Integrating Warship Bridge, Combat, and Deck Teams in LVC Environment

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ABSTRACT

This paper investigates means to integrate USN surface warship bridge, deck and combat watch teams in a Live, Virtual, Constructive (LVC) training environment. Issue: Currently the US Navy's LVC distributed training environment (called Fleet Synthetic Training - FST) only incorporates ship's combat watch teams and squadron staffs, participating from their ships in serious games (i.e., scenarios), but do not include integral decisions and actions made by bridge and deck watch teams. Yet bridge and deck watch teams are an integral part of the combat effectiveness of a ship, especially in the visual environment in which many actions take place. Some examples of required total watch team integration are defense against fast, small boat threats, critical infrastructure/critical asset protection, and vessel Visit, Board, Search and Seizure (VBSS) operations. But in FST the bridge and deck watch teams are role-played by the white cell, muting the team-building required to create a cohesive, effective combat crew, and missing the chain-of-command interactions from gun crews to other ships to the squadron commodore. Means: This paper looks at two possibilities for incorporating bridge and deck teams into scenarios. The first is to use a dedicated bridge training facility integrated into FST. The second is to use virtual reality or augmented reality headsets, worn by watchstanders aboard ship, and integrated into FST. Applications of both approaches are closely examined, including the Office of Naval Research current effort to connect key personnel from the bridge, deck crews and Combat Information Center aboard ship with helicopter crews in a common simulated scenario. Optimal use of both virtual and augmented reality is examined.

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Introduction

Since 2005, as a means to offset reductions in underway training time, flight time, and live range access, the US Navy has conducted a significant portion of pre-deployment ship, staff, and strike group training in a Live Virtual Constructive (LVC) distributed training environment called Fleet Synthetic Training (FST) (GAO, 2012). In FST, actual warships become virtual simulators. A pierside warship connects its combat system to a training network through a cable from the pier; its combat sensors and systems are placed in a training mode, and then remotely stimulated through a modeling and simulation (M&S) system. The ship's combat watch team in the Combat Information Center (CIC) perceives itself in a virtual environment as it operates its sensors, systems and consoles, and uses actual radios, intercoms, computers and other normal means of communication to develop situational awareness and respond to events in the same manner it would at sea. In FST multiple ships can be integrated into large, complex scenarios, requiring watch team coordination not only within CIC but also among ships and squadron commanders. FST scenarios are controlled from a remotely located "white cell" at the center of the training network, where M&S operators drive and role-play constructive friendly forces as well as opposing forces. Thus a single ship's crew in FST could find themselves part of a much larger, highly complex organization, in a dynamic synthetic scenario. FST events range from single-ship, standalone events of a few hours duration, to robust, multi-ship, multi-strike group events that last a week or longer. FST scenarios can encompass fabricated geography with fictional "color-coded" countries, or real geography with real-world scenarios. Participants can be integrated into a distributed training event from all major Fleet Concentration Areas (FCAs) anywhere in the world. FST has been sufficiently successful in complex, integrated training for carrier and expeditionary strike groups that it has been used as the final certification venue to qualify strike groups as "ready to deploy" (Ewing, 2009).

However, FST has limitations, especially in integrated training for ship's crew members who are not CIC watchstanders. The limitation is that although FST stimulates a warship's CIC watch team, no virtual environment is provided for the bridge, deck, and other functional teams. So while the CIC watch team may be immersed in a virtual training environment in FST, other ships' watchstanders such as the Officer of the Deck (OOD), Conning Officer, or lookouts do not participate, but instead are role-played by the white cell.

Yet bridge and deck watch teams are an integral part of the combat effectiveness of a ship, especially in the close-in visual environment in which many actions take place. Some examples of required ship's crew integration are defense against a swarm of fast, small boat threats (Fast Attack Craft and Fast Inshore Attack Craft, or FAC/FIAC), critical infrastructure/critical asset protection, and vessel Visit, Board, Search and Seizure (VBSS) operations. In such situations successful ship's defense and mission execution requires close command and control (C2) coordination between the ship's Bridge Watch team, the CIC Watch Team and deck teams such as the Small Craft Action Team (SCAT). Training is required to develop such coordination and teamwork. The authors propose that if bridge and deck watch teams could be incorporated into the FST environment, it would provide an opportunity for complex, controllable, repeatable training that would build teamwork in preparation for underway training events and combat deployments.

Investigation

The purpose of this paper is to investigate means of integrating warship bridge, deck, and combat crews in the FST LVC training environment. Since CIC and helicopter simulators are already part of FST, the need was to find a way to integrate the bridge and deck teams. The authors looked at two principal approaches for integration. The first approach was to use an existing standalone, dedicated bridge training facility integrated into FST. The second approach was to expand the FST environment aboard ship from CIC to bridge and deck watchstanders using virtual reality (VR) head-mounted displays (HMDs), or augmented reality (AR) HMDs, or some combination thereof.

Why Integration? Command and Control (C2) Training Considerations

The key functions of a warship are typically apportioned by the Captain to certain key watch standers and their teams (Figure 1). The Tactical Action Officer (TAO) in CIC, deep inside the ship, directs the tactical employment and defense of the ship. If a ship has aircraft such as helicopters flying in support, those aircraft are usually controlled from CIC, even when supporting an evolution in the visual environment, such as small craft threats. In a squadron of ships, the TAO will respond to direction and guidance from the squadron commodore, usually represented by the Force TAO (FTAO). The Officer of the Deck (OOD) on the bridge directs the safe navigation and general operation of the ship, receiving guidance from the TAO in the overall employment of the ship. Deck crews such as SCAT and VBSS teams are led by officers or petty officers, depending on the ship's organization, who may

Figure 1: Guided Missile Cruiser USS COWPENS with bridge, CIC, and deck C2 nodes highlighted (photo credit U.S. Navy)

receive direction from either the TAO or OOD or both, again depending on the ship's organization. Thus the Captain, TAO, OOD, aircrews, and deck crews must work together as a team, especially in the visual environment, and in a multi-ship environment, different ships must work together (Stavridis, 2007).

As an example, picture a group of three Navy warships transiting a narrow straight in an uncertain geopolitical environment. While not at war, there is the possibility of surprise attack, and because of this, the ships are in a mutually supportive, relatively close and fast formation. Each ship has defensive positions manned and ready: extra lookouts are on the bridge and deck; the SCAT is in place with gunners and lookouts at each crew-served weapon (CSW), consisting of a variety of M2 Heavy Barrel (M2HB) .50 Cal machine guns and M240 .762 machine guns. CIC has an operator at every console, including the Remote Control Station (RCS) for the 20mm Close-In Weapons System (CIWS) Gatling gun and MK-38 MOD-2 25mm Chain Gun. Finally there are two armed helicopters circling the formation providing both radar and EO/IR imagery linked back to the ship. Because there are no open hostilities and no defined enemies, the ships may fire defensively only after determining the hostile intent of an attacker. The essential steps to countering any attacker will be to 1) detect 2) identify 3) determine intent; and 4) engage. Execution of those four steps will require coordination between the entire ship's crew, particularly the TAO and OOD and SCAT, and also among the ships (Kolve & Tompson, 2012).

Figure 2: Iranian Swarm Attack Exercise (Photo credit DefenseTech)

Among the potential dangers facing the ships, a swarm consisting of numerous small, low radar-cross section FAC/FIACs will be one of the most difficult to counter (Figure 2). The crew has limited time to detect, identify, determine the intent of, and counter or engage the attackers. A ship's detecting radar at 50 ft above sea level has approximately a 10nm radar horizon. FAC/FIAC can travel at speeds of 50+ knots, and can employ weapons from beyond visual range to within visual range. If the warships are traveling at 25 knots, the combined closure rate could be over a mile a minute. If the ships rely on their own radars for detection, the time from detection to possible engagement might be ten minutes at best, and seconds at worst. Moreover, determining the identity and intent of inbound small craft is not always straightforward and obvious: for example, smugglers often transit the Strait of Hormuz in groups of small, fast craft, and may present the appearance of a swarm attack (Kolve & Tompson, 2012).

When faced with the possibility of a swarm attack, the warship's defensive response requires an immediate coordinated response between the OOD, TAO, the SCAT, the helicopter crews, possibly the ships' damage control and engineering watches, and the FTAO. The different weapons systems ranges dictate a layered defense, and a handoff of threats as they move from layer to layer, from an outer zone defended by helicopters, to inner zones progressively defended by ship's large-caliber guns, medium caliber weapons, and small-caliber crew-served weapons. In determining the intent of the threat, radio warnings might be issued from CIC or the Bridge; flares and/or warning shots from the helicopters or SCAT, and evasive maneuvers ordered from the Bridge or CIC. In a close-in scenario, the ships' missiles and larger guns may be ineffective, but CIC can still remotely control the CIWS while the bridge can remotely control the MK-38 Mod 2 25mm Chain Gun using electro-optical/infrared (EO/IR) cameras to observe, track, and engage threats. Thus any engagements from CIC must be coordinated with the bridge and GDO, well as with the armed helicopters, to ensure all threats are covered, not just the closest ones. The helicopters may be controlled from CIC, or they may be controlled from the bridge. Any helicopter support would have to be coordinated to ensure the helicopters are not placed in jeopardy from either the attackers or ships' defensive fire. For the gunners at the CSWs, even if they've been trained superbly, and understand when they may fire in self-defense and the muscle mechanics of aiming, it's still a tough situation. Their lines of fire may be toward another warship. They might have merchant traffic in the background. Haze, sea state, ship's motion, and a fast weaving boat bouncing among the waves may combine to make difficult target. Any defensive turns by the OOD must be coordinated with the TAO and GDO and CSW gunners in order to avoid spoiling gun crews' aim and/or sight clearance, as well minimizing confusion or worse the chance of a collision within the group of ships. If one ship is struck and disabled, the other ships may have to immediately change course and speed to stay clear, and then decide whether and how to maintain group integrity and defense. Any outside emergency support, such as air support, called in by the squadron FTAO should also be communicated and coordinated, both to prevent double-targeting as well as minimize the possibility of fratricide. In short, the complexity of the scenario illustrates the need for teamwork between CIC, bridge, deck, helicopters, and squadron.

Such teamwork must be developed through training. In a complex situation, it is insufficient to only know *what* to do: one must also know *how*; the interactions that develop teamwork must be practiced. Just as actors who know their lines must still rehearse together for a theater production, and sports teams train together for competition, sailors on warships must train as a team for close-in surface threat situations. Presently, for USN cruisers and destroyers the only integrated training for a close-in threat is underway, and subject the limitations already mentioned: weather, scheduling, availability, systems, and so on. In-port training is not integrated: just as in FST where the Bridge and SCAT are role-played for interactions with the TAO and CIC, when the SCAT and GDO train pierside, role-players are used for the TAO and OOD (R. Coates and A. Wilder, personal communication, June 2, 2015). An anecdote serves to illustrate the need for training: in meeting with various training representatives and ships' crews the authors discovered that the terminology for the person who directs CSWs is not standardized nor well-understood: some ships use the term Gun Direction Officer (GDO); others use the term SCAT Officer (SCATO); others use SCAT Coordinator; others use Gun Liaison Officer (GLO). Training could be integrated to some degree pierside, but there the limitation is the immersion of the crew in the training scenario – even if the key nodes were all stood up and participating in a training scenario, productive training requires an effort by participants to place themselves in the training scenario, to imagine, for example, that they are facing a small craft threat even though they are looking at pierside buildings. Synthetic training is a proven means to immerse participants in the training scenario, and allows complex, controllable, repeatable training that would build teamwork in preparation for underway training events and combat deployments. At the present time the USN has no standalone integrated in-port synthetic training capability for guided missile cruisers (CGs) or guided missile destroyers (DDGs); therefore the authors considered FST.

Prior Research: Fleet Integrated Synthetic Training/Testing Facility (FIST2FAC)

In August 2013, the Office of Naval Research (ONR) demonstrated a FAC/FIAC proof-of-concept integrated synthetic training capability at the Fleet Integrated Training/Testing Facility (FIST2FAC) at Ford Island, Hawaii. The primary objective was to "showcase the ability to conduct a multi-platform synthetic training event." The demonstration incorporated a mock-up of a destroyer's bridge (Figure 3) and bridge wings; a CIC station; a virtual non-lethal LA-9 laser dazzler;

Figure 3: OOD in FIST2FAC Destroyer Bridge mockup in FAC/FIAC demonstration (Photo credit John F. Williams)

constructive and virtual port and starboard SCAT stations (M2 .50 caliber); and an SH-60B simulator with pilot, Airborne Tactical Officer (ATO), integrated with a Door Gunner simulator (M2 .50 caliber). Fleet representatives manned each of the watch stations and positions in a FAC/FIAC attack scenario similar to the one described above, only as a single ship. The demonstration, which ONR published on YouTube (FIST2FAC, 2013), was highly successful. The key takeaways of the demonstration for the purpose of this paper were 1) the successful visual and geo-spatial integration of two-dimensional and three-dimensional M&S engines to include Joint Semi-Automated Forces (JSAF, the principal FST M&S engine), Unity 3D, X-Plane and Virtual Battle Space 2 (VBS2), indicating that the technical hurdles of software and system integration could be overcome; and 2) the enthusiastic fleet endorsement of the demonstration, indicating the validity of the concept of integrated synthetic C2 training (Office of Naval Research (ONR), 2013).

Integration Factors, Requirements and Approaches

In order for the bridge watch and deck teams such as SCAT to effectively participate with CIC in FST, the essential requirement, as FIST2FAC demonstrated, is for everyone to perceive the same virtual environment as CIC, through a combination of visual, aural, and combat system stimulation. With a view to simplicity, the authors considered two different approaches: a standalone bridge trainer with visual graphics and voice communications; or the use of VR or AR aboard the ship leveraging the ship's existing training systems and C2 infrastructure. Integration factors were divided into two broad categories: technical feasibility and functional feasibility. Technical feasibility addressed M&S compatibility, network access, assurance and integration, C4I, and similar issues – basically whether the device could be brought into the FST environment. Functional feasibility addressed whether the systems developed could provide the needed fidelity and function to execute individual and team tasks, considering aspects such as layout, ergonomics, displays, purpose, suitability, availability, and similar issues – basically whether the device should be brought into the FST environment. In order for any of the approaches to work, they needed to be both technically and functionally feasible.

First Approach: Standalone Bridge Trainers

Two types of dedicated USN bridge training facilities were investigated: the Navigation Seamanship Shiphandling Training (NSST) facility and the Conning Officer Virtual Environment (COVE) trainer. Each facility appeared to offer the possibility of integration. However, after visiting and investigating each, the authors determined that neither facility, as currently configured, was technically feasible or functionally suitable for integration into the FST environment.

NSST

The integration concept for NSST was to incorporate it into FST simultaneously with a ship, and while the ship's TAO and CIC watch participated in a training scenario from the ship, the ship's OOD and bridge watch and deck crew would participate in the same scenario from the NSST, with the bridge team in the bridge trainer, and the deck teams either within the simulator (if space allowed) or in the same facility using VR or PC-based displays. Thus although not physically collocated, the ship's crew would be tied together in a virtual environment for training. However, due to a variety of technical and functional limitations, the NSST was not a suitable venue for integrating crews.
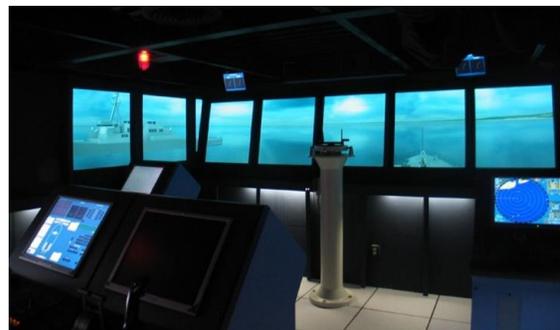

Figure 4: NSST Full Bridge Simulator (Photo credit Barco, Inc)

The US Navy has a NSST in each of its seven FCAs where ships are homeported, making it readily accessible to ship's crews. A NSST facility may have one or more bridge simulators. The San Diego and Norfolk NSSTs are plussed-up to have two full bridge simulators, one left-bridge wing simulator, and one compact desktop bridge simulator. Each full bridge simulator consists of a mockup of a generic ship's bridge, slightly smaller than most ship's real bridges, with a computer-generated panoramic display on screens approximately 6 to 8' outside the bridge windows (Figure 4). The simulators can be programmed to represent the bridge view and handling characteristics of any ship in the Navy, as well as day/night, sea state, currents/tides, and weather/reduced visibility conditions. The simulators within a NSST facility can be operated independently or networked together into a single

training scenario, and since its simulator engine is High Level Architecture (HLA) compliant, it could theoretically connect to FST if the same Run Time Infrastructure (RTI) were implemented.

The principal technical shortcoming of the NSST is one of security and classification: since FST is conducted over a secure network, the NSST would have to obtain Information Accreditation (IA) in order to connect, and the NSST building would have to receive security accreditation as well. A minor technical limitation is that the NSST has only two communications circuits, one to represent ship's bridge-to-bridge radio, and the other to represent ship's intercom. Additional circuits would be required to represent tactical communications nets, but those could be added relatively simply using Voice-Over-Internet-Protocol (VOIP). A final technical concern is that the system may not handle the high graphics processing load imposed by a dynamic maneuvering environment, since the system has frozen before under such a load (W. Kirkland, personal communication, May 12, 2015).

The functional limitations of the NSST for tactical employment are more numerous, and include visual, sensor, layout, and availability shortcomings. First, while the panoramic display is impressively clear and realistic, it presents at best a 243 degree horizontal field of view (FOV) and is limited vertically to essentially the view seen in Figure 3, so that the Bridge team cannot see the water in the immediate vicinity of the hull, or the sky overhead. Moreover, the Full Bridge Trainer does not include bridge wings, so the OOD cannot "step outside" to get a better view of the situation abeam the ship. In order for Bridge team to look left or right beyond the FOV shown, they must slew a camera display (called the "binocular" function) at the helm station using a joystick, or they can request the instructor console shift the main display left or right, e.g., "show the view to the left," but then the resultant perspective is somewhat disorienting, since the watch team is seeing a side view while still facing forward. In sum, the displays are not suited for the 360-degree view required in the visual tactical arena. In the sensor realm, the NSST includes a generic Automatic Radar Plotting Aid (ARPA) console to display radar contacts. An overlay representing the SPS-73 surface search radar symbology can be applied, but lacks full realism since the bridge simulator system does not incorporate any type of link track numbering or other tactical picture naming convention. There are no other tactical radar displays in the NSST. The layout of the NSST has no space, nor provision, for even one CSW position within the bridge simulators, let alone a full Small Craft Action Team (SCAT). There is classroom space for approximately four CSW stations using VR, but given the other limitations encountered, the authors did not pursue that line of thought. Lastly, the availability of the NSST for integration into an FST event is limited. The simulators are heavily used, often by two or three ships per day. The NSST Program Manager estimated availability for an integrated event would be approximately every 35 to 45 days (R. Liggett, personal communication, May 12, 2015). Altogether, while an admirable seamanship and shiphandling trainer, the NSST is not suited for FST integration for a variety of technical and functional limitations.

COVE

The integration concept for the second standalone trainer investigated, the Conning Officer Virtual Environment (COVE) was similar to the NSST: it would integrate into FST simultaneously with a ship, and while the ship's TAO and CIC watch participated from the ship, the ship's OOD and bridge watch and deck crew would participate from the COVE, with some slight differences that will be explained below. The COVE showed more promise than the NSST for integration, but also had technical and functional limitations against integration into FST.

Figure 5: COVE student with VR HMD and voice command microphone. The right monitor shows engine/rudder/speed status; the left monitor is a repeat of the student's FOV (Photo credit U.S. Navy)

Like the NSST, COVE is installed at FCAs. COVE is a family of scalable, reconfigurable PC-based simulators based on HLA-compliant commercial off-the-shelf (COTS) software (Naval Air Warfare Training Systems Division (NAWC TSD), 2011). The authors looked at the San Diego COVE 1 simulator, which uses a VR HMD interface. Whereas the NSST trains bridge watch teams, the COVE 1 trains conning officers individually. The essential approach is that a single student, wearing a VR HMD, "conns" a ship in COVE through standard voice commands to the simulator (Figure 5), e.g., if the student says "Right full rudder" into the voice command microphone, the simulator responds with "Right full rudder aye… my rudder is right full, no course given" and the ship commences a turn representative of its type's handling characteristics and responsiveness. The viewer's vantage

in the HMD is from the ship's bridge centerline or bridge wings, selectable through voice command. Though none of the immediate bridge environment is actually shown (as if the conning officer was standing on an open platform), the HMD display is high resolution with realistic background scenery. The HMD is approximately 2007 technology, and provides a 60 degrees diagonal monocular field of view (FOV) on a 1280x1024 60 Hz display, and uses inertial tracking (NVIS, 2011). The wearer can look 360 degrees in all directions, and there is no discernible latency. The HMD includes stereo sound speakers in the headband. Other displays at the student station include a rudder/engine bell/speed indicator, a Voyage Management System (VMS), an ARPA, and a monitor showing the HMD FOV. The HMD FOV can be zoomed in a "binocular" mode using a joystick. There are two microphones: one for VHF Bridge-to-Bridge communications, and one for voice-activated commands to the helm/computer. The San Diego COVE facility has nine cubicles, or stations, each based in a cubicle about six feet wide by nine feet deep. The nine stations can be integrated into a single scenario (A. Nottberg, D. Rodriguez and T. Vellalobos, personal communication, June 4, 2015).

The author's concept for COVE integration was that key bridge watchstanders would be integrated from separate cubicles onto the same virtual ship in the same virtual environment: the Conning Officer, the OOD, the GDO, and the bridge wing lookouts. The SCAT would occupy the remaining cubicles, and if more stations were needed they would use VR or PC-based displays. In discussions with COVE training officers, they felt such an approach would work to create an effective team-training synthetic environment.

However, the COVE has the same principal technical shortcoming as the NSST: it would require accreditation in order to connect to the secure FST network, and the COVE building would have to receive security accreditation as well (or the COVE move to a secure facility). Also, the COVE has only a single communications circuit to represent ship's bridge-to-bridge radio, though adding radio circuits via VOIP is feasible (and commonly done) in the FST environment. Another technical limitation is that COVE does not have deck-level CSW vantage points (perspectives), so those would have to be encoded in the graphics displays in order to allow the SCAT to effectively participate.

The most significant functional limitation to integrating COVE into FST is that it is already heavily used for training: the COVE supports the eight-week Basic Division Officer Course, which convenes with approximately 96 students six times a year (A. Nottberg, personal communication, June 4, 2015).. Therefore COVE availability to support other events is minimal to non-existent. Another minor functional limitation is that, as mentioned, the HMD graphics do not incorporate the actual images of being on the bridge, nor occlude the view when looking aft, though the authors felt that this would not significantly impact the objective of team training in a virtual environment.

Another variant of COVE, COVE Full Mission Bridge (FMB), is a full mockup of a ship's bridge with a 360-degree FOV in an inverted dome display. COVE FMB supports a six-to-eight person watch team not only in navigation, seamanship and shiphandling, but also tactical training to include maneuvering, weapons engagement, and communications. It includes electronic (virtual view) binoculars for target identification and helmet-mounted AR displays to supplement the primary on-screen display, which allows the wearer to look down from the bridge wings for close-in viewing. In addition to navigation and seamanship, COVE FMB is "designed with the fidelity to train watch teams in the dynamic decision-making process needed to defend against terrorist vessels and other force protection threats." (Naval Air Warfare Training Systems Division (NAWC TSD), 2011) The principal functional limitation of COVE FMB is that it is only located at the Surface Warfare Officer School in Newport, Rhode Island.

Second Approach: Virtual Reality (VR) or Augmented Reality (AR) Aboard Ship

The second approach considered was to extend the virtual FST environment aboard ship from CIC to the bridge and deck watch teams in their normal watch stations. The concept was, in essence, to temporarily install a system like COVE aboard the ship. VR or AR HMDs would provide the visual environment while watchstanders would use their normal systems and communications enabled by FST. The difference between VR and AR is that VR replaces the real world with a simulated world, whereas AR allows one to see the real world with computer-generated (CG) overlays – as in a fighter pilot's Heads Up Display (HUD). VR or AR aboard ship would combine the advantages of COVE with the advantages of existing shipboard communications, a secure environment, and team training aboard the ship. Technical considerations to maximize the immersion experience, as well as minimize eye strain and discomfort with VR and AR displays include: FOV (more is better, preferably >95 degrees, though 50 degrees is sufficient), high-resolution displays (>1080p per eye), high refresh rate (>90hz), low latency (the time delay

between movement of the HMD and the display showing that movement; <20ms is preferred) (Billinghurst, 2014 COSC 426 Lecture 2: Augmented Reality Technology, 2014). Those requirements, technically demanding just a few years ago, are now largely met by COTS VR equipment such as Oculus Rift, Samsung Gear, or NVIS nVisor ST50 (a follow-on variant of the COVE VR HMD).

VR

The VR approach would be to provide VR HMDs to those bridge and deck personnel who primarily focus on the visual environment – such as the lookouts, the OOD, the Conning Officer, the GDO, and gunners and lookouts at CSWs (Figure 6). Others, such as the helmsman, quartermaster of the watch, boatswain's mate of the watch, phone talkers and messengers would not need to be provided VR headsets in order to participate in the ship's tactical routine. The FST environment would be extended from CIC to the bridge using temporarily installed network cables connected to the VR graphics processing units (GPUs) temporarily installed on the bridge. Because they would be wearing VR headsets and not able to see and avoid the real environment if they moved about, those watchstanders would not walk around the bridge or deck but instead stay in one place, only turning their heads to view their virtual world. If they need to

Figure 6: The VR approach would have key watchstanders use VR HMDs from fixed positions aboard ship (Photo credit U.S. Navy)

change their VR vantage point – for example, the JOOD wants to walk out on the bridge wing, or perhaps zoom in as if using binoculars, he/she would do so through a keyboard or other device. Thus their headsets would only require 3 degrees-of-freedom (3DOF) sensitivity, meaning the headsets would change the virtual view in response to roll, pitch and yaw, but not in response to lateral, fore and aft, or vertical motion, which would require 6DOF. Finally, in addition to HMDs, the gunners at the CSW could be provided air-recoil training weapons integrated into the virtual environment, similar to those used at the FIST2FAC demonstration

The benefits to such an approach would be that the watch team would be training from their actual positions, using their ship's real radios, sensors and intercoms, and would be accessible to the other team members for pre-briefs and debriefs. Moreover, with the VR headset wearers stationed in one place, the headsets could be powered as well as connected to the network through cables, which avoids concerns of battery life and lessens the weight of the headsets, as well as the issue that wireless networks are not IA compliant for FST. Additionally, by staying in one place, the VR wearers avoid tangling their headset cords on objects or each other.

There are several functional limitations to the VR approach, none of which the authors feel is significant. First, it would require a pack-up kit (PUK) temporarily installed aboard ship. However, FST already requires PUKs, and the processes for temporary installation and network integration have been developed and refined over the past ten years. The FIST2FAC demonstration indicated that the VR server form factor could be shrunk to a single blade per HMD, indicating a manageable computer rack of less than two feet all around (similar to current FST PUKs), or the use of a simple desktop PC near respective stations. The second limitation is that the VR participants cannot physically move around, limiting access to fixed communication points and tactical displays. This limitation is offset by stationing the participants in front of their principal tactical display, and using hand-held radios (as many bridge and deck teams already do). The last limitation is that the participants—visually—are in a totally computer-generated (CG) environment which may lack full fidelity and introduce safety concerns in a shipboard environment that includes hatches, scuttles, ladders, low beams and ducting.

In summary, VR aboard the ship appears to be both technically and functionally feasible. Prior FST experience with shipboard PUK installation indicates that the VR installation would be manageable and could be made IA- and security-compliant. COVE and FIST2FAC indicate that VR can provide a valuable, immersive integrated synthetic training environment.

AR

To carry the VR concept a step further, the authors investigated incorporating AR for those watchstanders who require freedom of movement aboard the ship in the execution of their duties. The OOD and conning officer normally move about the bridge, and obviously the commanding officer needs freedom to roam. AR would allow

them sufficient real-world situational awareness to move about their watch station without the risk of hitting someone or something. AR could also enhance the virtual experience because it would augment, rather than replace with a completely synthetic CG image, the real bridge and topside environments. The AR approach would provide AR HMDs to those bridge watchstanders that move about (specifically the OOD, Conning Officer, and GDO), and provide VR HMDs to the rest of the bridge and deck watch teams, because they principally stay in one position (SCAT CSW gunners and lookouts; bridge wing lookouts).

There are two principal types of AR HMDs: video pass-through and see-through. Video pass-through uses a VR headset with forward-facing cameras oriented to the wearer's line-of-sight. The camera images (one for each eye) are sent to the wearer's display, showing—virtually—the real world around them, with any desired CG images overlaid on it. The advantages of video pass-through are that the display hardware is generally simpler, and the alignment (*registration*, more fully explained below) of virtual and real images is better, since both are digitized and processed before displaying. The disadvantages are that the real-world image is lower resolution than the real world; image latency may induce "simulator sickness," and since the cameras provide a fixed focus, the eyes cannot focus on different parts of the real-world scene, which may cause eye-strain and headaches. The second type of AR display, see-through AR, uses a translucent display that allows viewers to actually see the real world, with computer images overlaid on the display in front of the wearer's field of view. The advantages are that wearers use their natural vision, with their full field of view; simulator sickness is less of an issue, and eye strain is minimal. The disadvantage is that the translucent display screens may slightly shade the real-world image, and registration is more difficult. The scene is also limited to the real world images, so if a blue water environment is desired, and the wearer is in port facing a pier, a high degree of shading will be required to minimize unwanted objects in the scenario.

Two key technical requirements with AR are precise 6DOF headset *tracking* in order to properly orient the HMD and set its vantage point in the virtual world, and proper virtual object *registration,* or placement, in the real-world image. There are numerous tracking technologies, ranging from mechanical to inertial to RF to optical, and with a combination of approaches, AR tracking can be very precise, on the order of millimeters (Billinghurst, 2014), sufficient for the purposes of this paper's investigation. The second technical requirement, registration, requires both precise tracking as well as a software three-dimensional model of the real-world scene in order for the AR system to properly align synthetic images with the real-world scene. For example, if one were to overlay a synthetic radar picture on a real-world radar display, the AR system would need to know not only the vantage point of the HMD, it would also need to know where the radar display outlines were in 3D space. There are numerous approaches to resolving registration, ranging from pre-built CAD models to real-time optical and IR sensing systems, and as with tracking, a combination of approaches provides sufficient registration for the purposes of this paper (Lepetit, Vachetti, Thalmann, & Fua, 2003).

AR Video Pass-Through Approach

The authors looked at two options for AR. The first option was video pass-through "green screen" AR using combination of inertial and optical tracking. Just as moviemakers use "green screens" to fill in backgrounds around actors, the AR display can be programmed to display the synthetic environment on green screens. In this first approach, green screens would be placed on the bridge windows, and a green screen curtain on the bridge wings; in

the AR HMD, the green screens would display the synthetic environment, but otherwise the AR HMD would present the real bridge. AR HMD tracking would be passively provided by a combination of inertial and optical technologies, to include natural feature (bridge structures, such as consoles), edge (bridge window frames and green screen edges) and marker (passive spheres and/or active LEDs placed at key locations around the bridge) (Figure 7). Experimentation would be necessary to determine optimal marker placement. With video pass-through, registration is less of an issue because the images are merged in processing before they are displayed. Moreover, with the green screen approach, registration becomes a minimal issue, since the synthetic world is only visible on the green screens, which are fixed and thus fully registered in the real world. Also, the synthetic environment viewed through the green screens is relatively distant, and thus requires less precise registration.

Figure 7: The many lines and geometric shapes on a ship's bridge support AR HMD optical tracking (Photo credit U.S. Navy)

The advantage of video pass-through AR is that it is readily available technology that can be implemented today. It carries the disadvantages already mentioned, plus the additional PUK installation of green screens and tracking markers. Also, the green screens must be sufficiently bright and distinct for the system to detect them—it is possible that from one side of the bridge, for example, that the green screen on the other side would not be bright enough to be detected, and instead of a synthetic image, the AR viewer would see an obscured, indistinct bridge window. The compensation for brightness would be to temporarily install overhead lights that fully illuminate each green screen.

AR See-Through Approach
The second AR approach would use see-through AR, again using a combination of inertial and optical tracking. The "green-screen" approach could still be applied, although the authors believe tracking and registration would be sufficiently precise that green-screens could be done away with, and the synthetic image display areas could be derived from software alone. The advantage of see-through AR, in addition to its general advantages, is that would provide the most immersive experience, with a combination of a natural view of the immediate bridge environment, and a synthetic view of the world outside the ship. The disadvantages are that it requires more complex software algorithms for registration, possibly including pre-built (as opposed to real-time) software 3D mapping of the bridge. Also, the see-through display may slightly shade the real-world image, and conversely, the synthetic image overlay may not completely hide the real world behind it, although those are relatively minor limitations compared to the lower image quality and FOV of AR video pass-through.

Other AR Considerations
The proposed AR approaches would use wired HMDs, due to power and IA requirements. Even though the wearers would be trailing cords as they moved around the bridge, the authors postulate that wired AR headsets could be used successfully if they were limited to a few users (such as the three positions proposed) to minimize the possibility of tangling, and had sufficiently long cords to enable movement as far as the bridge wings. Future areas to investigate are wireless HMDs using IR or limited range RF connections, as well as other wearable display technologies such as retinal displays, waveguides and picoprojectors. VR and AR display technologies have advanced tremendously in the past five years, and promise in time to become ergonomically transparent technology.

Summary

Table 1 below summarizes the feasibility of each approach the authors investigated.

Table 1: Summary of Approach Technical and Functional Feasibility

Approach	Technically Feasible?	Functionally Feasible?
NSST	No. IA requirements; facility accreditation; requires additional communications circuits	No. Limited FOV display; limited space for SCAT; limited availability
COVE	No. IA requirements; facility accreditation; requires additional communications circuits	No. Limited availability. No viewpoints for SCAT CSW stations
VR	Yes	Yes. Only virtual mobility for VR HMD wearers. Requires PUK install for each ship
AR – video pass-through	Yes	Yes. Requires PUK install for each ship; green screens if used must be well-lit; tracking marker locations must be developed and tested
AR – see-through	Yes	Yes. Requires PUK install for each ship; tracking marker locations must be developed and tested; registration methods must be developed and tested

One can see from the table that of the approaches that the authors investigated, they deemed only the VR and AR approaches as both technically and functionally feasible. The standalone bridge trainers NSST and COVE were neither technically nor functionally suitable for integration into FST, though COVE does indicate the promise of VR for integrated training. Although one might consider building a separate facility like COVE FMB to support integrated training, and future Navy trainers such as the DDG-1000 and LCS Training Facility offer the promise of full synthetic integration within a trainer, the authors believe that leveraging FST aboard ship offers additional value because it requires the use of real shipboard sensors and communications systems. Given the rapid recent evolution

of VR and AR technology, a phased approach would be warranted, beginning first with a proven VR system, perhaps as simple as installing a few COVE stations aboard ship. The next phase would be to build on lessons learned from VR implementation to develop and test a video pass-through AR system, which again is a proven technology. The third phase would be to implement a see-through AR system, using tracking and registration lessons-learned from second phase. Some of this testing is already planned: as a follow-on to the FIST2FAC demonstration, ONR will test integrating into an FST event a VR PUK system aboard ship for the M2 .50 caliber CSW position.

Conclusion

A warship faced with an uncertain possibility of swarm attack is dealing with a complex, fast-paced problem that requires repetitive team training for the best chance of successful defense. However, today's crews receive comparatively little training for such a scenario, due to a lack of in-port training capabilities, and the difficulty and expense of executing such training underway, requiring coordinated underway time from several warships, small craft and other simulated threat support, helicopter support, and permissive weather conditions. However, a FAC/FIAC/swarm attack is well-suited to be presented in a synthetic environment: scenarios to train and test the teamwork and crew coordination among watchstanders could be presented again and again with different variations, honing individual skills as well as group coordination. The integration of warship CIC, bridge and deck crews in a Live Virtual Constructive training environment using virtual reality and/or augmented reality systems installed aboard ship for Fleet Synthetic Training events is a suitable and technologically feasible approach to such training.

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