with virtual entities and battlefield effects in their actual environment. Multiple units are wirelessly connected, allowing each FiST member to train together while seeing the same virtual scene from their own perspective. The MARTT system gives Marines the accessibility and affordability to practice with live virtual fire anywhere and at any time, an ability that was previously unavailable.

Since the first prototype was introduced in August 2019, demonstrations have been held at four Marine Corps locations. Feedback was positive, with Marines believing that the MARTT system provided a more realistic and immersive training environment compared to traditional computer simulations. While feedback also indicated some improvements are needed, these demonstrations showed that the MARTT system provides robust FiST training capabilities at an affordable price.

FIRE SUPPORT TEAM TRAINING BACKGROUND

FiST Training and Current Limitations

In the United States Marine Corps, Joint Terminal Attack Controllers (JTACs) are responsible for calling in close air support (CAS). CAS missions are “action by fixed-wing and rotary-wing aircraft against hostile targets that are in close proximity to friendly forces and require detailed integration of each air mission with the fire and movement of those forces” (United States Joint Chiefs of Staff, 2009, p. ix). While JTACs are also capable of calling in other supporting fire, those responsibilities are primarily reserved for Forward Observers (FOs) who direct supporting artillery, mortar, and naval fire assets. Both JTACs and FOs direct lethal arms in support of Marines on the ground, while ensuring their targeting does not conflict with friendly units. JTACs and FOs rarely work alone, typically operating in a FiST, a team of 4 or 5 Marines including a FiST team leader, JTAC, artillery FO, mortar FO, and possibly a naval FO depending on location. Constant communication among FiST members is imperative, as precise coordination is required to ensure timing and targeting is accurate and friendly fire incidents are avoided.

Figure 1. FiST training with live fire

Historically, FiST training has been hindered by high costs and limited availability of range time and associated supporting arms. JTACs, for example, must train with actual aircraft which cost tens of thousands of dollars per session and have limited availability. FOs are faced with similar constraints, especially when they need to train with live fire, which is only permitted at a small number of impact areas across the globe. FO training also faces the challenge of coordinating with artillery, mortar, and naval squadrons and their associated expense providing supporting fire. These problems are compounded when it comes to training an entire FiST, where the logistics and expenses of assembling JTACs, FOs, aircrafts, artillery, mortar, and naval squadrons at an impact area make practicing together in the field rare. After initial training is completed and certifications are awarded, JTACs and FOs still need access to these resources to maintain their proficiency and certification.

Over the years, a few technologies have attempted to address these issues. The Supporting Arms Virtual Trainer (SAVT), which was first fielded in 2010, is an indoor simulation where a team of Marine JTACs and FOs train in front of a large, 240° projector. Here, Marines can operate virtual CAS and Call for Fire (CFF) missions with customized gear designed to emulate the functionality of the operational equipment used in the field. The Deployable Virtual Training Environment (DVTE) is another training simulation which allows Marines to use a laptop to practice calling in supporting fire on virtual scenarios. While these systems have helped many JTACs and FOs over the years, both require Marines to remain stationary while training indoors. Additionally, SAVT is only fielded at seven locations around the world, as it is expensive, requiring construction of facilities specifically designed to fit its custom equipment. DVTE, without any hardware that replicates operational gear, is limited by its lack of immersion, forcing Marines to simply use their mouse and keyboard to train (Reynolds et al., 2013).

Inspiration for COTS System

During a keynote address at I/ITSEC 2015, General Robert Neller, the Commandant of the Marine Corps, discussed the importance of "increasing [Marine] readiness" by "providing rep after rep after rep" (*Gen. Robert B. Neller, USMC and Panel on "Training Innovation")*. Augmented reality can improve FiST training by creating a realistic, immersive simulation that increases the "sets and reps" needed to maintain proficiency at reduced cost. AR is a technology that inserts computer-generated virtual objects in the user's real-world environment. By creating all vehicles, battlefield effects, and hostile units virtually, AR eliminates the cost and logistical challenge of physically assembling these components for training. Unlike most virtual simulations which require training in fixed, indoor structures, AR can be used almost anywhere and delivers "a rich contextual learning environment to aid in acquiring complex task skills, such as decision making and asset allocation, while providing learners with a more personalized (self-direct / self-paced) and engaging learning experience" (Champney et al., 2015, Section 6).

Through ONR, the Augmented Immersive Team Training (AITT) program began a 5-year contract in 2010 focused on creating a unit-worn, AR simulator initially for observer training from fixed locations, and more recently for mobile force on force training (Schaffer et al., 2013). The first generation AITT hardware consisted entirely of custom-built computers and sensor heads. This system was difficult to mass produce and expensive, costing around $25,000 in components. Data collected from the original custom training system was positive, but the key feedback was clear: having just one simulator to individually train JTACs and FOs was inadequate. Since JTACs and FOs rarely work alone, multiple systems would be required to outfit a 4 or 5-person FiST, to allow for authentic team training. The custom training systems were too expensive and could not be produced quickly enough to meet these requirements. Research moved toward COTS hardware and how it could be used to redesign a new product that was affordable and easy to assemble.

The MARTT system is an affordable, COTS-based, unit-worn AR FiST trainer. This novel solution to FiST training uses no custom hardware and allows Marines in a field exercise to train with virtual entities and battlefield effects in their actual environment. Each member of the FiST wears an occlusive head-mounted display (HMD) while a camera inserts the real-world view onto the screen. High-performance computer vision-based tracking algorithms monitor user's position and orientation and, in conjunction with a detailed terrain model, accurately insert virtual objects into the scene. Multiple devices are wirelessly connected through Wi-Fi or other IP networks, allowing each member of the FiST to see the same scene from their own perspective. Batteries, GPS, and navigation sensors allow for untethered mobile training. Unlike many training simulations that must design physical props, the MARTT system allows Marines to train with much of their actual equipment including maps, protractors, notebooks, and tactical tablets. A FiST instructor controls all devices wirelessly using an iPad instructor station application, allowing for insertion of virtual entities to train around. With no custom hardware, the finished product costs approximately $5,000 in COTS components per Marine.

Figure 2. Two FiST members training with MARTT systems at Camp Lejeune

COTS HARDWARE OVERVIEW AND SELECTION

The MARTT system consists of three main hardware components: an occlusive HMD that projects virtual objects on top of a live video feed of the real-world, a navigation sensor capturing video for the HMD along with data to determine the user's current position and orientation, and an AR processing computer with built-in batteries that performs all rendering and navigation algorithms.

Head-Mounted Display and Navigation Sensor

The MARTT system uses the Goovis G2 as its HMD. The Goovis is designed primarily for consumer movie viewing and supports full HD video at a resolution of 1920x1080. While it cannot be worn with glasses, each lens has individual diopter dials that corrects vision for all users.

Attached to the top of the HMD is the Intel RealSense D435i, the system's navigation sensor. The RealSense has an HD camera, an Inertial Measurement Unit (IMU), and an electro-optical stereo camera pair with global shutters. The RealSense's HD camera sends video directly into the HMD, while its stereo camera pair and IMU are used by the navigation software to calculate position and orientation.

Figure 3. The HMD and navigation cameras

The system described above is known as a video see-through (VST) HMD, where AR insertions are placed over a live video feed on an opaque display. In an optical see-through (OST) display, AR insertions are shown on a transparent holographic lens. For the MARTT solution, a VST HMD was selected as they are less expensive, more widely available, have higher fidelity screens, and allow for virtual insertions to occlude the real-world behind them.

AR Processing Computer and Additional Components

At the core of the MARTT system is its AR computer processor, the MSI VR One. Fitted with two nylon backpack straps, the VR One is designed to be worn as a backpack and was originally built for mobile virtual reality (VR) gaming. Unlike most standalone AR devices which offer performance more in line with a mobile phone, the VR One provides the performance of a high-end gaming laptop, allowing it to run the system's graphically intensive AR software. The computer is powered by two rechargeable batteries which last a combined 1.5 hours. The batteries are hot-swappable, meaning they can be replaced without having to power down the system. A quad charger and spare set of batteries are included to support long run times.

Attached to the VR One is a portable speaker for sound effects, a GPS for location data, and a pouch containing a Wi-Fi router. Only one router is needed per FiST as it is used to connect all units so that each Marine sees the same scene from their own perspective. On one strap, a dedicated pouch holds a four-key keyboard used to simulate the functionality of a Vector 21, Marine Corps binoculars described later in the paper. Finally, all MARTT units in a FiST are controlled by a single iPad using an instructor station application called ARInstructor.

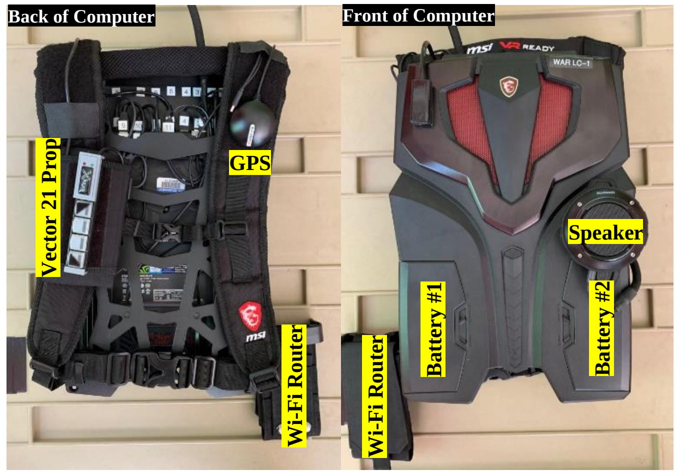

Figure 4. MSI VR One backpack AR processor

Previous Hardware and COTS Selection

The earlier AITT training solution was dependent on custom hardware due to COTS limitations at the time regarding affordability, performance, and ruggedness (Schaffer et al., 2015). More recent developments in COTS technology have resulted in products that are less expensive and have similar or better performance than their custom-designed counterparts. While this technology is still not as rugged as custom solutions, it is durable enough to allow Marines to execute required training scenarios. AR systems generally consist of three main components which drive their cost – navigation sensor, AR processing computer, and HMD. For our FiST trainer, the Vector 21 prop is added as a fourth component at additional cost.

Figure 5. Original AITT navigation sensors (top right) and HMD (center)

The original AITT navigation sensors used a custom stereo camera design with high-end IMU, a color camera board, and a magnetometer to help with heading calculations, all enclosed in a rugged package. More recently, several similar COTS stereo camera solutions with built-in IMUs have been evaluated and ultimately the Intel RealSense D435i was selected. Neither the RealSense, nor any of the other evaluated COTS stereo cameras, have a magnetometer; the next section describes a new software modification that helps resolve this issue. The RealSense was chosen as it provides excellent video quality under a host of lighting conditions, is readily available, and comes in a small, robust package.

The original AITT custom-designed AR computer processor consisted of a rugged enclosure around embedded CPU and GPU boards. To get to a manageable affordable product, we explored using VR gaming backpacks as our AR processor. The VR backpacks do have reduced battery life compared to the custom solution, but multiple batteries were purchased to offset this issue. No additional work is required to make them wearable and they provide significant CPU and GPU resources. Solutions from MSI, HP, and ZOTAC were compared, ultimately settling on the MSI VR One based largely on its longer battery life of 1.5 hours. After months developing with the MSI VR One, it was discontinued by the manufacturer. Using COTS components creates the added challenge of relying on products whose development and lifecycle is out of one's control. Luckily, other backpack computers were still on the market, and little additional work was required to port to a new HP backpack computer. For this paper, we will continue referring to the VR One as our AR processor because the hardware is similar, and most demonstrations were performed using it.

The custom solution's HMD was the Trivisio SXGA61, which is specifically designed for AR and VR devices. The COTS HMD uses the Goovis G2, a display meant for watching movies in full HD. Unlike the Trivisio that has a native aspect ratio of 5:4 which is more closely aligned with the human eye, the Goovis comes with a native 16:9 aspect ratio that is rarely used in AR HMDs. It also comes with a reduced temperature specification along with less robust packaging. While these issues make the Trivisio a better HMD, it was prohibitively expensive and the Goovis provides acceptable image quality in durable packaging for nearly a fourth of the price.

Figure 6. Original custom Vector 21 prop

The Vector 21 is a binocular laser rangefinder used by JTACs and FOs in the field. This essential piece of equipment has two 7x magnifying eyepieces and consists of a distance and an azimuth button, where multiple combinations of presses between the two can provide Marines with a target's range, bearing, height above ground, and other measurements. The original AITT system had a custom-designed Vector 21 prop that looked and functioned identical to the actual set of binoculars and contained a dedicated camera with a 7x zoom lens (Oskiper et al., 2013; Oskiper et al., 2014). A limitation of the MARTT solution is that it only has a 1x camera lens. Adding an additional camera with a 7x lens to the system was considered, however it would have unacceptably increased the final price and added design and assembly time. Since the RealSense has an HD camera, a 7x digital zoom was implemented which resulted in images with a high enough fidelity to use in the field. For the physical COTS interface, a simple 4 button USB keyboard was found. This interface is described in more detail in the next section.

By using only COTS hardware, the cost of the major components of the MARTT system has been reduced by roughly 80%. The time it takes engineers to assemble a system has been reduced from approximately 20 hours to 4 hours. The resulting package meets or exceeds training requirements and is durable enough for use in the field. Modifications have been made to account for reduced battery life, lack of a 7x camera lens, and absence of a magnetometer.

SOFTWARE OVERVIEW

Rendering Software

Figure 7. Virtual scenario with weapon effect

ARRender, the MARTT system's rendering software, is built on the Unity 3D game engine. The software relies on an accurate terrain model of the training location, which must be generated prior to use in the field. Terrain data can be gathered through a drone collect which uses photogrammetry, or through conventional raster data sources such as digital elevation models provided by the National Geospatial-Intelligence Agency (NGA) or the United States Geological Survey (USGS). While drone collects provide more detailed terrains as they include data on vegetation and structures in the area, they are more expensive and time-consuming than downloading the data online, which provides terrains with the Earth's general topography. Once collected, the terrain is then processed into a standard obj format that can later be converted into a binary format for ARRender to quickly parse. Terrain models with less resolution have been made as large as 20 square kilometers, while more detailed ones from drone collects are typically around 1 to 2 square kilometers. The image received from the RealSense HD camera is rendered to the background, followed by the transparent terrain model, and finally any virtual entities and weapons effects. By rendering virtual elements to the depth buffer, the terrain can occlude all entities and effects, such as those placed behind hills and mountains. With a powerful dedicated graphics card, the system's gaming backpack allows ARRender to run at a 1920x1080 resolution with a 60Hz refresh rate.

The MARTT system is controlled through an iPad instructor station application called ARInstructor. The instructor station displays a large satellite image of the current training location. The FiST instructor clicks specific locations on the map to add friendly and hostile entities for trainees wearing the system to see virtually in front of them. Instructors can assign unit-specific behaviors, such as fixed locations for vehicles to move between or assign a target for a tank to fire at. These virtual scenarios can be created on the fly, or instructors can load saved scenarios that they generated earlier. When virtual hostile units are spotted, the FiST team lead, JTAC, and FO begin coordinating to call in supporting fire. This information is relayed to the instructor, who uses the iPad to create the requested weapon effects and/or CAS mission. All trainees can see their requested actions rendered virtually in front of them from their own perspectives. Instructors can pause execution of the scenarios and bring up overlays in real-time that illustrate what trainees are doing correctly or incorrectly. During virtual CAS missions for example, instructors can toggle on a target icon displaying final attack headings on the terrain, helping trainees to visualize CAS conflicts.

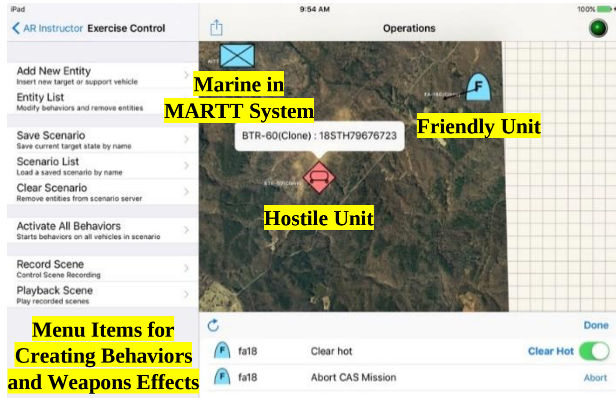

Figure 8. ARInstructor iPad application

The 4 button USB Vector 21 prop allows ARRender to simulate the binocular's full functionality. When in use, the user holds the interface in front of the HMD and presses either of the center two buttons to enable the 7x digital zoom and mil reticle. This action mimics raising an actual Vector 21 in front of one's eyes. The actual binoculars use a diode laser, compass, and an inclinometer for calculations. Using the position and orientation data from the navigation software along with the software's terrain model, ARRender can simulate all Vector 21 calculations.

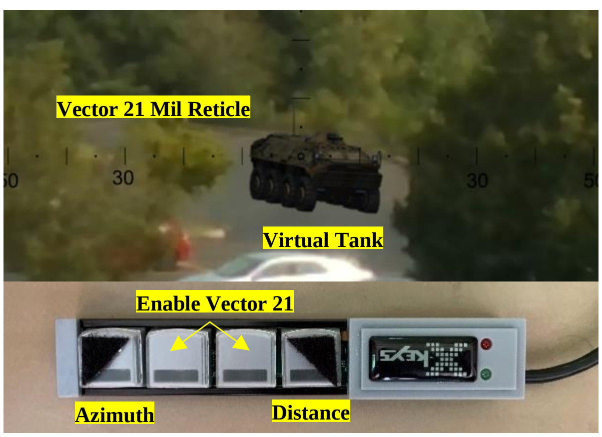

Figure 9. Vector 21 mil reticle (top) and affordable prop (bottom)

ARRender's team training capability uses the High Level Architecture (HLA) network standard. All MARTT systems connect to the same portable Wi-Fi router and then join a shared HLA federation. ARInstructor interfaces directly with one MARTT solution to generate a virtual scenario. This system acts as a server and uses HLA's Run-time Infrastructure (RTI) and Federation Object Model (FOM) to broadcast its data to all others on the same network and federation. The result is a complete team training platform where all Marines can see the same virtual scene from their own perspective. Since the MARTT system is designed for FiSTs, at most 4 or 5 Marines will be wearing one at any time. However, this architecture does support connecting an arbitrary number of MARTT systems, provided they are all connected to the same network and federation.

This networking model also enables the MARTT system to interface with other HLA applications. HLA is an international IEEE standard and is used in most simulations throughout the U.S. Armed Forces. DVTE, the laptop-based Marine training simulation mentioned earlier, is built with the HLA network architecture. ARRender has been integrated with a flight simulator that is a component of DVTE called GENSIM CobraSim. By using GENSIM with ARRender, FiST trainees can interact with a virtual helicopter flown by an actual pilot. In addition, ARRender has been run with another HLA application called the JTAC Virtual Trainer (JVT). JVT is a simulation funded through ONR, where an instructor station creates VR scenarios for JTACs to train around. The JVT Instructor Station operates much like ARInstructor but is more intuitive and supports many additional features Marines have requested, such as a complex after-action report tool. The 3D WAR team has completed a first pass at integrating this software with ARRender, allowing JVT to create virtual scenarios on the MARTT system.

Navigation Software

The MARTT system's high-performance, computer vision-based navigation algorithms provide ARRender with the user's current position and orientation. For detailed information on the core implementation of the navigation software, see Oskiper et al., 2012. While Marines could train with the original custom AITT solution while moving, it was primarily designed to be used in fixed, outdoor locations. Since FiSTs need the flexibility to train while walking, the MARTT system's tracking algorithms were updated to improve system accuracy while in motion. While the navigation algorithms can determine a user's position and orientation without the aid of a GPS, the MARTT system does not need to operate in GPS-denied environments. To counter odometry drift accumulation that occurs over time, updates were made to the navigation algorithms allowing them to fuse global measurements from a non-differential GPS for heading and location correction.

Using the WGS-84 ellipsoid model, the first GPS reading is transformed from the earth-centered earth-fixed (ECEF) coordinate system to a local north-east-down (NED) coordinate system. The initial horizontal position of the sensor is set to the origin of this local NED frame. Since the GPS does not provide accurate height above ellipsoid (HAE) information, this data is obtained through a terrain elevation model that is generated alongside the ARRender terrain. Now that a Euclidean local world coordinate frame has been established, GPS readings are expressed as horizontal position measurements and are used together with HAE data from the stored elevation model. For all subsequent GPS readings, the latitude and longitude values received from the GPS are combined with the HAE from the elevation model, converted from their geodetic position into the ECEF coordinate frame, and finally transformed into the local reference world frame. As the user walks, the GPS-based local path is compared to that of the path generated by the odometry pipeline. A separate process in the background continuously tries to align these two path segments by searching for a robust least-squares fit to obtain the initial heading as degrees from north. Finally, the data is converted from the local coordinate frame back to ECEF and sent to ARRender.

The result is an algorithm that allows for precise tracking while both stationary and in motion. In Figure 10, you can see the accuracy of the updated navigation algorithms. In this test, the user was continually walking for about 15 minutes and traveled nearly 1500 meters. The purple line represents raw differential GPS, which is treated as ground truth. The yellow line represents the path generated by the navigation algorithms. The median error between the two paths is just 1.48m and visually, you can see how well they line up.

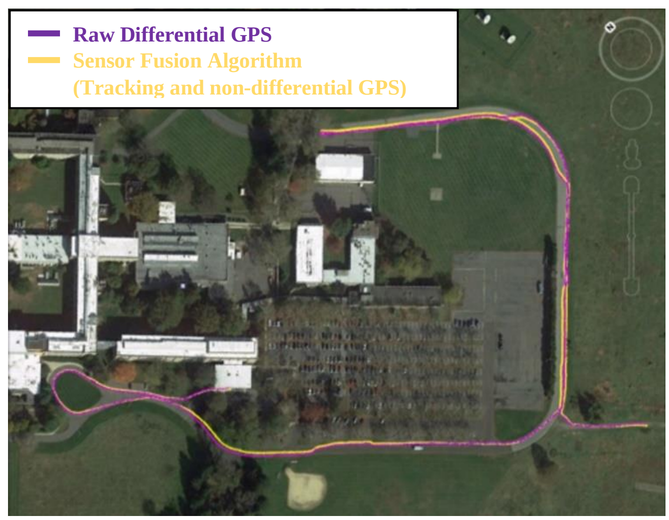

Figure 10. Experiment results comparing tracking performance to differential GPS

The navigation algorithms also needed to be ported from the original custom sensor head to the COTS Intel RealSense. While both sensor heads contain a hardware synchronized IMU and a stereo camera pair, the original custom solution also had a magnetometer and an additional camera with a zoomed 7x lens. Modifications were made to the tracking algorithms so that they could operate without these two components.

The original sensor head used a magnetometer to determine the user's current heading. The new GPS fusion algorithm described earlier eliminates the need for a magnetometer. Now at system startup, the navigation software can calculate a Marine's current heading after they walk 10 meters in the same direction. This process continues in the background as every subsequent 10 meters traveled, current heading is updated to reduce error caused by drift.

The original custom sensor allowed for feature tracking on its zoomed 7x lens, helping to eliminate jitter in AR insertions. This custom sensor had two cameras arranged as a stereo pair that provided video with a 640x480 resolution, but feature tracking was performed at a lower 320x240 resolution. The RealSense's stereo cameras also provide video at 640x480. To get around the issue of not having a zoomed lens on the RealSense, feature tracking is also performed at 640x480. This was accomplished by taking full advantage of the IMU in reducing the search space and using parallel computation over multiple CPU cores. In addition, a more intelligent track selection mechanism was implemented which focuses on high quality features that have the longest tracks with the nearest depth, resulting in better pose estimates with lower drift and jitter.

FEEDBACK AND DEMONSTRATIONS

In August 2019, two prototype MARTT units were demonstrated at OP-2, Marine Corps Base Camp Lejeune for 1st Battalion, 6th Marines (V1/6). The systems were well received, with the V1/6 commanding officer commenting, "I think this thing is almost perfect as is for fires training." Having shown how two units can wirelessly work together, the go ahead was given to develop two more to outfit a 4-person FiST. In October 2019, four units were delivered to V1/6 while they were training at Marine Corps Air Ground Combat Center Twentynine Palms. Additionally, separate demonstrations were held at Marine Corps Base Quantico in September 2019 and Fort Sill in December 2019. Demonstrations at Camp Lejeune were held overlooking the largest impact area on the East Coast, while those at Twentynine Palms, Quantico, and Fort Sill were held in smaller lots to show the system's accessibility. Data was collected through recording oral feedback and written responses to survey questions. The following data is based on these demonstrations and is compared to previous data on the earlier custom counterpart.

Close Air Support and Call for Fire Training

For the demonstrations, FiST trainees would put on the AR gear while an instructor used the iPad to place virtual friendly and hostile units on the terrain. Using the Vector 21 prop along with their actual notebooks, maps, protractors, and tactical tablets, FiST trainees located enemy units and practiced calling in CAS and CFF operations. The instructor inputted information overlaid from the trainees into the iPad, allowing for virtual scenarios with the requested specifications to be replicated in their actual environment. In addition, the GENSIM flight simulator was set up, allowing for a rotary-wing controlled by an actual pilot to be virtually flown overhead.

While standing in a parking lot at Fort Sill or on a golf course fairway at Quantico, FiSTs were able to execute countless CAS and CFF exercises in locations where training was previously impossible. Marines were quick to respond positively to the accessibility that the AR system provided, with one Lieutenant at Fort Sill mentioning that "it would help us get some of the sets out in the real world that we do not get as much." Another commented, "if you can't go to the field this week, we are still getting sets and reps, still working on missions, after actioning, everyone is building that muscle memory." Marines also believed that by allowing FiSTs to train together while blending the real-world with virtual entities, the MARTT system provided a heightened sense of immersion that traditional fire support trainers lacked. "Getting out and being able to sit on something and see it in front of you, I can see the usefulness of this, more so than sitting behind a DVTE," a Marine commented referring to the laptop-based fire support training simulator.

Figure 11. Marine FiST training with four MARTT systems at Twentynine Palms

While Marines were impressed with the accessibility and immersion the MARTT system provided, they did not believe that it could replace training with live fire altogether. "I still wouldn't cover this as live, at all," a Staff Sergeant began. "I would not make the fight to say that [AR] is so good we will call that live." Marines argued that AR technology has not developed to the point where it can completely replicate the "actual stress of a live aircraft, a real person in a real environment." Marines agreed that while there is still a need for live fire training, the MARTT system can supplement these exercises by increasing "sets and reps" through providing the ability for FiSTs to train as a team anywhere anytime. Marines also requested additional CAS and CFF software features to help support their training needs. While ARRender includes a logging feature that captures video and data of the exercises for instructors to review with trainees later, a more robust after-action report tool is also needed. The JVT Instructor Station mentioned earlier, contains these requested features, and work is ongoing to fully integrate it with the MARTT system.

The demonstrations showed how the MARTT system promotes teamwork and communication amongst trainees. In many existing FiST trainers, such as DVTE, each trainee can individually control the simulation (Reynolds et al., 2013). With the MARTT system however, FiST trainees must verbally communicate their requests to the FiST instructor who has the only iPad instructor station. Instructors control the simulation's pace and can pause execution if the team is not operating together. The result were demonstrations filled with teamwork and communication.

Reactions to COTS Hardware

Figure 12. Marine wearing MARTT system at Quantico

A concern with moving to COTS products was whether Marines would accept and be comfortable with consumer hardware for combat training. With no custom hardened components, the final product looked less like a FiST trainer and more like a gaming machine. However, by moving away from in-house components to those mass-produced for the average consumer, the resulting system was more intuitive and easier for Marines to use. In a 2015 study of the original custom-built AITT solution, Marines commented that the large, metal-hardened computers and sensors looked intimidating. They believed that they "would need the support of a technical person to be able to use this system" and felt as though they needed to "learn a lot of things before [they] could get going" (Champney et al., 2015, Section 6). In contrast, when a Master Gunnery Sergeant in V1/6 first saw the backpack computer built by the popular manufacturer MSI, he commented that his son loves their equipment and uses one of their computers for gaming at home. A Staff Sergeant at Fort Sill, who considered himself a gamer, mentioned that he had also seen these backpack computers online and had used AR HMDs before. The MARTT system seemed approachable, and many Marines already knew how to operate some of the components before demonstrations began.

Marines did express concern regarding the hardware's durability though, especially at Twentynine Palms where intense heat, dust, and sand all provide daily risks. However, the four units that were used by V1/6 at Twentynine Palms returned with all parts in working order. In addition, no MARTT system has been damaged at any of the demonstrations and training exercises so far. Marines also expressed concern with the overall backpack form factor as it prevented them from training with the backpacks and gear they typically carry with them on the battlefield. While the system does allow Marines to use their notebooks, maps, protractors, and tactical tablets, a custom training solution that integrates with their packs would need to be designed to allow for training with all gear.

Display Fidelity, Vector 21 Prop, and Simulator Sickness

The HMD received mixed reviews, with some Marines commenting that the display did not provide enough fidelity to make out objects that were far away. The demonstration at Camp Lejeune was held at OP-2, on top of a 20-meter tower overlooking the largest impact area on the east coast. From that vantage point, the landscape stretched for kilometers, and Marines complained that it was difficult to make out hostile targets more than a kilometer away. Some Marines liked how it was challenging to see distant targets since this would only make it easier to spot hostiles during real exercises. One Marine commented that "we have been fighting in the desert now for seventeen years; [where] it is pretty easy to see. We are talking about Pacific Islands now, and we are not going to see anything. That is why I like this, that it is more of a challenge to see." Demonstrations at Quantico, Fort Sill, and Twentynine Palms were held in small lots, ranging from less than one to about two square kilometer(s) in size. Here, feedback on the fidelity of the display was positive, as smaller vistas eliminated the need to spot targets kilometers away. A way to improve on this issue would be to switch to one of Trivisio's HMDs that the custom solution employed. These HMDs are made specifically for VR and AR devices, with a better aspect ratio and clearer displays. While Trivisio HMDs are readily available for purchase online, they cost nearly four times as much as the Goovis. For now, Marines agreed that the current HMD was sufficient for training.

Feedback on the Vector 21 prop's 7x digital zoom was similar, with Marines at the large Camp Lejeune impact area commenting that the digital zoom made it difficult to make out hostile targets more than two kilometers away, and those at Quantico, Fort Sill, and Twentynine Palms' smaller lots responding positively to the digital zoom's fidelity. An additional camera with a 7x lens could be integrated later to address this issue, however Marines here also agreed that adding a camera was not worth the increased cost or development time as the current solution still allowed for robust training. The physical Vector 21 interface also received positive feedback, with many Marines commenting that the prop and simulation software performed much like the actual binoculars.

Some Marines did express concern regarding simulator sickness when using the MARTT system for extended periods of time. This concern was more common when FiSTs were training while in motion, as opposed to working in fixed locations. Research is underway searching for solutions that will reduce system latency, a major contributor to simulation sickness. Typical demonstrations found that Marines could wear the system continuously for 15-20 minutes with few issues. At Twentynine Palms, however, a four-person FiST wore the system for about two and a half hours with no complaints. It is important to note that during FiST training, trainees are constantly looking away from their HMD to their notebooks and tactical tablets to call in CAS and CFF. This regularly gives their eyes a break from the AR simulation, and could explain why these Marines had no issues wearing the system for extended periods. Marines agreed that despite the possible discomfort caused by using the system for long durations, it did not interfere with training.

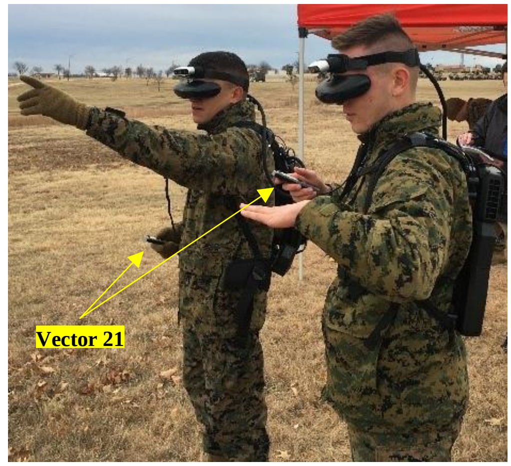

Figure 13. Two FiST members using Vector 21

Academic Interest

Demonstrations at Quantico unveiled an unintended additional use for the MARTT system. Here, many in attendance were university professors who believed that the system's low price point and ease of assembly could help with their AR research. Currently, there are not many complete AR devices readily available for purchase. The few that are available, such as the Microsoft HoloLens 2 and the Magic Leap One, offer performance more in line with a mobile phone. Professors were intrigued by the MARTT system's high-end gaming performance, relatively cheap price point, and ease to assemble. The Naval Postgraduate School purchased one MARTT system, and there is continued interest from other university professors who have commented that the system would be perfect for their research needs.

Feedback Conclusion

"Properly designed, next generation training is designed to augment and enhance training by replicating live training capability at home units, and to provide through the use of synthetic environments the ability to train in real world operations" (Defense Science Board, 2013, p. 63). These demonstrations show how the MARTT system can be used to increase the accessibility and realism of FiST training by allowing training in any location. As one Staff Sergeant commented, "FiSTs and smaller would benefit greatly from the AR portion of the system…I can see huge benefits for training battalion teams and using it as a teaching tool to give real-time feedback and after-action points post-execution." Feedback from Marines did show that improvements are needed, most notably with adding additional training software features and better display fidelity. However, the technology has been successfully ported from the individual custom solution to an affordable COTS variant that enables team FiST training, maintains performance, and costs a fraction of the original. The V1/6 commanding officer who used both the custom AITT solution and the new COTS variant said he prefers the MARTT system due to its price, team training capability, and ease of use.

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REFERENCES

Champney, R., Lackey, S., Stanney, K., Quinn, S. (2015). Augmented Reality Training of Military Tasks: Reactions from Subject Matter Experts. In *Virtual, Augmented and Mixed Reality: Systems and Applications*. Berlin: Springer.

Defense Science Board, (2013). *Report on Technology and Innovation Enablers for Superiority in 2030*. Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C.

Expeditionary Advanced Base Operations. Retrieved May 6, 2020, from https://www.candp.marines.mil/Concepts/Subordinate-Operating-Concepts/Expeditionary-Advanced-Base-Operations/

NTSA Today. (2015, December 11). *Gen. Robert B. Neller, USMC and Panel on "Training Innovation"*. YouTube. https://www.youtube.com/watch?v=LDTnh9U2qD8

Oskiper T., Samarasekera S., Kumar R. (2012). Multi-sensor Navigation Algorithm Using Monocular Camera, IMU and GPS for Large Scale Augmented Reality. In 2012 *IEEE International Symposium on Mixed and Augmented Reality*.

Oskiper, T., Sizintsev, M., Branzoi, V., Samarasekera, S., Kumar, R. (2013). Augmented Reality Binoculars. In *2013 IEEE International Symposium on Mixed and Augmented Reality*.

Oskiper, T., Sizintsev, M., Branzoi, V., Samarasekera, S., Kumar, R. (2014). Augmented Reality Binoculars on the Move. In *2014 IEEE International Symposium on Mixed and Augmented Reality*.

Reynolds, J., Smith, C. (2013). *Virtual Environment Training on Mobile Devices* (Publication No. 0704-0188) [Master's thesis, Naval Postgraduate School]. Semantic Scholar.

Schaffer, R., Cullen, S., Meas, P., & Dill, K. (2013). Mixed and Augmented Reality for Marine Corps Training. In R. Shumaker (Ed.) *Virtual, Augmented and Mixed Reality: Systems and Applications*. Berlin: Springer

Schaffer, R., Cullen, S., Cerritelli, L., Kumar, R., Samarasekera, S., Sizintsev, M. Oskiper, T., Branzoi, V. (2015). Mobile Augmented Reality for Force-on-Force Training. In *Interservice/Industry Training, Simulation, and Education Conference 2015*.

United States Joint Chiefs of Staff. (2009) *Joint Publication 3-09.3 Close Air Support.*