KC-135 Boom Operator Training Hi-Fidelity Stereoscopic Display Technology Demonstrator

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ABSTRACT

KC-135 boom operators are responsible for flying the refueling boom trailing from their aircraft into the refueling receptacle of receiving aircraft. The task requires them to maneuver a refueling knuckle on the end of a 30-ft assembly into the receptacle of the receiver under widely varying lighting and weather conditions. The potential for damage to the receiver is high. Small scratches and dents at best compromise corrosion resistance; larger collisions can reduce stealth characteristics and mission effectiveness of coated aircraft, or even cause fires in receiver cockpits when the refueling tube punctures cockpit glass.

This paper describes a technology demonstrator built around commercial off the shelf (COTS) PC-based image generators and an innovative autostereoscopic image display system to evaluate the effectiveness of depth perception cues to support future boom operator training systems. Using infrared face imaging for eye tracking, two liquid crystal on silicon (LCOS) light-valve based projectors, an arrangement of beam splitters and mirrors mounted to a motion platform, the system steers collimated and focused stereo images at full HDTV resolution directly into each of the moving viewer's eyes. The associated image generator adjusts rendering viewpoints in both channels simultaneously, providing an intensely immersive experience with no perception of a screen or projection surface. Brightness and contrast levels are unprecedented; yet, the system's eye strain and energy exposure are substantially lower than what the viewer would receive from a large CRT or flat-screen.

ABOUT THE AUTHORS

Mr. Warren Couvillion is a Senior Research Engineer in the Training, Simulation and Performance Improvement Division of Southwest Research Institute. He has over twelve years experience in electrical and computer engineering in areas ranging from electrostatic discharge control, computer security, computer graphics and visualization, and virtual reality. He received a B.S. in Electrical Engineering from The University of Texas at Austin, and M.S. degrees in Electrical and Computer Engineering from Mississippi State University.

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Mr. Bruce D. Newell is a Senior Scientist at Eastman Kodak Company. He began his Kodak career in the analytical laboratories where he was responsible for the development of optical and electron image analysis technology for application to Kodak R&D and manufacturing issues. In 1997, he moved into the Digital and Applied Imaging business and held several positions in product development and commercialization. Mr. Newell has had a variety of assignments including business development and product management positions. In mid 2002, he joined the System Concepts Center within the Research & Development Laboratories and is currently responsible for the technical management of Kodak's Immersive Imaging Program.

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INTRODUCTION

This paper describes the development of a technology demonstrator designed to evaluate the benefit of depth perception cues provided by commercial off-the-shelf (COTS) image generators (IGs), and a new, autostereoscopic display developed by Eastman Kodak Company. We discuss the advantages of the new display system, as well as advantages offered by newer image generators. We also discuss the metrics chosen to evaluate the display system of the demonstrator.

BACKGROUND

The KC-135 is a Boeing 707 modified for in-air refueling. The KC-135 can carry over 203,000 pounds of fuel, which is delivered through an aft-mounted boom that can extend up to 50 ft. The KC-135 has been used by the United States Air Force (USAF) since 1957 and has undergone several improvements. A recent upgrade is expected to extend the life of the aircraft beyond 2020, as described in Grey et al (1992) and Michel (1998).

A boom operator, or "boomer," controls the refueling boom from a "pod" in the aft end of the aircraft. Boomers fly the boom (which has two wing-like "ruddevators" to provide lift and steering) while lying face down in cramped quarters as shown in Figure 1. The boomer lies on the center cot, resting his chin on the gray pad. The boomer views the boom and receiver aircraft through a sighting window directly in front and slightly below his head. The boomer's controls consist of a control panel directly below his sighting window, as well as a yoke below and to his right (not shown).

Training boomers is difficult and expensive. Training flights require not only a KC-135, but a receiver aircraft as well. To help reduce these costs, the Air Force developed a Boom Operator Part-Task Trainer (BOPTT), a simulator for the KC-135 boomer station. The original BOPTT used physical models to represent the boom and receiver aircraft.

Figure 1: KC-135 Boom Operator Station

Over 20 years ago, these models were replaced by computer graphics. Although state of the art at the time, the technology used in the BOPTT was not capable of providing visual cues that can be produced using currently available and emerging display systems. In particular, the technology lacked the ability to display high fidelity textured models, to render realistic shadows and to display stereo images, which are believed to be critical elements in providing high-quality depth perception in a visual simulation.

An experiment described by Banks et al (2001) shows that patterns on an object are used to determine their slant relative to the viewer. Current computer graphics systems typically display these patterns via texturing.

Thompson et al (1998), Hu et al (2000), and Madison and Kersten (2002) showed that cast shadows are one of the most important visual cues used to determine the relationship of two computer generated (i.e., virtual) objects, especially whether or not the objects are in contact.

Most display systems used in training today present only a two dimensional (2D) image to the student. For applications such as boomer training, a projection screen would typically be only a few inches farther from the student than his controls, so that even when he is supposed to be focusing on distant objects, his eyes are focused much nearer. These conflicting cues may detract from the student's sense of presence.

OBJECTIVES

The primary objective of this project was to select and integrate a three dimensional (3D) display system with COTS PC-based IGs to build a technology demonstrator to evaluate the use of depth perception cues to support future boomer training. Preferably, the display system would not require any special glasses to be worn by the user, i.e., the display would be autostereoscopic.

The demonstrator was to be evaluated by instructors and students at HQ AETC/XPRF and the 97th Air Refueling Squadron (ARS) at Altus AFB, Oklahoma using a simplified simulation of the refueling of a C-17 on a clear day with the sun directly overhead. The interior of the KC-135 refueling pod was to be mocked up with sufficient fidelity to perform this task. This required simulating the boom yoke and extension lever, several gauges, and indicator lights.

TECHNICAL APPROACH

Display System

Initial efforts focused on the selection of a display system that met the criterion of providing a 3D display without requiring special headgear. Several COTS autostereoscopic displays using lenticular screens are available. Unfortunately, these systems lack the field of view (FOV) required to give the boomer the full view outside the sighting window.

The Cambridge Autostereoscopic Display described in Dodgson (2000) is capable of providing the required FOV. The Cambridge Display uses multiple “sweet spots” to present fifteen stereo views to the user. While initial investigations suggested this may have been an acceptable display for the study, it was not selected as it was in the prototype stage in Cambridge, UK and, therefore, not easily accessible to the development team in San Antonio, Texas or the evaluation team in Altus, Oklahoma.

Another display considered was the New York University (NYU) autostereoscopic display, described in Perlin et al (2001). The NYU display is similar to COTS lenticular displays, but instead of using a fixed lenticular lens over the image display, a liquid crystal screen is used to create a diffraction grating. The slits of the grating are adjusted based on an eye tracker so that a stereo image pair is properly focused on the viewer's eyes. This is a very promising technology. It is inexpensive and has no moving parts. However, the current prototype does not provide the required instantaneous FOV. While we believe the NYU display is an excellent way of providing a low-maintenance autostereoscopic view, this system was not selected due to the restricted FOV and the risks associated with removing artifacts visible in the prototype system given the short development time for the project.

We ultimately decided to use an autostereoscopic display developed by Eastman Kodak Company (Cobb et al, 2003). This design uses pupil imaging with a curved mirror and employs a monocentric configuration to enable a wide field of view (90 degrees) and large pupils while keeping the lens diameters small to fit them within the interoccular separation. For each eye, image formation was accomplished using 1920 _ 1200 (HDTV) liquid crystal on silicon (LCOS) spatial light modulators in a 3-panel configuration. The design employs custom curved diffusers, which were developed to optimize throughput, contrast, and pupil illumination uniformity. The display system provides a very realistic and immersive stereoscopic virtual image; and, the technology is scalable to even higher resolution, wider field, and a smaller physical footprint.

Using infrared (IR) face imaging, the user’s eye position is tracked, allowing the pupil images to be moved with the viewer’s eyes. Eye position information is also fed to the image generator, which adjusts rendering viewpoints in both channels simultaneously, providing an intensely immersive experience with no perception of a screen or projection surface. Brightness and contrast levels are unprecedented, yet the system's eye strain (due to the virtual image focused at (near) infinity) and energy exposure are substantially lower than the viewer would receive from a large CRT or flat-screen. Because the output of the system is collimated, viewers feel as if they are looking out into the distance.

Graphics System

Using a single COTS PC-based IG, we developed a simulation which, in addition to rendering stereo images, provided visual cues through texturing, shadows, realistic motion of the boom and receiver aircraft, and ability to view the scenario from multiple viewpoints.

Highly textured models were developed showing realistic gradation in color on the receiver aircraft as well as seams and rivets on the boom. Based on the previous research cited above, it is believed that the textures on the boom and receiver aircraft will make it easier for students to judge their orientations in space.

Algorithms were implemented to render the boom's cast shadows which followed the contours of the receiver aircraft. It is believed that these shadows will allow trainees to better evaluate the distance of the receiver aircraft from the boom as well as their relative orientations.

On an orientation ride in a KC-135, the demonstrator developers were struck by the amount of movement of the tip of the boom and the receiver aircraft and its engines. We believed that these motions should be modeled visually in the graphics system to provide the degree of realism necessary to support the evaluation. The boom vibration was necessary because students who train themselves to look at a steady boom nozzle may have trouble when trying to position a real boom with its oscillating nozzle. A slight bobbing motion was modeled in the receiver aircraft position during refueling. The motion was small, so that it did not make the connection task harder, but still added to the realism. We also added receiver engine vibration because, while it does not directly affect boom operation, it would enhance the realism of the simulation and might also have a training benefit. Boomer students, on their first real flights, would not be as surprised by the receiver engine vibration and could more fully concentrate on operating the boom.

The demonstrator system provides the ability to show the student alternate viewpoints. In addition to the regular pod view shown in Figure 2, the demonstrator operator may display the session from directly above, from the side as shown in Figure 3, or directly outside the receptacle. Student data are not recorded in sessions where the student can view from alternate viewpoints; but, this ability was provided to determine its value to future boom operator trainers.

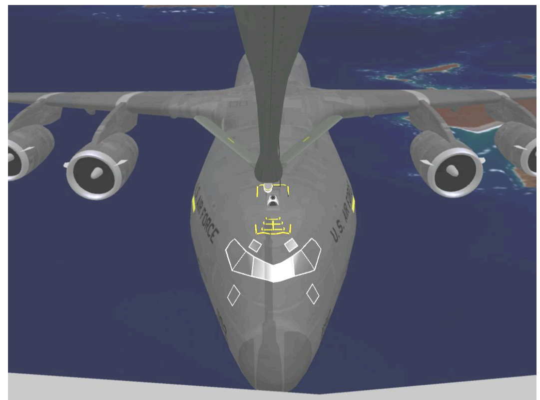

Figure 2: View from Pod Sighting Door

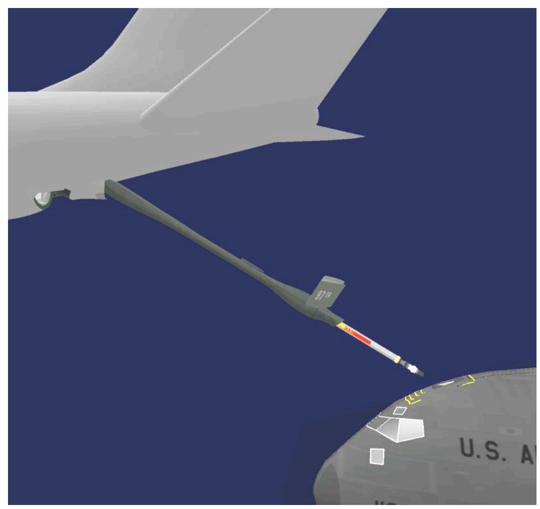

Figure 3: Air Refueling Side View

Boom Simulation

For the project, an actual KC-135 pod was used to construct the mock-up. Boom controls required for the contact task were constructed and connected to an analog-to-digital (A/D) card with a built-in ethernet port, so the simulation computer could easily read them. The output from these controls drive the simulation of the boom motion which was based on the dynamics model used in the BOPPT. The BOPPT algorithms were used; however, they were ported from the original FORTRAN to C++.

Although not originally intended as part of the demonstrator, control loading was added to the ruddevator control stick so students could feel the effect of the receiver aircraft's bow wave. The subject matter experts (SMEs) alleged the display system could not be properly evaluated without the haptic response, as evaluators might unfairly blame the display system for the improper “feel” of a session. (Experiments described in Lécuyer et al (2000) on the relationship between visual stimulus and perceived haptic responses lend credence to the SMEs’ opinion). A force feedback response based on the distance of the approaching aircraft, the trim setting of the ruddevator control stick, and the force of pneumatics attached to the control stick was incorporated. The force feedback response of the control stick was evaluated by the SMEs and adjusted until they felt it matched the actual response of the stick on the KC-135.

Eye Tracking

As described earlier, the Kodak display system uses eye tracking to position the image pupils to keep the images focused on the viewer's eyes. The COTS eye tracking system uses an IR light-source to illuminate the viewer's face. Normally, the viewer's eyes would reflect the most IR, and the eye positions could be determined. Unfortunately, during development, we found the eye tracker would too easily pick up other sources of IR reflections including jewelry, teeth, shiny skin, and most importantly, glasses. False reflections (that is, bright IR reflections from anything other than the eyes) made it difficult for the display system motors to adjust the mirrors to keep the image in the user's eyes.

The source of these problems was attributed to limitations in the COTS eye tracking software and could not be corrected within the project timeline; therefore, eye tracking was not used for the evaluation. However, it is assumed that this will have minimal impact on the evaluation, as video taken on orientation flights showed that the boomer's head motions are small. Even without eye tracking, demonstrator users should have no trouble keeping their head in the display's “sweet spot.”

Instructor/Operator Station

The demonstrator is to be operated by boomer instructors, who will also be evaluators. We were careful to keep the operation of the demonstrator simple so that instructors' evaluations of the display system will not be affected by the difficulty of operating the demonstrator. Kodak engineers were able to construct their display system so that it could be powered up or down with a single switch. The demonstrator's simulation is controlled by a single graphical user interface.

The demonstrator instructor/operator station (IOS) shows the same view as in the pod (albeit in 2D). The demonstrator IOS contains graphical representations of the most important boom display gauges and panel lights, as shown in Figure 4. Boomer instructors are thus seeing familiar controls, minimizing the time required to train in the operation of the demonstrator. The IOS allows the instructors to easily control the receiver aircraft location, and open and shut the sighting door and the receiver's Universal Air Refueling Slipway Installation (UARSI) cover.

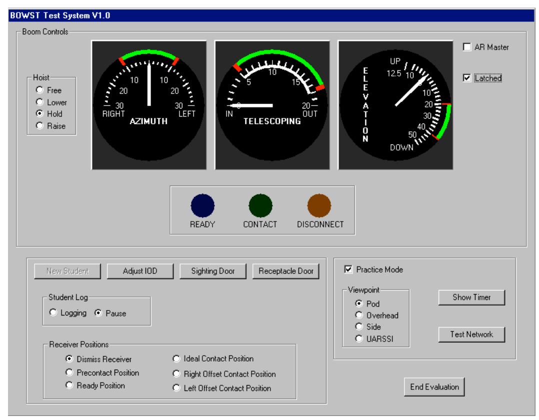

Figure 4: Operator Station GUI

Evaluation Metrics

While the demonstrator was being constructed, SMEs worked to develop metrics for its evaluation. The metric first proposed was the time required for a student to successfully make a connection. It was later determined this was not a good metric, because a poor simulation that made the task seem easier than it actually was would receive a good score while providing negative training. The SMEs pointed out that the boomer instructors were far more concerned with accuracy than the time to connect. A slow connect where the boom is inserted directly into the receptacle is preferable to a quick connect where the boomer accidentally makes damage-causing contact with the receiver aircraft outside the receptacle area.

The SMEs contend that spatial data were more useful than time-to-connect. Based on this input, we developed the demonstrator to record the number of successful and unsuccessful connection attempts. For the latter, we record the region where the boom made contact with the receiver aircraft, as shown in Figure 5. The gray area represents the UARSI receptacle. Contact anywhere in that region would result in a successful connection, as the UARSI walls would guide the boom end into the connection point.

We also recorded the 3D position relative to the UARSI origin (shown as a black dot in Figure 5); so, the exact locations where the boom hit the receiver aircraft could be determined. These data may be useful to determine if students regularly hit in a particular region, which may indicate problems with depth perception. For example, if students consistently underestimate the receiver distance and extend the boom too quickly, they would hit below the acceptable region.

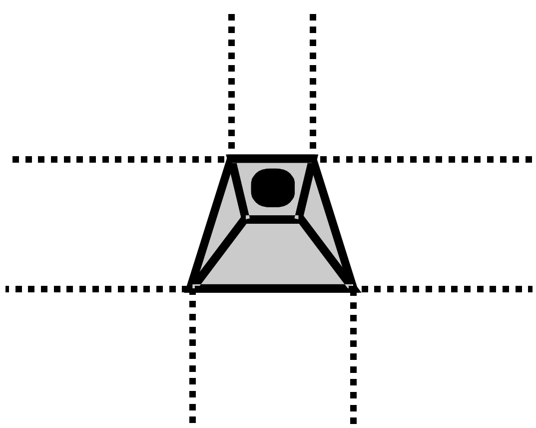

Figure 5: Contact Regions

RESULTS

For this project, we were able to successfully integrate Eastman Kodak Company's autostereoscopic display into a technology demonstrator for the purpose of evaluating the effect of depth perception cues lacking in current training systems. While the emphasis of the evaluation was to be focused on the display system, additional features had to be supported in order to conduct a reasonable evaluation. This included visual and dynamic models of the boom and receiver aircraft in addition to the simulation of user interface controls.

We identified and implemented visual cues which we believe are necessary for properly judging the positions of the KC-135 boom and C-17 receiver aircraft in the simulated environment. These cues included texturing, rendering of shadows, and motion of the boom and receiver aircraft which were provided by COTS image generators. In addition to visual cues, the technology demonstrator was developed to reproduce the KC-135 boom operator station to sufficient fidelity to simulate a single air fueling scenario.

Boomer instructors and students are currently evaluating the demonstrator. Results have not yet been analyzed. However, prior to the delivery of the demonstrator to Altus AFB, it was demonstrated to numerous people, both military and civilian. SMEs observed that demonstrator users made the same mistakes as new students when first operating the boom. This implies the technology used in the demonstrator could be used to build a future boom simulator. Military personnel who used the demonstrator before the formal evaluation were particularly impressed and showed an eagerness to incorporate it into student training.

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The demonstrator pod control hardware was designed and constructed by Randy Jenkins of AETC Trainer Development.

Eric Peterson of Southwest Research Institute ported the BOPTT simulation code and modeled the boom and C-17 receiver aircraft.

Our subject matter experts were boomer instructors, CMSgt Ted Carrier and MSgt Todd Salzmann, without whose invaluable contributions we would have been unable to complete this project.

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