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THESIS

**USE OF VR TECHNOLOGY AND PASSIVE HAPTICS
FOR MANPADS TRAINING SYSTEM**

by

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September 2017

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**USE OF VR TECHNOLOGY AND PASSIVE HAPTICS FOR MANPADS
TRAINING SYSTEM**

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ABSTRACT

Man portable air defense systems (MANPADS) are point-defense weapons that typically form the penultimate layer of defense against aerial threats. Deployed at close ranges to the installation being defended, MANPADS operators get little reaction time to engage attacking aircraft. The situation becomes more complex in a multi-threat scenario such as an airfield under attack. Dealing with such situations requires high proficiency and the capability to make tactical decisions quickly.

Live training opportunities allow few operators to fire during live exercises. Simulation training is effective, but customized high-fidelity immersive training facilities are limited. Moreover, low trainee throughput from such high-end facilities is an ongoing obstacle.

The main focus of this thesis research is a feasibility study for building a low-cost MANPADS training solution that uses commercial off-the-shelf components. The developed prototype leverages a fully immersive virtual reality system with head-mounted display, game engine, and passive haptics. It provides MANPADS operators with alternative training opportunities in target acquisition, tactical decision making, and situational awareness in a multi-threat scenario, and has the potential of addressing the current training gap. This development experience will provide valuable insights that can be employed to design and create a new generation of low-cost training solutions in other domains as well.

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LIST OF ACRONYMS AND ABBREVIATIONS

API	application programming interface
ATC	air traffic control
BCU	battery and coolant unit
C2	command and control
CAVE	Cave automatic virtual environment
COTS	commercial off-the-shelf
DOD	Department of Defense
FOR	field of regard
FOV	field of view
FPS	frames per second
GUI	graphical user interface
HMD	helmet mounted display
IDE	integrated development environment
IFF	identification friend or foe
IMTS	improved moving target simulator
IR	infra-red
ISMT	indoor shooting marksmanship trainer
IVR	immersive virtual reality
LSO	landing signaling officer
LVC	live virtual constructive
MANPADS	man portable air defense system
NPS	Naval Postgraduate School
SA	situational awareness
SAM	surface to air missile
SDK	software development kit
SHORAD	short range air defense
UI	user interface
USMC	United States Marine Corps
VA	vulnerable area
VE	virtual environment
VP	vulnerable point
VR	virtual reality

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I. INTRODUCTION

A. AIR DEFENSE SYSTEM

Since the advent of aerial warfare, air strike tactics and techniques have been developed for ensuring maximum target destruction and neutralization. Nowadays, aerial strikes are conducted using sophisticated attack helicopters and fighter/bomber aircraft. The weapon delivery is carried out at high, medium, and low altitudes and can also be accomplished at considerable standoff ranges using precision-guided munitions. The advancement in aerial attack technology has also led to the development of systems capable of defending own assets against such aerial threats. These systems, known as air defense systems, form an integral part of any military in today's world. A modern air defense force is composed of airborne and ground-based sensors, surface-to-air missiles, surveillance and intelligence systems, and command & control (C2) centers that network all assets into a bigger ecosystem.

Air defense capability ranges from small systems for defending army units deployed at war fronts to complex defenses for protecting infrastructure like dams, bridges, military bases, and even cities. Modern air defense is a combination of systems such as active and passive sensors, weapons of varied range, and communications to network all these assets. All components are knit together in a hierarchical C2 network for uninterrupted real-time flow of information from various sensors and relaying of decisions from C2 centers to weapons. Conceptually speaking, air defense looks after the aerial frontiers of a country and responds to any emerging threat with suitable weapons deployed at various locations.

The air defense weapons deployment follows the concept of layered defense. The outermost ring or layer consists of weapons with greater range capability; as the distance to target (infrastructure to be defended) is reduced, weapons with decreasing range are deployed. The outermost layer is formed by the interceptor fighter aircraft along with long- and medium-range surface-to-air missiles (SAM). Then comes the layer of

MANPADS, followed by the last line of defense formed by anti-aircraft artillery or Ack-Acks.

B. RESEARCH DOMAIN

Man portable air defense system (MANPADS), also termed as shoulder-launched SAM, mainly serve as point defense weapons. Generally, they form the penultimate layer of defense against aerial threats. MANPADS are deployed in close proximity to the vulnerable areas (VA) or vulnerable points (VP) and are very flexible in terms of installation and use. They can be easily carried, installed, and used in any kind of terrain for shooting targets of opportunity. Being deployed at closer ranges from the installation being defended, they engage incoming aircraft during or just before final attack maneuver. In hilly terrain areas, they are deployed in approach corridors of the attacking aircraft and therefore may get limited exposure time offered by the target. In this restricted timeframe, missile operators have to pick a target visually, make a positive identification as an enemy, aim and acquire the target, and finally fire the missile.

Maintaining combat readiness of air defense troops is imperative for achieving success in the battlefield. This can be assured through rigorous training for developing and maintaining the required skill level. Moreover, as these weapons are operated in varied environments and terrains, MANPADS operators must keep their knowledge and skill up to date for all such varied scenarios and conditions. The focus areas for training of MANPADS operators include system handling, weapon operating procedures, and tactical employment (United States Department of the Army, 1984). Furthermore, weapon employment in varied tactical situations demands decision-making capabilities and maintaining situational awareness (SA) of the scenario in context of the overall exercise or battle (United States Department of the Army, 1981).

C. RESEARCH PROBLEM AND MOTIVATION

The operators of MANPADS systems have very little reaction time in which to engage an incoming attack aircraft or helicopter; this is especially the case when one considers MANPADS employment in critical situations. The situation becomes even more complex in a multi-threat scenario, especially on an airfield under aerial attack. To

deal with limited reaction time available in such situations, the MANPADS operators are required to be highly proficient in operating these weapons; they should be capable of making tactical decisions quickly and successfully. To achieve an adequate level of proficiency, military professionals of this domain must maintain a subset of skills at high proficiency level at all times. This necessary subset of skills includes practicing target acquisition, rehearsing firing procedures, and building situational awareness of the aerial scenario. Like in any other weapon system, the MANPADS training force has two main choices of practical training to build these requisite skills: live field training and simulation center training. Both require significant cost, effort, and infrastructure and can easily affect training throughput due to the non-availability of any one of these factors.



Figure 1. Stinger weapon system (MANPADS). Source: “FIM-92 Stinger” (n.d.).

It is also commonly understood that few operators get a chance to fire during live exercises, which are carried out no more than once or twice a year (United States Department of the Army, 1984). Moreover, the exercises are planned for canned scenarios that do not represent a full-scale aerial threat such as engaging air strikes during an armed conflict. Field exercises involving the use of drones for targeting also involves effort and time (United States Department of the Army, 1984). Another option adopted for training is to take advantage of the routine military flights or air traffic around an

airfield where these operators can practice target acquisition and firing procedures using dummy missiles. An inherent limitation in this type of setup is that the aircraft profiles as they are approaching the runway for landing or flying straight-and-level above the airfield are not the same as those followed by aircraft during an attack. Additionally, a second person to supervise procedures and monitor timings is required. The operator can have feedback from an instructor during the exercise, but there is no mechanism to check whether the target will lie within missile hit criteria. Although this setup does allow ascertaining drill proficiency in terms of time consumed to complete the sequence and its correctness, and helps in brushing up on the steps involved in operating the weapon, it does not address skills development in terms of maintaining SA or quick decision making in a time-compressed scenario.

In a report by the U.S. Army Research Institute (Smillie & Chitwood, 1986), it is highlighted that effective employment of a line-of-sight weapon in a combat zone requires operator expertise, such as proficiency in weapon operation and employment of tactics or techniques. It further hints that successful acquisition of these skills can be made possible through rigorous training that employs realistic tactical scenarios and use of effective training solutions. One of the options available to the training force are virtual training systems that allow cost-effective practice of skills in situations and conditions that would not be available or would be too risky otherwise. Such training facilities are generally not available in air defense units and so training programs must rely on military training institutes that house high-fidelity simulation systems. There, the operators undergo training sessions to brush up on weapon operation skills and practice their employment in a variety of tactical scenarios generated for simulation. The biggest limitation in such training setups is their low throughput as these are centrally located and so cannot be visited frequently. This research looks into the possibilities of developing a low-cost training solution using commercial-off-the-shelf (COTS) technologies. The resulting system focuses on part task training of MANPADS operators by providing all types of environmental and tactical conditions. The system is envisaged as a low cost, small footprint training solution that can be easily deployed and maintained in air defense units. It thus proposes to offset the limitations inherent in most current training in daily

routines that lacks realism and leads to deterioration of weapon operation and tactical employment skills.

D. RESEARCH QUESTIONS

Given the problem at hand, the main research questions for this feasibility study are as follows:

1. Is it feasible to develop a prototype simulation system that employs immersive virtual reality (IVR) technology and passive haptics in support of a selected set of skills and allows training for man-portable point defense weapons in a multi-threat scenario?
2. Is it possible to use COTS equipment to realize this part task trainer and provide necessary training conditions in an immersive environment?

E. HYPOTHESIS

The hypothesis underpinning this thesis is that it is possible to develop a low cost, small footprint, mobile part task trainer using COTS technologies to support MANPADS training. That being said, the research assesses whether it is possible to reach satisfactory technical performance like latency and frame rate, while generating the sensory stimuli needed for this type of training—visual, auditory, and haptic. An even more considerable limitation that might still be present in the training system is in the fidelity of the passive haptic stimuli; that is, will the passive haptic have the full fidelity of a MANPADS weapon system (i.e., no recoil, the same weight, and comparable exactness of the geometry and functionality of all triggers on the weapon).

F. SCOPE

This research effort focuses solely on undertaking a feasibility study on the design and development of a prototype simulation for MANPADS operators using COTS equipment. The study tests whether it is possible to achieve the necessary technical performance for that system (i.e., having optimal inclusion of necessary sensory stimuli while maintaining high frame rate and low latency).

The system selected for this study is a Stinger FIM-92 missile system. The prototype simulator has the potential to provide operators with training opportunities in the domains of target acquisition, tactical decision making, and maintenance of SA in a multi-threat scenario. The scope of the study does not include conduct of a formal user study to test training effectiveness of the prototype trainer.

G. METHODOLOGY AND APPROACH

The approach adopted for this feasibility study was first to perform a literature review of virtual environment (VE) elements to study military manuals, materials, and videos related to Stinger missile operation and employment. The information gathered was used to perform a task analysis. The training system was then designed; this included the selection of a hardware and software environment for the system's development. The next step included system development and development of challenging training scenarios. In the end, a test of the fully developed system's technical performance was carried out.

A major part of this system consists of the software application and so the approach adopted for developing the application was to create a VE simulating an airfield or a hilly terrain. Aerial targets are generated by incorporating fighter aircraft or military helicopters flying in attack and evasion profiles. The user (operator) is expected to visually acquire and shoot the targets presented in VE by using the virtual Stinger missile system while holding a prop (passive haptics object) in his or her hands.

H. THESIS CONTRIBUTION

The main thesis contribution is in prototyping an approach for developing a training simulation for weapon systems typically carried by the human operators; specifically, the approach is to use COTS systems to develop a portable low-cost training solution that stands as an alternative to expensive, non-portable high-fidelity solutions that currently prevail in the training community. The study conducted for this thesis increases community understanding of how computer gaming hardware and software technologies can be used for producing realistic military simulations. This research can also provide useful guidance to design teams when they develop learning or training

systems in both military and civilian domains; a common denominator in those systems would be the situation in which the operator needs to hold a physical device while learning or practicing a specific procedure needed to operate that device.

I. THESIS STRUCTURE

Chapter II discusses the use of simulation in training and covers some of the training systems currently used for training of MANPADS operators. Chapter III throws light on the background research done in the domains of IVR technology and passive haptics. Chapter IV presents the results of the task analysis focused on MANPADS operation for engaging targets. Chapter V describes the elements of design of the MANPAD training system and the work required to craft a custom-made MANPADS launcher to simulate a passive haptics device. Chapter VI discusses the development of an application using the Unity 3D game engine, virtual environments, and scenarios generated in support of the MANPADS prototype simulation system. Chapter VII summarizes the conclusions of this work and outlines directions for possible future work.

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II. BACKGROUND

A. SIMULATION AND TRAINING

Training in many domains and aspects of human existence has taken advantage of advancements in computer science and information technology (IT). One of the remarkable manifestations of these technological achievements can be seen in the form of simulators being used to support learning, training, and in some cases, operation. The IEEE document “IEEE Standard Glossary of Modeling and Simulation Terminology” defines a simulator as “a device, computer program, or system that performs simulation” (IEEE 610.3-1989, 1989, p. 15) and defines simulation as “the process of developing or using a model” (IEEE 610.3-1989, 1989, p. 14). “The use of simulators in training involves an operator learning some skill *s* with a device *d* (the simulator), in the hope or expectation that he will then perform some skill *S* with a device *D* (the real equipment)” (Hammerton, 1967, p. 8). In simple words, a simulator can be defined as a machine or a system that mimics or represents some real world condition, or phenomenon, or a system, developed for the purpose of training, research and development (R&D), analysis, or test and evaluation (T&E). As described by Aldrich (2003), simulations act as a linkage between knowledge acquired through recurring classroom instruction and skills gained during on-the-job training. According to the U.S. Department of Defense (DOD), “Training simulations are developed for those who need to learn how to operate, support, maintain, or otherwise interact with these systems” (Hodson & Hill, 2014, p. 1). Both training simulations and simulators are proven to have a potential to help improve human performance and skills, assist in human decision making in various situations, and increase overall productivity by increasing output and efficiency.

Owing to their time-tested advantages, training simulators and simulations are now considered as a regular part of any training solution package. In the military domain, training simulations constitute an important component of an overall training solution, especially where interaction of personnel and weapons is involved. The commonly used simulators include flight simulators, ship bridge simulators, tank simulators, air traffic control (ATC) simulators, radar simulators, marksmanship simulators, driving simulators,

convoy simulators, etc. One of the biggest advantages of these simulators is that they allow trainees to experience situations that otherwise cannot be recreated due to the risks involved, limited availability of physical resources, and constrained training budgets. Simulators provide users with a chance to experience and train for situations which they may not be able to train for using traditional training solution. As explained in a report by the Institute of Defense Analysis:

In simulated environments, aircraft can be crashed, expensive equipment can be ruined, and lives can be jeopardized in ways that range from impractical to unthinkable. Simulated environments also provide other benefits for training. They can make the invisible visible, compress or expand time, and reproduce events, situations, and decision points over and over. Simulation-based training is not a degraded reflection of the more realistic environments we would prefer to use. It allows us to train aspects of performance that would otherwise be inaccessible. (Fletcher & Chatelier, 2000, p. V-1)

This ability to synthetically create unachievable situations and scenarios therefore makes them a compulsory tool in some domains of today's military training; the best example of such a situation are flight simulators that today serve as mandatory training solutions in the training of pilots.

Depending on their intended use and training objective, simulators have varying levels of fidelity and abstraction. For example, a fledgling pilot learning to fly a certain type of aircraft might train on a full flight simulator that includes an exact replica of the aircraft cockpit in appearance and flight behavior. On the other hand, if a flight simulator is required for tactical combat training and weapon employment during battle, the simulator might not be an exact cockpit replica, rather it could be a part task trainer replicating only those features that are used during combat, such as airborne intercept radar, radar warning receiver, link system, and weapons. The rest could be an abstraction of the actual features, for example, a throttle, control stick, out-of-window display, etc. The difference here is the focus of the training (i.e., a skill set that is targeted at that point in a trainee's training regimen).

One of the main concerns in military training is the correct implementation and application of simulation systems for professional grooming of personnel; good

implementation should result in positive transfer of skills gained in training simulation. Furthermore, good application should guarantee that a certain simulation is used at the appropriate point in a trainee's training regimen, in correct way, and with requested frequency. Simulators can provide success in skill acquisition and improving performance of military personnel only if the simulators are adequately integrated into the overall training program.

B. CURRENT TRAINING SYSTEMS FOR MANPADS

A variety of simulators are used by militaries for training MANPADS operators. Each solution offers a different level of immersive synthetic environment through a variety of display solutions and system setups. The main components of any MANPADS simulator include following:

- Real-time image generation system.
- Monoscopic or stereoscopic visual display solution.
- Underlying models: Missile flight simulation and sensor model, special effects including weapon 3D model, smoke trail, missile 3D model simulation, weather model and time of the day simulation, model of the human body (to simulate the operator's body, or the visual appearance of other humans in the simulated environment).
- Haptic display in the form of physical weapon mockup, i.e., physical prop (passive haptics).
- Scenario generation mechanism for creating various types of aircraft and helicopter profiles to generate targets.
- Auditory displays to support sound effects such as missile launch burst and aircraft engine sounds.

The rest of this chapter discusses the details of some MANPADS simulation systems that are currently used in the military domain.

1. Improved Moving Target Simulator

The Improved Moving Target Simulator (IMTS) is a training system that has been developed by Aegis Technologies Group, Inc. for the U.S. Army and U.S. Marine Corps (USMC). The display solution used in this simulator consists of a hemispherical dome construction that is 40 feet in diameter (Figure 2). Within the dome is a tiled projective surface composed of multiple screen panels that collectively display a seamless image all around the 360-degree dome. The system has a capacity to accommodate three Stinger teams of two persons each, and it allows them to engage target aircraft. The operators use real Stinger launchers (dummy versions) to carry out the simulated engagements (“Aegis Simulation Training Systems,” n.d.).



Figure 2. IMTS with dome projection for immersive display.
Source: Weirauch (2013).

IMTS provides the trainees with a fully immersive environment augmented by high-fidelity visual and auditory effects, weather effects, and surrounding ground environment typical for that type of operational condition. One issue related to visual effects generation using dome projection, though, reduces realism: the missile visual effect and smoke generation upon missile launch. As the missile is fired, the launch effect gets generated on the projection screen, which in reality is very far from the actual

launcher being held in operator's arms. This type of solution is not realistic and represents a potential source of "break in presence" (Slater & Steed, 2000). Furthermore, a major drawback with this type of simulation facility is the maintenance of the system. In addition to requiring substantial physical space to accommodate this large structure and its large operational costs, projector lamps used in this visual display have a limited lifetime and need to be changed periodically, thus causing maintenance costs to grow. The synchronization of the image generators and their proper fit with the physical display surface is imperative for having seamless projection and, if disturbed, requires laborious re-calibration. Another issue is that IMTS centers are located at only few places within the United States, and they cannot be accessed on a routine basis by MANPADS operators serving in air defense units that are not co-located with IMTS centers. As a result, IMTS systems offer very few chances for training of an individual operator, thereby yielding lower throughput as compared to a facility installed locally to the air defense units.

2. Konus Igla-Type MANPADS Simulator

The Konus MANPADS simulation system has been designed and developed by the Joint Stock Company of Russia. The simulator provides training for a range of MANPADS, including the Igla-1, Igla, Igla-S, 203-OPU Dzhigit SLU, and Strelets SEM. The system consists of a launcher unit, conical display system, and instructor workstation. The projection system offers 192 x 60 degrees field of regard (FOR) and allows a single person to be trained in one session (Figure 3). The system features include target maneuver generation, infra-red (IR) decoys, simulation of weather conditions, various terrain features, and land platforms. During the session the trainee's performance can be evaluated using simulator control and evaluation features. The system playback feature allows for the analysis of a trainee's performance along with automatic evaluation (Joint Stock Company Research and Production Corporation [Konstruktorskoye Byuro Mashynostroyeniya], n.d.).

An instructor is required to generate aerial targets and to control other environmental effects like weather, jamming, and platform selection. The biggest

limitation of the system is the projection system, which consists of multiple vertical columns joined to form a conical, curved screen; that being said, any displacement of the display structure or projectors requires re-calibration of the entire system.



Conical projection display with 192-degree horizontal FOV.

Figure 3. Konus Igla missile simulator. Source: Joint Stock Company Research and Production Corporation (n.d.).

3. Breeze MANPADS Simulator

The Breeze MANPADS Simulator has been developed by Breeze Simulation of Israel. This system is designed to train MANPADS gunners operating from mobile anti-aircraft battery units, including IGLA, Strela, and Stinger units. The simulator includes a visual display for presenting a 3D world view, a scenario generator that creates targets and tactical situations, and debriefing capability. The system has the capacity to train a single operator in one session (Breeze Creative, Ltd., n.d.).

The main limitation of the system is its non-immersive display solution, which consists of flat screens that offer limited FOR (Figure 4).



Flat screen projection of Breeze MANPADS simulator.

Figure 4. Breeze MANPADS simulator. Source: Breeze Creative, Ltd. (n.d.).

C. ISSUES WITH CURRENT SIMULATION SYSTEMS

The general conclusion that can be drawn for all high-fidelity immersive training facilities is that there are very few of them and that they are centrally located. This, in turn, provides limited training opportunities to all individuals who need that kind of training environment. As an example, the IMTS, which has 40-foot-high dome that provides a 360-degree FOR, is installed at only a few locations in the United States, such as Fort Still, Oklahoma, and Fort Hood, Texas. Also, there is only one training simulator that provides simulator-supported training for landing signal officers (LSO), and it is in Oceana, Virginia.

The size of the visual displays in those systems varies as well. For example, only the Cave Automatic Virtual Environment (CAVE) or dome solutions offer a fully immersive environment surrounding the operator with 360-degree FOR. Other visual displays use only a fraction of the dome or segment of CAVE, and as such they are not fully immersive (they do not offer 360-degree FOR). Regardless of their size, the most significant drawback of these solutions is their initial setup cost, as well as the running maintenance and operation cost (Figure 5).



Under construction dome projection setup.

Figure 5. Setup construction for dome projection.
Source: AegisTechnologies Group (n.d.).

D. OTHER TRAINING SOLUTIONS

In places where the simulation facility is not available (or does not exist) or it is inaccessible for training when training is needed, manual practice drills on physical training ranges serve for much of the training. The procedure involves an actual MANPADS launcher loaded with trainer missiles. The training session is usually organized with the presence of an actual aircraft that flies above or close to the airfield. The operator can go through an entire sequence starting from target sighting to fire trigger press but without actually firing the missile at the end. This mechanism is commonly used to check the knowledge of procedures, improve the timings on parts of the procedure or the entire procedure itself, and to improve a trainee's response, as repeated practice conditions the trainee to follow the right sequence without getting stuck at any point. In such a setup, the instructor can provide feedback on following procedures but there is no way to tell whether the target would be hit. Secondly, this setup also does not offer a variety of challenging scenarios needed for good training as the aircraft are mostly flying in landing or take-off patterns.

E. CHAPTER SUMMARY

This chapter discussed the role and benefits of simulation in military training, and reviewed some of the MANPADS simulators used worldwide. The discussion on these simulators also gave the opportunity to discuss the advantages and disadvantages of each one of them. We use that information as input when proposing a new system that is designed and developed as part of this thesis research.

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III. IMMERSIVE VIRTUAL REALITY

A. DEFINITION

Various definitions of virtual reality (VR) have been advanced by researchers in this field. A few are mentioned here:

- “Virtual reality is the use of computers and human-computer interfaces to create the effect of a three-dimensional world containing interactive objects with a strong sense of three dimensional presence” (Bryson, 1996, p. 62).
- The VR experience is defined as “any in which the user is effectively immersed in a responsive virtual world” (Brooks, 1999, p. 16).
- “The term virtual reality typically refers to three-dimensional reality implemented with stereo viewing goggles and reality gloves” (Krueger, 1991, p. xiii).

While all those definitions differ in some elements, they all refer to common core components. Those were best described by Dr. Frederic P. Brooks, Jr. during a panel session at the IEEE VR 2010 conference as “VEs [virtual environments] or IVR has four ingredients:

1. Real immersion—World is life-size, the rest is blocked out.
2. Real time—Viewpoint changes as head moves.
3. Real space—3D worlds are concrete or abstract.
4. Real interaction —One manipulates virtual objects.”

This being said, in general both viewpoint movement (user navigation) and object manipulation should be supported with freedom of movement that conforms to the six degrees of freedom (6DOF) criterion.

B. MAJOR CONCEPTS IN IMMERSIVE VIRTUAL REALITY

As elaborated by Slater, “a typical IVR system today delivers stereo vision that is updated as a function of head tracking, possibly directional audio and sometimes some type of limited haptic interface. For example, the CAVE (Cruz-Neira, Sandin, & DeFanti, 1993), is a system where between four and six walls of an approximately 3m³ room are back-projected stereo projection screens” (2009, p. 3549). With advancements in technologies that are used to make head mounted displays (HMD), accelerated advanced graphics rendering, 3D audio (spatialized) techniques, and haptics devices, one could argue that very high fidelity experience can now be gained from IVR that use that type of system architecture as well.

Concepts typical for IVR that are most directly relevant to the research effort for this thesis include immersion, sense of presence, and representation of the user in a 3D environment.

1. Immersion

A definition of immersion that is frequently used in the research domain has been made by Slater and Wilbur: “Immersion is a description of a technology, and it describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant” (1997, p. 3). This understanding suggests that immersion is the extent to which the technical setup surrounds or wraps around the user, engaging all his or her sensory systems and replacing the sensory stimulation that originates from the physical world in which the user is living. One could therefore say that dome or CAVE displays are more immersive than a single or even a few tiled screens that inevitably have more limited FOR than CAVE. In that regard, for example, visual displays that provide users with larger FOV are more immersive VR systems. Another aspect that enhances immersion is the range of sensory modalities used for inducing inputs to the human operator. Such inputs from the virtual world include visual, auditory, haptic, and olfactory stimuli.

2. Presence

Presence—or a sense of presence—is defined as the sense of “being there” in a VE (Slater & Wilbur, 1997, p. 3). As mentioned by Witmer and Singer, “Presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another” (1998, p. 225). In relation to VE, the same authors also say that “presence refers to experiencing the computer-generated environment rather than the actual physical locale” (1998, p. 225). As defined by Dr. Frederick P. Brooks, all four components of IVR contribute to overall human experience in that environment; a mismatch of sensory stimuli, a lack of some sensory information, or an interruption of any kind could potentially reduce a sense of presence in a VE. For example, if the user moves his head and the visual scene is not updated due to latency in head tracking or slow refresh rate, it is highly likely that this would reduce a level of presence in that VE.

One of the main discussions among the researchers regarding presence has been about the ways and means of measuring presence a user has experienced in a VE. Researchers have resorted to mostly subjective methods using questionnaires, informal interviews, and informal grading on Likert scales during and after the experience. Examples of such studies include Heeter (1992); Slater, McCarthy, and Maringelli (1998); Witmer and Singer (1998); and Slater, Sadagic, Usoh, and Schroeder (2000). In addition to user questionnaires, other studies have attempted to find objective means of measuring presence (e.g., use of a range of physiological measures like heart rate, skin temperature, and skin conductance) (Meehan, Insko, Whitton, & Brooks, 2002; Slater et al., 2006).

Any leakage from the outside world presents a disturbance that hinders or distracts the user from the virtual world. An example could be the ringing of a phone bell while the user is having a virtual camel ride in a desert. That phenomenon is called a break in presence (Slater & Steed, 2000).

3. User Representation

Interactions within a VE often require a representation of the user’s body within that VE. In the real world, a human being is aware of his movements in two ways: one is

by visual awareness of his or her different body parts and the second is through proprioceptive movement, which is a cognitive awareness of the position of one's various body parts. Similarly, in a VE if a user moves his or her hand, the user expects to see it moving through visual means; if it is not there or not moving, that creates a dichotomy and breaks the presence. The paper titled "Body Centered Interaction in Immersive Virtual Environments," describing a study on body-centered interactions, explains that

proprioception results in the formation of an unconscious mental model of the person's body and its dynamics. This mental model must match the displayed sensory information concerning the virtual body (VB). The VB is then under immediate control of the person's motor actions, and since the VB is itself part of the displayed VE, the person is immersed in the VE. We call such environments "Immersive Virtual Environments (IVEs)." (Slater & Usoh, 1994, p. 2)

For this reason an adequate body representation is necessary in a VE, but the level or fidelity of representation depends on the type of task to be performed.

C. TECHNOLOGY REQUIREMENTS FOR IVR

An IVR system should ideally support all sensory modalities that are needed for any input or system feedback in a VE.

1. Visual Display

The display systems have come a long way from the bulky cathode ray tube monitors to sleek and curved LED (light emitting diode) screens. HMDs are now common, and they use advanced stereoscopic vision technology for better depth perception. "The displays are mounted close to the eyes and head tracking ensures that the left and right images are updated according to the head movements of the participant with respect to the underlying virtual environment. The separated left and right images for each eye ensure stereo vision" (Slater, 2009, p. 3550). Advanced projection systems include displays in the form of dome, CAVE, hemispherical, table, and tiled grid solutions.

2. Auditory Display

The human auditory system can generate a mental picture of the surrounding environment by perceiving the presence and nature of the objects that produce sound. In a VE there are situations that require generation of sound for certain events (e.g., a soldier fighting amid a virtual battlefield expects to hear the sounds of bullets and explosions once he or she sees them happening in the surroundings). Auditory displays that present 3D sound generate highly immersive effects, and they enable better recognition of proximity and movement of objects and events in the VE.

3. Haptic Display

A number of general haptic devices are available as COTS gear. That includes haptic gloves with tactile feedback actuators, jackets with pressure points, and even body suits to provide tactile feedback at various parts of the body. The haptic systems available today are generally designed to provide haptic sensation for certain parts of the body or might be covering certain portions of the skin to stimulate required tactile sensation. A gadget that can serve as a true haptic device for the entire body seems hard to achieve as it will require a mechanism by which input can be provided for the infinite tactile points on the human body. As a result, makers of this type of display resort to producing devices that have much lower fidelity and are easier to maintain.

Passive haptics can be defined as “a technique that incorporates passive physical objects into virtual environments to physically simulate the virtual objects” (Insko, 2001, p. 9). A lack of passive haptics for certain environments (e.g., a marksmanship simulation system) can affect tasks an operator has to perform. As an example, in the absence of a hefty launcher the user can move the imposter weapon much more swiftly than the actual launcher. Also, a particular haptic setup (or complete absence of a haptic system) may give the operator’s head more freedom of movement than it would have while holding an actual launcher. All these factors could result in negative transfer of training that may jeopardize acquiring the correct requisite skill.

4. Body Tracking

In any VR system, body tracking is performed to capture movements of various body parts so they can be appropriately generated for the virtual body. This is done to satisfy and match a user's kinesthetic (i.e., the sense that indicates whether the body is moving with required effort) (Proske & Gandevia, 2012), and proprioceptive senses (i.e., the sense of knowing the relative position of body parts and awareness of one's own posture) with the visual sensory input regarding depiction of body movement in the VE, thereby maintaining presence. For this purpose, various techniques are currently being used, including motion tracking cameras and sensors. Computer games now commonly utilize devices like Microsoft Kinect and Leap Motion to track different parts of a player's body in games.

D. VR TECHNOLOGY AND TRAINING DOMAIN

The VR technology offers promising training opportunities in various civil and military domains. The main reason VR trainers are finding popularity in military training is that they are cost effective (they may save considerable resources), and when portable they are not restricted by time and location. Additionally, they can present military operational scenarios that cannot normally be achieved due to risks involved or simply because such situations are unattainable during peacetime. Among the most common examples of VR trainers are Tactical Flight simulators that are used extensively to train fighter pilots for employment of air-to-air and air-to-ground weapons in varied kinds of air combat scenarios. Other examples include bridge simulators for ships, car driving simulators, tactical ground combat simulators, and marksmanship trainers. VR technology is now also being employed in various areas of medical training like surgery procedures, administration of medicine injections, patient check-up and diagnosis based on physical symptoms, and many more (Seymour et al., 2002; Jacobus & Griffin, 1998). Even more so, now researchers approach the study of different phenomena in the education field using VR trainers to teach and evaluate the skills enhancement of students (Mantovani, 2001; Psotka, 1995).

The goal of any training system is to improve the performance of the trainee and enhance the trainee's skills for executing an assigned task efficiently and effectively. For this purpose, various teaching methods and tools are used to ensure maximum transfer of training. In the field of education and training, simulators and VR trainers are also considered as tools for achieving those goals. This consideration automatically connects the use of IVR technology with transfer of training, which leads to task performance improvement.

Examples of VR trainers include parachute simulators by Parasim® used for para-jump training in various scenarios and is installed at the 182nd Airlift Wing (U.S. Air National Guard, 2013). Another example of VR technology in military simulation training is the Future Immersive Training Environment for infantry personnel, which works in a networked environment (Pellerin, 2011). In both simulators, the trainees wear headsets to experience the VE in visual and auditory sensory modality.

An example of a more recent study that focused on the feasibility of designing and developing a training system using COTS solutions was done by Lt. Gruenke of the U.S. Navy. In his thesis study (2015), Greunke used VR technology to develop a lightweight trainer for the LSO community. The apparatus used in the study included an Oculus Rift HMD, Leap Motion controller, and game controller. Leap Motion was used to track hand movements so that the system could simulate the user's interaction with the virtual LSO display system. The software was developed in Unity3D and used a number of high fidelity 3D models of different air assets and the carrier. The study concluded that it was possible to use COTS technologies to achieve an immersive environment of high performance and present a complex scenario with necessary visual, auditory, and haptic information while tracking the head and hands motion (Greunke, 2015).

E. USE OF PASSIVE HAPTICS IN TRAINING

Use of physical objects to provide feedback to the user through an object's shape is a technique called passive haptics (Lindeman et al., 1999). One example of passive haptics designed for a study used visually-immersive environment coupled with real walking (Insko, 2001). In that study, the user wore an HMD, and the actual physical

objects were never seen directly, only felt. Moreover, certain compelling results were found in favor of using passive haptics in training. Results showed that passive haptics actually enhanced transfer of training when the participants performed in actual situations. These trainees had better cognitive mapping of the physical world than the ones who were trained without passive haptics.

In another study, by Sallnäs et al. (Sallnäs, Rassmus-Gröhn, & Sjöström, 2000), it was found that haptic feedback significantly improved task performance and perceived virtual presence in collaborative distributed environments. While implementing passive haptics in VEs, one of the metaphors more widely implemented is “a virtual hand that maps movements of the participant’s hand in movements of a virtual object” (Viciano-Abad et al., 2010, p. 199). Regarding use of passive haptics in VEs, it was suggested in same study that providing haptic feedback “enhances interaction by increasing both the sense of presence and the task performance” (Viciano-Abad et al., 2010, p. 208).

Few studies have been conducted where VR technology and passive haptics have been used in developing solutions for military applications, claiming their significance for training transfer and improving skill acquisition. One study conducted by William W. Yates quantitatively assessed the training transfer effectiveness of an indoor shooting marksmanship trainer (ISMT) for the M-162A Rifle (Yates, 2004). During the course of this study, the comparison of score performance for test and control groups indicated no statistical difference between those getting marksmanship training on ISMT and those without it. However, it was revealed that training on the system improved the proficiency of the subjects qualitatively. The study further noted that the ISMT system does contribute toward training by helping instructors understand trainees’ mistakes and take remedial actions.

Passive haptics have a range of potential applications in the field of medical training. In a study that focused on the role of passive haptics in medical simulators (Coles, Meglan, & John, 2011), many specializations have been discussed where commercial haptic devices and related software development kits (SDK) have found implementation in medical simulators. The haptic devices were deemed of vital importance where diagnosis and treatment relied on physical examination and touch,

such as palpation in which the fingers are used to locate presence or absence of different parts of human anatomy beneath the skin. Similarly, the procedures involving needle insertion, endoscopy, laparoscopy, endovascular procedures, and arthroscopy were the domains where the medical simulators used various devices that produced force feedback and tactile sensation. The research also concluded that high fidelity is required for medical tools training while for clinical skills low fidelity medical simulators might also be helpful.

F. COMMERCIAL-OFF-THE-SHELF SYSTEMS

VR technology has become robust, has good performance, and is affordable, which has ensured its becoming very common. One of the promising fields where it may find its main potential is the computer gaming industry. Many input and output devices intended for VR use offer special SDKs and application programming interface (API) for developing and incorporating that VR hardware into the applications. Some of the popular VR supporting hardware includes HMDs like the Oculus Rift, HTC Vive, and Samsung VR Gear; while for body tracking there is Leap Motion and Microsoft Kinect. In the computer gaming industry, Unity 3D is a popular gaming engine as it features tools that provide a variety of graphical effects, and development using such tools is much easier when compared to other SDKs such as Microsoft DirectX and OpenGL. A variety of online support in the form of technical how-to manuals and ready-made packages enables rapid application development.

The shift toward COTS technologies in development of military simulators mainly revolves around initial cost that is very low when compared to special purpose custom-made devices; the costs associated with operations and support are also low. Military specification simulators come with an exorbitant purchase price and correspondingly huge maintenance costs. Being confined to only a few specialized vendors, purchasers find the operations and support are also very expensive and difficult. COTS technologies, on the other hand, are not constricted by such limitations; they have much cheaper maintenance and offer a large number of modules without fees. Owing to the compatible interfaces among commercial devices and the provision of specialized

APIs in different programming languages, a wide variety of mix-and-match hardware and software approaches can be implemented to develop training solutions. As a result, a much larger number of users or trainees can now get easily familiarized with the commercial devices and use such systems.

Several investigations have focused on the feasibility of building some highly demanding training solutions by employing only COTS. Maj. Jesse Attig of USMC used COTS software and hardware technology in his thesis to develop a supplemental training solution for helicopter marine light attack pilots (Attig, 2016). The prototype simulation system was focused on combat air support missions and was proposed as an intermediary training solution for transitioning from ground-schooling to actual flying or flight simulators. Maj. Attig used Unity 3D to build a synthetic environment that was depicted as a single view with first and third person perspectives. The application was originally made for tablet, and it was also ported on a PC or a laptop. The application was designed to be lightweight enough to be run by trainees on their personal devices.

Similarly, Capt. Nick Arthur of USMC selected COTS apparatus for his thesis research. Using Unity 3D he built a proof of concept part task trainer for instrument approach procedures in the aviation domain (Arthur, 2017). The prototype could be run on a laptop, tablet, or a PC. Such solutions are free from the limitations of being tied to one location or specialized hardware and can yield maximum productivity in terms of usage for training and trainee throughput.

G. CHAPTER SUMMARY

This chapter reviewed the basic definition of IVR and discussed various characteristics of those systems. Implementation of VE demands certain technologies that can interact with human sensory systems and provide the expected input. Major contribution types of technology are broadly discussed followed by the use of VR in training domain. Various studies have been mentioned that discuss passive haptics application in the medical training domains. At the close of the chapter, the expanded use of COTS equipment for military training was discussed in the context of studies that used VR software and hardware technologies in their respective research.

IV. TASK ANALYSIS

A. INTRODUCTION

Task analysis is “any process that identifies and examines the tasks that must be performed by users when they interact with systems. It is a fundamental approach which assists in achieving higher safety, productivity and availability standards” (Kirwan & Ainsworth, 1992, p. vii). At another place in the same publication, Kirwan defines task analysis as “the study of what an operator (or team of operators) is required to do, in terms of actions and/or cognitive processes, to achieve a system goal” (1992, p. 1). It is a process that requires comprehensive collection of action data, as well as elaborate description and representation of all the tasks that are performed to do a prescribed job. Detailing task performance specifications is an important ingredient of task analysis. “These specifications describe how the task is actually performed (performance steps), under what conditions it is performed, and how well the individual must perform it (performance standards)” (United States Department of Defense, 1997, p. 47).

In order to design and develop a training system or solution it is imperative to study, understand, and analyze all the tasks for which the user is going to be trained on the system. In military operations training, it calls for understanding concept of operation, equipment features, operating procedures, and tactics.

The information in Sections B, C, and D of this chapter is derived from U.S. Army field manual (FM 44–18-1): *Stinger Team Operations*, U.S. Army field manual (FM 44–18): *Air Defense Artillery Employment Stinger*, and the U.S. Marine Corps publication (MCRP 3–25.10A): *Low Altitude Air Defense (LAAD) Gunners’ Handbook*.

B. STINGER MISSILE SYSTEM: AN OVERVIEW

The full nomenclature of this system used in the military world is “FIM-92 Stinger” weapon system. It is a man-portable, shoulder-mounted weapon and has IR homing (heat seeking) guidance system. Being a fire-and-forget technology, it requires no control by the gunner once fired. It falls in the category of short-range air defense (SHORAD) system and is highly effective against low-level, high speed ground attack

aircraft and helicopters. Due to good agility, it can target the aircraft during attack maneuvers and can engage them at all aspects. The system was developed and produced by General Dynamics and later by Raytheon Missile Systems USA. The different components of the missile system are briefly discussed in this section based on information available from the United States Marine Corps (2011) and the United States Department of the Army (1984).

1. Launcher Assembly

The Stinger weapon consists of the following components (Figure 6): missile round, detachable gripstock, and battery coolant unit (BCU) (United States Marine Corps, 2011).

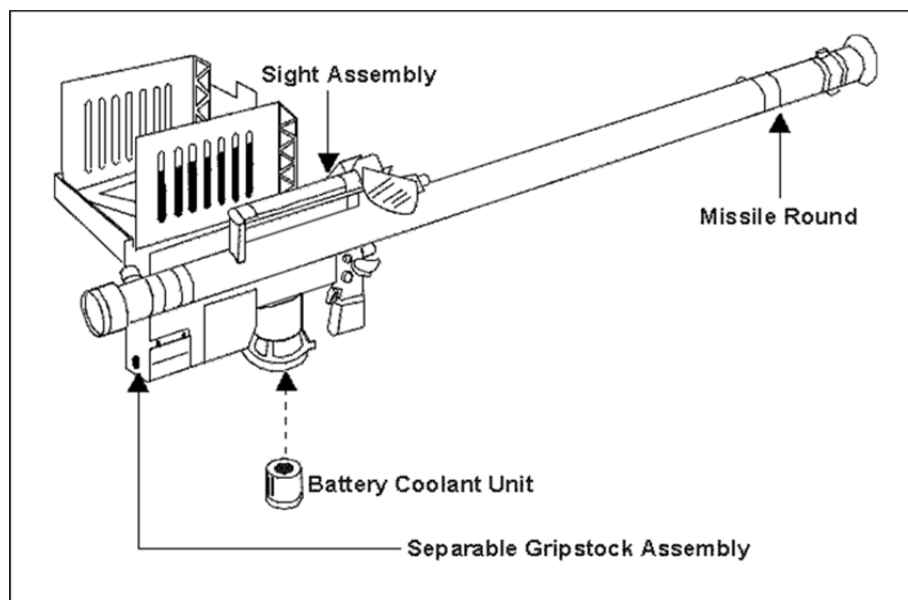


Figure 6. Stinger weapon launcher with missile round.
Source: United States Marine Corps (2011).

a. *Missile Round*

The missile round is enclosed in a glass fiber launch tube, which is sealed at both ends with glass for protecting the missile seeker from humidity, heat, and dust. A sight assembly is attached to the launch tube, which allows the operator to range and track

aircraft. It is retractable and can be brought to its active position after the launcher is taken out of the case. Two acquisition indicators are also located on sight assembly. The first indicator is the speaker for generating tones representing IR acquisition and IFF (Identification Friend or Foe) identification; second is a bone transducer that generates vibrations and allows the gunner to feel acquisition signals on his cheekbone. The tube also has an IFF antenna that can be folded (United States Marine Corps, 2011).

b. Detachable Gripstock

The gripstock assembly is detachable and consists of the gripstock and the IFF antenna assembly. It houses all the circuitry and components required to initiate and prepare the missile for a launch. The IFF antenna can be folded before securing into the launcher case or once it is to be carried by the personnel (United States Marine Corps, 2011).

c. Battery and Coolant Unit

The BCU is a consumable item containing a thermal battery that provides power for pre-launch system operations. It also supplies argon gas for cooling down the IR detector and the missile seeker. After a single use, it is removed from the gripstock BCU housing and immediately discarded (United States Marine Corps, 2011).

2. Missile Features

The main missile components are shown in Figure 7.

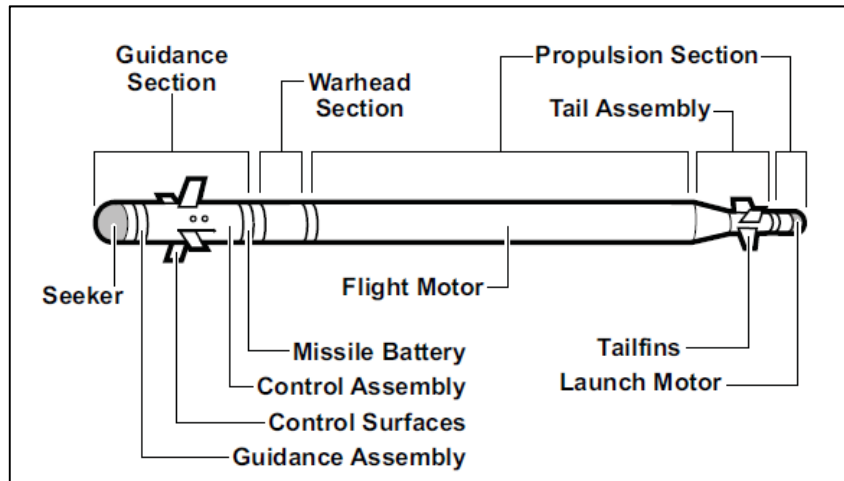


Figure 7. Stinger missile components. Source: United States Marine Corps (2011).

a. Guidance Section

“This section comprises the seeker assembly, guidance assembly, control assembly, a missile battery, and four control surfaces to provide in-flight maneuverability” (United States Marine Corps, 2011, p. 2-2).

b. Warhead Section

The warhead section consists of a fuze assembly along with high explosives enclosed inside a pyrophoric titanium cylinder casing. The fuze is of proximity type and detonates the warhead once in close enough proximity of the target or it detonates upon penetrating the target (United States Marine Corps, 2011).

c. Propulsion Section

This section comprises a launch motor and a flight boost motor. The launch motor safely ejects the missile from the tube. The missile covers a distance of roughly 09 meters before the flight boost motor ignites and provides thrust for attaining maximum speed rapidly (United States Department of the Army, 1984).

The dimensions and few salient features of the Stinger missile are shown in Table 1.

Table 1. Stinger missile salient features

Features	Parameters
Length	1.47 m
Diameter	69 mm
Weight	22 lb
Warhead	6.0 lb
Max Speed	Mach 2.2
Min Range	0.2 km
Max Range	4 km
Self-destruction time	15 – 19 sec

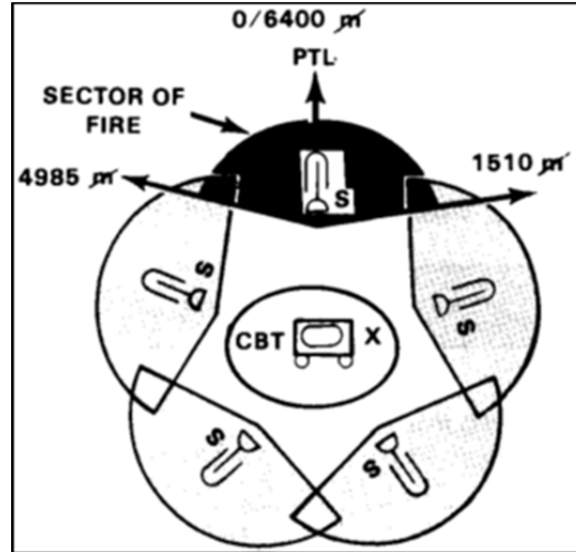
Adapted from United States Marine Corps (2011); Jane's IHS (n.d.).

C. CONCEPT OF OPERATIONS

The MANPADS posts are part of a bigger air defense deployment plan and structure in which own VAs and VPs are defended using a variety of weapons and sensors. In any military conflict, a threat perception is conducted in which VAs and VPs of strategic and tactical importance are first marked, as they are targets for the enemy. These include bridges that link lines of communication, forward airfields from where airstrikes on enemy land forces are conducted, army units deployed close to conflict borders, power houses, fuel dumps, etc. The air defense plan is usually laid out in layers with outer weapons having farther ranges and lesser range weapons deployed in the inner layers. The outer layer weapons are normally augmented by sensors and have long-range guidance systems. If the target escapes a weapon system, it is assigned to the next inner weapon layer to be engaged. In situations where sensor coverage is not available and short-range weapons are the only defense; target aircraft are visually acquired and identified on-the-spot as friendly or hostile. In other situations, the short-range weapons get early warning with necessary information about the target from the higher echelon.

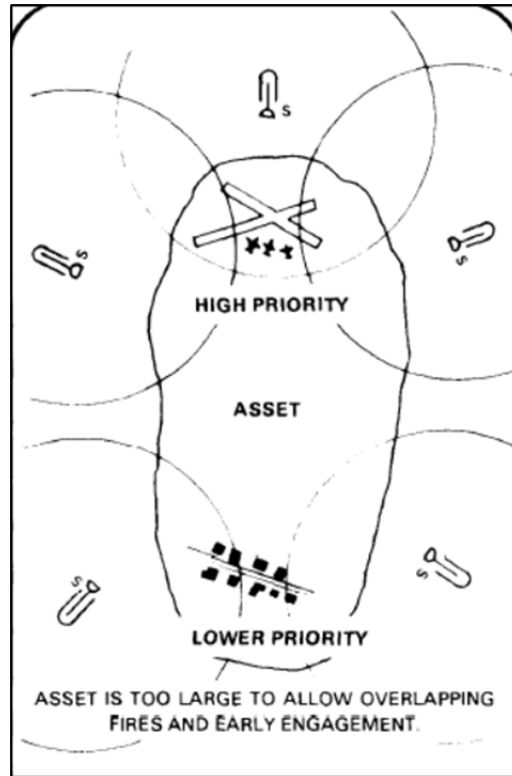
1. Weapon Deployment

The system is deployed normally in conjunction with other air defense assets and is integrated into an overarching aerial defense plan. Before deployment around the installation to be defended, requisite reconnaissance of the area is carried out. Threat corridors are analyzed for probable attack approaches. This requires meticulous planning, taking into account type and size of VP to be defended, terrain around the VP, probable aircraft platform, and type of ammunition load likely to be used in an attack. Adequate missile sites are then marked for covering all probable threat corridors. Selection of a particular site requires having the area clear of any obstruction like high-rise building, trees, electric wires, etc. Installations like airfields and runways may require five to seven missile sites to be deployed in order to cover all approach corridors. Also, the teams have to be deployed in a manner such that they overlap each other and do not leave any gaps for the intruders to sneak in or exit. Some of the general deployment patterns are depicted in Figures 8 and 9 (United States Department of the Army, 1981).



Overlapped coverage of missile engagement sectors from all sides, the black arch shows main missile sector of threat.

Figure 8. Missile post deployment pattern around army unit.
Source: United States Department of the Army (1981).



High priority target having overlapped coverage to safeguard from all sides; low priority target only covers likely threat approaches with possible gaps in all around coverage.

Figure 9. Missile posts deployment for high and low priority targets.
Source: United States Department of the Army (1981).

2. Command and Control

There can be several missile posts deployed for the defense of VA or VP depending upon the area of operation. All missile posts fall under a single command post headed by a section chief (United States Department of the Army, 1984). The command post is primarily responsible for coordinating and controlling the under-command missile posts. A command post is usually located at long distances from missile posts, and uses tactical radio and landline links for communication. Using these links, various commands and control orders are passed to the subordinate missile posts that include fire control orders, state of readiness, and air defense warning issuance. Each missile post has to update the command post with information that includes readiness state, weapon status, and situation reports. The command post has the overall picture of the area regarding

incoming threats, target assignments, neutralized targets, and status of every under-command missile post. This picture is built on info provided by the higher echelon and updates provided by missile posts. Based on this picture and rules of engagement, the section chief is able to assign targets to missile posts. The fire control orders given by the section chief, along with their interpretation, are shown in Table 2 (United States Department of the Army, 1984).

Table 2. Fire control orders with description. Adapted from United States Department of the Army (1984).

Fire Control Orders	
Engage	Engage the allocated target. Latest order voids any fire control order passed previously.
Cease engagement	Stop taking any action against the target and prepare to engage another target. It is also used in cases where a more threatening target is detected or is of high priority. It can also be used to avoid a single target being engaged by multiple missile posts.
Hold fire	This fire control order is used in emergency situations to immediately stop firing. This may be used in situations to prevent friendly aircraft being fired at or due to other safety reasons.

3. Stinger Team

Each missile post is manned by a Stinger team, which consists of a team chief and the gunner. The team chief is primarily responsible for making the target engagement decision. He is also responsible for visually searching, establishing contact, and visual identification of the aircraft before finally ordering gunner for target engagement. The team chief also keeps communication with the section chief for updating status and receiving orders. The gunner is primarily responsible for operating the weapon system and holds the missile launcher once a threat is imminent. He waits for the team chief to give a go ahead before firing at the detected target. In the case of multiple threats, both

gunner and team chief operate separate weapon systems to neutralize maximum target aircraft (United States Department of the Army, 1984).

4. Early Warning

Early target detection and identification provides requisite time for the gunner to step through the firing procedure and ensure successful target kill. Early warning is a necessary element that greatly enhances the chances of target kill in a time-critical scenario. Any aircraft heading toward the defended area is identified as a positive threat and declared as hostile, all weapons are alerted by the command post. Depending on the direction of the approaching threat and its range from own defended area, that target is allocated to the weapon post located in the approach corridor along with initial information (e.g., threat direction, heading, speed, height, and probable aircraft type). This information is generally relayed over tactical links and sent as voice or text messages depending on the type of data link and display devices available at the weapon posts.

5. Methods of Engagement

The method adopted for target engagement depends on the number of aircraft in a scenario. Aircraft attacking a ground target is known as a raid. A raid may consist of single or multiple aircraft flying in a certain formation with the same speed and certain distance (United States Department of the Army, 1984).

a. Multi-Aircraft Raid

Two or more aircraft that fly on the same heading, with same speed, and maintaining mutual distance of less than 1000 meters, constitute a multi-target raid (United States Department of the Army, 1984). The aircraft in this kind of raid are engaged using shoot-new target-shoot technique. It requires firing of missiles in a successive manner in order to achieve maximum target kill. In this case, both the gunner and team chief can fire simultaneously, targeting different aircraft in the raid to shoot down maximum aircraft. In case a friendly aircraft is present in the vicinity of the target, the engagement is called off (United States Department of the Army, 1984).

b. Single Aircraft Raid

A single aircraft raid consists of a single aircraft carrying out an attack and can be any composition of aircraft other than that defined in a multi-target raid (United States Department of the Army, 1984). The firing strategy adopted in this kind of scenario is shoot-look-shoot. Once the team gets initial information about an incoming raid, the gunner gets the launcher into shooting position and the team chief starts to scan area in the given direction. Once the aircraft is spotted, the team chief visually identifies it to be positively hostile and then orders the gunner to engage (United States Department of the Army, 1984).

D. STINGER WEAPON SYSTEM EMPLOYMENT

The steps and procedures involved in the employment of stinger weapon system are discussed as follows:

1. Target Search and Detection

In the case of an imminent aerial threat, a warning is issued to the stinger team, which is assigned to search in a certain sector. The sector is defined in both azimuth and elevation. Detection is easy if the threat sector is small, such as 30 degrees; but if it is large (e.g., 90 degrees), target detection becomes a difficult task. This can lead to delayed target detection and subsequent acquisition. Certain scan patterns are followed to visually search the area and focus on certain spots, keeping in view sun direction and background terrain. Two systematic methods are followed to search the area for aircraft; these methods are discussed as follows (United States Department of the Army, 1984):

- In the first method, as shown in Figure 10, the observer starts to search at 20 degrees above the horizon and scans by moving his eyes across the sky horizontally. He goes all the way up to the maximum azimuth and then across to work downwards to the horizon and further below to detect any aircraft flying nap-of-the-earth (United States Department of the Army, 1984).



Figure 10. Horizontal scan pattern of the threat sector.
Source: United States Department of the Army (1984).

- In the second method, as shown in Figure 11, the observer keeps the horizon as the reference and moves his eyes vertically up-and-down in short movements as he scans the terrain horizontally. Areas below the horizon are also scanned for aircraft flying nap-of-the-earth. Once the sector's horizontal limit is reached, the observer scans up into the sky and follows the same pattern while moving his eyes across horizontally in the opposite direction (United States Department of the Army, 1984).

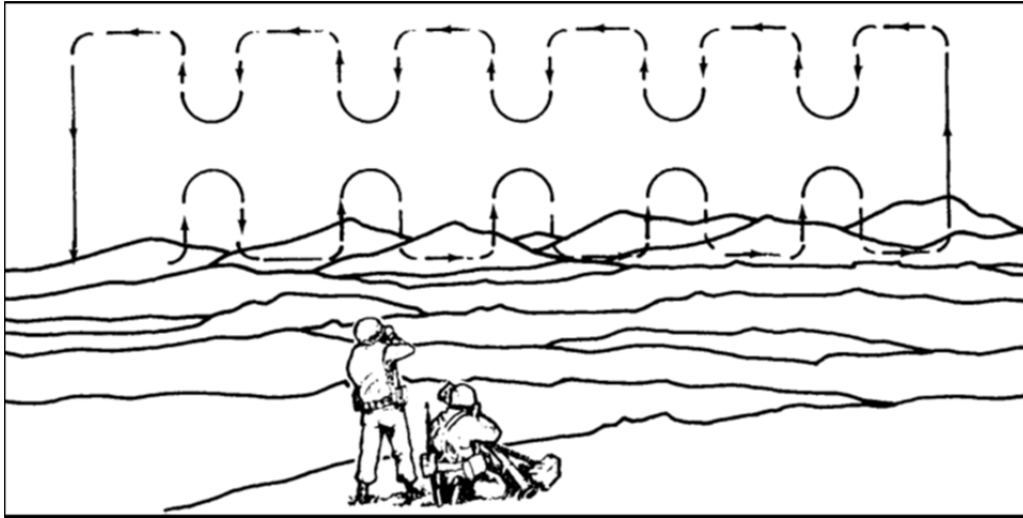


Figure 11. Vertical scan pattern of threat sector. Source: United States Department of the Army (1984).

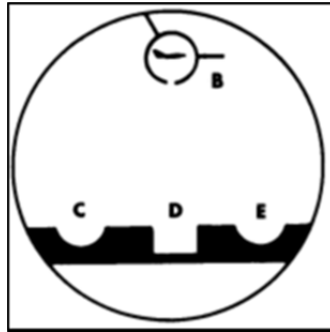
2. Target Engagement

Engaging high-speed aircraft is a challenging task, as it may allow only 10–20 seconds after aircraft detection (United States Department of the Army, 1984). This demands a rapid and automatic response to accomplish a successful engagement. Certain aspects that need to be considered while making a decision for engagement are discussed in the sections that follow (United States Department of the Army, 1984):

a. Aircraft Direction

Once the aircraft has been visually detected, the first step is to ascertain the aircraft's direction. This is done by weapon sighting; that is, aligning the aircraft image within the range ring of the weapon sight (shown in Figure 12). The gunner must adopt the correct posture at this point by stepping toward the target with the left foot and leaning toward the target. Now the gunner's body movement will indicate the aircraft movement direction. Any horizontal movement of the gunner's arms and upper body will indicate that the aircraft is crossing. Lack of significant horizontal body movement will indicate the aircraft as incoming or outgoing. Any vertical body movement will also indicate the aircraft to be incoming or outgoing. As the target appears bigger or smaller it

also helps to indicate whether the aircraft is crossing over or incoming/outgoing (United States Department of the Army, 1984).



As seen through the optical sight, aircraft image aligned in range ring with rear reticle in the bottom.

Figure 12. Assessing aircraft direction through launcher optical sight.
Source: United States Department of the Army (1984).

b. Aircraft Posture

During wartime, if an unidentified aircraft is detected, the team chief has to make the engagement decision. Any aircraft entering into the defended territory is considered as hostile unless positively identified as friendly. IFF equipment installed on a Stinger is used to challenge the aircraft. If the aircraft does not respond correctly, it is considered as hostile and the gunner is ordered to proceed for engagement. In the case of positive IFF response, the engagement is canceled. The engagement decision will also depend on the standing orders, local operating procedures, and standard operating procedures conveyed by the higher command (United States Department of the Army, 1984).

c. Aircraft Type

The aircraft have been divided into two categories for the purpose of a Stinger engagement, such as the jet and the propeller. The jet type includes all jet aircraft while the propeller type constitutes all other propeller-driven aircraft as well as helicopters. This determination is important and should be done as early as possible as it effects aligning of the aircraft inside the weapon's sight. The time limit available for

engagements also differs for each aircraft type (United States Department of the Army, 1984).

d. Aircraft Range

Range evaluation must be done by the gunner to determine if the target is within the effective missile range. Depending on the range and type of aircraft, engagement rules would be applied while making the engagement decision. This process allows the gunner to make the decision to fire within effective missile launch parameters in that particular situation or conversely withhold fire for targets lying outside launch boundaries (United States Department of the Army, 1984).

1. For incoming/outgoing jet aircraft, the decision is dependent on the range ring measurement. This is done by bringing the aircraft image into the range ring to evaluate its size, which is measured with reference to the range ring size as shown in Figure 13. For example, the aircraft size can be one-half of the range ring or one-quarter of the range ring, and the launch is done once the image reaches a certain size. The measurements guiding launch decision are classified and mentioned in FM 44-1A (United States Department of the Army, 1984).

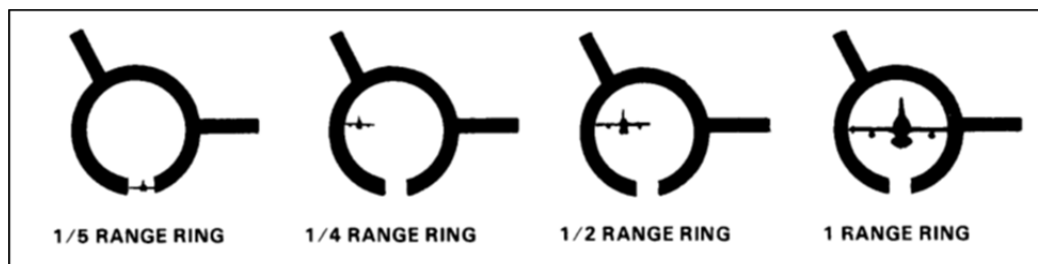


Figure 13. Incoming/outgoing aircraft size measurement with reference to range ring. Source: United States Department of the Army (1984).

2. For jet aircraft that have been determined as crossing, the decision is made on a time count rule (United States Department of the Army, 1984). In this procedure, the gunner keeps the weapon sight slightly ahead of the aircraft

and then holds it stationary as shown in Figure 14. As soon as the aircraft nose touches a certain point in the sight, the gunner begins counting in seconds (i.e., one thousand one, one thousand two, and so on). As the aircraft horizontally travels and reaches another fixed point, the gunner stops counting. If the number of seconds counted is equal to or below the correct reference time, the launch is made. Otherwise, the launch is withheld. The time count references for missile launch, hold fire, or activate are classified and mentioned in army FM 44-1A (United States Department of the Army, 1984).

3. For propeller aircraft, including both fixed wing and helicopters, neither range ring measurements nor time count is required. The gunner can fire as soon as the missile is activated and IR lock-on is achieved (United States Department of the Army, 1984).

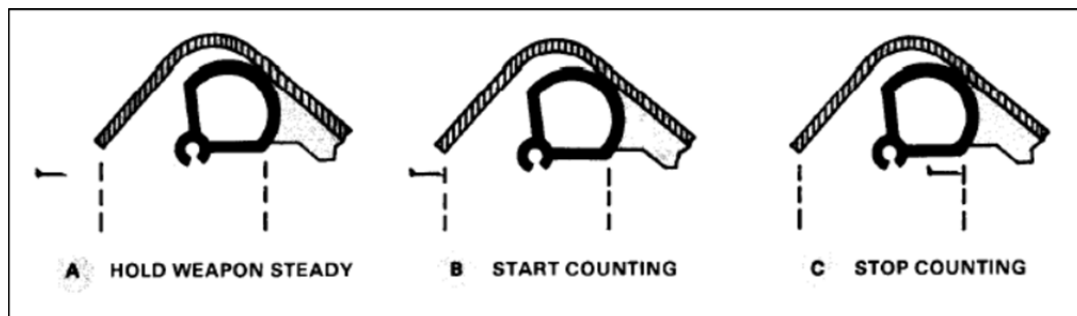


Figure 14. Jet aircraft crossing time count using Stinger optical sight.
Source: United States Department of the Army (1984).

3. Target Identification

IFF is a basic identification system used both in military and civil aviation. It has two main components: the interrogator and the transponder. The interrogator is installed at ground as an integrated module within the radar or as a separate piece of equipment; the transponder is installed on the aircraft. The interrogator is also known as the secondary radar and challenges aircraft by sending out electromagnetic pulses carrying mode and code information. The transponder receives the signal, processes it, and sends

back the response. If the IFF of the aircraft is off or does not respond, it is considered as unidentified. The IFF mode and code selections are done at both the interrogator and transponder ends based on a pre-decided plan.

The Stinger launcher is also equipped with the IFF interrogator, and aircraft can be challenged against the pre-decided IFF modes and codes. If an unidentified aircraft enters into a defended area, the next step after detection is to identify the aircraft via IFF. This is to be done in tandem with range estimation as the aircraft's image is brought inside the range ring. The aircraft is challenged by pressing the IFF interrogator switch as shown in Figure 15.

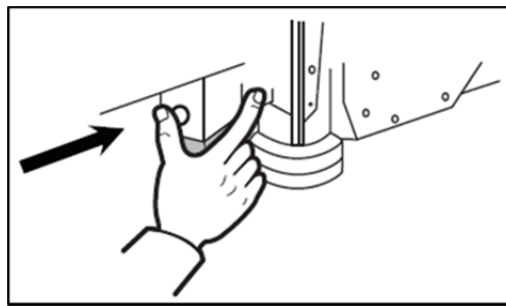


Figure 15. IFF interrogator button on Stinger launcher.
Source: United States Marine Corps (2011).

The IFF response is in the form of beeps that are interpreted as follows (United States Marine Corps, 2011):

- Many beeps mean aircraft not identified
- Two beeps show a positive friend
- One beep represents possible friend
- No beep is an IFF malfunction

4. Missile Launch Sequence

Having gone through the procedures for target detection, ranging, and positive identification, the operator initiates the final launch sequence for firing the missile. It involves operating various switches on the launcher in order to successfully fire the missile. These steps are discussed as follows:

1. Weapon activation is done by operating the safety and actuator device, which activates the BCU. The safety and actuator switch is located behind the grip assembly. It can be operated by the thumb while the operator is holding the launcher and pulling the switch out and down (as shown in Figure 16). After weapon activation the gunner has 45 seconds to fire the missile. Failure will necessitate the replacement of the BCU with a new one (United States Marine Corps, 2011).

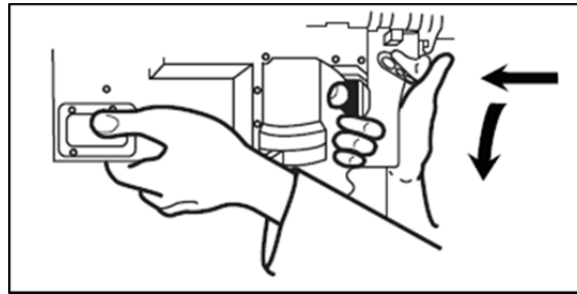


Figure 16. Safety and Actuator switch operation indicated by arrows.
Source: United States Marine Corps (2011).

2. The weapon warms up as it activates certain electrical and mechanical components and the gyro spin-up noise can be heard, which indicates the system is working. The missile seeker starts receiving an IR signature from the atmosphere. The IR input is processed and represented by an audio tone that starts off as the weapon is activated. If the weapon is pointed toward the aircraft, the tone gets louder, and quieter if moved away. The clarity and intensity of the audio tone represent the seeker level of IR acquisition from the aircraft. A Stinger missile seeker can

distinguish between IR coming from a small source such as aircraft exhaust and from a large source (e.g., the terrain or cloud lining) (United States Department of the Army, 1984).

3. After the missile seeker has acquired the aircraft, the uncage button is pressed to release the seeker so that it can freely rotate to track the aircraft. The uncage button is located at the front edge of the grip-stock, and when required, it is pressed and held using the thumb (as shown in Figure 17). After the uncaging of the seeker, the audio tone gets louder and stable, which is an indication that seeker has acquired the aircraft and is tracking it. If the audio tone does not get louder, the uncage button is released, which cages the seeker again. If upon uncaging the tone is weaker or unstable, the seeker could be locking on background. The aircraft is again brought inside the range ring and then the uncage button is pressed (United States Department of the Army, 1984).

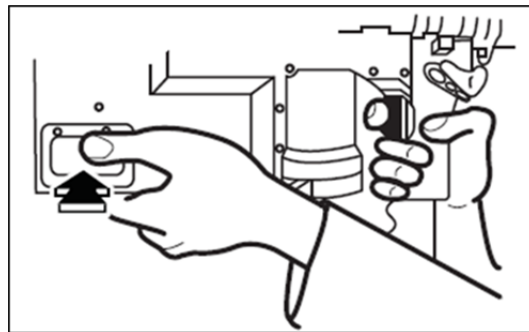


Figure 17. Uncage button press using left hand thumb.
Source: United States Marine Corps (2011).

4. This is followed by super-elevating the weapon by raising its front (as shown in Figure 18). It caters for gravity effects on the missile before the missile motor ignites. After super-elevation, a lead is added by moving the aircraft image from range ring to one of the reticles below it, depending on type of aircraft and its heading (as shown in Figure 19). Finally, the operator presses the trigger to fire the missile. Before firing the operator

needs to make sure that the acquisition tone is clearly audible and that he or she keeps pressing the uncage button while pulling the firing trigger. The breath is held once pulling trigger and is kept still until the trigger is released in order to avoid inhaling the toxic fumes from missile. The gunner should move away from his or her position if the fumes persist at that point (United States Department of the Army, 1984).

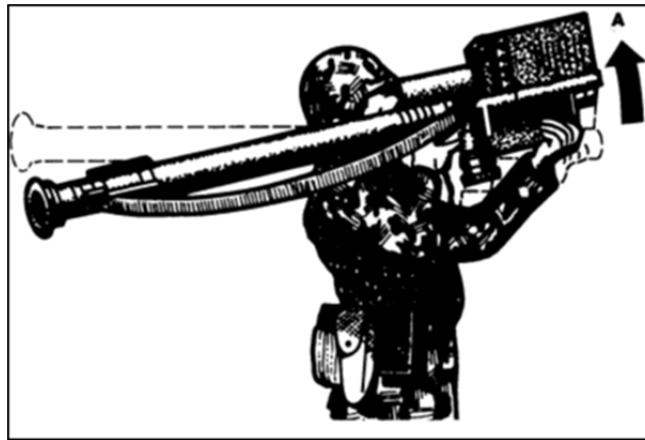


Figure 18. Applying super-elevation to compensate for gravity effect on the missile.
Source: United States Department of the Army (1984).

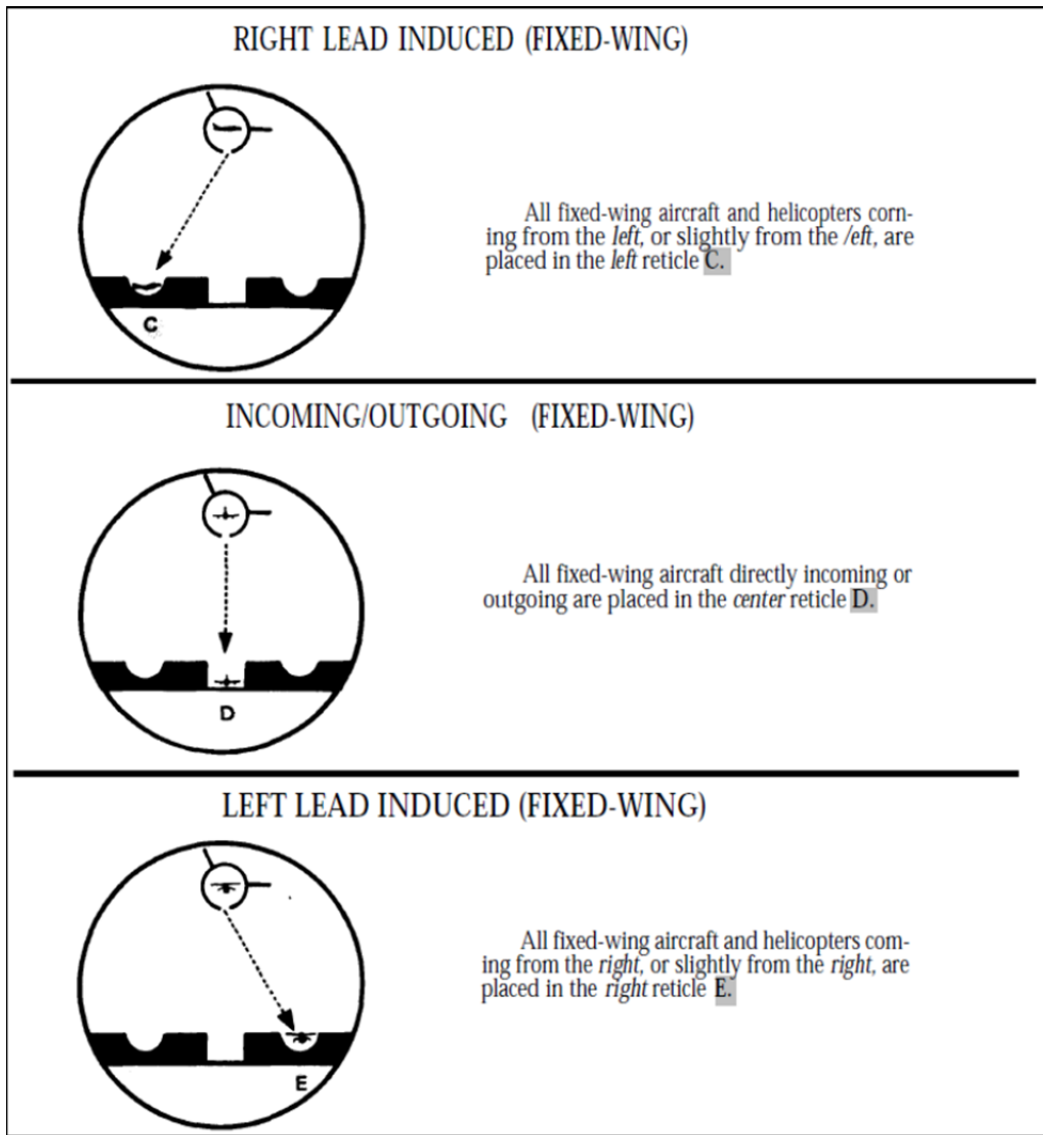


Figure 19. Lead as per type and direction of aircraft. Source: United States Department of the Army (1984).

E. WEAPON OPERATING PROCEDURE SUMMARY

The Stinger round is packed and transported in containers to the deployed site. Owing to its nature of employment, the system is designed such that it can be transported, unpacked, and brought to operational status in a few minutes. After uncaging the weapon from the container, the operator unfolds the IFF antenna and retracts the sight assembly before initiating the launch operation. Before starting the fire sequence it is imperative for the operator to have initial information regarding the approaching threat. This

information is provided by the missile command post (United States Department of the Army, 1984). The following sequence of operation steps is used to operate the Stinger missile system against an aerial threat:

1. Visually search and detect the aircraft.
2. Make sure the BCU is attached to the launcher.
3. Hold launcher in the direction of aerial target and center it in the range ring.
4. Press the IFF interrogator switch to identify the target.
 - If the target is identified as friendly, a beep sound will go off that will last for one and a half seconds. This calls for terminating target tracking and the operator needs to inform the command post of positive friend identification.
 - If a series of short beeps go off, it means the target identity is unknown.
 - No beep sound means the IFF interrogator is defective.
5. After positive target identification, begin to track and range the target through the range ring and wait until the target is in range.
6. Next, pull the safety and actuator device and listen for the acquisition tone.
7. Press the uncage button using the left thumb to free up or uncage the missile seeker.
8. Super-elevate the launcher and give lead by placing aircraft image in one of the lower reticles.
9. Finally, pull the trigger to fire the missile.

F. CHAPTER SUMMARY

This chapter detailed the elements of task analysis; this work has been done to support the development of a tactical MANPADS part task trainer. Successful weapon employment requires correct understanding of the weapon's operation and procedures. In the same context, developing a training system for the operators requires a clear understanding of the tasks that are necessary in operating the weapon system and for the successful accomplishment of a weapon's employment. Various phases for Stinger missile operation and employment have been discussed in detail and need to be considered for any system intended for MANPADS operators' training.

V. SYSTEM DESIGN AND ARCHITECTURE

A. INTRODUCTION

This chapter presents details of the MANPADS simulation system architecture and various aspects that were considered while designing the system. The approach used was to first derive inferences from task analysis and form a firm basis for the system design and considerations therein. This included identification of all sensory stimuli and system requirements that would support required standards of human performance. That step was followed by selecting the most suitable integrated development environment (IDE) for the final hardware and software solution. The resulting prototype training system included virtual terrains, aircraft, missile flight model, and compelling training scenarios. The work also involved crafting of a physical custom-made missile launcher (passive haptics) that provided haptic stimuli to the operator who would hold the launcher, aim, and pull a trigger as in an actual operational environment.

B. TASK ANALYSIS BASED DESIGN REQUIREMENTS

Considering VR essential constituent elements such as presence, immersion, and user representation, it becomes imperative to design an IVR solution that would maximize the conditions for achieving these VR components (different aspects of this domain were discussed in Chapter III). Task analysis outlined in Chapter IV highlighted all necessary decision-making cues and steps required to operate the weapon system, along with the sensory cues available to the operator via simulated environment that integrates visual, auditory and haptic modalities. Along with these cues, the system would also require mechanisms with which the trainee can interact and provide input to the virtual weapon while experiencing a haptic sensation and proprioceptive movements. A multitude of visual and auditory cues were made available to the operator immersed in VE; this included physical interaction with the passive haptics and instrumented elements of the physical prop (triggers and clicks). Those elements were specifically incorporated to help maintain a high level of presence and thus have a better potential to increase the training effectiveness of the entire system.

The necessary elements of operator experience and the steps required to operate a Stinger weapon system in a tactical scenario were inferred from the task analysis outlined in Chapter IV. These understandings helped this author form the requisite system design considerations; they suggested that the following elements of the system needed to be designed and integrated:

- Relevant 3D scenes with considerable environment details so that trainee gets a feeling of being in a realistic surrounding. For example, in the case of an airfield details should include a runway, airfield infrastructure comprising ATC tower, aerodrome traffic signs, and hangars etc.
- Operations characterized as “valley deployments” simulated in a hilly terrain 3D scene with considerable details including vegetation, mountains, and valley corridor for helicopter attacks.
- High fidelity 3D model of a stinger weapon launcher; visualized model would be very close to the observer’s eye and that individual would expect to recognize minute details of the weapon being held.
- Input mechanisms similar to the ones used when operating the Stinger launcher; this mechanism would include triggers and buttons placed at their actual locations.
- Physical launcher body—a prop of compatible dimensions that would provide haptic input to the operator and augment a sense of presence in the VE.
- Model that simulates audio tones representing BCU activation, IR acquisition, as well as bone transducer vibrations generated by the weapon during various phases of firing operation.
- Target acquisition algorithm and missile flight model ‘good enough’ for a prototype simulation.

- Missile launch effects such as sound blast, smoke effects, and ignitor motor detachment to increase the level of realism in the VE and contribute to a greater sense of presence.
- Aircraft bombing profiles with requisite maneuvering for simulating the attack profile; this would provide the necessary amount of difficulty for the operator and increase the level of realism.
- Options to select different times of the day and weather conditions; this would enable practicing weapon employment in different environmental conditions.
- Tracking of the operator's hand movements and their replication in VE; this would ensure a good match between visual stimuli inside VE and the operator's own proprioceptive feedback.

C. CONCEPTUAL SYSTEM DESIGN

There are two basic elements of conceptual system design for the MANPADS training system. The first one is the core simulation module consisting of the software application and related hardware, and the second is the physical missile launcher prop that would act as a passive haptic.

The final training simulation is imagined to have two basic components (modules): one supporting the trainee and another one supporting the instructor. The basic premise behind the two-component idea is that the instructor would be provided with the tool that allows fast generation of the tactical environment (terrain and scenarios), and the trainee component would provide the trainee with an opportunity to experience those and engage the aerial targets in the simulated scenario that was generated by the instructor.

The instructor and the trainee components were initially conceived to be two software applications running on separate stations or PCs connected over the network, which would communicate the data in real time using a network protocol such as UDP

(User Datagram Protocol) or TCP (Transmission Control Protocol). The final solution was to opt for a more flexible setup in which the instructor would generate and save a range of profiles (scenarios) off line. Later these profiles could be selected and executed by the trainees during their individual training sessions.

D. SYSTEM ARCHITECTURE

The system architecture consists of the following functional components along with their respective salient features (Figure 20):

1. Gaming Desktop PC:

- PC Model Dell Alienware Area-51 R2 desktop
- Processor Intel Core i7-5820k 3.30 GHz
- RAM 16 GB
- Graphic card NVIDIA GeForce GTX 1080
- Operating System Windows 10

2. Simulator Application:

- Virtual environment comprising multiple scenes
- High-fidelity Stinger missile 3D model
- Low-fidelity aircraft 3D models of fighter aircraft and helicopter
- Stinger missile IR sensor model and flight model
- Stinger launcher firing sequence simulation
- Aircraft profile generation
- Weather and time of day simulation

3. HTC Vive:

- Headset with front-facing camera and controllers
- Tracking sensors ('lighthouse' tracking approach)
- Working area setup

4. Leap Motion:

- Leap motion device
- Installation kit for HTC Vive headset
- Unity package for integration with VR applications

5. Launcher Mockup:

- Physical prop emulating actual Stinger missile launcher

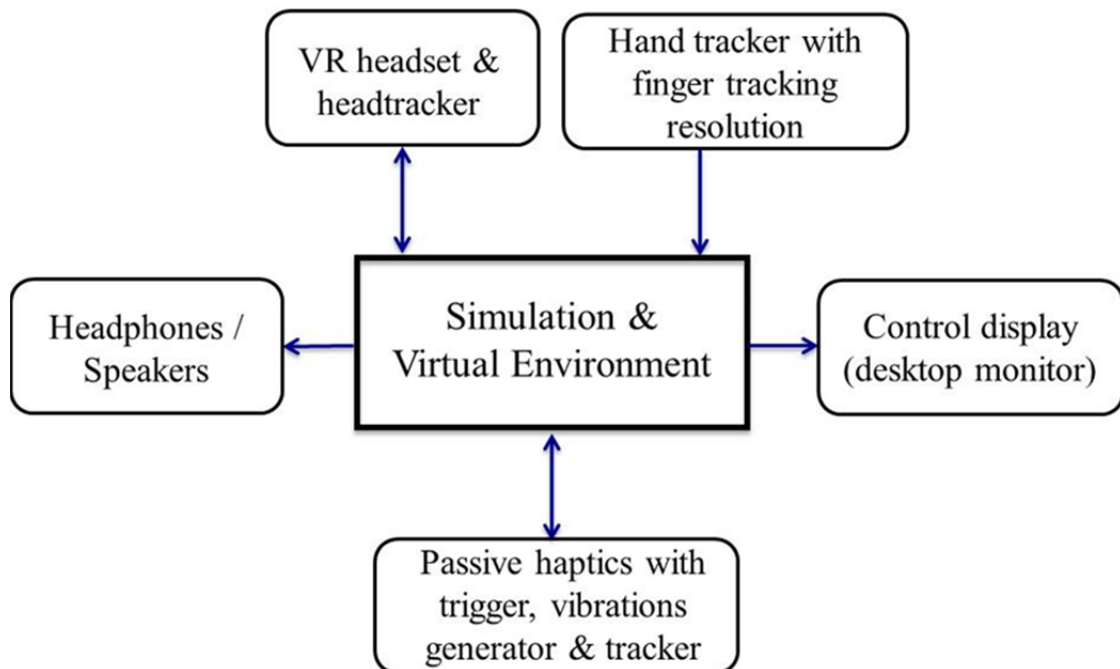


Figure 20. MANPADS conceptual system architecture

The system was designed such that the VE scene was generated by the Unity3D game engine running on the gaming PC. The HTC Vive kit was set up in the room and attached to the gaming PC for relaying generated scenes to the headset. The Vive controller was attached to the launcher physical prop and it tracked the position and orientation of the prop. This tracked data was relayed to the application, which updated the position and orientation of the virtual launcher in the scene. Leap motion was installed on the Vive headset and it tracked the user's hand.

E. CHAPTER SUMMARY

This chapter discussed the various design aspects of the MANPADS prototype system and details of its system architecture. While designing the MANPADS prototype system, this author made several considerations with respect to the claims stated in the hypothesis. The basic idea was to develop a simulation system that made use of fully immersive VR technology along with a physical launcher mockup that acted as passive haptics for the trainee.

VI. SYSTEM DEVELOPMENT

A. INTRODUCTION

This chapter discusses the various phases of development of the prototype MANPADS training simulation. The effort is broken down into two sections: the development of the VR application and the construction of the physical launcher prop. The application development included a detailed design of the application architecture, code implementation in Unity3D and C#, building of scenarios, and testing. The launcher prop construction included a design of the launcher 3D model (used as a part of the virtual environment), followed by construction of the launcher body and additive manufacturing of additional launcher parts using the capabilities of a 3D printer.

B. HARDWARE AND SOFTWARE ARCHITECTURE

The hardware and software architecture was based on the conceptual architecture discussed in Chapter V. Each module of the conceptual architecture was analyzed in terms of its capabilities and features to enable the selection of the right combination of hardware and software (Figure 21). Compatibility among the different modules was a major consideration.

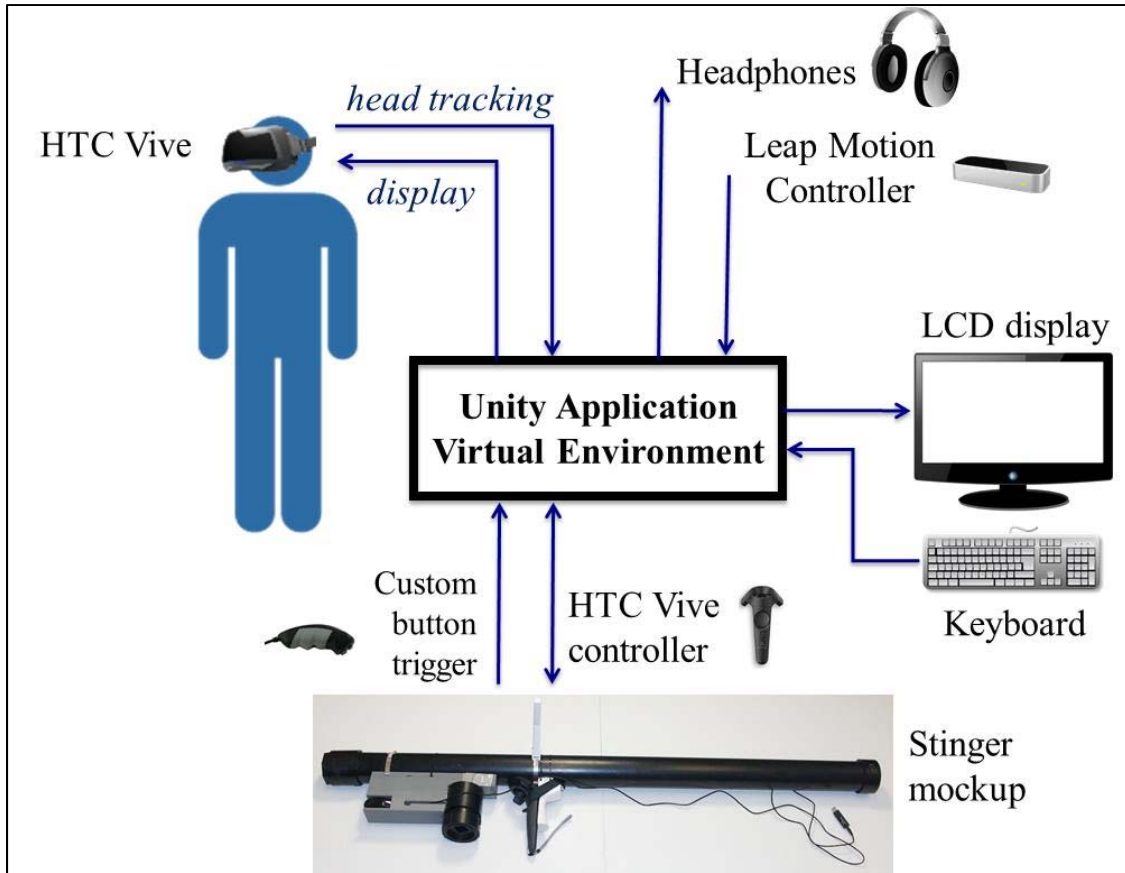


Figure 21. Hardware and software architecture

C. DEVELOPMENT ENVIRONMENT: HARDWARE AND SOFTWARE COMPONENTS

The main elements of the development environment used to support our work included: a fully immersive VR system, hand tracking, passive haptics, Unity 3D game engine, and C#.

1. Fully Immersive VR System

Two VR headsets were considered as fully immersive display solutions for our training system: the HTC Vive and the Oculus Rift.

Salient features of the HTC Vive VR headset are as follows (Davies, 2016):

- (110 horizontal x 113 vertical) degrees field of view (FOV) that provides a wrap-around feeling to the user.

- Resolution: 1200 x 1080 per eye.
- Refresh rate: 90 Hz.
- Pair of handheld controllers (Vive Controllers) that track hand position, orientation, provide controls to perform various actions, and have haptic feedback in the form of vibrations.
- Front facing camera that enables the display of walls and objects as a safety feature.
- IR based 360 degrees laser tracking using base stations.
- Play area: 4 x 3 meters.
- Sensors used in the headset: gyroscope and accelerometer.
- Headset cable allows movement within a maximum distance of 16.5 feet from the station.
- Mechanism to adjust inter-lens distance to fit the characteristics of user's face.
- Lens distance from face can also be adjusted.

Oculus Rift features can be summarized as follows (Davies, 2016):

- FOV: 94 horizontal x 93 vertical degrees.
- Resolution: 1200 x 1080 per eye.
- Refresh rate: 90 Hz.
- Pair of trackable game controllers (Oculus Touch) with motion control and keys.
- Optical 360 degrees IR LED tracking using base station.

- Play area: 2.6 x 1.5 meters.
- Headset cable allows movement within a maximum distance of 13 feet from the station.
- Sensors used in the headset: magnetometer, gyroscope, and accelerometer.
- Mechanism to adjust inter-lens distance.

Based on technical specifications and a need to support larger working volume (tracking area), the author selected the HTC Vive as more suitable for the prototype simulation system.

2. Hand Tracking

Two possible options were considered for hand tracking: Microsoft Kinect and Leap motion. The Leap motion controller was selected for tracking and visual representation of the operator's hands inside the VE because of its flexibility and the fact that it was headset-worn, enabling it to cover the entire volume within which the operator needs to move (Figure 22).



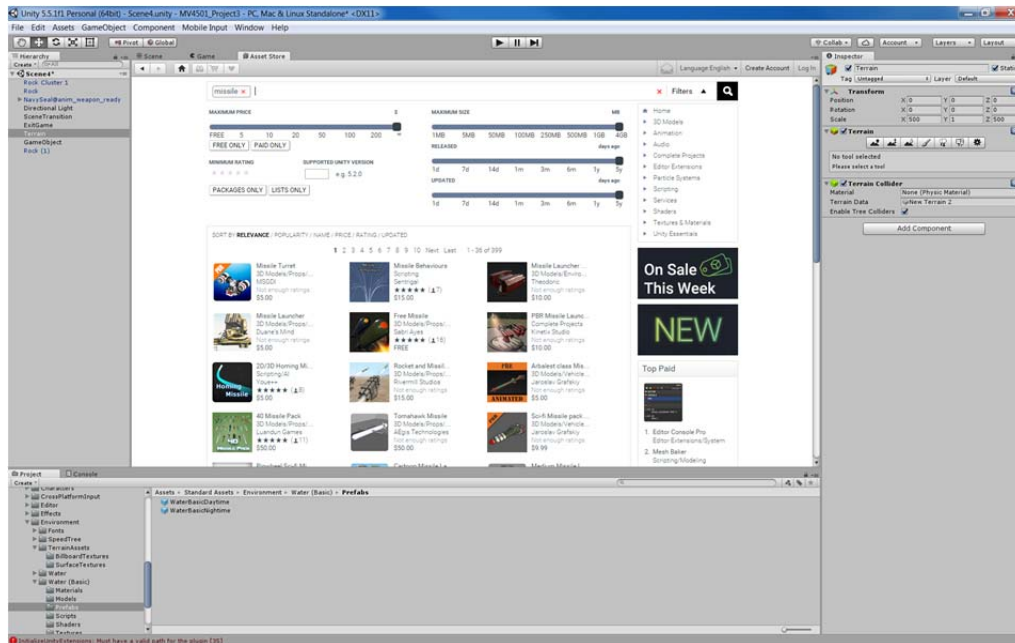
Figure 22. Leap Motion sensor installed on HTC Vive headset.
Source: Leap Motion (n.d.).

3. Passive Haptics

An instrumented physical prop (passive haptics) was built to provide proprioceptive cues to the user and get inputs from the user while he or she is immersed inside the VE. The idea was to craft a Stinger missile launcher mockup of the same weight and dimensions as the actual launcher and have it as a near-real passive haptic device. The author decided that this device would also house the HTC Vive controller to get the position and orientation of the physical launcher mockup and synchronize movement of the 3D launcher inside the virtual environment. Moreover, buttons on the Vive controller were to be used as inputs for the missile launch sequence. The vibration effect of the Vive controller was used to mimic the functionality of the cheek bone transducer that is in the actual launcher.

4. Unity 3D Game Engine

The selection of the underlying game engine was an important element of defining the development environment. The ready answer to this question was Unity3D IDE that also has a game engine. Unity3D is COTS game development software used extensively in the video gaming industry. This system provides an intuitive 3D interface and supports 3D objects in various formats including .obj, .fbx, .dae, .Max, .3ds, .Blend, and .dxf (Unity, 2017). The software provides tools for quick prototyping, and it could be used to build a 3D model with the desired characteristics. Various built-in Unity modules (both no-cost and paid) with specific features and functionalities are available online (Figure 23), allowing the development team to create elaborate scenes and effects very quickly. Additionally, the system has an extensive user base community with online forums where developers can discuss solutions and even collaborate on various problems. All this support comes in very handy and helps accelerate application prototyping.



Access to development packages from within Unity interface supports quick application development.

Figure 23. Unity3D IDE with “Asset Store” interface

5. C# Scripting

Unity3D supports programming using scripting in the C# language. The script files containing program code can be attached to objects as components, which are then invoked upon desired events during application runtime. The scripting can be performed in Visual studio as well as in the MonoDevelop programming interface provided by Unity3D.

D. 3D ASSETS AND TERRAIN

Unity3D IDE allows a programmer to directly incorporate 3D models into the scene by simply importing them via menu option or by drag-and-drop actions. The terrain is also incorporated as a game object that can further be refined using tools that allow adding different elements like vegetation, water, and custom textures.

3D models used for the simulation application included a Stinger missile launcher, terrain model, models of various aircrafts, and a skybox.

1. Stinger Missile Launcher

A high-fidelity Stinger missile launcher with appropriate visual details was used for the prototype simulator application (Figure 24). This model, together with all the other 3D models, was procured and downloaded from turbosquid.com. The model was in .fbx format and was ready for use in the Unity application.



Stinger launcher 3D model used for simulation application developed in Unity3D.

Figure 24. 3D model of FIM-92 Stinger launcher. Source: TurboSquid (n.d).

The model acquired through turbosquid.com required a small number of edits inside the optical sight as it did not have a rear reticle and range ring built inside it. These adjustments were done using the Blender 3D modeling tool. The Army field manual *FM 44-18-1 Stinger Team Operations* (United States Department of the Army, 1984) was referred to for replicating inner details of the optical sight. These modifications made the model of the launcher ready for incorporation in the Unity application. Once the model was imported, the launcher object properties were configured for a realistic weapon look. This was done by selecting the correct rendering maps, including albedo, metallic, normal, height, and occlusion maps, and fine tuning their values. Moreover, tiling, offset, and UV set values were also corrected.

2. 3D Terrain Model

Two 3D models of terrains were used to support the work of the application. The first terrain was a model of an airport (Figure 25), which was also procured from turbosquid.com. The airport model had detailed installations including runways, tarmac, ATC tower, airfield lights, traffic sign boards, communication antennas, and a range of different buildings across the terrain. The other model was a mountainous terrain that was fully built by the author using the 3D object modeling capabilities of the Unity3D IDE (Figure 26).



Commercial airport 3D model downloaded from Unity asset store.

Figure 25. 3D model of a commercial airport. Source: Unity (n.d.).



Mountainous terrain used for valley deployment scenarios.

Figure 26. 3D terrain scene developed by author in Unity3D IDE

3. Aircraft

Various types of 3D aircraft models were required to support a challenging aerial scenario. Fighter aircraft included SU 27 Flanker (Figure 27) and F-20 Tiger shark (Figure 28), and helicopters included MI-24 Hind (Figure 29) and AH-1 Cobra models (Figure 30). These were low-fidelity object models as they were not intended to come in close proximity of the user (represented by a viewpoint), and so the user would not be able to notice a lack of details in the model.



Su-27's 3D model used for application developed in Unity3D.

Figure 27. 3D model—SU-27 Flanker fighter/bomber aircraft.
Source: TurboSquid (n.d.).



T-38's 3D model used for application developed in Unity3D.

Figure 28. 3D model—Fighter trainer T-38 Talon.
Source: TurboSquid (n.d.).



Mi-24's 3D model used for application developed in Unity3D.

Figure 29. 3D model – Mi-24 Hind helicopter. Source: TurboSquid (n.d.).



AH-1's 3D model used for application developed in Unity3D.

Figure 30. 3D model – Bell AH-1 Cobra attack helicopter.
Source: TurboSquid (n.d.).

4. Skybox

Various skyboxes purchased from turbosquid.com were used to simulate a variety of times of day and weather effects (a skybox simulating a sunset is shown in Figure 31).

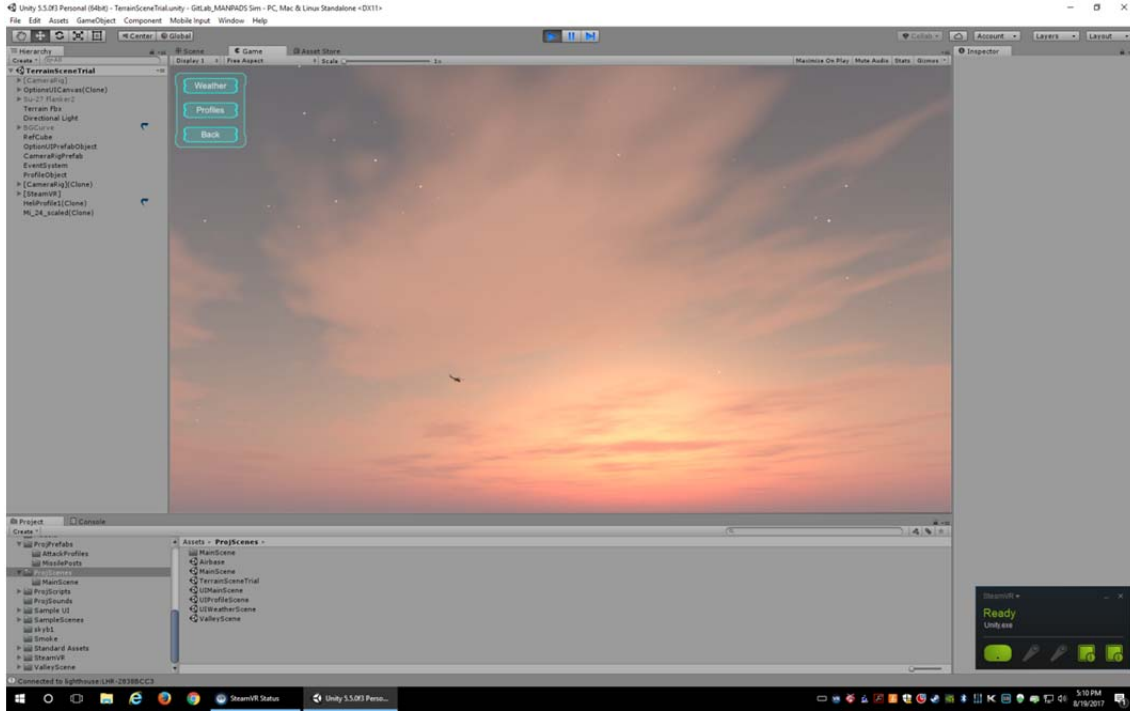


Figure 31. Skybox as viewed inside Unity interface

E. APPLICATION DEVELOPMENT

The application development for creating MANPADS prototype simulation comprised of various phases. These are described as follows:

1. Application Development in Unity3D

Unity3D IDE provides a 3D interface and a wealth of programming tools for developing applications like 3D games. Unlike DirectX SDK or OpenGL, where 3D models are integrated and rendered via programming the graphics pipeline, Unity3D allows for easy integration of 3D models by simply importing them as game objects. Like so many contemporary graphical user interfaces (GUIs) it also allows drag-and-drop action that achieves the same. The objects can then be programmed using scripting in C# (C-Sharp) or JavaScript. Multiple instances (clones) of an object can be created and manipulated further as the application requires. The Unity development environment and its GUI allow a programmer to conduct visual tests during run time; at that time the application can be paused and properties of objects can be altered at will. Unity3D also

has its own physics engine that allows easy incorporation and simulation of physics effects and phenomena such as collisions, gravity, force, and realistic weather effects.

2. Application Startup

The initial test scene was developed using a low-fidelity terrain that was created by the author who used the capabilities of Unity3D IDE. A low-fidelity Stinger launcher 3D model was imported into the trial scene as an application start-off. The model was subsequently replaced by a high-fidelity launcher model shown in Figure 32.



Figure 32. Stinger launcher 3D model as seen inside developed application

3. HTC Vive Integration

The HTC Vive was integrated and registered into the application using the SteamVR package for Unity. The camera rig for the HTC Vive VR headset was initially configured at a default location on the terrain. Both Vive controllers were synchronized and localized with the Stinger launcher 3D model in the application. At the beginning of the prototype's development one controller was positioned near the top of the launcher body (shown in Figure 33), while the other controller was fixed next to the trigger assembly. A make-shift physical launcher prop was also built to which both the controllers were tied at their respective positions; this setup was used during the initial

application development and trials. The controller positioned on the trigger assembly was also used to simulate assembly switch actions and generate vibrations. Using both controllers created problems at application startup as each controller could not be permanently connected with its corresponding virtual controller in the application. This dynamic registration of virtual controllers with the physical controllers resulted in incorrect launcher orientation. The issue was resolved by resorting to a solution that used only one controller that was attached to trigger assembly.

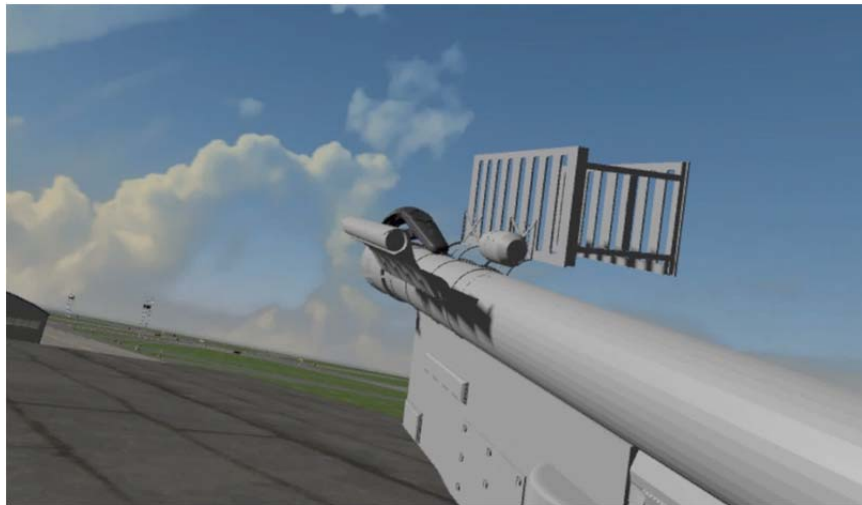


Figure 33. HTC Vive controller adjusted on Stinger launcher model inside application

4. Scene Development

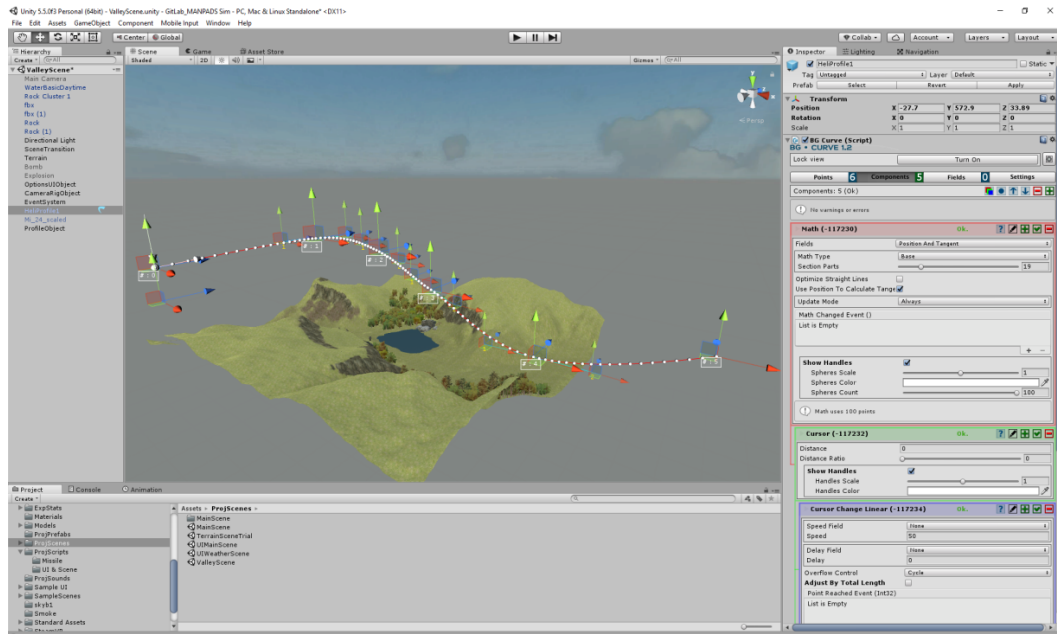
A total of two scenes were developed in support of the training scenarios. The first scene represented an airfield in which a 3D model of an airport was incorporated. Geometry that was not needed, like inside of the airport buildings, was removed to reduce the total number of polygons to be rendered, and to reduce the size of application data. This scene supported airfield deployment training, and it was later used with fixed wings and rotary wings for aircraft attack profiles. The second scene was a mountainous terrain that was built inside the Unity IDE (Figure 34.) The scene was used in support of training for a valley deployment environment (rotary wing attack profiles were also added).



Figure 34. Mountainous terrain scene developed for application

5. Aircraft Profiles Generation

Aircraft profile development was done using a 3D path-making module called “BG Curve” (which was downloaded from the Unity asset store). The module was used to generate profiles for each scene and terrain; its 3D interface for building profile paths is shown in Figure 35. The attacking aircraft or helicopter could then be attached to the generated profile and configured as needed.



Red line represents the path while dots are the individual points for movement, with vector lines indicating orientation in 3D space. The path can be adjusted in 3D space using vectors while other configurations can be done from right panel.

Figure 35. Aircraft 3D profile development using BG Curve package in Unity3D

6. Missile Simulation Model

The next important feature developed for the application was the missile flight model; to accomplish that work a seeker missile package was downloaded from the Unity asset store. Scripting was used to allow firing of the missile from the launcher tube. The package, however, had inherent problems as the model was designed to simulate shooting in the direction of the target rather than the direction of the launcher body (tube). Unable to correct downloaded missile flight model, the author developed another model with target seeking behavior. The missile was programmed to look as if it was shot from the launcher with locked target info in the direction of the launcher tube. The missile then guided itself toward the target depending on locking criteria, simulated IR reception cone, and angular distance from the target (Figures 36 and 37).



Missile's boost motor exiting the launch tube while missile main motor takes over. Visual effects for smoke and flame were applied to the missile after boost motor detachment.

Figure 36. Stinger missile fire



Figure 37. Missile flight toward the target

The effect of gravity, motor burn out time, minimum range, and target prioritization were also incorporated. Visual and audio effects included the detachment of the launch motor after launch, smoke effects, and missile blast-off.

Visual cues that reflected the behavior of the missile included target direction with respect to the launcher, missile movement, and guidance toward the target as shown in Figure 38. These cues were removed after completion of the missile model as shown in Figure 39. The functionality developed in the application was such that upon target hit, both visual representation of the missile and the target aircraft appeared visually as destroyed. The missile proximity fuze was also simulated; if the missile came within a certain range of the target, the detonation occurred.



Figure 38. Red line shows line of sight from missile to target



Figure 39. Missile in close proximity to the target with visual cue removed

7. Weapon Operation

Stinger weapon operation and target acquisition were also incorporated as part of missile simulation; this provided locked target information to the missile before the launch. The operation sequence that was studied in task analysis was replicated in the application, and it started from BCU activation by the user pressing the “Safety and actuator” switch. This action was programmed on the Vive controller side buttons; once the button was pressed, an acquisition tone would go off representing IR acquired from the surroundings. The activation was limited to 45 seconds (representing BCU life time). The “Uncage” button was initially programmed on the keyboard, and was later replaced by a generic trigger switch. The fire action was programmed on the Vive trigger button.

8. Trigger Switch Integration

The launcher operation required a physical button for simulating the uncage switch. For this purpose a generic trigger switch was placed in the fore end of the gripstock assembly and was integrated into the Unity application. This was done by mapping the button press for the keyboard key press; programming required Unity functionality that controlled mapped keys. The trigger switch device and its USB adapter are as shown in Figures 40 and 41, respectively.



Figure 40. Trigger switch device containing three buttons.
Source: Fentek Industries (n.d.).



Figure 41. USB adapter for trigger switch device.
Source: Fentek Industries (n.d.).

9. User Interface

A GUI was developed in the application that allowed the user to initiate various features provided in the application. After the start of the application, a main menu allowed the operator to select one of four scenes (Figure 42). When the user pressed a button, the corresponding scene got loaded.

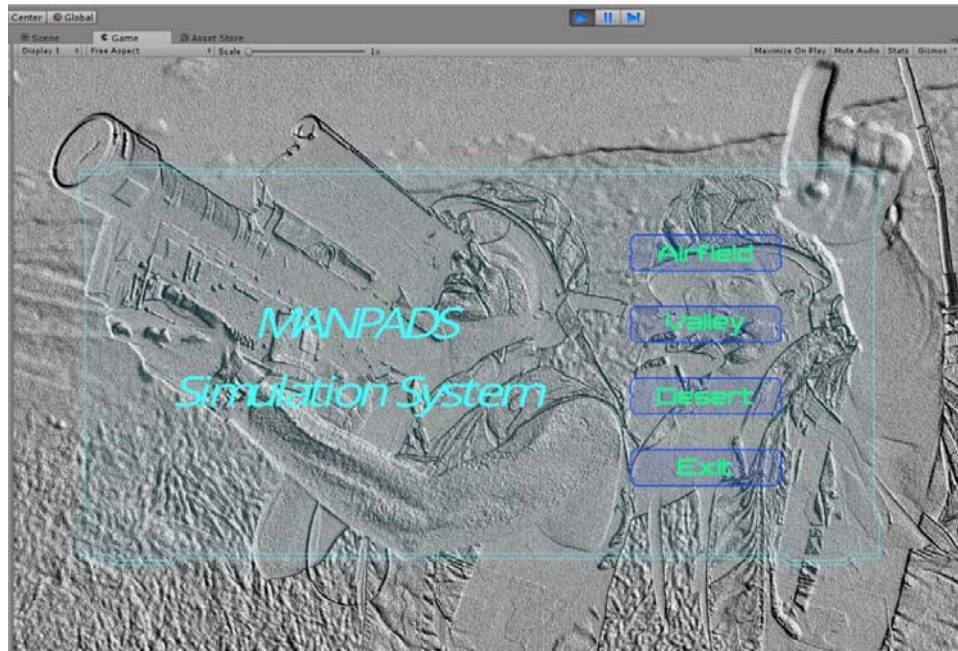


Figure 42. Application's main menu

Once inside the selected scene, a small menu in the top left corner allowed a user to select one of three possible options: “Weather,” “Profiles,” and “Back” (Figure 43). Pressing the “Back” button returned the user to the main menu.

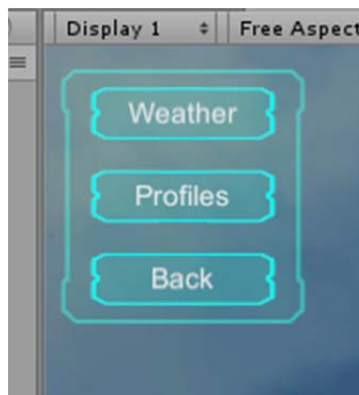


Figure 43. Menu for displaying weather, profiles, and main menu

The user interface (UI) was only available on the display monitor connected to the PC, and it was not visible inside the Vive headset. This way the instructor could make a

selection for the trainee who wore the headset, and avoid the trainee experiencing a break in presence.

10. Weather Settings

The application allowed environment conditions to be set inside the scene using the weather GUI. This could be started by selecting the “Weather” option on the small menu in the top left corner. Selections generated dawn, dusk, sunny, or cloudy conditions (Figure 44).

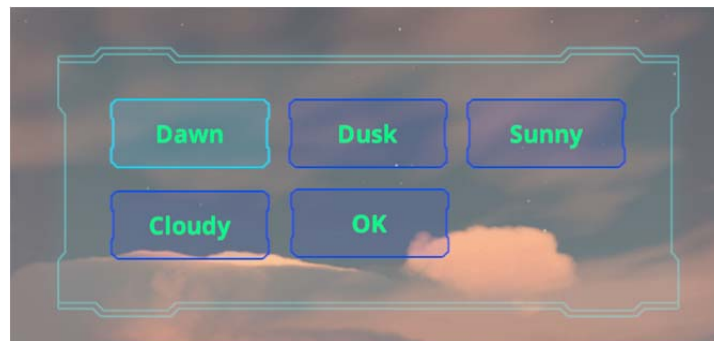


Figure 44. Weather selection menu

11. Scenario Creation

The application allowed the instructor to generate training scenarios and save them as pre-fed attack profiles. The required GUI was displayed by pressing “Profiles” button in the top left menu option. The desired profile could be selected along with selection of the type of aircraft (Figure 45). Separate GUI controls allowed selecting fighter and helicopter profiles along with the selection of desired aircraft. The interface also provided an option to select a missile post from a list of predefined deployment locations in the scene. This capability provided an opportunity for the trainee to engage in air defense and attack aircraft from different locations on a defended area. Any number of desired locations could be fed into the application in design time. Moreover, multiple aircraft profiles can be integrated and be part of the same scenario; this provides a target-rich environment and highly stimulating tactical decision-making practice for the trainee.

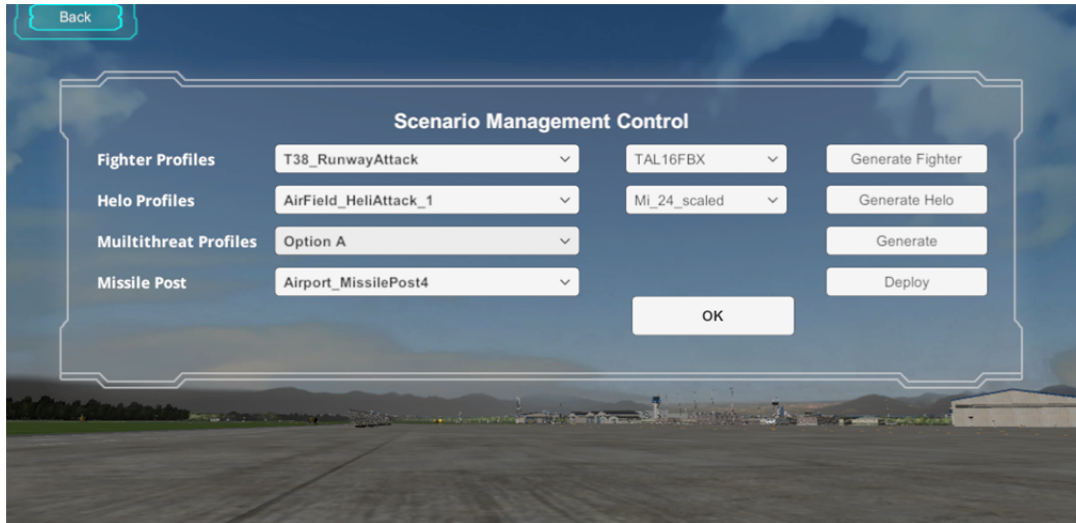


Figure 45. GUI for generating training scenarios

12. Leap Motion and Hand Tracking

A desire to enhance user's sense of presence led us to consider integrating the Leap Motion controller in the application. The Leap sensor was first attached on the Vive headset and then calibrated for accuracy. Orion software was downloaded from the company website and run to install Leap Motion for Windows and for compatibility with VR hardware, which in this case was HTC Vive. The latest Unity core assets were downloaded and used as Leap Motion SDK for Unity IDE.

After having gone through the setup, the Leap Motion module for Unity was imported into the simulation application from Unity asset store. Various trials were performed to achieve full integration of the virtual hands and the synchronization with real hands. Several different types of hands (geometry and textures) were tested, and a skin-covered virtual hand was preferred over the wireframe skeletal one owing to the visual imitation of the real hand (Figure 46).



Figure 46. Virtual hands depiction in the VE as detected by the Leap Motion controller

F. LAUNCHER DESIGN AND DEVELOPMENT

The process for developing Stinger launcher prop to act as passive haptics for the user is described as follows:

1. Stinger Launcher Physical Prop

The Stinger launcher mockup was designed and built to represent a passive haptic device for the MANPADS prototype simulator. A couple of options were considered for this purpose. One option that was considered was to get a non-functioning body or an actual launcher on which Vive controllers could be fixed. That option had to be dropped due to the non-availability of such dummy launcher. A design option that was adopted in the end was to break the launcher into separate parts, build them separately, and assemble them afterwards. The Naval Postgraduate School (NPS) RoboDojo lab was approached and various options for constructing launcher parts were discussed before a practical solution was achieved. Keeping in view mockup design considerations, the launcher was broken down into its constituent parts: launcher body, gripstock, trigger part, optical sight, and battery and coolant unit.

a. *Launcher Tube*

The main part of launcher was the tube. For this purpose, a black ABS plastic water pipe of the same diameter and length as the actual launcher was purchased in the store along with covers for both ends.

b. *Gripstock Assembly*

The initial intention was to cut wooden panels using a laser cutter and join them together to form the complete part. The housing for a generic trigger switch along with cable management made that process overly complex, and so the assembly was finally constructed using a 3D printer.

c. *Trigger Assembly*

This part was first designed for the controller housing and then built using 3D printing. This part of the prop was to be attached to the Vive controller.

d. *Optical Sight*

A physical prop had to be attached at the location of the optical sight; its main purpose was to prevent forward movement of the user's head beyond a certain point. This was also necessary with regard to presence in VE. If the trainee were to advance his or her head toward the optical sight, the head with the VR headset should be prevented from further movement at the place where it touches this optical sight prop (this corresponded to the 3D model presented as a part of VE).

e. *Battery and Coolant Unit*

An ABS plastic commercial component with approximately the same dimensions as the parts of an actual launcher was purchased and used for this purpose.

2. *Stinger Launcher 3D Modeling and Construction*

A 3D model of the Stinger launcher was designed and modeled following the requirements provided in the military manual *FM 44-18-1 Stinger Team Operations* (United States Department of the Army, 1984). At the start the Stinger missile 3D model

was downloaded from cadnav.com in .3ds format. The editing tool Sketchup Pro was used to make further changes (see Sketchup Pro interface shown in Figure 47.) The model was scaled to actual launcher size by referring to measurements given in relevant launcher manuals. The model was broken down into manageable parts; individual parts were trimmed, edited, and configured for 3D printing.

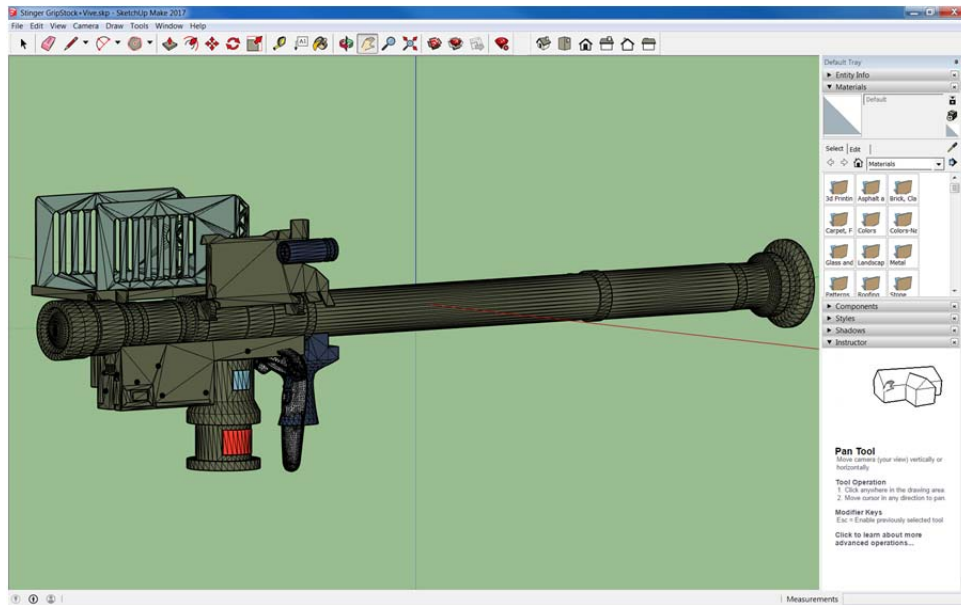


Figure 47. Stinger launcher 3D model in Sketchup

The trigger assembly was edited so that it could house the Vive controller as shown in Figure 48. This was followed by 3D printing of several samples of the trigger assembly using 3D printing facilities at NPS RoboDojo Lab and MOVES Savage Lab. The final 3D printed trigger assembly was done at NPS RoboDojo Lab (Figure 49).

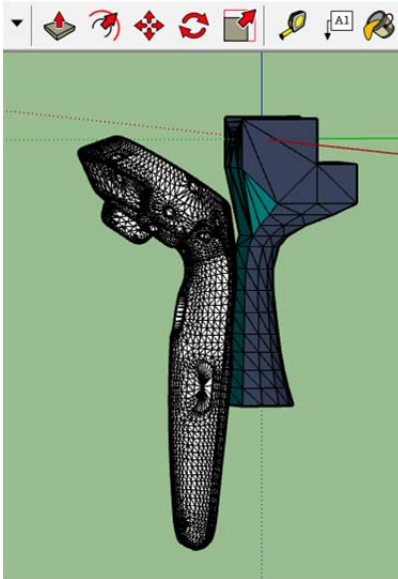


Figure 48. Trigger assembly edited for Vive controller adjustment

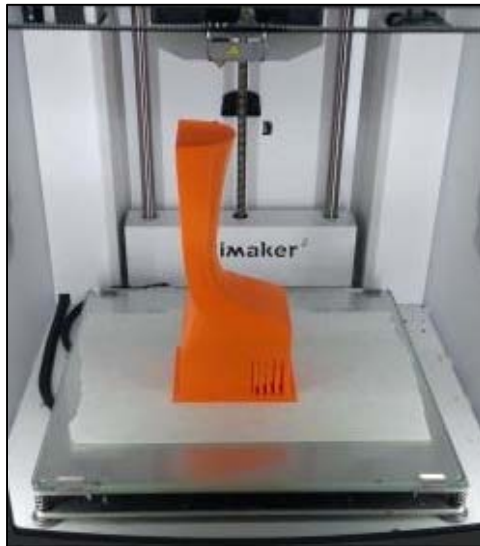


Figure 49. Completed 3D printed trigger assembly

The gripstock assembly model was also trimmed to remove parts that were not needed. It was then edited to make adjustments for fixture with launcher tube and to house a trigger switch along with cable management and clamping requirements (Figure 50). Due to the complexity of its structure, the model was rebuilt in Blender as shown in Figure 51. A research associate from the MOVES Institute's game development lab was

approached and asked to assist in this task. During this process several smaller-scale prototype 3D prints were done to test the model and remove any error from the model before setting up for a full scale 3D print (Figures 52 and 53).

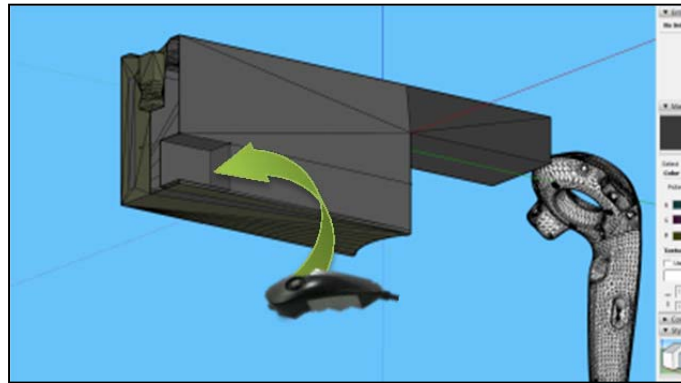


Figure 50. Trigger switch housing inside gripstock assembly. Designed in Sketchup.

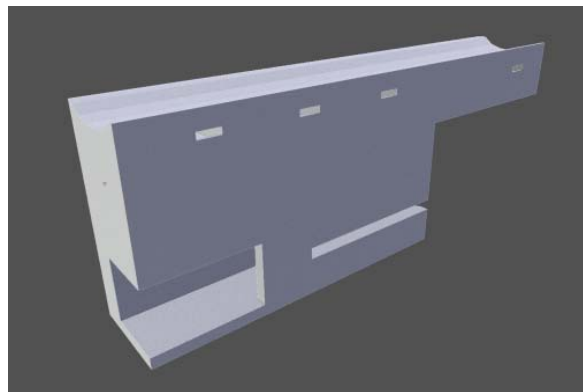


Figure 51. Gripstock assembly redesigned in Blender

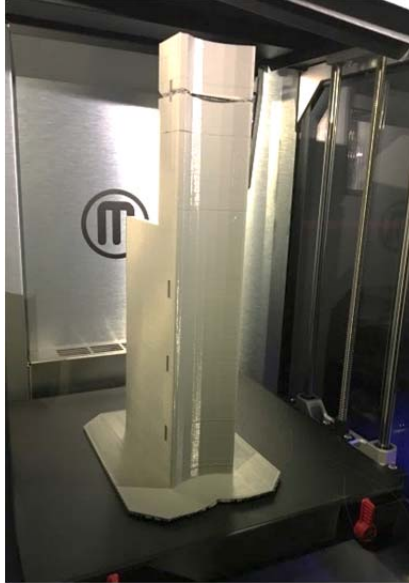


Figure 52. Full scale 3D print of gripstock assembly inside printer



Figure 53. 3D printed gripstock assembly

After 3D printing, all the parts were assembled to form a complete launcher mockup. The gripstock assembly, trigger assembly, and optical sight prop were attached to the tube using metal clamps and plastic tie wraps as shown in Figure 54.



Figure 54. Trigger assembly and optical sight prop attached to main tube using metal clamps and plastic tie wraps

The trigger switch was fixed inside the gripstock housing along with the cable adjustment (Figure 55). This was followed by fine tuning the Vive controller position on the launcher in the Unity application, and adjusting other physical props accordingly on the physical prop (Figure 56 shows the complete launcher prop).



Figure 55. Trigger switch fixed inside housing with slit for cable adjustment



Figure 56. Assembled Stinger launcher mockup

After development completion, the launcher mockup was tested with the application to study system performance (Figure 57).



Figure 57. Developed prototype simulation along with launcher mockup

G. CHAPTER SUMMARY

This chapter elaborated the development of the prototype MANPADS simulation. 3D assets used in the simulation were presented, and details of the application's development and physical launcher mockup construction were discussed.

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VII. RESULTS AND CONCLUSION

A. INTRODUCTION

This chapter discusses the results of a feasibility study centered on a prototype training simulation and details the conclusions drawn from this research. The text also includes recommendations for potential future work to extend the research efforts in this domain

B. RESULTS OF THE FEASIBILITY STUDY

A set of tests related to system performance were done in support of the feasibility study; our goal was to ascertain system performance and acquire general observations about the overall functioning of the system. These are discussed as follows:

1. A working simulation prototype was successfully developed along with a software application incorporating required features and functionalities for MANPADS tactical training. This showed that using COTS technology and hardware, it is possible to create all visual, auditory, and haptic sensory stimuli identified in task analysis.
2. It was observed that the Stinger launcher 3D model was occasionally unstable when it was pointed in certain directions in space. After careful analysis, it has been concluded that the problem was mainly due to the occlusion of the Vive controller attached next to the trigger assembly under the tube. At certain angles the line of sight between the controller and sensors was occluded by the operator's body and the launcher tube.
- The issue of the model's instability can be resolved by using a separate Vive tracker and placing it on top of the tube where it would not cause issues with occlusion. The tracker could then be dedicated for capturing launcher position and orientation, while the controller would be used for switch actions and to generate vibrations.

3. Frame rates were recorded to observe the dependency of frame rate on the size of the scene that has been rendered. To do that, the camera view was moved in different directions inside one scene.
- In the mountainous terrain scene, the frame rendering remained almost constant at 105 frames per second (fps). The main reason for that is the low number of vertices in the scene. The frame rate remained unaffected by the launcher 3D model inside the view; however, integration of the Leap Motion controller and the rendering of virtual hands reduced it to 97 fps (note that the HTC Vive maximum display frame rate is 90 fps).
 - In the airport scene, the frame rate varied depending on the camera view. The highest frame rate was 104 fps, with approximately 2.5 million vertices being rendered as shown in Figure 58. The lowest observed was around 24 fps, with 14 million vertices (Figure 59), which brought jitter in the rendered display. In that case, the camera view included most of the airport infrastructure including the ATC tower. Integration of Leap Motion further decreased the frame rate to 15 fps.



Figure 58. Airport scene rendering. Camera view with high frame rate due to fewer vertices



Figure 59. Airport scene rendering. Camera view with low frame rate due to pronounced vertices of building infrastructure

4. Integration of Leap Motion controller functionality was done to visually augment the operator's proprioceptive movements of hands and have a potentially positive effect on the operator's sense of presence. After the integration and calibration were concluded, it was observed that virtual hands did not coincide with the actual positions of the operator's hands in reality (on passive haptic). In other words, if the actual hand was holding the gripstock assembly, the virtual hand appeared to be inside the Stinger 3D model as shown in Figure 60. This created a disconcerting feeling that could also negatively affect a sense of presence. Based on these observations it was concluded that until we pinpoint what caused this, not having a virtual hand was better than having the wrong representation of the actual hand inside the VE. Preliminary hypothesis about the causes of this problem is that it could be issues with calibration or sensor occlusion (hands as seen by optical sensors in the Leap Motion controller). Simulation of a virtual hand was therefore removed from the current version of the training simulation.



Figure 60. Hand tracking by Leap Motion and wrongly positioned virtual hand in VE

5. The Leap Motion controller also created a problem with the optical sight prop; when the operator wore a headset with Leap Motion attached to it, the headset kept hitting the optical sight prop and risked damaging the body of the controller that was attached in front. Moreover, the prop also occluded the Leap Motion sensor from detecting the operator's hands, and that could have led to the wrong rendering of hands in VE.
6. While closing in toward the virtual optical sight, the 3D printed prop created a hindrance as the Vive headset hit against it. Moreover, as this head stoppage is not assisted by any pressure effect around the eye, it actually felt better operating without the prop. Additionally, the user tended to stop at the correct position next to optical sight that was rendered in the scene. The operator got the correct visual cue presented on displays inside the headset, and it did not appear that additional cue (haptic cue) was absolutely necessary.
7. Regarding HTC Vive, it was observed that headset connectivity wires at times created a hindrance during simulation. At times the operator's arms and legs were becoming entangled with the wires. Having a wireless

solution would resolve the issue and give more freedom of movement to the operator.

8. The assistance of a second person was required for getting the scenarios started while the operator wore the VR headset and participated in the simulation session. It was suggested that this second person could be an instructor who would select and launch aircraft profiles for the operator (trainee).
9. One of the special effects used in the simulation caused the missile to disappear with a blast after it hit the target aircraft; this seemed unrealistic. This can be improved using graphic effects to simulate the aircraft catching fire and diving toward the ground.
10. It was observed that the scene outside the optical sight at times became visible even if the camera view (operator's eye) was positioned next to the optical sight. As a remedy, it was suggested that a sprite could be loaded around the optical sight once the head gets close enough to the sight, so that it prevents (outside optic sight) the camera view from getting displayed.

C. CONCLUSIONS

Our experience in developing this part task trainer has proven that it is possible to use COTS technology to create the auditory and visual cues needed to support training situations relevant to a MANPADS system, and present them to the operator (trainee) in real time.

The study gave us valuable insights into the issues relevant to the development of similar systems. We also acquired lessons about additional areas that need to be addressed and refined in future versions of a MANPADS training system. The results are especially encouraging knowing that it only requires effort and time to exploit commercial technologies that already exist on the market. It is also anticipated that future development of this type of training solution will provide additional valuable insights that

can be employed to design and create a new generation of low-cost training solutions in both the military and civilian domains.

D. FUTURE WORK

Numerous areas of potential future research that are envisioned include:

- Incorporation of a realistic missile model into the prototype simulation. Many efforts have dealt with modeling of IR seeking missiles, and those could be utilized to make this simulation more realistic.
- A dedicated instructor station can be developed with elaborate features for controlling the virtual environment and having tools for generating aircraft profiles for helicopters and fighters. This would support a flexible solution that would allow dynamic scenario generation capability.
- An interoperability module could be developed to support connectivity with other simulators. This can be helpful in achieving a distributed training architecture where personnel serving in other domains could take active part in MANPADS scenarios.
- Integration of the simulator into an LVC (live, virtual, constructive) training environment. Inside a simulation session, the weapon could be virtually deployed in the same exercise area while getting data input from real aircraft that could then be targeted. This way, the operators would have an opportunity to be part of a live exercise while staying in units. It can also have good training value for the pilots conducting missions over an area deployed with IR guided weapons.
- A usability study involving subject matter experts can be done to study technical system performance, as well as efficiency and user satisfaction with the interface. The work would highlight features that could be added to make it an effective training system in air defense units.

- A training effectiveness study can be carried out to analyze the proposed skills that can be gained using the system.
- A transfer of training study can be carried out to analyze the effectiveness of skills gained using the simulator; and to ascertain how those skills affect the performance of an operator during live fire (operational environment).

E. CHAPTER SUMMARY

This chapter discussed various results and observations along with suggestions for improvements in current system. A range of future work has been put forth in order to explore the training potential of this system more fully. In conclusion, it is suggested that same approach can be adopted in developing a range of low-cost training systems in the military and civilian domains to address training gaps and limitations identified in current training systems.

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