

Near-Eye Augmented Reality Tower Controller Displays: Human Performance Issues

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Abstract

The primary means by which air traffic controllers in airport towers obtain information is by direct head-up, out-the-window (OTW) viewing. However, controllers spend a considerable amount of head-down time looking at flight strips, panel-mounted displays, and other information sources in the tower. The U.S. Air Force recognized that tower controllers may benefit from near-eye augmented reality (NE/AR) display technology to increase head-up OTW time and increase situation awareness (SA), especially during limited visibility conditions. Therefore, the U.S. Air Force Research Laboratory tasked us to develop a prototype NE/AR display that enhances tower controller performance and SA, and that will be accepted and used by tower controllers. We developed or adapted prototypes of (1) a video see-through held-to-head virtual binoculars display (VBD) slaved to an external pan-tilt camera, and (2) an optical see-through head-worn display (HWD). Relevant text (e.g., aircraft identity) and graphic images (e.g., runway outline), are overlaid on real-time, head-tracked video (for the VBD), or on real-time, untracked OTW scenes (for the HWD). We performed usability assessments with Air Force tower controllers using 1) user/task observation, 2) user review of an early physical mockup, 3) rapid prototyping involving user review of airfield movement scenarios with text/graphics overlays, and 4) user trial of a partially functional system. We discuss heuristics for selecting the best display concepts, design challenges and engineering tradeoffs, and the results of our usability engineering and assessment efforts. Finally, we discuss key human performance issues affecting the functionality and controller acceptance of NE/AR displays.

ABOUT THE AUTHORS

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Roger Labbe is a senior software engineer at DCS Corporation where he is providing software engineering support for the analysis, design, development, testing, and integrating of large and small-scale avionics systems, as well as for avionics computer-based training. He has a BS degree in Computer Science from Clarkson University. Previously, Mr. Labbe supported the development of a Mission Analysis and Review System (MARS), a 3D post-flight visualization tool which plays back flights using data from a flight recorder. His responsibilities included all phases of software development using Object-Oriented methodologies: systems analysis, software design, software development, and test technologies. He is the senior software engineer for the Air Force SBIR Phase II tower controller display project.

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INTRODUCTION

Air traffic controllers in the tower environment are responsible for control of traffic on the ground and in the air within the airport traffic control area. Ground control, departure and arrival sequencing, and surface management are continuous challenges. Tower controllers live in an information-rich world, processing data from a multitude of sources, such as out-the-window (OTW) observations; head-down displays; departure, arrival, and traffic patterns; ground operations, pilots, other controllers, and flight progress strips. Controllers must frequently divert their attention away from the OTW external scene, which is their primary source of information.

In this paper we discuss work we conducted as part of an Air Force Small Business Innovation Research (SBIR) project, which leveraged our previous work with the Federal Aviation Administration (FAA). The goal of the effort is to develop and evaluate user-acceptable hardware and software solutions, using near-eye (NE) display and augmented reality (AR) concepts and technology. These solutions will help reduce diversions and augment tower controller capabilities, especially at night and in limited visibility. We discuss heuristics for selecting the best display concepts, design challenges and engineering tradeoffs, and the results of our usability engineering and assessment efforts. Finally, we discuss key human performance issues affecting the functionality and controller acceptance of NE/AR displays.

THE PROBLEM

Tower Controller Positions

The two key positions in military and civilian towers are the *Local Controller* (LC) and the *Ground Controller* (GC). The LC is primarily responsible for handling arriving and departing traffic at the airport. The LC position interfaces with GC and other air traffic control (ATC) personnel. The GC is primarily responsible for directing aircraft to and from the runway via taxiways. The GC is also responsible for directing other aircraft/vehicular movement on the airport movement area and disseminating information to support operations (e.g., traffic, weather,

equipment status, flight plans). In short, the ATC tower is a dynamic environment in which the LC and GC must adjust traffic flows, evaluate new information, and closely coordinate and communicate their efforts (see Figure 1).



Figure 1. Air Traffic Tower Controllers

Information Elements and Sources

Tower controllers obtain information required to perform their duties from many sources. Information on individual flights and their intended airborne or ground path is transferred to the controller through the use of flight progress strips, radar displays, verbal communications, and surface map displays. The primary source of information about aircraft location is the out-the-window view from the tower. However, the controller must also continually monitor a large number of console displays that provide information on local weather conditions, status of runways, as well as arrival and departure information that must be relayed to pilots as needed.

To acquire and maintain situation awareness (SA), controllers must know at a minimum, aircraft and/or ground vehicle identity, their location, and their intent (Piccione, Krebs, Warren, and Driggers, 2002). A critical part of knowing aircraft location and intent is the capability to identify aircraft that are being controlled. This capability is augmented at some facilities with radar displays that show the identity and location of aircraft in the airspace surrounding the airport. At larger airports, information about objects on the airport movement area may be shown on a surface map.

Flight progress strips are used as an analogy for the flight and are manipulated on the console during the hand-off process between tower positions (Dattel et al., 2005; Truitt, 2006). They provide detailed flight information for each aircraft, including the aircraft type, first departure fix, flight plan information, and aircraft identification. The strips are marked with updated information as an additional means of information storage, inter-controller coordination, and aircraft transfer. Taken together, the map display, flight strips, and the Digital Bright Radar Indicator Tower Equipment (D-BRITE) display (a repeater display of the terminal radar control [TRACON] display) provide a good picture of the current state of the terminal airspace and airport surface, and help the tower controller build and maintain SA from multiple look-down sources.

Scanning Requirements

The controller must use a scan pattern outside and inside the tower to assimilate, correlate, and integrate information for building and maintaining situation awareness. The information inside the tower is presented on a variety of displays that may be imbedded in the console, placed on the console as a freestanding unit, or mounted overhead of the tower windows. The controller must determine what information is needed, retrieve that information from displays throughout the tower cab, and mentally integrate the information.

Tower controllers frequently cite problems associated with the requirement to use large scan patterns to monitor displays inside the cab that detract from their out-the-window task of monitoring the airspace, runway, and airport movement area (i.e., taxiways and ramps) (Piccione et al., 2002). These types of typical display options currently used in a control tower all require distance viewing across a wide field of regard. This presents a challenge where user-centered solutions that reduce look-down time and improve information management for controllers would be beneficial.

Effects of Reduced Visibility

The OTW scene is severely degraded during night and limited visibility conditions. When visibility is restricted, controllers may be able to maintain some degree of SA by increasing radio and interpersonal communications, following established procedures, and forming expectations of key events. However, their overall SA is still significantly degraded. Controllers must establish and maintain a mental image of the airport layout using graphical aids (e.g.,

taxiway diagrams) and position reports from pilots and vehicle drivers to determine the location of aircraft and other objects on the surface, sometimes resulting in radio frequency congestion. From this assembled and integrated information, controllers must form expectancies of where an aircraft or vehicle should be, and the spatial interrelationships among aircraft and vehicles. This often results in an increase in workload and reduction or loss of SA (Piccione et al., 2002).

Near-Eye Augmented Reality Displays

A promising solution is to provide the controller a display with text and symbology overlaid on key elements of the OTW scene to augment their scene perception and understanding. This can be accomplished using a near-eye augmented reality (NE/AR) display. NE/AR displays can take the form of a head-mounted/head-worn display (HWD), or a held-to-head virtual binoculars display (VBD). The NE/AR display concept can be implemented with daytime displays as well as enhanced vision (e.g., infrared) displays for low visibility conditions. In this research we examined near-eye displays, which provide electronic and miniaturized viewing capabilities in a display placed generally within one inch from the viewer's eye and magnified with optics.

The use of a NE/AR display allows the presentation of *context sensitive* information and the *scene linking* of text or imagery that can cue the location of aircraft and highlight the location of runways. Scene linking associates information with a scene object as it is dynamically presented, such that the symbology appears to undergo the same 2-D physical transformations (e.g., change apparent size) as the associated 3-D objects.

PROJECT OBJECTIVES

The research reported here has four objectives:

- (1) To understand tower controller tasks, and how a NE/AR display system might support these tasks.
- (2) To analyze the technical requirements (e.g., resolution, tracking,) so a feasible design of required display capability can be developed.
- (3) To understand form and use factors as well as the technical and social challenges for implementing such a display system.
- (4) To perform an assessment of NE/AR display usability and acceptability by controllers.

PREVIOUS RESEARCH

We began by gaining an understanding of the tasks performed by tower ground controllers and local controllers, how they performed these tasks, the information they need

to perform the tasks, and the sources they relied on for this information. The interested reader is referred to Ruffner, Fulbrook, and Foglia (2005) for a summary of key findings from early tower controller studies. Relevant findings from two recent studies sponsored by the FAA and NASA are noteworthy, and are briefly summarized below.

FAA Tower Controller Study

Researchers at the FAA William J. Hughes Technical Center, Atlantic City, NJ, (Koros, et al., 2003) found that the most important information *elements* common to the LC and GC, in descending order of importance, were: (1) aircraft position, (2) aircraft identification, and (3) route to be followed during taxi operations. The most common information *sources* were: (1) out-the-window visual observation, (2) flight strips, (3) communication with the pilot, and (4) the D-BRITE radar display. Visual observation was considered the first or second most important source of information for over 60% of the information elements.

NASA Surface Management System Study

Under NASA sponsorship, researchers from Booz, Allen, and Hamilton, and Ohio State University conducted a human factors assessment of the developmental Surface Management System (SMS) (Hitt et al., 2002). The SMS was developed as a decision support tool to provide controllers and airline personnel with aircraft-specific information and predicted departure demand information to facilitate the management of aircraft on and around the airport surface.

The results indicated that both LCs and GCs desired aircraft identification and flight-specific information to be presented via data blocks on a surface map display. The specific information provided, as well as the desired area to be covered by the map display, depended on the controller position. The controllers desired to have integrated information located in one place and cited display clutter (i.e., excessive text and graphical information) as a critical issue. Also, because tower controllers interact frequently to exchange information and coordinate actions, the respondents desired that tower displays be clearly visible to all tower controllers, and that color-coding schemes and symbology be standardized.

The SMS study identified the major tasks and subtasks for the GC and LC positions, and developed procedural flow diagrams for the tasks. The report describes the tasks to be executed and the times

where decisions were required for the tasks (e.g., Maintaining Runway Balance) and subtasks (e.g., Determine Delay to Runway Threshold). In addition, the report lists the information requirements (e.g., aircraft type, aircraft identification) for each task and subtask, and the source(s) from which information can be obtained (e.g., out-the-window, map display).

TYPES OF NE/AR DISPLAYS

AR systems use “see-through” displays to view 2D or 3D computer generated objects superimposed on the corresponding real-world scene. This can be done using either an *optical-see through* or a *video see-through* display (Rolland and Fuchs, 2001). Both display types are capable of providing users with either screen-referenced, situation-relevant symbology (e.g., wind direction and speed) or scene-linked symbology (e.g., aircraft identification). In optical see-through displays, the symbology is optically superimposed on the real world scene. In video see-through displays, the symbology is superimposed on a real-time video image of the real scene.

In this project we investigated two NE/AR display concepts: (1) an optical see-through HWD and (2) a video see-through VBD to determine their strengths and weaknesses with respect to the tower environment. We used the findings from our Phase I feasibility study to guide our selection of a display concept for further development during Phase II. In the following subsections we discuss strength and weaknesses of the two NE/AR display concepts.

Optical See-Through Display

With an optical-see-through HWD, the real world is seen through half-transparent mirrors placed in front of the user’s eyes. The mirrors are also used to reflect the computer-generated images into the user’s eyes, thereby optically combining the real and virtual world views (Rolland and Fuchs, 2001). An optical see-through approach has the following advantages over a video see-through approach (Azuma, 2001):

- *Simplicity.* Optical blending is simpler and cheaper than video blending, since there is only one “stream” of video.
- *Resolution.* The real world view is not degraded by conversion to video, while the graphics resolution is display limited.
- *Safety.* When power is removed from an optical see-through HWD, the user still has a view of the real world.
- *No eye offset.* There is no eye offset, as with video see-through displays, which shifts the user’s viewpoint from the eye position.

Weaknesses in the optical see-through HWD concept are that attaining reliable and accurate see-through registration (real-world/virtual world alignment) is very difficult and motion tracking requirements are extremely complex. Because the controller will need to walk anywhere in the tower cab, six degrees-of-freedom (DOF) tracking over a wide area is required. A hypothetical HWD see-through display concept for the tower controller is shown in Figure 2. In this research effort, we examined the Microvision Nomad™ monocular retinal scanning display as an example of an optical see-through display.



Figure 2. Head-Worn Optical Display Concept

Video See-Through Display

With a video see-through display, the real-world view is captured with one or two video cameras mounted either on head gear or at a remote location. The computer-generated text and video imagery are electronically combined in a computer with the video representation of the real world. A video see-through approach has the following advantages over an optical see-through approach (Azuma, 2001):

- *Flexibility in composition strategies.* It is possible to completely block out the real-world scene with a computer-generated graphic, since both the real-world and virtual scenes are digital.
- *Wider field of view (FOV).* Optical distortions are easier to correct (digital correction) with video see-through HWDs, resulting in a wider FOV.
- *Better display view matching.* Temporal mismatches between the real-world scene and the virtual image are more easily corrected and matched.
- *Available registration strategies.* Image properties (e.g., shape) of the real-world scene digitized image can be used to facilitate image processing and registration.

- *Matching object brightness.* Because both the real and virtual objects are digital, it is easier to match their brightness levels.

The major weaknesses of a video-see through display system are that the resolution provided by the camera will be lower than the resolution of the unaided human eye, the total field of regard will be less than with an optical-see through system, and there may be a parallax problem if the camera is offset far from the VBD. From an ergonomics perspective, the requirement to hold the display to the head for very long may result in hand and arm fatigue. A hand-held binoculars display concept is shown in Figure 3.



Figure 3. Hand-Held Virtual Binoculars Concept

Based on a systematic comparison of the two types of displays on several key criteria, as well as feedback from the Air Force Research Laboratory technical monitor, display SMEs, and tower controllers, we decided that the held-to-head VBD approach was most practical for the tower controller application, and to focus our efforts accordingly in Phase II. Our team developed a VBD using commercially available off-the-shelf (COTS) components, including state-of-the-art micro displays and eyepieces, which would provide a bright, sharp, high contrast, full color, 40 degree diagonal image.

Form Factors and Use Factors

Form factors and use factors are important considerations for ensuring the usability and ultimate user acceptance of a NE/AR display. We understand form factor to mean the physical platform or mechanism that serves as the host for the display, or into which the display is attached or integrated. Similarly, we understand use factor to mean a commonly accepted or adopted means of using a device.

A head-worn or clip-on see-through display, such as the one shown in Figure 2, has a form factor/use factor similar to standard eyeglasses, and can be designed to be lightweight,

unobtrusive, and wearable for longer periods. For example, the Microvision Nomad™ can be worn on a visor or mounted under a ball cap. Many controllers (especially younger ones) do not wear eyeglasses, and may not want to wear them while on duty. In addition, we have observed some degree of resistance among controllers to wearing a ball cap, or a HWD in general, in the tower.

A hand-held VBD, as illustrated in Figure 3 utilizes a different form/use factor (i.e., binoculars) from eyeglasses that is already used and accepted by tower controllers. In comparison to eyeglasses that are typically lightweight and worn to over an extended period of time, binoculars can be heavy and are held up to the user’s head intermittently when there is a specific need for up-close viewing. Therefore, if the VBD is not designed well and integrated into the tower environment properly, controllers may only use it when augmented viewing is required, or not at all.

Thus it is important to obtain a good idea early in the design process when and how often controllers might use the VBD by conducting systematic observations with models or prototype systems, and interviewing users. Table 1 compares the two NE/AR display concepts on key system performance and user acceptability criteria. This information provided the foundation for our NE/AR selection heuristics.

DESIGN CHALLENGES AND ENGINEERING TRADEOFFS

There are several technical issues and design challenges that must be addressed before NE/AR displays are practical in an operational ATC tower environment. These include determining minimum acceptable FOV and resolution, the required tracking and registration precision, and the implementation strategy for selecting and superimposing text and symbology on the OTW display FOV. Many of these have implications for facilitating human performance with NE/AR displays, the major thrust of this paper, and therefore are addressed briefly.

Visual Display Technology

Field of view and resolution are key parameters of any NE/AR display system, and are often traded off during the design process. Studies of pilot performance with HWDs indicate that, up to some point, wider FOVs generally result in better performance and situation awareness, and are preferred by users. However, increasing FOV while maintaining display resolution, or vice versa, requires using optical and structural components that increase

size, weigh, and cost. Research by Schmidt-Ott et al. (2002) at NASA-Ames suggests that a FOV of approximately 40-45° diagonal and a resolution of 800 x 600 pixels per eye should be sufficient for the tower controller application.

Table 1. Comparison of NE/AR Display Concepts

Criteria	VBD	HWD
Optical System	<i>Biocular</i>	<i>Monocular</i>
See-through Capability	<i>Video See-through</i>	<i>Optical See-through</i>
Text and Graphics Overlay	<i>On Video Camera Image via PC</i>	<i>On Outside Natural Scene via PC</i>
Scene Field of View	40° H x 30° V	160° H x 130° V
Symbology Field of View	40° H x 30° V	23° H x 17° V
Scene Resolution	<i>Medium</i>	<i>High</i>
Symbology Color	<i>Full Color</i>	<i>Monochrome Red</i>
Zoom Capability	<i>Yes</i>	<i>No</i>
Enhanced Vision Support	<i>Excellent</i>	<i>Poor</i>
Form Factor	<i>Handheld Binoculars</i>	<i>Eyeglasses/ Head Unit</i>
Motion Tracking	<i>Moderate</i>	<i>Difficult</i>
Mobility	<i>Limited now, wireless in the near future</i>	<i>Limited now, wireless in the near future</i>

Note: VBD = Virtual Binoculars Display
HWD = Head-Worn Display

Augmented Reality Technology

As noted previously, AR technology can help users to increase their understanding of complex visual scenes by superimposing supplementary information relevant to the current task and referenced to real world objects. AR display enhancements that support operator tasks include providing supporting textual or graphical information and presenting cueing information to guide attention throughout the visual scene. AR technology has advanced in recent years, but it still has technical design challenges that must be overcome (Azuma, 2001).

Examples of NE/AR visual display and AR technical challenges include: (1) sensing (detecting and identifying objects in the environment), (2) precision of registration (aligning objects in the real and virtual scene), (3) precision of head tracking required and (4) minimizing latency (lag between the display presentation of the actual and displayed event). As with aircraft head-up displays (HUDs) and helmet-mounted displays (HMDs), the timeliness and accuracy of the information is critical.

USABILITY ENGINEERING AND ASSESSMENT

In addition to being functional, a NE/AR display system for tower controllers must be comfortable, usable, and accepted by the controllers. Poor usability is likely to constrain human performance. Therefore, we considered it essential to follow usability engineering best practices and to conduct early and frequent usability assessments.

Usability Defined

Usability is the degree to which something (e.g., software, hardware) is easy to use and a good fit for the people who use it. It is a quality or characteristic of a product and determines whether a product is efficient, effective and satisfying for the users (Nielsen, 1993).

Usability Engineering and Assessment

Usability engineering is a process that helps designers avoid or mitigate usability problems by involving users early on and continuously throughout a product's development lifecycle, and making successive improvements based on the results of early product trials. Although usability engineering is more often applied to software interface development, it is equally applicable to the

development of physical devices such as NE/AR displays (Gabbard et al., 2002; Nielsen; 1993).

There is a wide assortment of usability engineering and assessment techniques, and each method has its advantages and disadvantages. Our approach to usability engineering and assessment was based on a set of basic techniques recommended by Nielsen (1993) as relatively inexpensive, easy to implement, and cost-effective: 1) user and task observation; 2) hands-on assessment of early physical mockups; 3) interactive reviews of surface movement scenarios with candidate overlaid text and symbology; and 4) an end-to-end evaluation of a partially functional system. These are discussed below.

User and Task Observation

Early in the project we visited towers at Dover Air Force Base (AFB), DE, Langley AFB, VA, and Scott AFB, IL. Dover AFB and Langley AFB are representative of air bases with different types of missions and environments, specifically, Air Mobility (Dover) and Air Combat (Langley). Scott AFB is home to the Air Force Air Mobility Command, and the Scott AFB tower is responsible for controlling military and civilian aircraft. We talked to novice, mid-level, and experienced controllers about how they performed their jobs and the kinds of information they used in accomplishing specific tasks, and observed them working in their physical environment. We also discussed in broad terms the NE/AR display concepts we were investigating, and invited the controllers to look through an optical see-through display showing a short aircraft data block to give them a sense of what a NE/AR display would look like.

Physical Model Evaluation

We examined the physical characteristics (e.g., physical shape, weight, size) of binoculars typically used in Air Force control towers, and considered their implications for the design of the VBD. This included the size and shape of the VBD outer shell, the location of the physical controls, and the choice of the micro-displays and optics. The team then constructed several foam models, based on ergonomics design guidelines and best practices, for hands-on controller evaluation (see Figure 4).

The models were first subject to a heuristic evaluation (i.e., adherence to best practices) by project team members with extensive experience in customized near-eye display mechanical and optical design. A subset of these models were judged to be superior based on ergonomic considerations (e.g., shape, ease of fit in the hand). They were made into more elaborate models that were closer to the actual VBD size, with buttons placed on the top surface. The models were judged to be acceptable with respect to hand grip comfort and button placement.

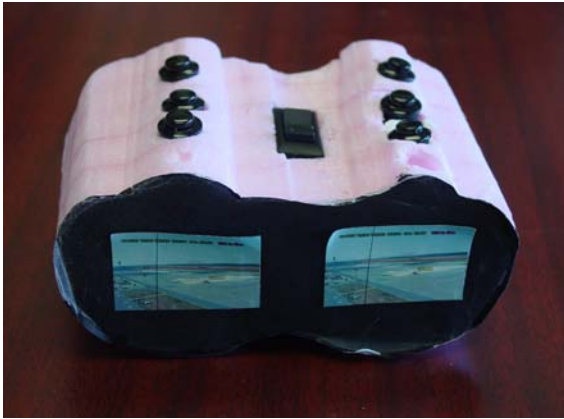


Figure 4. Foam Model Mockup of the VBD

The top two-rated models were shown to Air Force tower controllers during hands-on demonstration visits to Dover AFB and Scott AFB. The controllers overwhelmingly preferred the model shown in Figure 4, which had three buttons symmetrically arranged on the left and right. This arrangement enabled us to implement two user control options: 1) single-handed operation with three functional buttons (e.g., symbology mode selection, zoom, brightness), which allows the controller to keep one hand free to key the intercom; 2) two-handed operation with six different buttons which allows more flexibility in future designs. This model was used for developing CAD drawings and a functional version of the VBD. It should be noted that the controllers expressed interest in a wireless version, which we plan to explore in future work.

Rapid Prototyping With Scenarios

To maximize our time and project resources, we decided to develop the user interface and screen design elements in parallel with the physical system design, development, and integration. To accomplish this, we conducted early and frequent usability assessments of overlaid text and imagery symbology on an OTW scene. Specifically, we shot original video or obtained existing video footage of airfield surface traffic (e.g., aircraft taxiing to a runway) at Air Force bases and commercial airfields. We augmented these videos with overlaid AR symbology (i.e., aircraft identification, weather information) using Adobe Premier Pro™ 7.0 video editing software. Figure 5 is a screen shot from an augmented video of a C-5 taxiing at Dover AFB.

We showed these videos to controllers at Dover AFB and Scott AFB, and in the DCS lab facilities in Alexandria, VA. The controllers viewed the scenarios through an early prototype VBD (an eMagin Z100

Visor™) that had the same micro-displays, optics, and resolution (800 x 600 pixels), planned for the final prototype. The feedback from these reviews helped guide our decisions about the content, format, and timing of the overlaid symbology. It also helped us evaluate the adequacy of the candidate micro-displays and optics with respect to key parameters such as resolution, brightness, contrast, and FOV. We repeated this process as the availability of tower controller participants permitted.



Figure 5. Screen Shot of NE/AR Display Format Used During Rapid Prototyping

Partially Functional System Evaluation

The fourth type of usability assessment procedure, which is in progress, consists of a hands-on evaluation of a partially functional early prototype NE/AR system. We are conducting the evaluation in our lab, which has west- and north-facing OTW views. As shown in Figure 6, the west-facing view is of a middle school and its surrounding access roads, parking lot, and grounds. These serve as surrogate features for an actual airport surface. The north-facing view (not shown here) looked toward the Washington Monument and Reagan National Airport (DCA) control tower.

The participants for this evaluation are Air Force controllers, DCS scientists and engineers, and Human Factors and AR researchers from scientific organizations (e.g. FAA, NASA-Ames, Navy Research Laboratory). The participants are asked to use the VBD as if they were observing and controlling aircraft on the airport surface. This enables the team to gather valuable information about the system usability by observing how participants use the VBD, by recording their OTW view, and by recording their “think aloud” observations. This provides an additional opportunity to make early usability assessments about key system features that we can subsequently improve.

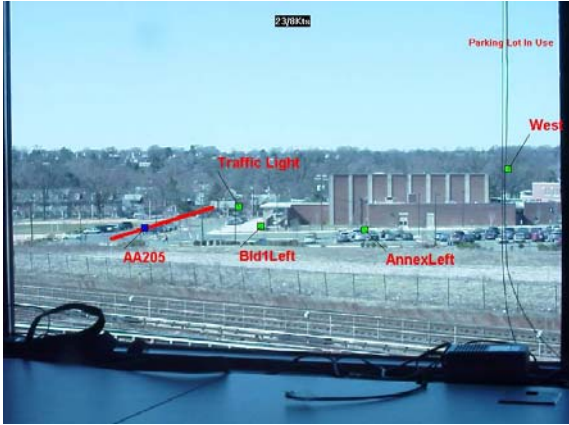


Figure 6. External Scene Through the NE/AR Display with Real-Time Overlaid Symbology

In addition, we are collaborating with the FAA to demonstrate a mature version of the NE/AR system at the Technical Center Tower Mock-up Research Facility. This will provide us an excellent opportunity to safely test our ability to integrate the system with the Technical Center's surveillance data infrastructure, and will give the team a chance to gather additional system performance and usability data in a controlled environment without the risk of disrupting tower operations.

HUMAN PERFORMANCE ISSUES

The final section discusses several NE/AR tower controller display human performance issues that are critical for determining its eventual success and user acceptance, and which we plan to address in future work. Our discussion focuses on four areas: 1) attention, 2) memory, 3) situation awareness, and 4) NE/AR display as a performance support system.

Attention

As noted previously, a NE/AR display concept involves superimposing text and screen-referenced or scene-linked symbology on an OTW scene. This is similar to what is done with aviation or automotive HUDs. The rationale behind using a HUD is that it eliminates, or minimizes, the need for refocusing and for extensive eye scan movements between head-down panel-mounted instruments and the head-up OTW scene.

There is evidence that, in addition to their benefits, HUDs may have undesirable attentional effects on human performance. Research (e.g., Yeh and

Wickens, 2001) has shown that the division of attention across stimuli belonging to separate domains or perceptual groups (e.g., a HUD digital altimeter readout vs. a wire-frame outline of a tank target) may lead to attentional capture or narrowing. Specifically, the user allocates an inappropriate amount of attention on either the symbology or the visual scene to the exclusion of the other component. This effect is more pronounced when real world events in the visual scene are infrequent or otherwise not expected, such as a runway incursion.

The research on divided attention suggests that attentional capture or narrowing will be less likely with scene-linked symbology than with screen-referenced symbology. This is a testable hypothesis which has important implications for the design of NE/AR displays for tower controllers. Therefore it should be investigated in future research. In addition, research is needed to determine what amount and detail of scene linking is appropriate, since the labor and computational costs for implementing the scene linking can be high.

Memory

In addition to improving the allocation of a controller's attention, a tower display, whether heads-up or heads-down, must support working memory and short-term memory. Researchers have investigated operational errors (OEs) by tower controllers to determine the extent to which they may result from failures of working and long-term memory, in addition to attentional failures. An OE is an action of an air traffic controller that results in less than the required minimum separation between two or more aircraft, or between an aircraft and obstacles (e.g., vehicles, equipment, personnel on runways), or an aircraft landing or departing on a closed runway.

For example, a study by Cordosi and Yost (2001) at the Volpe National Transportation Systems Center in Cambridge, MA, found that the most commonly occurring tower controller errors were failures to remember that: 1) an aircraft was on runway; 2) a runway had been closed; or 3) a clearance that had been issued to land, takeoff, or cross a runway. In a more recent study by researchers at the FAA Civil Aeromedical Institute (CAMI) in Oklahoma City, OK, Bailey and Xing (2005) found that roughly 60% of the OEs were associated with exceeding the capacity limits of controllers' attention and memory. More specifically, they found that the top factors contributing to the OEs were: 1) memory overload; 2) disruption of memory consolidation, and 3) attention failures.

The findings of Cordosi and Yost (2001), as well as those of Bailey and Xing (2005), have important implications for NE/AR display system design. Specifically, it is

extremely important to determine how NE/AR displays can best be used, both alone and in conjunction with head-down displays, to reduce the frequency of these types of errors and to minimize their impact. Future research should focus on the content, placement, and timing of overlaid, augmented information.

Situation Awareness

Research has consistently indicated that tower controllers need to acquire quickly, and maintain a strong sense of SA over long periods of time to perform their jobs safely and effectively. The most frequently used definition for SA (Endsley, 1995) is “the perception of the elements in the environment with a volume of time and space (Level 1), the comprehension of their meaning (Level 2), and the projection of their status in the near future (Level 3).” In the context of ATC controllers, Durso et al. (1998) suggested that SA is “the understanding of the dynamic situation, including the current and likely future states...including knowing the situation in which one finds oneself, when that situation has changed, what to do in the situation, what should follow from that situation, and how the situation relates to the controller’s goals.”

Endsley, et al. (2000) noted that that the ability of controllers to maintain an up-to-date mental model of a dynamic and complex traffic situation depends on their ability to integrate information about many aircraft into a cohesive internal structure. This allows them to understand relationships between aircraft (and in the case of surface traffic, between aircraft and ground vehicles). Their findings suggest that key elements for Level 1 SA (i.e., perception of the ground traffic situation) are aircraft identification, location, type, level of control, groundspeed, and heading. Given this, a well designed NE/AR display could assist tower controllers in performing visual surveillance tasks and establishing the appropriate level of SA by providing this information at the right time, in the right place, and in the right format.

NE/AR Display as a Performance Support System

The objective of a (human) performance support system is to put critical knowledge at the fingertips of operators, technicians, and knowledge workers (Cichelli, 2005). Given this, NE/AR displays may be considered a type of Electronic Performance Support System (EPSS) and can benefit greatly from the extensive research on, and guidelines for, developing and applying effective EPSS systems.

In this context, Durso et al. (1998) suggested that that tower controller SA may sometimes involve simply knowing *where* in the environment to find a particular piece of information, rather than remembering *what* that piece of information is. Selectively placing critical information elements in the forward field of view in the right *place* and at the right *time* on a tower controller NE/AR display could make that information easier to access on an as needed basis, lessen controller memory requirements and workload, and thus support controller performance.

CONCLUSION

The concept of a NE/AR display for tower controllers has the potential for improving controller capabilities, SA, safety, and ultimately increasing airport capacity. We discussed our work to develop a NE/AR virtual binoculars display, technical challenges that need to be overcome for NE/AR displays to be practical in the ATC tower environment, the results of usability assessments, and key human performance issues. Advances in the enabling technologies for AR (e.g., tracking and registration) are continuously being made, and workable systems are expected to be available in the near future.

However, even the most technologically sophisticated NE/AR display will not be used by tower controllers if they consider to be is too heavy, cumbersome, intrusive, or otherwise difficult to use. Accordingly, a fair question to ask is “Will tower controllers actually use a NE/AR display for extended periods?” The answer will likely be reduced to whether the advanced capabilities and benefits afforded by the technology offset the problems and costs induced by the physical encumbrance and potential sensory conflicts. Ultimately, a thorough understanding of the key human performance issues, as well as of best practice human factors and ergonomic design, will be critical for achieving ultimate user acceptance.

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