Immersive Simulation, Prototyping, and Evaluation of Infrared Sensor and Augmented Reality Technologies

John Graybeal, Ph.D.
U.S. Army CCDC C5ISR Night Vision and Electronic Sensors Directorate
10221 Burbeck Road, Fort Belvoir, VA 22060
UNITED STATES OF AMERICA

Jacob Quartuccio, Ph.D.
KINEX, Inc.
P.O. Box 3107, Manassas, VA 20108
UNITED STATES OF AMERICA

Todd Du Bosq, Ph.D.
U.S. Army CCDC C5ISR Night Vision and Electronic Sensors Directorate
10221 Burbeck Road, Fort Belvoir, VA 22060
UNITED STATES OF AMERICA

ABSTRACT

The U.S. Army CCDC C5ISR Center's Night Vision and Electronic Sensors Directorate (NVESD) is tasked with the development of low-light and infrared sensor technologies, which can range in form from air/vehicle mounted sensors, to infantry weapon sensors, and to head-mounted sensors and displays. In this paper, we discuss an immersive testing environment recently acquired by NVESD that is capable of virtual prototyping exercises for different sensor systems, and is likewise capable of serving as an immersive environment examining variations of AR displays and methods of presenting AR information to human operators. The immersive environment consists of a "green room," consisting of plexiglass panels that emit green light via controllable, electroluminescent tape. A pair of cameras, paired with a Vive virtual reality headset (HTC Corporation), are used to form a composite view of real objects and virtual overlays; any object observed in the immersive testing environment is visible to the user, but open green space is replaced by the virtual environment. We describe the new system and simulation use cases for both sensors and AR technologies, describing how such simulation technologies can allow for strict control of empirical scenarios, providing a vigorous evaluation of device characteristics. Ultimately, such simulations will allow Soldiers to experience sensor characteristics and AR displays before the first physical prototype is ever constructed, soliciting valuable user feedback early in the design phase of the acquisition lifecycle.

1.0 INTRODUCTION

One of the missions of the U.S. Army CCDC C5ISR Center's Night Vision and Electronic Sensor's Directorate (NVESD) involves evaluating, simulating, and modeling sensor performance, among many other tasks related to the development and acquisition of electro-optical and infrared sensors (EO/IR). In addition to measuring the optical properties of a sensor, such as sensor resolution, signal to noise ratio, and parallax error, evaluations of human performance with the sensors are also necessary for a comprehensive evaluation. Consequently, NVESD is continually working to improve methods of evaluating, modelling, and simulating human use of EO/IR sensors.

In this paper, we present a simulation tool recently acquired by NVESD, the gaps in our simulation capabilities that it addresses, and its planned use cases. The tool, which we refer to as the Virtual Prototyping Holodeck (VPH), consists of simulation software, computers, virtual reality displays, cameras and sensors, and a physical environment. Collectively, these components allow users to be placed in a virtual environment. If desired, by utilizing visible cameras mounted to the VR headset, users can also see physical objects in the room while within the virtual environment. This enables NVESD's research team to conduct experiments at different points on the extended reality spectrum (ranging from entirely real to entirely virtual experiences), and experiments conducted with this simulation tool are best described as ranging from pure virtual reality (VR) to augmented VR (Azuma, 1997).

One key area of sensor simulation at NVESD, and a planned use case for the VPH, is developing virtual prototypes of EO/IR sensors. Virtual prototyping refers to the creation of a computer simulation of a product for presentation and evaluation (Wang, 2002). Building physical prototypes of a sensor is expensive, and it is a slow process compared to simulating a prototype of proposed or desired sensor specifications. Virtual prototyping, through simulation, can give decision makers and operators a chance to "try out" sensor designs before the first physical prototype is even constructed to better ensure that resources are spent on a solution that meets operational requirements. Virtual prototyping also enables operators to try out various proposed sensors or sensor configurations for a given operational task, and generates an opportunity for operators to provide feedback early in the design process. Objective performance on a task with the virtual prototype can even be measured through simulation.

The human factors or user experience (UX) literature has made it clear that the best approach to designing technology for human use often involves rapid, iterative prototyping (e.g., Nielsen, 1993; Jones & Richey, 2000). Rapid prototyping involves presenting early and progressive prototypes to users, and collecting user feedback and/or measuring performance repeatedly throughout the design cycle. In other words, users should be consulted early in the design process and should test progressive prototypes as soon as they become available so that iterative improvements can be made. This approach yields better results than waiting until a fully functional prototype is completed, produces improvements in usability faster and shortens the time needed to acquire a fully usable product, and ultimately generates cost savings over the product development cycle. Furthermore, in a military context, if user testing is deferred until after the product is already fully developed (from an engineering prospective), it may be too late to make substantial design changes.

Not only does this approach lead to greater cost savings, it leads to a better product. Scientists, engineers, and developers – while skilled in their respective disciplines – rarely have the same exact perspective of the intended user, despite their best intentions. Thus, there is always a need for tools that can facilitate user testing so sensors can be redesigned at a much earlier stage in the product development cycle. With such tools, users could give their feedback through a variety of methods such as cognitive think aloud protocols, performing simulations of real world tasks, surveys, interviews, and focus groups.

In summary, there is a broad need for immersive testing at NVESD. Currently, defining human performance with a sensor often involves presenting the visual imagery from the sensor on a computer monitor (Graybeal, Monfort, Du Bosq, & Familoni, 2018). In some applications, this may be exactly how the sensor's imagery will be displayed for a human operator (e.g., unmanned aerial system sensor feed displayed on a computer monitor). However, in other situations, the imagery will never be displayed on a computer monitor (e.g., imagery viewed through head-mounted sensors). Although we have observed very similar results between field trials and laboratory based perception tests using the same imagery collected in the field (e.g., Hixson, Teaney, May, Maurer, Nelson, & Pham, 2017; Hixson & Graybeal, 2018), the human use of the sensor may not be fully replicated when presenting users with a single static image. In other words, although humans perform similarly when looking at a single image regardless of whether they are viewing it in the field versus in the laboratory, a static image may not represent the task well, such as with driving or route clearance visual tasks. In such cases, more immersive perceptual testing might derive better estimates of human performance.

The following sections present the design and capabilities of the newly acquired immersive simulation, intended use cases, and progress made towards those use cases.

2.0 SIMULATION APPARATUS AND METHODOLOGY

2.1 Virtual Prototyping Holodeck (VPH): Design and Construction

The immersive environment was designed by KRATOS Defense and Security Solutions using commercial “off the shelf” hardware and software components. The central purpose of the VPH is to provide immersive, mixed-reality experiences that are either entirely VR or are VR augmented with some real objects (i.e., augmented virtuality).

At the heart of the system is a “master” computer that controls all of the software for the simulations. Software components of the system include Steam VR, an image generator to render the visual imagery, a lighting controller for the immersive chamber, and an audio controller (for headset communication with those in the immersive chamber), among others. The first image generator software platform we used was Titan, but the system is designed to be compatible with any image generator so that simulations can be created using any software platforms.

This “master” computer connects wirelessly to “slave” wearable backpack computers (Hewlett Packard). A Vive VR display (HTC Corporation) connects directly to the backpack computer, and thus receives and displays imagery sent from the “master” computer. The system is also meant to be VR display agnostic, so that better displays can be incorporated as they become available, or so that different displays can be used, as determined by the specific requirements of a simulation and the strengths/weaknesses of various displays. Currently, two separate backpack and VR display pairs are linked to the “master” control computer, which enables two participants to use the VPH simultaneously. The two displays can run the same simulation simultaneously (i.e., users are placed in the same virtual environment) or the displays can be used separately to run two independent simulations.

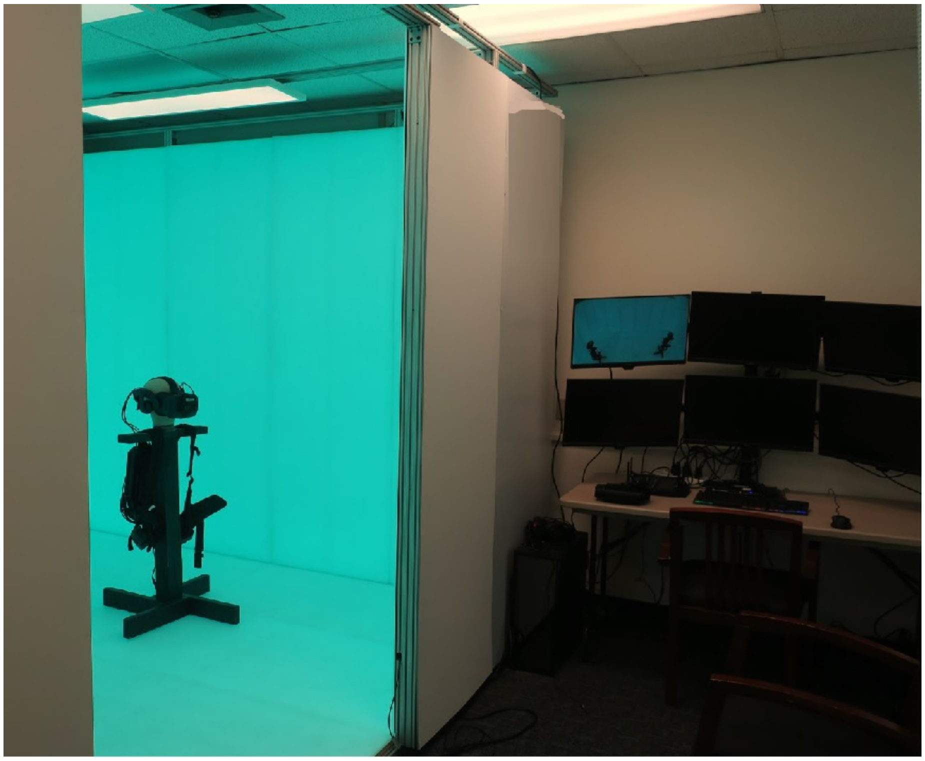


Figure 1: The NVESD Virtual Prototyping Holodeck (VPH). Participants enter the immersive simulation chamber through a permanent doorway in the walls of the 10 by 15 foot chamber (left). The research team controls the simulation through the master control suite (right).

The simulation chamber itself consists of plexiglass panels that emit green light via large strips of controllable, electroluminescent tape (see Figure 1). While this feature is unnecessary for pure VR experiments, lit panels provide constant illumination throughout the chamber (i.e., no shadows), and they provide a background that the system can use to merge VR environments with real objects, similar to the standard “green screen” technologies used in the film industry. A pair of cameras, custom mounted and integrated into the Vive display, are used to form a composite view of real objects and virtual overlays (see Figure 2); any object viewed by the cameras in the immersive testing environment is visible to the user, but open green space is replaced by the virtual environment (see Figure 3). To increase the user’s sense of immersion, a “virtual” wall and ceiling are each configured so that the user sees only the virtual environment when looking at the doorway or ceiling (i.e., in a direction where there are no green panels).

Figure 2: The wearable backpack computer system and the modified Vive display rest on a holding rack (left). A pair of cameras integrated into the Vive display enables the research team to display real objects in an otherwise virtual world (right).

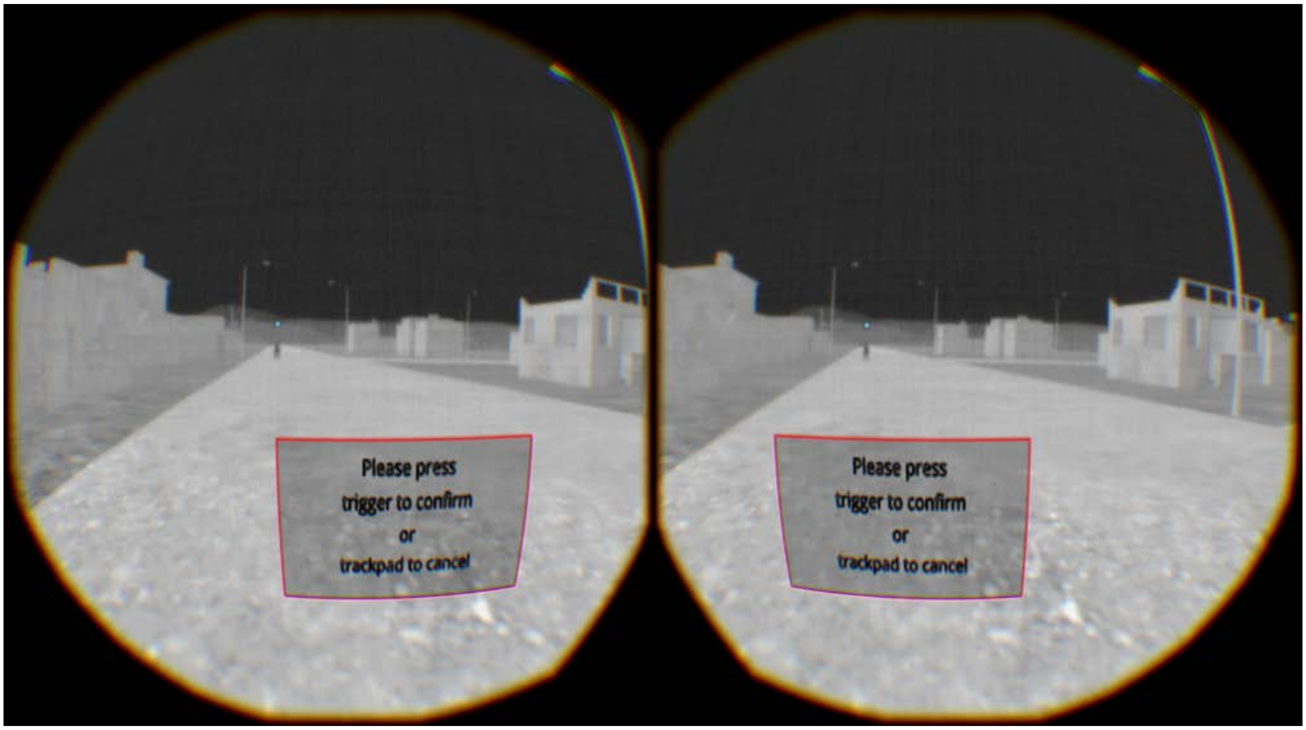
Sensors mounted to the top of the chamber are used to track objects within it; Vive virtual reality system trackers (HTC Vive Corporation) are inexpensive tracking accessories that can be mounted to various objects, such as training rifles, sensor prototypes, and other objects that must interact with virtual environment. So far, the VPH has incorporated modified training rifles and a 3D-printed sensor prototype, which send wireless signals to the "master" computer (i.e., when a button or trigger is pressed), and the Vive virtual reality tracking system accessories allow this information regarding use of an object to be combined with three-dimensional orientation information about the object.

Figure 3: A soldier gives a hand signal inside the VPH immersive testing and simulation chamber (left). When viewed through the virtual reality display inside the VPH, the Soldier appears in the middle of a virtual environment (right).

2.2 Integration of the Night Vision Image Generator (NVIG) Software

One of the core system enhancements needed for our simulations was the integration of the Night Vision Image Generator (NVIG) software into the VPH. NVIG is a simulation tool developed by NVESD, capable of rendering scenes from the perspective of various visible and infrared sensors (Hixson, Miller, & May, 2015). In NVESD's Advanced Sensor Evaluation Facility, the optical properties of a sensor, such as blur, noise, and sampling, can be characterized and these measurements can be used to create a sensor profile in NVIG. Thus, the integration of NVIG into the VPH allowed us to immediately leverage our existing simulation capabilities. This work consisted of modifying NVIG to utilize the Steam VR Software Development Kit in order to display the NVIG imagery in the VPH's VR displays.

Additionally, NVIG had to be configured to support the atypical displays in the Vive DR displays. Many of our past simulations consisted of a single viewport in NVIG, and this single viewport was configured for displaying imagery on a standard computer monitor. However, because VR displays are much closer to the eyes, and because each eye is looking through a separate visual pathway (i.e., like binoculars), NVIG had to be configured to utilize two viewports, one for each eye, in a configuration that matched the pixel layout of the VR display. Figure 4 shows how a scene might be rendered in NVIG through two unique but overlapping viewports. Although the imagery presented to each eye is different, the human perceives a single uniform image with depth.


Please press
trigger to confirm
or
trackpad to cancel

Please press
trigger to confirm
or
trackpad to cancel

Figure 4: Example output from NVIG as it is configured to be displayed in the HTC Vive VR display. When pixels are mapped correctly, the stereo images are perceived by the participant as a single image within the VR display.

3.0 VIRTUAL PROTOTYPING APPLICATIONS AND PROGRESS

The U.S. Army strives to provide each Soldier with the right sensor to perform their assigned mission, taking performance along with size, weight, power, and cost (SWAP-C) into account. The Night Vision Integrated Performance Model (NV-IPM) is a system engineering tool that can be used to evaluate a wide variety of EO/IR systems (Teaney & Reynolds 2010). NV-IPM is commonly used to assess the performance of military target acquisition systems. The blur, noise, sampling, and contrast degradations from each component of the imaging system (target, background, atmosphere, optics, detector, electronics, display, etc.) are calculated by NV-IPM with a typical output of range performance. As each parameter within the model is changed, such as the size of the optics or the frame rate of the sensor, the range performance curve can change.

Typically, NV-IPM is used by system designers to determine the range performance curve of a proposed sensor. However, virtual prototyping allows a visual representation of the proposed sensor to be provided to the user without the time and expense of first building the sensor and performing a field collection. Virtual prototyping will also provide a visual representation of a proposed system during the analysis of alternatives and system design trade studies phases of development. This allows visualization differences of any sensor parameter (field-of-view, quantum efficiency, frame rate, optics diameter, etc.) to be quickly shown to the observer for a particular task and scene, or even a specific mission scenario. In addition, virtual prototyping can be used to test and evaluate both the optical properties of the sensor, as well as other elements of the technology, such as proposed display configurations for the human operator, including how various elements of AR symbology could be implemented. Conventional user research methods, such as heuristic analyses, user tests, surveys, interviews, and focus groups can also be facilitated by the VPH because it can provide context for the devices being developed, and can enable Soldiers to have hands-on interactions with many key aspects of the virtual prototype.

Overall, virtual prototyping, concept exploitation, and initial system integration executed early on in the design phase of imaging sensor system development reduces overall program cost, schedule, and performance risks. In the following sections, we discuss some specific applications for the VPH. We also discuss current goals, progress towards each application, and challenges experienced thus far.

3.1 Augmented Reality Simulations

One use of the VPH is to conduct simulations of augmented reality (AR) interfaces, as AR interfaces have become an increasingly important research topic at NVESD. The VPH is well suited to test how operator performance can change as a function of additional information provided to an operator during a given military task. The VPH can be used to both evaluate specific instances of technology (e.g., determining whether a proposed AR symbology layout will improve human performance, whether elements of an AR display are distracting, etc.), and also to understand human use of AR in broader contexts and generalizable experiments.

As we presented at last years' NATO MSG symposium, NVESD began an “AR Red Team” research program (Graybeal & Du Bosq, 2018). This was a collection of experiments designed to adapt our existing simulation capabilities into tools capable of simulating human performance with AR assistance. The initial AR Red Team experiments (Graybeal & Du Bosq, 2018) were focused on developing simulation capabilities to study target acquisition performance (Graybeal, Nguyen & Du Bosq, 2019), visual search (Monfort, Graybeal, de Visser, & Du Bosq 2018), vehicle identification performance (Graybeal, Nguyen & Du Bosq, 2019), and navigation with augmented reality assistance. Collectively, the results of these simulations demonstrated that the accuracy thresholds required for AR systems to improve human performance vary as a function of both the specific task itself, and the difficulty of various perceptual judgements within the same task (*i.e.*, distant versus close targets).

Another lesson learned from these initial simulations was that having an accurate measurement of the baseline difficulty of the task is essential to deriving accurate assessments of human performance with AR, as all changes to human performance are calculated relative to baseline performance. The VPH represents a way to conduct similar experiments in a more immersive environment than using simple computer monitor displays. For some visual tasks, such as using an infantry weapon optic to search for a target, displaying still images on a monitor would not be the way a Soldier would naturally experience that imagery. In theory, an immersive test chamber could be used to give the Soldier control of a simulated sensor in the same way they could use a real sensor operationally. This may lead to both more accurate baseline assessments of performance for some tasks (i.e., without AR assistance) and, consequently, better estimates of changes in performance due to AR assistance.

Our first planned augmented reality simulation in the VPH is an immersive target acquisition study. In contrast to using simulated sensor controls to search a scene for a designated target, the planned study will simply feature a VR display and a 360° virtual environment for participants to search in the VPH. This will enable us to more realistically simulate how a dismounted infantry Soldier would orient to a new AR target designation. We have successfully repurposed our existing target acquisition experimental structure in NVIG for use in the VPH, and we are working on developing an intuitive interface that enables participants to select and designate virtual entities. While our previous target acquisition simulations used a reticle in the center of the screen to designate targets (left), and the user rotated the screen's field of view with the sensor controls, this is not a good option for designating targets within head-mounted displays because orienting the head to point directly at a target can be difficult and uncomfortable. We are currently experimenting with giving the user a handheld wireless controller, which they can use to point at virtual entities, and while visually displaying the precise beam in NVIG (see Figure 5, left).

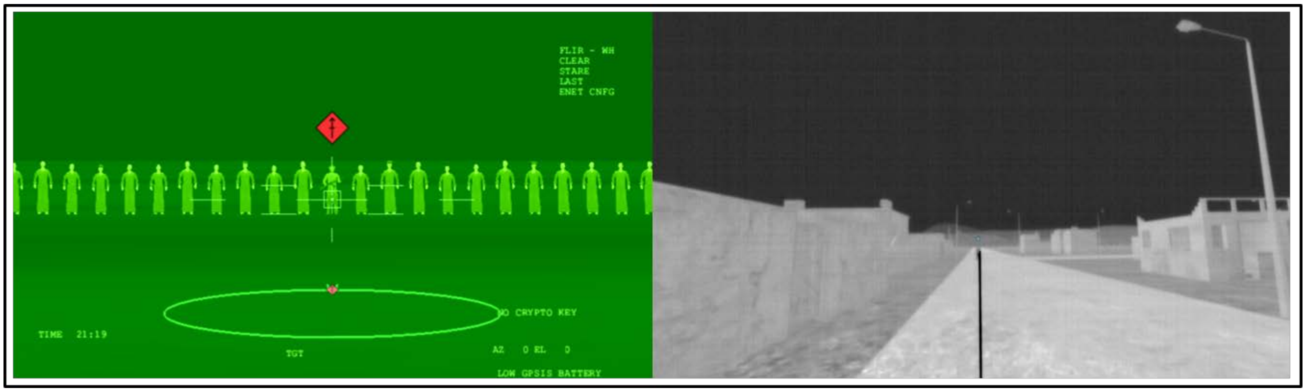


Figure 5: Human machine interface for target acquisition simulations. Our previous target acquisition task utilized a reticle at a fixed point in the center of the screen (right). We are developing ways to visualize the way a wireless controller is pointing into a virtual scene in the VPH (right). In the current VPH interface, a black beam radiates out from the users point of view towards the virtual entity being selected.

Another way we plan to utilize the VPH is to conduct simulations of various AR display symbology components and head-mounted displays (HMD). For example, a long term goal is to be able to ask sensor specific questions regarding optimal display symbology. Consider a situational awareness ring inserted into a warfighter's HMD night-vision goggles. Various characteristics of the situational awareness ring, such as its optimal size, pitch (*i.e.*, viewing angle ranging from vertical to horizontal), the location of the ring within the display, etc., could be varied and used by participants to identify the best design layout. Compared to showing users pictures of display “mock-ups” and asking for feedback, the VPH will enable participants to utilize and “try-out” various AR display designs. This would enable the research team to collect higher quality subjective feedback and to even measure objective performance with the various display designs in immersive scenarios.

To this end, we have recently purchased eye-tracking devices (Pupil Labs), which are designed for integration into the HTC Vive displays in the VPH. These eye-tracking devices will enable us to record where participants are looking throughout the course of a simulation (gaze direction, dwell time, etc.). This will also enable us to identify if there are defects in a proposed AR display that are distracting, pulling an operator’s attention away from the field of regard at inappropriate times, and it will also enable us to assess information transfer efficiency. The best AR visual overlay is the one that provides all of the required information while minimally capturing the operator’s gaze (relative to the field of regard). In other words, even when using AR displays, operators should be focused on their field of regard, and eye-tracking simulations in the VPH will help us identify AR symbology layouts that transfer information without becoming overly distracting.

3.2 Perception Experiments and Simulations

Another use of the VPH is to conduct virtual, immersive perception testing. Perception testing at NVESD is typically focused on detection and identification tasks. Detection tasks require a person to perceive a target visual sensory event when it occurs, while identification tasks require a person to assign a categorical label (of varying specificity) to a perceived object (DiCarlo, Zoccolan, & Rust, 2012).

NVESD’s Perception Laboratory often assists with defining sensor requirements for a specific military task by showing real (or in some cases, simulated) imagery to human observers. This often involves showing sensor imagery that ranges in quality, enabling researchers to identify the minimal image quality needed in order to complete a given military task. In addition to defining sensor requirements, perception tests are conducted regularly at NVESD to understand displayed imagery in broader contexts, such as how range to the target, blur, sensor noise, and other variables affect detection and identification performance. Again, more operationally representative perception tests may eventually be possible when showing participants fixed imagery on a computer screen does not represent the task well. This may be especially true for cases when the human’s interaction with a sensor is critical to performance, as human use of a sensor can be simulated in the VPH.

Of the applications presented in this manuscript, immersive perception testing is perhaps the most challenging because the visual fidelity of the simulation is incredibly important to task performance. In contrast to augmented reality simulations, which can test how a human would interact with additional information provided during a task with a simple visual display, the performance during a perception task depends entirely on the visual fidelity of the imagery.

The integration of NVIG into the VPH is a substantial step towards this goal, as NVIG has been used previously to render high quality simulations of objects and object signatures (e.g., Graybeal, Nguyen & Du Bosq, Hixson et al., 2017; see Figure 6). Another NVESD experiment we are currently developing is designed to validate the visual representations being displayed in the VPH. The experiment will display images of basic shapes (e.g., triangles), and will ask participants to determine the orientation of the triangles (Bijl & Valeton 1998). The results from this study will be the first step towards confirming that targets being rendered in NVIG are appearing correctly in the VPH’s VR displays with an equivalent modelled task difficulty.

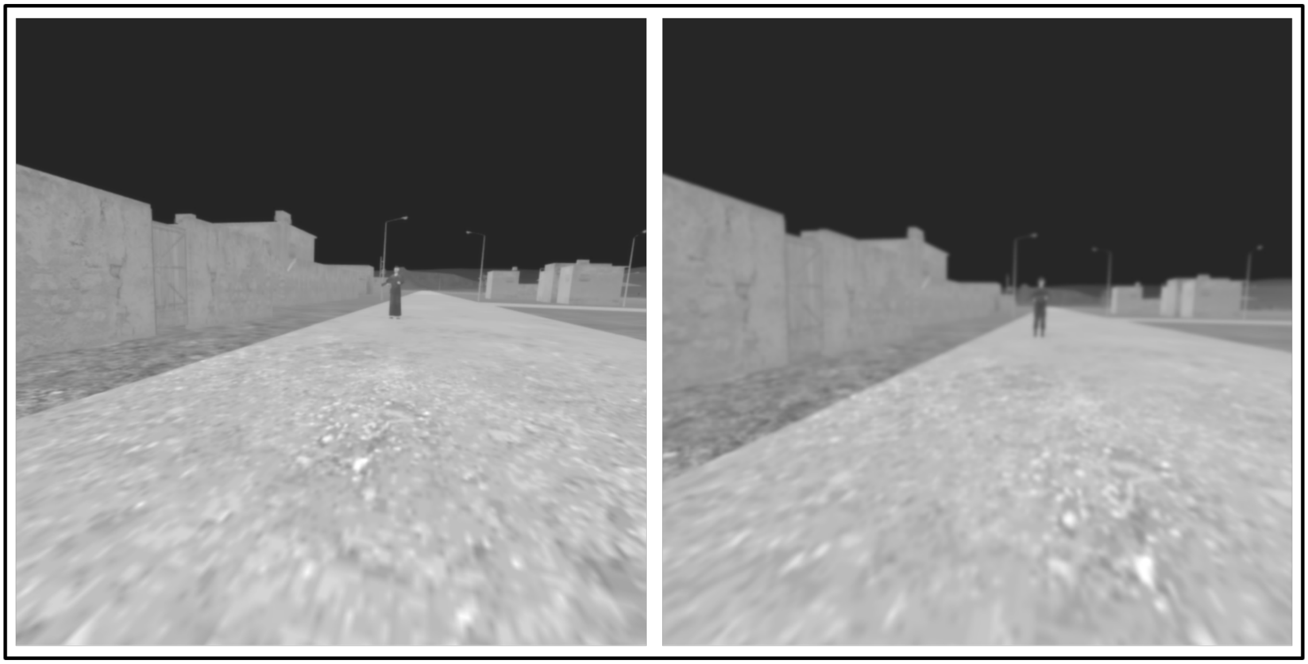


Figure 6: Example scenes from a perception task rendered by NVIG for display in the VPH. The task was designed to compare perceptual performance between an ideal sensor (left) and a lower quality sensor (right). Participants viewed virtual persons and attempted to determine whether each one was holding a weapon.

One challenge we have encountered is the correct modelling of the immersive VR display, which is much more complicated than a standard computer monitor. For example, pixel densities are uniform for a computer monitor but are not uniform for many VR displays, as they feature a higher density of pixels in the center of the display, with a lower density of pixels in the peripheral vision. Another challenge we encountered is the Vive's display resolution is low enough that some our visual tasks would be "display limited," meaning that the perception test would not be able to accurately display some visual stimuli due to insufficient pixels on target. Therefore, the system will need to be upgraded in the future by improving the quality of the VR displays in order to successfully accomplish our goals for all of our various perception testing applications.

CONCLUSION

Immersive simulation has great potential to improve and expedite technology development because it can enable users to work with virtual prototypes long before a physical prototype becomes available. This allows user feedback and performance to be incorporated earlier in the iterative design process. In addition to general virtual prototyping, the VPH is well suited for simulations of AR displays and for immersive perception testing. This provides NVESD with new research mechanisms to understand EO/IR sensor performance, a tool to study digital augmentation of EO/IR sensors, and a method of conducting tests where the participant has greater control over the imagery being displayed (because they can interact with the immersive scenarios).

REFERENCES

[1] Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355-385.

[2] Bijl, P., & Valeton, J. M. (1998). Triangle orientation discrimination: the alternative to minimum resolvable temperature difference and minimum resolvable contrast. *Optical Engineering*, *37*.

[3] DiCarlo, J. J., Zoccolan, D., & Rust, N. C. (2012). How does the brain solve visual object recognition? *Neuron*, *73*(3), 415-434.

[4] Graybeal, J., & Du Bosq, T. (2018). Augmented reality: Understanding human performance with imperfect systems by using virtual simulations. In *Proc. of NATO MSG-159*.

[5] Graybeal, J. J., Du Bosq, T. W., & Nguyen, R. T. (2019, May). Simulating human vehicle identification performance with infrared imagery and augmented reality assistance. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXX* (Vol. 11001, p. 110010A). International Society for Optics and Photonics.

[6] Graybeal, J. J., Nguyen, R. T., & Du Bosq, T. (2019, December). Simulating augmented reality spatial accuracy requirements for target acquisition tasks. In *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*.

[7] Graybeal, J. J., Monfort, S. S., Du Bosq, T. W., & Familoni, B. O. (2018, April). Human perception testing methodology for evaluating EO/IR imaging systems. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXIX* (Vol. 10625, p. 106250T). International Society for Optics and Photonics.

[8] Hixson, J. G., Miller, B., & May, C. (2015, May). Enhanced modeling and simulation of EO/IR sensor systems. In *Modeling and Simulation for Defense Systems and Applications X* (Vol. 9478, p. 947807). International Society for Optics and Photonics.

[9] Hixson, J. G., Teaney, B. P., May, C., Maurer, T., Nelson, M. B., & Pham, J. R. (2017, May). Virtual DRI dataset development. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXVIII* (Vol. 10178, p. 101780Q). International Society for Optics and Photonics.

[10] Hixson, J. G., & Graybeal, J. J. (2018, April). Virtual DRI incorporating the effects of vibration on existing imagery. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXIX* (Vol. 10625, p. 106250L). International Society for Optics and Photonics.

[11] Jones, T. S., & Richey, R. C. (2000). Rapid prototyping methodology in action: A developmental study. *Educational Technology Research and Development*, *48*(2), 63-80.

[12] Monfort, S. S., Graybeal, J. J., de Visser, E. J., & Du Bosq, T. (2018). Reliability requirements for augmented reality in visual search tasks. In *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*.

[13] Nielsen, J. (1993). Iterative user-interface design. *Computer*, *26*(11), 32-41.

[14] Teaney, B. & Reynolds, J. (2010). Next generation imager performance model. In *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXI* (Vol. 7662). International Society for Optics and Photonics.

[15] Wang, G. G. (2002). Definition and review of virtual prototyping. *Journal of Computing and Information Science in engineering*, *2*(3), 232-236.