A review of head-worn display research at NASA Langley Research Center

Jarvis (Trey) J. Arthur, III, Randall E. Bailey, Steven P. Williams, Lawrence J. Prinzel, III, Kevin J. Shelton, Denise R. Jones, and Vincent Houston,

NASA Langley Research Center, Hampton, VA

ABSTRACT

NASA Langley has conducted research in the area of helmet-mounted/head-worn displays over the past 30 years. Initially, NASA Langley's research focused on military applications, but recently has conducted a line of research in the area of head-worn displays for commercial and business aircraft. This work has revolved around numerous simulation experiments as well as flight tests to develop technology and data for industry and regulatory guidance. The paper summarizes the results of NASA's helmet-mounted/head-worn display research. Of note, the work tracks progress in wearable collimated optics, head tracking, latency reduction, and weight. The research lends credence that a small, sunglasses-type form factor of the head-worn display would be acceptable to commercial pilots, and this goal is now becoming technologically feasible. The research further suggests that a head-worn display may serve as an "equivalent" Head-Up Display (HUD) with safety, operational, and cost benefits. "HUD equivalence" appears to be the economic avenue by which head-worn displays can become main-stream on the commercial and business aircraft flight deck. If this happens, NASA's research suggests that additional operational benefits using the unique capabilities of the head-worn display can open up new operational paradigms.

Keywords: Head-Worn Display, Helmet-Mounted Display, Commercial Aviation

1. INTRODUCTION

A significant portion of NASA Langley's Crew Systems branch mission is to conduct research to advance the state-of-the-art in flight deck interface technologies, including visual displays. The heritage of this work was tied closely to the Department of Defense (DoD) activities but has changed over the last two decades to focus on research to provide commercial flight crews with proactive, intuitive tools to conduct a safe and efficient flight. Since the late 1990's, this research was driven by the White House Commission on Aviation Safety in 1997.[1,2] While these safety initiatives firmly remain, NASA research is also closely tied to the modernization of the National Airspace System (NAS) known as the Next Generation Air Transportation System (NextGen). The goal of NextGen is to remove many of the constraints in the current air transportation system, support a wider range of operations, and deliver significantly increased system capacity to that of current operating levels. The NextGen concept for the year 2025 and beyond envisions the movement of large numbers of people and goods in a safe, efficient, and reliable manner. Operating concepts emerging under NextGen require new technology and procedures not only on the ground-side but also on the flight deck. One of the key elements is to create a NAS that is resilient, if not immune to the impacts of weather.

This paper provides a high-level overview of NASA Langley's Helmet Mounted Display (HMD) and subsequent Head-Worn Display (HWD) research as it relates to advancing the state-of-the-art to develop technology and data for industry and regulatory guidance. The work indicates direct support of proactive, intuitive tools to conduct a safe and efficient flight in a NextGen environment and possibly suggests that the unique capabilities of the head-worn display can open up new operational paradigms in commercial and business aircraft operations.

2. BACKGROUND

NASA Langley Research Center's (LaRC's) work while advancing the state-of-the-art has primarily focused on the human factors of HWDs, roughly categorized into four areas.

Further author information: Jarvis (Trey) Arthur, E-mail: Trey.Arthur@nasa.gov, Telephone: 1-757-864-6609

2.1 Research Issues

First, NASA's research has focused on the ergonomic or anthropomorphic issues of head-worn displays. Fortunately, the consumer market and its drive for small, lightweight displays for consumer applications has not required significant technology investment to move the state-of-the-art for commercial flight deck applications.

The second research area is physiological. HWDs may induce a variety of visual-vestibular interactions, each of which can have a significant impact on the user.

Third, perception and perceptual issues figure prominently on a list of human factors research-needs. The visual perception, comprehension, and understanding of HWD information depends on many parameters, not the least of which includes the optical performance characteristics of the HWD. In short, perception issues create significant challenges to match the human visual system with the human mind as it relates to the processing and interpretation of the visual stimuli.

Finally, the fourth area of human factors research-needs is operational. According to Velger,[3] how much and what type of information and how it should be displayed represent perhaps the, "...most indeterminate and insufficiently defined subjects" (p. 179). Some years later, the issues associated with operational needs and how to meet these needs with appropriate informational display content still looms large as significant human factors concerns and research-needs include:[4]

- What is the appropriate amount and type of information to be displayed?
- What is the most effective presentation of that information?

3. HWD/HMD RESEARCH AT NASA LANGLEY

Figure 1. Monochrome, binocular HMD circa 1988, 9 pounds.

Figure 2. Monochrome, binocular HMD circa 1991, 6.5 pounds.

Figure 3. Full color, binocular prototype HMD by Microvision circa 2003, 10 pounds.

3.1 Early HMD research

The HMD has a theoretical existence that dates back a hundred years. However, it was not until the 1980s that advanced display capabilities really started to emerge where information beyond a simple gun-sight could effectively be employed in a head-worn device. The equipment during the 1980s was extremely technologically advanced but in reality, not viable for use on a flight deck (see Fig. 1). This state-of-the-art system used binocular optics with 80° circular oculars and a 40° stereo overlap generated by monochromatic green Cathode Ray Tubes (CRTs) drawing 875 scan lines each. The system employed an alternating current (AC) head-tracker. The head-borne weight was approximately 9 pounds, not including the active cooling provided by the air conditioning cooling hose. This particular HMD was not used in any published research and was the predecessor of the HMD used in the High Angle of attack Research Vehicle (HARV) research (see Fig. 2).

3.1.1 High angle of attack research

This HMD and others like it supported numerous military applications including Apache, emerging Comanche program requirements, and high angle-of-attack research, such as that deployed on the NASA thrust-vectored F-18 HARV.[5–9] LaRC's research emphasized stereo/bi-ocular effects and off-boresight informational constructs.

For the HARV Program, HWD research targeted the obvious emphasis of off-boresight capabilities especially as it applies to the extreme maneuvering envelope provided by this vehicle. NASA Langley-developed research HMD had a wide-field-of-view (30° vertical by 40° horizontal) binocular optics and holographic optical elements for high brightness and transmissivity (see Fig. 2). Two high-resolution 1280x1024 CRTs were used as the image sources. The HMD weighed approximately 6.5 pounds and could be worn by most pilots for over an hour without discomfort. The HMD was driven by a graphics workstation at 1280 horizontal by 1024 vertical resolution and updated at a 60 Hz non-interlaced rate. A Polhemus magnetic head tracking system was utilized.

A piloted simulation study was conducted to determine whether attitude information (pitch ladder, velocity vector symbol, and waterline symbol) displayed in a HMD should be presented with respect to the real world (conformal) or to the aircraft (body axis) for spatial awareness in a fighter aircraft. With the conformal presentation, the appearance of the displayed information was dependent on the pilot's head position. The horizon line would always overlay the horizon of the outside scene, if it was in view; however, the attitude of the aircraft (nose position) could not always be easily obtained unless the pilot's line-of-sight was aligned with the aircraft's body axis. With the body-axis concept, the information was displayed as if the pilot was always looking directly out of the front of the aircraft, no matter which direction the pilot moved his head. This concept was analogous to physically mounting a Head-Up Display (HUD) to the helmet. Although the pilot could directly determine the aircraft's attitude, in situations where the pilot's line-of-sight was not aligned with the aircraft's body-axis, the horizon line, if in view, would not overlay the horizon of the outside scene. The two display concepts were evaluated using simulated air-to-air intercept tasks where the pilot was to obtain a gun solution on a maneuvering, but not interactive, target.

The quantitative results favored the body-axis concept. Although, no statistically significant results were found for either the pilots' understanding of roll attitude or target position, pitch judgment errors were made three times more often with the conformal display. The subjective results showed the body-axis display did not cause attitude confusion, a prior concern with this display. In the post test comments, the pilots overwhelmingly selected the body-axis display as the display of choice. The pilots stated that the conformal display was hard to interpret and confusing because of the symbology motion caused by the aircraft and head movements. However, the pilots commented they were more familiar with the body-axis display format because they used HUDs. With more training, the conformal display may have been more useful to the pilots.

3.1.2 Microvision HMD

In 2004, research was conducted using a military style helmet (see Fig. 3) for Synthetic Vision System (SVS) flight deck concepts.[10] The HMD was part of the Virtual Cockpit Optimization Program (V-COP) effort under the US Army and using the Microvision virtual retinal display concepts. The HMD was full color, fully binocular, fully overlapped, 1280x1024 pixel resolution display. The Asension LaserBird was used for head tracking (see Fig. 10). The optical performance data showed some outstanding characteristics although the system suffered from reliability issues typical of many prototype technologies.[11]

NASA's use with this clearly military display focused on the potential for a helmet display with an unlimited field-of-regard to greatly increase pilot situational awareness (SA) both in flight and on the surface. The data showed the value of off-boresight information in commercial operations, especially for surface operations; however, the data also clearly indicated that a large, military style helmet would be a non-starter for commercial crews. Pilots expressed a desire for a light-weight, sunglasses form-factor type display (see concept in Fig. 4).

3.2 Why an HWD for commercial and business aircraft?

From this military heritage, several factors emerged that created a confluence of needs and capabilities for HWD research at LaRC targeting commercial and business aircraft flight decks. These factors were: a) consumer displays technologies; b) head-up displays and safety of flight; and, c) vision system technologies.

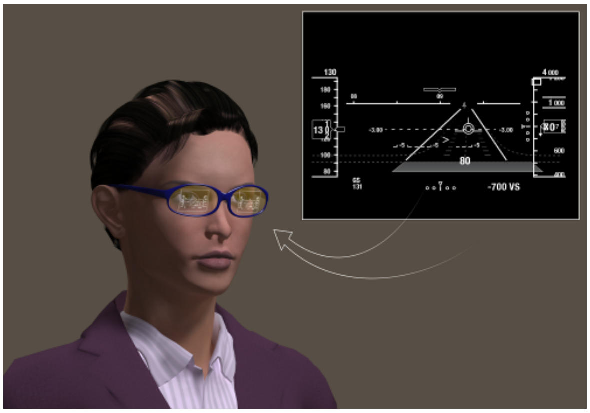

Figure 4. Concept picture of a light-weight, sunglasses form factor HWD for commercial aviation use.

Figure 5. Lumus DK-32 display glasses coupled with a prototype inside-out head tracker made by Thales Visionix.

3.3 Synthetic and enhanced vision system

Starting in the early 1970s, vision system technologies - Synthetic Vision (SV) and Enhanced Vision System (EVS) and related instantiations - were being researched by NASA. EVS technologies were maturing rapidly as evidenced by a large FAA flight test,[12] with NASA and others,[13] highlighting the operational potential of these systems. Vision systems technologies - SV/EVS - creates an electronic means of visibility for the flight crew, independent of the prevailing natural lighting or atmospheric conditions.

Vision systems technologies moved to the forefront of NASA's aeronautics mission directorate as part of a project to develop and deploy SV systems technologies, as a complement to EVS, to mitigate the leading cause of commercial aviation accidents world-wide, Controlled Flight Into Terrain (CFIT).[14] The focus of this program was to get these technologies into existing flight decks in order to have the greatest impact on CFIT accident reduction.

In 2004, the concept of vision systems technologies took-off when the FAA amended the operating regulations for takeoff and landing under Instrument Flight Rules (IFR) contained in Section 14 of the Code of Federal Regulations, §91.175 to allow the use of an Enhanced Flight Vision System (EFVS). This rule change set an important precedence as the first operational credit provided to an imaging sensor system, creating an allowable electronic means of vision for the flight crew.

Similarly, the fundamental technologies for SV - a computer-generated rendering of stored terrain topography from the perspective of the pilot - were beginning to emerge at program launch. In fact, when the program started, it was felt by many as being too revolutionary. The state of the art computer at program launch (circa 1997) was a 266 MHz Pentium Processor, 32 Mbytes RAM, 5 Gbyte Hard-drive. Fortunately, by the program's end in 2007, the three key technologies - Global Positioning System (GPS), computer graphics rendering and flash memory were common-place and the requisite technologies could be found in everyone's cell phone today. SV is now seen as the baseline standard in flight deck designs.

Today, vision system technologies and the concept of an electronic means of visibility for the flight crew, independent of the prevailing natural lighting or atmospheric conditions, is a critical piece of the NextGen architecture.

3.4 HUD

HUDs have been available on commercial and business aircraft for many years and by the mid 1990s, was becoming an accepted flight deck staple, although still not universally adopted. The HUD has proven itself as a valuable addition to the flight deck providing many safety and operational benefits. The advantages of HUDs for commercial aircraft is primarily the situational awareness enhancement. The HUD allows an "eyes-out" conformal view of the outside world without the requirement to go "heads-down" to look at flight instruments. The conformal display of attitude, flight path, and energy management information is key. The Flight Safety

Foundation (FSF)[15,16] concluded that Head-up Guidance System Technology would likely have positively influenced the outcome of hundreds of accidents included in a study of turbine-powered, modern glass cockpit aircraft accidents.

These HUD capabilities became an integral part of the EFVS rule making. The HUD is the only display currently certified and approved for use as an EFVS. The operating paradigm of the EFVS is the conformal display of imaging sensor data on the HUD, with conformal flight symbology overlaying the real-world, when natural vision is available. The EFVS operational credit (as per §91.175 (l) and (m)) explicitly expressed that the use of a HUD was an essential "characteristic and feature" of the EFVS operation.

In developing the new rule, the FAA recognized emerging technologies and placed within the rule, provisions for the use an "equivalent display."

3.5 The HWD for commercial aviation

As NASA and industry were maturing HUD and vision systems technologies, the small display form-factor that the pilots desired was just emerging. The technologies for a viable HWD on a commercial flight deck were approaching.

LaRC's HWD research with this emerging technology was primarily driven by two operational paradigms:

1. The HWD can provide unlimited field-of-regard; hence, the HWD may provide operational enhancements (safety and/or efficiency) which can take advantage of this capability especially since there are now vision systems technologies that are unlimited in field of regard and can be effective independent of the prevailing natural visibility.
2. The HWD may be a "HUD equivalent." In this scenario, the HWD can be advantageous where: a) HUD installation is not possible or practical by volume or weight; b) HUD retro-fit is not cost-effective; and, c) HWD installation has a return-on-investment advantage to the HUD.

The 'easy' part of the research was defining the HWD requirements for these operational paradigms. The requirements are simply:

1. Equivalent optical performance as today's HUD (as defined in such documents as SAE ARP-8105).
2. No more encumbrance to the pilot as that provided by today's head-worn devices.

The extremely challenging part of this task is to meet these two requirements. These requirements are diabolically opposed:

- State-of-the-art HUDs are fantastic optical devices, with outstanding clarity, transmissivity, and - by design and also because they are firmly attached to large aircraft - outstanding symbolic and image stability. In a recent EFVS flight test, the end-to-end latency in an EFVS presentation on a HUD was measured to be greater than 200 msec due to the combination sensor, image processing and HUD processing.[17] Nonetheless, each of the test pilots found the presentation to be excellent and latency was never once considered an adverse factor.
- A rough summary showed a variety of head-sets that pilots sometimes, but not always wore. The type, size, and function varied. The one item of head-worn gear that almost all pilots wore was sunglasses (with the obvious exception of night operation). As such, the goal was set to sun-glasses' "equivalent encumbrance."

Figure 6. Monochrome, monocular HWD circa 2010, 4 ounces.

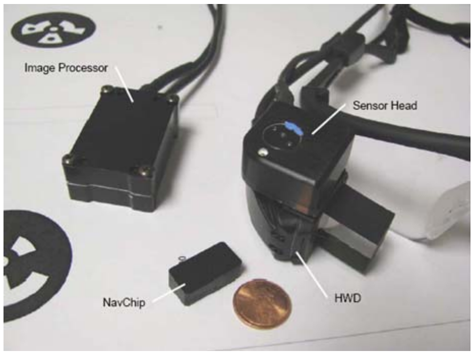

Figure 7. Intersense prototype tracker developed for NASA Langley.

3.6 Head-tracking technology

To meet the operational paradigms and their associated performance requirements, the HWD must be coupled with a high performance head-tracker. The tracker, while being lightweight and unobtrusive, must meet HUD-like static and dynamic accuracy requirements.

Under the Small Business Innovative Research (SBIR) program, NASA Langley awarded a contract to Intersense, Inc. (now Thales Visionix) to develop a head tracker to meet these performance requirements and that the HWD system be minimal encumbrance.

Research examined these innovative augmented reality approaches to HWDs for commercial surface operations.[18]

Intersense delivered two prototype head trackers under the SBIR contract. The first tracker was a prototype based on their IS-1200 VisTracker that is an inertial tracker where the inertial drift is corrected by image processing (see Fig. 7). The focus of the prototype was miniaturization of the tracker by utilizing a cell phone camera. Though small in size, the tracker used visible light detection of circular bar codes, which under certain lighting conditions, could adversely affect the performance of the tracker.

To improve upon the short comings of the first tracker, Intersense delivered an infrared based camera thus solving the visible light issue of the previous tracker but at a cost of a larger tracker (see Fig. 5). This second tracker was also inertial with optical tracking and image processing to correct the drift.

3.7 System latency measurement

Head-tracker latency dictates the dynamic symbol/imagery positioning accuracy. An end-to-end latency requirement of no more than 20 milliseconds has been proposed for Virtual HUD applications based on previous work.[19] However, the acceptable latency may become significantly smaller if dynamic stability is a driving requirement. The SAE AS8055 document, the "Minimum Performance Standard for Airborne Head Up Display (HUD)," standards suggest that this is the case.

The technical challenge is that this allowable latency is an 'end-to-end' requirement. A basic HWD with head tracking system, from end-to-end, is comprised of: 1) a near-to-eye display, 2) the head tracking system, 3) one or more symbology or image sources, 4) and the display/image processor. Each element and the communication between them contribute a portion to the total latency. No commercial or standardized device is available to measure and quantify end-to-end latency. NASA has developed a prototype Head Mounted Display Latency Measurement Rig (HeLMR) for this purpose.[19] The HeLMR apparatus consists of an anatomically correct,

Figure 8. HeLMR System (Head, Camera, Rotary Stage, Stage Controller, DC Light Source).

human head which is able to 'wear' available commercial and custom HMD systems (see Fig. 8). A camera is installed in place of the eye(s) in the correct image plane location. The head is mounted on a precision rotary stage that moves the head in a left-right-left 'No-No' fashion at a precise angular rate. To measure the end-to-end latency, a space-stabilized symbol is rendered on the HWD along the boresight. As the head is slewed, the space-stabilized symbology becomes misaligned with respect to the outside reference, proportional to the end-to-end system latency and the head form angular rate.

4. HUMAN-IN-THE-LOOP HWD RESEARCH

4.1 Monocular, biocular and binocular displays

HWD may be monocular, binocular, or bi-ocular in design and each have their advantages and disadvantages and individually impart different human factors concerns. For example, binocular rivalry and disparity are known physiological issues caused by HWD design and affect perception. And other human factor design issues involving rotational, magnification, and luminance difference between the eyes significantly minimizes the display potential. Double imagery, adaptation, motion effects, and many other human factors concerns can impact not only the perception of the imagery, but also the cognition of the user (e.g., effects on decision-making, response time, accuracy, judgments, change blindness, cognitive tunneling, visual search, memory, problem-solving, situation awareness, attention, etc.) as well as physiological consequences due to the perceptual and/or cognitive mismatch (e.g., eye strain, disorientation, headaches, and sickness). Each of these issues are addressed in many ways throughout the existing HMD literature but much of this existing literature is also heavily biased toward the military application or academia and its youthful subject population. Our application, conversely, has to consider pilots up to the age of 65, if not older, with a variety of vision conditions, corrections, and color-deficiencies. HWD design considerations, especially that of the use of color and the optical design, as they interact with the HWD user age, are somewhat unique in this new application of HWDs.

Honeywell performed research for NASA to examine issues with monocular versus biocular HWD displays.[4] Honeywell utilized Microvision Nomad displays with an Ascension Phasor Bird head tracker to create the monocular and biocular HWD display conditions. The three display conditions examined: monocular display on the dominate eye, monocular display on the the non-dominate eye and a biocular display. Results showed no significant differences in flight performance between the three display concepts. An interesting result from the Honeywell study was that the monocular display was significantly more accurate in terms of visual acuity compared to a biocular display. No binocular rivalry effects were found in this seasoned group of aviators. Thus, NASA began surface operations research with a simpler, light-weight monocular HWD.

4.2 Taxi operations

Our research showed that one operational area where off-boresight information for commercial and business transport aircraft was critical was in surface operations. Further, at the beginning of the 21st century, the

National Transportation Safety Board (NTSB) continually included runway incursion prevention on its "top most wanted" list for aviation safety.[20] The application of HWD technology to address this surface operations was born.

On the flight deck, the available out-the-window visibility provides the 'truth' and at least one pilot is always head-out during the flare and during surface operations. The HUD or HWD must be designed to not obscure this outside view. Today, HUDs are certified only after demonstrating that they are in compliance with Part 14 of the Code of Federal Regulations §25.773, showing that the HUD design still gives the pilots "a sufficiently extensive, clear, and undistorted view, to enable them to safely perform any maneuvers within the operating limitations of the airplane, including taxiing takeoff, approach, and landing." The HUD or HWD should ideally augment the prevailing visibility - providing sufficient information to enhance or enable the operation - without significantly obscuring it.

Full-color HWD display concepts were evaluated in surface operations in direct or indirect comparison using previous research against HUD equipage for taxi route awareness, traffic awareness, taxi efficiency, and runway incursion prevention.

Figure 9. Full color, monocular HWD circa 2007, 2 pounds. Outside-in laser head tracking.

Figure 10. Ascension LaserBird head tracker. Three prong sensor mounted on the back of the HMD shown in Fig. 9.

4.2.1 HWD down-select usability study

A HWD usability study was used to down select concepts for feasibility.[21–23] The usability study was conducted in the medium fidelty, fixed-based Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) simulator. The usability study was designed to demonstrate the efficacy of a head-worn display which provides unlimited field-of-regard Synthetic Vision for surface operations. The results demonstrated that providing pilots with the ability to virtually see well beyond visual range can significantly increase situation awareness and task performance on the airport surface. Pilots were better able to perform the taxiing evaluation task and reported significantly higher situational awareness with the HWD concepts compared to an electronic moving map or paper charts of the airport environment. Furthermore, the study provided tremendous insight into future design and development of head-worn displays, including hardware considerations and methods for integration of display modes.

The usability study highlighted two significant hardware considerations. Nearly all pilots rated the higher resolution (800x600), see-through HWD over the lower resolution (640x480), opaque HWD. Pilots commented that the higher resolution improved the readability of the display especially for text and numbers. Additionally, the pilots preferred not to have their forward vision blocked; even by the small 640x480 pixel display. The see-through capability allowed the pilots to continue their nominal out the window surveillance of the airport environment during taxi. Also, the see-through display provided the pilots with confidence that the display was aligned with the scene. For surface operations, it is important for a HWD to be see-through because, for all practical purposes, the HWD will always be providing an "augmented reality" not a "virtual reality" condition.

4.2.2 High-fidelity simulation experiments

From the results of the usability study, two experimental studies were conducted to determine the efficacy of using HWDs to enhance taxi operations.[24, 25] For both experiments, full-color HWD display concepts were evaluated in surface operations to address previously witnessed display technology limitations.

The experiments were conducted in NASA's high fidelity simulator known as the Research Flight Deck (RFD). The RFD was equipped with a 30° horizontal x 24° vertical HUD on the captain's side. The HWD, worn only by the captain, was a Liteye LE-500 800x600 pixel, full color display with see-through capability (Fig. 9). The head tracker was laserBIRD tracker by Ascension Technology Corporation. A skateboard helmet was used as the mounting location for the display and tracker. The helmet was not grossly heavy but was sturdy enough with good fit and comfort for good stability. It also had some acceptance from an aesthetic viewpoint.

The pilots placed the display just above their right eye so that it was visible by glancing up which maintained unimpeded stereoscopic vision for out-the-window monitoring. The resulting display was conformal to the real-world (out-the-window scene) if the pilot tilted his or her head down. This "semi-conformal" presentation allowed pilots to bring the display into view when they desired.

The pilots conducted simulated taxi operations at Chicago O'Hare International Airport. The display conditions were varied by having no HUD, a HWD or a traditional HUD. A head-down Electronic Moving Map (EMM) display was varied from a basic moving map to an advanced moving map which included routing and other traffic. The display condition and weather were experimentally varied. A total of 27 different taxi scenarios were used in the study. Three of the 27 scenarios were "rare-events" to test off-nominal, safety-critical stress cases. All taxiing tasks involved exiting the active runway and taxiing to the airport movement area boundary. The weather state for the out-the-window scene was varied between night-time with unlimited visibility Visual Meteorological Conditions (VMC), and daytime with 700 Runway Visual Range (RVR).

From the post-test analysis for this experiment, there were no significant differences between the HUD and HWD concepts.

A second experiment was designed to be a follow-on to the experiment mentioned above to improve the color of the displayed traffic and to evaluate additional display concepts to the baseline condition of an airport paper map in order to fully complete the matrix of possible display comparisons. From the first experiment, even though traffic was displayed, some crews missed the displayed traffic and ended up in a "nose-to-nose" situation for the rare event scenario. For the second experiment, none of the crews who had traffic displayed got into a nose-to-nose situation and, therefore, it appears likely that the color and size of the traffic icon were the main factors for the differing results from the first experiment.

The performance data showed that better route accuracy and faster taxi speeds can be obtained using the HWD and HUD compared to paper charts alone. On average, the pilots were able to complete the taxi route 15% faster with the HWD and HUD concepts compared to paper charts.

From both experiments, the results with the HUD were similar to the results from previous surface operations research conducted by NASA Ames and NASA Langley. No quantitative performance differences differentiating head-up versus head-down display concepts (when displaying essentially the same or similar information) were found in these studies. Additionally, the crews made significantly more navigation errors with the paper charts than with any of the other three advanced display concepts. Comparing the HWD and HUD concepts across both experiments, there were no display effects, visibility effects, or interaction effects of these two main factors for the three measures listed above. Therefore, in terms of taxi performance, the HWD and the HUD were statistically the same.

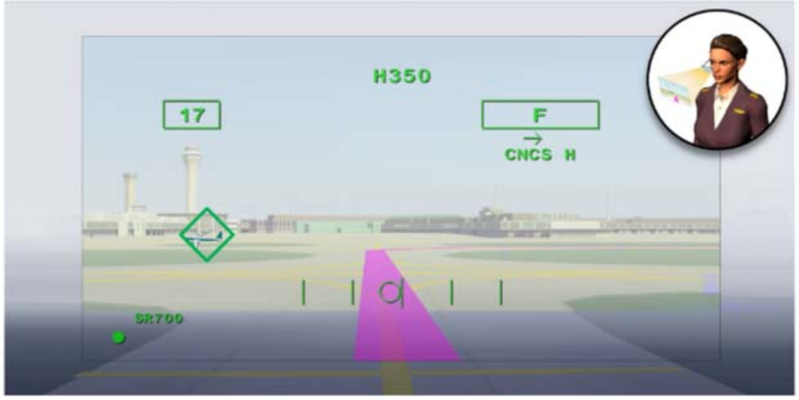

Figure 11. Surface concept with the HWD.

4.2.3 Augmented reality surface operations

Instead of using a 'semi-conformal' display, an alternate approach was developed to augment the scene and not obscure the prevailing natural visibility. Figure 11 graphically depicts an instantiation of the augmented reality HWD concept for surface operations. The boxed area containing symbology and the virtual airport represents the view as it would be rendered on the HWD. Outside the boxed area represents the visibility of the actual airport environment with natural vision. In this example, the figure represents a reported visibility of 700 RVR. The augmented reality concept draws the S/EV imagery (i.e. the 'virtual airport environment'), beyond the reported 700 RVR, which represents that "Beyond RVR." Note that the SV airport is not shown in the HWD up to 700 RVR as this portion of the actual airport can be seen with the unaided eye. Essentially, the SV airport was culled up to 700 RVR to allow pilots to view the actual airport environment. The cleared route (shown as the magenta ribbon) was drawn on top of the yellow taxiway centerline to denote the cleared path. The cleared path always overlays the taxiway centerline if in view on the HWD as it is critical information for runway and taxiway incursion prevention. Traffic, within the conformal view, are depicted with the augmented reality traffic diamond.

Pilots were asked to taxi complex routes, under simulated low-visibility conditions (300RVR, 600RVR, 2400RVR), in a large commercial transport aircraft simulator at Chicago O'Hare (FAA identifier: ORD). The test conditions evaluated the "Beyond-RVR" concept and augmented reality traffic depictions compared to the virtual reality presentations used in prior studies. The augmented reality concept rendered virtual airport objects (such as runways, taxiways, centerlines, tower(s), buildings) obscured by the weather in the HWD. In other words, the HWD virtually displays only airport objects and traffic that cannot be seen naturally (i.e., beyond the reported runway visual range) and thus, not obscuring naturally visible objects. If the object was neared than the RVR value (i.e., 300RVR, 600RVR, or 2400RVR), then the "curtain," drawn at the reported RVR, would allow pilots to see naturally that scene. Beyond the reported RVR, the visibility curtain would obscure the natural scene and instead a synthetic scene and real-time imagery (e.g., Forward Looking Infrared (FLIR)) would conformally depict the world beyond that distance.

The results of the research evinced that the HWD, regardless of concepts tested, significantly enhanced situation awareness compared to more traditional displays used during aircraft taxi. Although no quantitative differences were found, the usefulness of the Beyond-RVR concept had merit only at higher visibilities. At very low-visibility operations, there were no discernable difference to the pilots between the concepts tested (i.e., the 300RVR and 600RVR condition practically looked the same regardless of display used during taxi). It was further observed that higher fidelity simulator or real-world aircraft would increase the differences as the aircraft simulator used did not emulate actual conditions as well. Pilot comments supported the value of Better than Visual (BTV) to increase capacity and safety in the airport movement area and that innovative approaches for intuitive display of Synthetic and Enhanced Vision (S/EV) have merit and research should continue.

The results from these surface operations with HWDs led to NASA patenting the technology.[26] Follow-on experiments continue to refine surface operations research with HWDs.

4.3 Simultaneous Offset Instrument Approaches using a HWD

A significant hurdle to overcoming capacity constraints are simultaneous dependent parallel runway operations at runways separated by less than 4300 feet. In particular, very closely spaced parallel runways have equipment and procedural requirements which significantly limit their use in degraded visual conditions. When the weather drops below visibility or ceiling minima, an airport is reduced to single runway operations substantially reducing arrival rates (from 65 to 30 aircraft per hour at San Francisco (SFO) airport).

Simultaneous dependent parallel runway operations require a pilot to see-and-avoid parallel traffic. To meet the "weather-independence" goal of NextGen, game-changing technology is needed to safely overcome these constraints. Arthur, Prinzel, et al. (2009)[25] reported on representative study that demonstrated the usefulness of HWDs, paired with other technologies, to more effectively address the problem prescribed for NextGen. The research examined the use of a S/EV HWD concept, in concert with Flight deck Interval Management (FIM) technologies, to conduct very closely spaced simultaneous dependent parallel runway operations under restricted visual conditions. The simulation experiment evaluated head-down and head-up displays (both HUD and HWD), paired with vision systems and FIM technologies, to conduct these dependent arrival operations.

In general, pilots rated using a HWD in Instrument Meteorological Conditions (IMC) the same as the visual approach (unlimited visibility) in terms of situation awareness and mental workload. The results were based on some simplifying technological assumptions but nonetheless, provide an outlook of the potential of HWDs to serve as an enabling technology and flight deck display platform to facilitate the envisioned path toward the goals set forth by NextGen and future air transportation systems.

4.4 HWDs for spacecraft

In 2007, NASA began exploring technology for a human-mission to the moon known as the Constellation Program.[27] The lunar lander spacecraft, known as Altair, was to have significantly reduced out-the-window look-down angle compared to the Apollo lunar lander.[28,29] A part-task simulation was conducted to explore using a monocular HWD (see Fig. 6) for a lunar lander spacecraft.[30,31] During Apollo, the constraints placed by the design of the Lunar Module (LM) window for crew visibility and landing trajectory were "a major problem." Optimal fuel saving trajectories render the natural vision of the crew from windows inadequate for the approach and landing task. Thus, a light-weight HWD system with SV and perhaps Enhanced Vision (EV) technologies offered a potential solution for spacecraft crews.

In general, pilots thought the HWD had great potential but was not optimized for this lunar landing task. The performance data shows there were no significant performance differences when using the HWD in conjunction with the head-down displays (HDDs). Also, there were no significant workload or simulator sickness effects with the HWD. Regarding SA, the data is anecdotal. Some pilots felt the HWD provided greater SA because the HWD allowed for an eyes-out view while still being able to perform the task. Pilots preferred this eyes-out view as it provided "truth" data as to what the actual situation is, rather than relying on a computed navigation solution which can be subject to errors. These comments were from pilots who were familiar with and frequently flew night vision systems which are monocular and monochrome green; therefore they were used to and familiar with having a monocular display over one eye while flying.

However, those pilots who had not flown such systems were distracted by the HWD at times. The artifacts associated with a head tracked display, such as blurry text and numbers, caused pilots to abandon using the HWD and rely solely on the HDDs. Thus, pilots would try to keep their heads still in order to reduce latency effects which reduced the readability of the HWD. All pilots agreed that a HWD with a larger field-of-view (FOV) would be desirable; however, pilots were not asked to quantify how much larger the FOV should be.

Binocular rivalry effects were not observed with the HWD system used in this experiment. Binocular rivalry is a well documented phenomena where two vastly different images are presented to each eye. When two disparate images are presented to each eye, the brain involuntarily suppresses one of the images. Even though a monocular HWD system was used in this experiment, binocular rivalry was not so much an issue as the transparent HWD allows for similar images to the eyes.[32]

With head tracked HWD systems, many factors can affect the image quality, thus the acceptability of the HWD.[33] In this experiment, synthetic terrain was rendered on the HWD. The alignment of the synthetic terrain to the real terrain (out-the-window is considered truth for this experiment) is dependent on the static boresighting as well as the system latency. Latency will cause an apparent misalignment during head movement, but as the pilot's head comes to a stop, the terrain will appear to "catch-up." This terrain "swimming" can lead to simulation sickness and loss of confidence in the fidelity of the system. For this experiment, neither simulation sickness nor integrity of the HWD system was a concern.

4.5 HWD as an equivalent HUD

As mentioned, the FSF identified significant safety benefits of head-up/HUD flight operations.[15] In addition to safety benefits, "operational credits" are now being derived from HUD equipage that a HWD might also obtain if "HUD equivalence" can be shown. In particular, the EFVS operational credit (as per §91.175 (l) and (m)) explicitly expressed that the use of a HUD was an essential "characteristic and feature" of the EFVS operation. Two tests were conducted to assess the state of the HWD technologies to meet the provisions for the use of a HWD as an equivalent display to the HUD.

4.5.1 Simulation experiment

Under the Vehicle Systems Safety Technologies (VSST) project in the Aviation Safety Program (AvSP), one specific area of research is the use of small HWDs (see Fig. 5) as an equivalent display to a HUD.[16] A simulation experiment was conducted to evaluate if the HWD, coupled with a head-tracker, can provide an equivalent display to a HUD. Comparative testing was performed in the RFD Cockpit Motion Facility (CMF) full mission, motion-based simulator at NASA Langley. Twelve airline crews conducted approach and landing, taxi, and departure operations during low visibility operations (1000' RVR, 300' RVR) at Memphis International Airport (Federal Aviation Administration (FAA) identifier: KMEM).

The HWD used in this experiment was coupled with a prototype head tracker that provided head orientation and was mounted on the left side of a pair of Lumus DK-32 glasses. The Lumus eye-wear is see-through, full color which utilizes patented Light-guide Optical Element (LOE) technology to generate an image that appears at "practical" infinity similar to a HUD. For this experiment, only monochrome green symbology and imagery were displayed on the HWD as to not introduce a confound when comparing to the monochrome HUD.

The results showed that there were no statistical differences in the crews performance in terms of touchdown and takeoff. Further, there were no statistical differences between the HUD and HWD in pilots' responses to questionnaires.

4.5.2 Flight demonstration

Using the same HWD system described above, a flight demonstration was conducted at NASA LaRC.[34] The purpose of the flight test was primarily to evaluate the use of HWDs during actual aircraft taxi and approach operations. Approach and taxi testing was performed on board NASA Langley's experimental King Air aircraft in both VMC and simulated IMC conditions. Seven highly experienced test pilots with HUD experience participated in the flight test. Since NASA's King Air did not have a HUD installed, pilots were asked to compare the HWD, in which they used to fly the airplane, with a HUD based on previous experience.

The pilots flew straight-in Instrument Landing System (ILS) approaches wearing the HWD. The HWD symbology consisted of a 'virtual-HUD' concept where a typical HUD symbology was rendered if the pilot was looking at the area where a HUD combiner glass would be mounted. In addition to typical flight symbology, a simulated FLIR image was rendered on the HWD and was conformal to the outside world. During simulated IMC, the pilots view through the HWD was blocked leaving only symbology and simulated FLIR imagery (FLIR on/off was experimentally controlled).

Pilots were able to fly the approaches and stay within a dot of precision on the localizer and glideslope using the HWD. Pilot comments showed acceptance of the concept though provided comments to improve the HWD system. The most requested improvement was to stabilize the symbology which essentially translates to reducing the system latency.

When pilots flew simulated IMC, the FLIR imagery was not misaligned with the "real world" since it was not visible,thus, no eye strain even on turbulent approaches was reported. Pilots reported that this configuration reduced workload significantly and pilots commented they were able to focus on pertinent information much easier. For pilots that encountered light to moderate turbulence, system latency created a "jittery, bouncy" display that was difficult to read and follow. The latency combined with turbulence resulted in eye strain and headaches (although minimal) causing increased workload. This combination of turbulence and latency is manifested in temporary discrepancies in the conformal image to the actual image.

5. FUTURE DIRECTIONS

The work to date indicates that a Head-Worn Display for commercial and business aircraft is viable. The data also suggests that the business case to make this happen is through the path of "HUD equivalency." The data also shows that the technology is not ready quite yet. The form factor and static and dynamic accuracies are not where they need to be for HUD equivalence. The other open question is how to best meet the challenge of obscuration and contamination of the pilot's view outside the aircraft when there is prevailing natural vision, such as surface operations.

The application domain for this technology lays strongly in three areas: a) HUD installation is not possible or practical by volume or weight; b) HUD retro-fit is not cost-effective; and, c) HWD installation has a return-on-investment advantage to the HUD, such as a weight reduction. Once installed, the HWD-equipped aircraft can then pursue HUD operational credits for reduced operating minima for landing and take-off. More importantly, if the HWD can get installed as a HUD equivalent, the data suggests that several HWD-unique applications will open up. Improvements have been shown for surface operations and in flight operations where off-boresight and expanded field-of-view information for traffic identification and extended runway centerline awareness is important.

The other "game-changing" application could be enabling an emerging NextGen concept termed, Equivalent Visual Operations (EVO). EVO is an electronic means to provide sufficient visibility of the external world and other required flight references that enable the safety, operational tempos, and VMC-like procedures for all weather conditions. The HWD, coupled with SV and EVS technologies, would create an intuitive interface or an electronic Visual Flight Rules (E-VFR) operational capability. A step further, EVO would be one component of a "better-than-visual" operational capability; replicating the capacity of today's VMC flight and more importantly, meeting and improving on the safety of today's VMC flight in all-weather NextGen operations. NASA research aims to extend the present-day S/EV concepts using HWDs to enable VMC-like operational tempos and maintain and improve the safety of VMC while using VMC-like procedures in all-weather conditions.

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