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# Design of Augmented Reality Tools for Air Traffic Control Towers

Ronald J. Reisman*
*NASA Ames Research Center, Moffett Field, CA 94035*

*and*

David M. Brown†
*Science Applications International Corporation, Moffett Field, CA 94035*

**A series of head-tracking, see-through, head-mounted display prototypes were developed and evaluated by five controllers at Moffett Field air traffic control tower. The controller cadre identified several deficiencies in the initial prototype, such as low optical transmissivity of the display, unacceptable compensation for tower lighting conditions, inadequate symbology and data block information display, and unacceptable discomfort caused by wearing the head-worn displays. Though the cadre found the initial prototype too immature for operational use, they were unanimously supportive of the potential for augmented reality technology to eventually address operational tower issues. These issues include surface control, coordination with facilities and vehicles, information acquisition and runway incursion.**

## I. Introduction

The long-range vision for the future Next Generation Air Transportation Systems (NGATS) includes objectives for operating as efficiently in low-visibility conditions as in high-visibility conditions.[1,2] An aspect of attaining equivalent operational capability is in the Tower, where large economic and operational costs are incurred when weather conditions impair the tower controllers' visibility. These costs include but are not limited to creating bottlenecks in the national traffic flow management system. The benefits analysis for potential savings that could be realized from effective low-visibility tools for the tower has been estimated in the hundreds of millions of dollars per year.[3]

Although various analysts may have estimated the benefits of an effective low-visibility tower tool, they rarely specified how such tools would be designed and operated. One approach proposes using augmented reality (AR) technology to achieve the desired functionality. Augmented differs from Virtual Reality (VR) insofar as AR allows users to view the 'real' world along with superimposed or composited computer-generated displays. The content of these displays is determined by the observer's point of view, usually by tracking head orientation and motion.[4,5] This concept for an augmented reality tower tool (ARTT) has become increasingly popular over the past decade. [6-9]

NASA and the FAA have collaboratively explored ARTT concepts, with emphasis on fundamental requirements analysis via iterative cycles of prototype development field evaluations. These evaluations are performed by controllers in their own tower, using real-time air traffic control (ATC) radar data to 'shadow-control' (but never *actually* control) local aircraft. The results of each evaluation cycle become a component of the next prototype's requirements analysis and design.

* Research Scientist, Aviation Operation Systems Development Branch, MS 210-8. *Ronald.J.Reisman@nasa.gov*
† Software Engineer, NASA Ames Research Center, MS 243-6. *dmbrown@mail.arc.nasa.gov*

## II. Background

Tower controllers are required to gaze out of the windows of their cabs to visually observe relevant vehicles. Although a discussion of the tower controller methodology is beyond the scope of this paper, one essential difference between them and the other ATC domains is that the duties of tower controllers require them to look out of their cab windows at the natural, 3-D world. They must also scan the several ‘heads-down’ displays found in the tower cab.

The concept for using computer graphics to ‘augment’ visual reality for Air Traffic Control Towers was proposed by the late Lloyd Hitchcock at the FAA Technical Center in the 1980s. No prototype construction was attempted at that time, and little was published, though many recall how Mr. Hitchcock speculated on several methods that could aid tower controllers. Some of these speculations included a head-tracked, head-mounted, see-through display.[‡]

In the 1970s and ‘80s there were several experiments with 3-D Cockpit Displays of Traffic Information (CDTI).[10,11] There were also very successful demonstrations of flight-deck heads up display (HUD) technology for surface movement under low-visibility conditions,[12,13] and synthetic vision.[14]

Recently there has been increasing interest in using augmented reality technology to enable tower controllers to operate equivalently under Visual (VMC) and Instrument (IMC) Meteorological Conditions. Such tools may use head-mounted augmented-reality systems that innovatively fuse relevant data from tower systems (e.g., air traffic control and surface surveillance radar) and display appropriate information as an overlay on the tower controller’s view of airborne and surface vehicles.

A tower controller’s vision must not be impaired, therefore the head-worn displays must not constitute a vision impairment, e.g. the device’s housing must not block peripheral vision. The AR systems should effectively mitigate visibility problems for tower controllers, such as weather or other obstructions, such as architecture or vehicles, and synthesize data from other systems. Sensor fusion for tower controllers has come to signify (at least in ‘gedanken’ experiments) the presentation of situation-specific appropriate information. The displayed information may be synthesized and extracted from multiple data sources, as opposed to the current practice of scanning multiple screens, paper slips, etc., and filtering the essential information from clutter and data that may not be relevant.


**Figure 1. Situation Awareness Virtual Environment (SAVE) used realtime ATC radar to represent aircraft as ‘cubes’ viewed over a 3-D display of the airport.**

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‡ Private communications from Stephen Ellis and Earl Stein. Unfortunately none of Mr. Hitchcock’s writings on this subject appear to have survived.

In 1998 NASA demonstrated that contemporary commercial 'web-based' technologies could be used to create inexpensive and portable 3-D ATM displays. The proof-of-concept prototype was called Situation Awareness Virtual Environment (SAVE). A screen shot of SAVE, in this case running under the Netscape browser on an SGI workstation, is illustrated in Figure 1. This prototype used Java, VRML, and browsers to create 3-D displays of both the terminal area and the positions of arriving and departing aircraft. The real-time air traffic control radar data were served to SAVE by NASA's Center TRACON Automation System (CTAS) software. Specifically, the CTAS 'Communication Manager' (CM) process acquired live ATC radar data and then served a filtered stream to SAVE. The SAVE software integrated the radar positions with the 3-D airport database, rendered in the VRML graphics standard. SAVE ran in most browsers that supported Java and VRML plug-in modules, and therefore was portable-by-design across different operating systems and hardware.[15]

One innovative aspect of SAVE was its re-use of flight simulation 'out-the-window' display databases. These highly accurate 3-D visual databases of specific airports that meet the visual requirements recommended by the FAA as one of the attributes of flight simulators that merit 'Level-D' certification, the FAA's highest rating for flight simulation performance. Flight Safety International collaborated with NASA to adapt their visual databases so that the accuracy of the survey and other features would be retained, while details and features deemed unnecessary for ATC applications were deleted. A 60 Mb flight simulation visual database of Atlanta Hartsfield International Airport (encoded in a proprietary format) was filtered to produce a 1.25 Mb VRML model. This model became a principal 3-D display component for the SAVE engineering prototype. The exercise with the Atlanta Hartsfield database demonstrated the proof-of-concept of re-using flight simulation databases for (potentially) an entirely different application, e.g. real-time air traffic control instrumentation. There are visual databases for over 300 airports that are meet accuracy requirements for Level-D flight simulator certification. Each of these databases may be inexpensively filtered into highly accurate 3-D data sets that may be used in TOWER AR and VR systems.

Although SAVE demonstrated the feasibility of creating 3-D radar displays with a modern software and network architecture, it retained a conventional computer-human interface, i.e. screen for output, keyboard and mouse for input. There was no head-mounted display capability in the initial SAVE prototype. Following SAVE, several AR and VR tower collaborations between ATM and human factors (HF) researchers were conducted at Dr. Stephen Ellis's Advanced Displays and Spatial Perception laboratory. This laboratory's interests focused on spatially calibrated position sensing and low latency, high update rate rendering of spatially stabilized, world referenced virtual objects.[16] Recently their system demonstrated responses below most users detection levels for a variety of conditions.[17]

The resultant prototypes did not re-use much SAVE code, except for the interface to the CTAS Communication Manager (CM) module. This CTAS CM interface provided the human factors systems with access to both pre-recorded samples and live TRACON radar data. One prototype used live Dallas-Ft. Worth (DFW) Terminal Area radar data for remote real-time visualization of the DFW TRACON traffic. This North Texas traffic was remotely visualized in a VR display located at NASA Ames. Flight plan data provided type and airline information for the 3-D animated aircraft types. The DFW radar aircraft-position data provided 'key' frame information every 4.8 seconds, so more than 50 'fill' frames per second were rendered to create the 3-D animated VR display. These prototypes were never intended for operational use, though they provided proof-of-concept experience for later development.

Another motivation for developing effective ARTT is to provide a bridge technology between the current tower system and mid-21$^{st}$ Century 'Virtual Tower' facilities in the NGATS vision. Air Traffic Control Tower (ATCT) construction and staffing are extraordinarily expensive. The current NGATS long-range vision foresees 'Virtual Towers' facilities that will be less expensive to operate and maintain than the current system of 'brick and mortar' Tower facilities. The Virtual Towers would permit consolidation of resources, since there is no requirement to co-locate the future facilities on the same sites as the airports they control.

A variety of 'Virtual Tower' concepts have been proposed, ranging from traditional VR to facilities in which photo-realistic real-time rendering systems create a 360-degree virtual tower view. Although this concept may take decades to perfect, there are strong financial, safety, and security incentives to develop this technology.

One of the principal risk areas associated with Virtual Tower operation is the confidence level that the digital 'virtual world' contains all the necessary and sufficient visual cues that tower controllers currently use in the course of their duties. There is considerable uncertainty on the definition and extent to which a

Virtual Tower's virtual 'world' must resemble the referential real world, e.g., the airport and the behavior of its vehicles, environmental conditions, and activities.

If an augmented reality tower tool became certified and operational in the next several decades, it is expected that the user community of tower controllers would report any discrepancies between the real world that they observe and the virtual world that was presented via the see-through AR displays. The ARTT technology could therefore be used to validate, verify, and certify the Virtual Towers' representations of reality. In this manner ARTT could be used to maintain verisimilitude quality.

Tower AR systems may become a critical path item for 'virtual tower' R&D. These systems can become interim products sooner than purely VR systems, so the intermediate benefits of AR technology would accrue to the current, physically co-located tower facilities. The use of ARTT operationally would generate discrepancy reports from the controllers every time they noticed a difference between the computer-generated displays and the real world. Conversely, the inability of controllers to detect such discrepancies would become valuable data for the validation, verification and certification of the virtual worlds for use in future Virtual Tower facilities.

Some of technologies that are critical to AR product development are still too immature for practical operational use, e.g., the lack of adequate light-weight, bright, commercially available, see-through HMD hardware. Apart from these technological obstacles, there are a variety of issues and ideas that will require investigation before an ARTT would be certified for operation. Rather than wait until all obstacles are removed before addressing these issues, we propose using the build-evaluate design methodologies that are commonly employed by modern software and hi-tech commercial enterprises. These build-evaluate cycles are components of several product development management philosophies, are variously described as 'user-centered design,' 'iterative prototyping,' 'build-evaluation cycles,' 'usability engineering,' or other terms of art. This approach differs greatly from studies conducted expressly in controlled laboratory settings, or from efforts that are limited to evaluating the usefulness a particular prototype. The user-centered design approach is often characterized by using a prototype to assist a subject-matter expert to understand a novel technology or idea. The evaluations and suggestions of these subject-matter experts are then used to influence the requirements, designs, and stages of development of successively refined prototypes. The engineering prototypes are therefore typically evocative, rather than definitive.[18,19]

## III. ARTT 1.0: Initial Prototype Development & Evaluation

In 2004 a version of the VR system used for human factors experiments was slightly modified and re-used as an initial augmented reality tower tool prototype. Much of this prototype, illustrated in Figure 2, was made from integrating commercially available off-the-shelf components. The see-through head-mounted display was a Sony Glasstron PLM-S700.[§] The head-tracking technology was provided by the InterSense InertiaCube3[**] hardware (a three degree of freedom inertial sensor with a flux gate compass to control drift and accelerometers to determine the direction of the gravity vector), with AuSIM[††,20] motion-tracking software.[21]

This prototype, called ARTT 1.0, also used the CTAS Communication Manager to acquire pre-recorded and live ATC radar data. The prototype used a FAA Northern California TRACON (NCT) data feed to track aircraft in the Moffett Field vicinity. This data stream was served by the FAA William J. Hughes Technical Center via secure network. A subset of CTAS software ingests the NCT radar information, re-using the same method developed for SAVE. The CTAS Communication Manager (CM) serves data to the ARTT software modules, including aircraft flight plan (e.g. aircraft type, equipage, flight route) and state (e.g. latitude, longitude, altitude, ground speed, vertical speed, heading). A CTAS Planview Graphical User Interface (PGUI) is used to provide a conventional 2-D view of NCT radar data. The data represented on the PGUI may be quickly compared with the tower's operational radar display. This feature is often useful in identifying differences and anomalies between the operational and research versions of the NCT data feeds.

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[§] Sony Corporation of America, 50 Madison Ave # 9, NYC, NY 10022.

[**] InterSense Corporation, 36 Crosby Drive, Suite 150, Bedford, MA 01730, USA

[††] AuSIM, Inc., 3239 El Camino Real, Suite 205, Palo Alto, California 94306. The AuSIM software driver for head position sensors was the end product of a development sequence done in the Advanced Displays and Spatial perception lab.

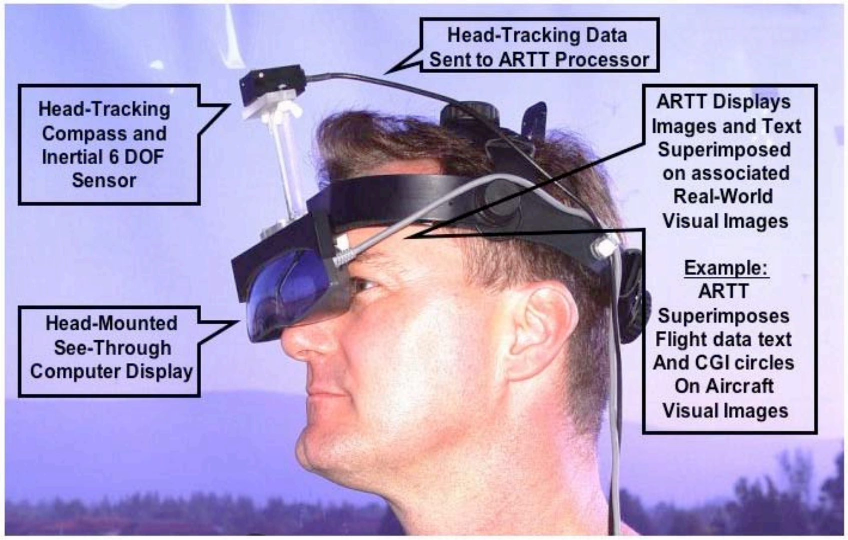


**Figure 2. Initial Augmented Reality Tower Tool engineering prototype, ARTT 1.0.**

Unlike the operational radar display or the PGUI, an ARTT system presents the NCT date from the point of view of the controller, not from a top-down view. The head-motion detector determines the heading, pitch, and roll of the controller's view. The ARTT software performs 3-D clipping operations to superimpose the position of the aircraft on the see-through display. The baseline symbology used a red circle (typically 2-degrees in diameter) to indicate the location of the aircraft. A data block containing flight information (e.g., aircraft id, distance from tower, altitude) was positioned near each of these circles.

In 2005 Moffett Field Aviation Management authorized ARTT development and field evaluation at Moffett Tower. A cadre of five Moffett Tower controllers were the subject matter experts who evaluated the initial ARTT prototype. They had an average of 13.6 years of tower experience (max: 20; std dev: 6.0), and an average of 4.6 years Moffett Tower experience (max: 10; std dev: 5.5). The controllers were encouraged to contribute ideas for future ARTT enhancements, symbology, decision support tools, and general observations for ARTT requirements analysis. The initial Moffett Tower ARTT field study was the first time AR technology was evaluated by a tower controller team in their own tower using real-time ATC radar data and observations of live air traffic.

The initial ARTT prototype was not, of course, intended for operational use. The ARTT Field Study Safety Plan requires that the on-duty controller is unencumbered, while a second controller (who does not control traffic while evaluating ARTT) uses the prototype in a purely evaluation 'shadow' mode.

Figure 3. illustrates the floor plan of Moffett Tower, including the relative positioning of the on-duty controllers, the experimenters, and the off-duty controller who is nominally 'shadow-controlling' and evaluating the ARTT 1.0 prototype. Though Moffett Field has a relatively small tower, note the variety of systems the controllers use: (clockwise from bottom, starting at the ladder) Typewriter (for reports); workstation reserved for air force administrative applications; Automated Surface Observing System (ASOS) Controller Equipment - Information Display Systems (ACE-IDS); Flight Data Input/Output (FDIO) subsystem; the Flight Data Console; Automatic Terminal Information Service (ATIS); the Ground Control Console; Remote Automated Radar Tracking System (ARTS) Color Display (RACD); the Local Control Console; the Supervisor Console. The ARTT 1.0 system ran on two laptops located in front of the Supervisor Console.

The prototype served as both an instantiation and an evocative illustration of AR technology. The initial ARTT prototype was evaluated for usability, benefits, and insufficiencies. It was intended to be evocative, illustrating the potential of AR technology along with the limitations of current commercial off the shelf (COTS) AR components. The questionnaires in the initial study had sections covering AR Technology per se and other sections addressing the performance of the initial ARTT prototype. Other sections covered potential benefits of using ARTT for specific tower operations, and the potentials for integrating the other Tower systems with ARTT.

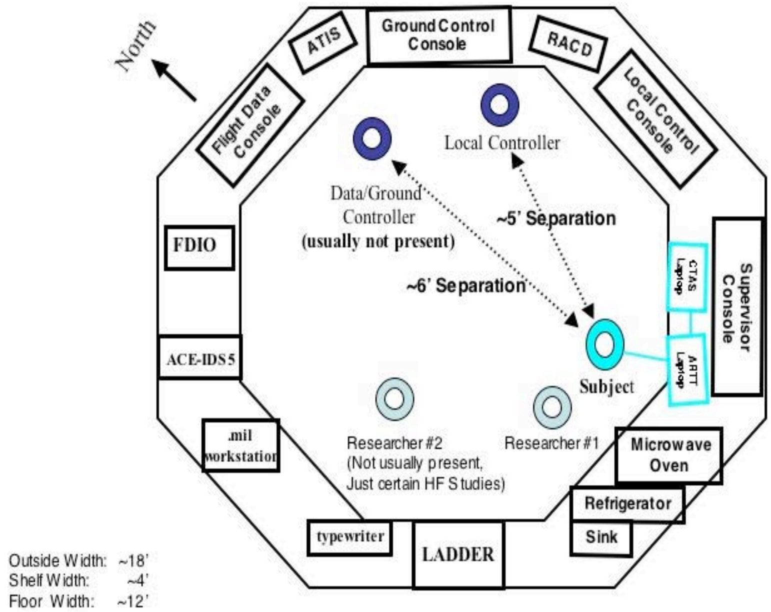


**Figure 3. Floor plan of Moffett Air Traffic Control Tower, showing positions of operational controller (dark blue), off-duty controller evaluating ARTT (light blue), and researchers (grey).**

The controller evaluations for ARTT 1.0 influenced the requirements analysis and subsequent research objective and design decisions that led to the next engineering prototype, ARTT 2.0. The cadre identified several prototype deficiencies, such as low optical transmissivity of the head mounted display (HMD), unacceptable compensation for tower lighting conditions, inadequate symbology and data block information display, and unacceptable discomfort caused by wearing the HMD. The cadre was unanimous both in supporting ARTT technology and its potential, while at the same time finding the ARTT 1.0 prototype too uncomfortable, immature, and insufficient for practical use.

Each controller completed a survey that included professional history, a brief optical examination, 140 Likert test questions, an evaluation of system maturity level, and post-session video interviews. As an example of how the controller evaluations were used in the design process, we present a subset of the evaluation data, most notably those items where the controllers showed a great deal of agreement with each other, as indicated by the standard deviation of evaluation scores. For instance, one set of questions dealt with the effect of ARTT technology on standard tower tasks and duties. This set was predicated by a usability question: "How useful would ARTT technology be in performing the following tasks?" Altogether there were sixty-four questions in this set. Results from a dozen questions in which the controller cadre took consistently strong positions are summarized in Figures 4. and 5.

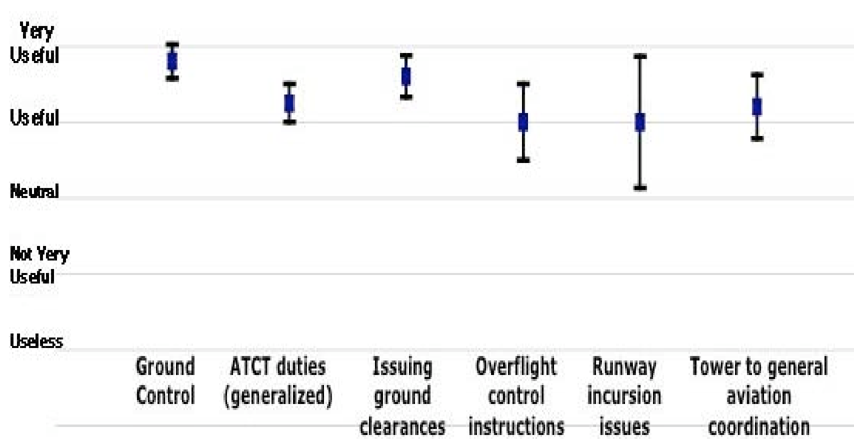


**Figure 4. Six Tasks & Duties: Controller responses to usability questions posed in the form "How useful would ARTT technology be in performing the following tasks? The range bars represent the standard deviation of the opinion scores (n=5).**

In the six usability questions illustrated in Figure 4. the cadre were instructed to use the prototype as an illustration of AR technology. The controllers were not judging the effectiveness of ARTT 1.0 in this section of the survey. They were asked to use the prototype to visualize a mature version of ARTT. The essential question for the controllers was: ‘If ARTT was working properly, with all the bugs fixed and hardware limitations overcome, would this technology be useful, or would it simply be extraneous and provide little practical benefit?’

Most controllers indicated that the AR technology could be useful for surface control and issuing ground clearances, particularly when visibility is impaired by IMC. They also felt that AR technology would be useful for a variety of tower duties, as well as issuing overflight control instructions, coordinating with general aviation aircraft, and (perhaps most importantly) addressing runway incursion issues.

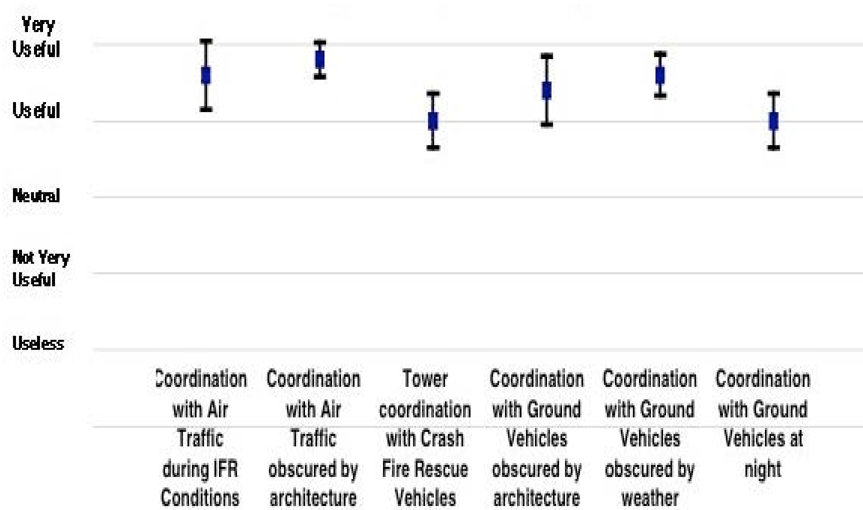


**Figure 5. Six more “Tasks & Duties” usability questions that also elicited strong responses and agreement among the controller cadre.**

The controller cadre strongly agreed that AR technology could be useful for coordinating with a variety of traffic and vehicles. For instance, as illustrated in Figure 5, there was strong feeling among the controllers that ARTT would be useful under IMC weather, and when air and surface traffic is obscured by architectural obstructions. They also felt strongly that ARTT could be useful when coordinating with surface vehicles that were obscured by weather or architecture, and could generally benefit coordination with a variety of surface vehicles, particularly Crash & Fire Rescue Vehicles.

The controllers also had strong and largely uniform opinions that ARTT technology would be useful in acquiring information on aircraft location and heading, along with other specific information on the aircrafts’ flight data blocks. They also strongly agreed that ARTT technology would be useful for acquiring surface vehicle location and increasing situation awareness.

In the summation questions, illustrated in Figure 6, the controller cadre indicated strong agreement on the immaturity and inadequacy of the as-built ARTT 1.0 prototype. This response was supported by many other questions in the Likert test survey. The controllers expanded on their lack of satisfaction in their video interviews, often detailing specific faults and recommendations for improvements. Special attention was paid to these responses when determining the specifications, objectives, and design of the follow-up prototype, which became ARTT 2.0.

The evaluations indicated that the ARTT 1.0 computer generated displays were insufficient. In spite of the prototype’s immaturity, the controllers also strongly felt that the AR technology provided the opportunities for new data block information presentation and formats. Perhaps most importantly, most of the controllers used their experience with the ARTT 1.0 prototype to stimulate their imaginations and brainstorm suggestions on how AR technology could be used to create new kinds of tower decision support tools.

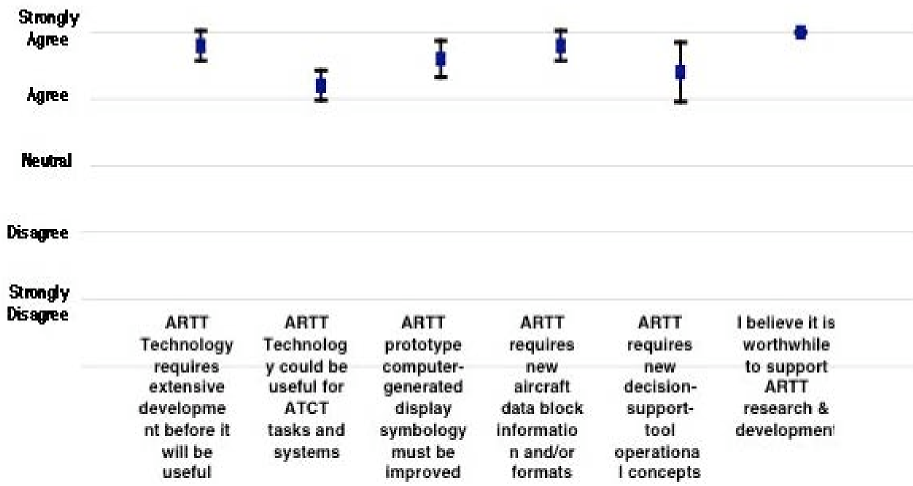


**Figure 6. Six questions concerning the value of ARTT technology to acquire information items. Note that not all question in this section elicited such uniformly strong responses.**

Most of the controllers' serious complaints were directed at the Sony Glasstron 'see-through' HMD. The minimum requirement for an operational ARTT is that the display device must not impair the controllers' vision. The Glasstron HMD failed this test, and to date no display device has conclusively demonstrated that it meets the minimal ARTT display requirements. Most of the controllers found the Glasstron uncomfortable, some found it intermittently disorienting, and one became nauseous from using it. The HMD also made it difficult for the controllers to scan the airfield, since it required an unacceptable amount of manual adjustment to compensate for lighting conditions that could change from window to window, and was often difficult to read against bright back-lighting. The Glasstron optics have a 20% transmissivity, similar to dark sunglasses, so they could not be used at night. Everyone agreed that the Glasstron seriously impaired the controllers' vision, and that ARTT could not be considered for operational use unless the HMD was improved. They also agreed that it functioned well as a representation of immature AR technology, and were enthusiastic about this technology, providing it could mature and become reliable and usable.

The cadre unanimously gave the highest ratings and support for the potential of ARTT technology to benefit Tower operations. This was only question (out of 140) in which all the controllers gave identical responses, and it was gratifying that they all strongly agreed that it is important to support continued ARTT research and development.

## IV. ARTT 2.0: Resultant Engineering Prototype

NASA developed a second ARTT engineering prototype whose design was greatly influenced by ARTT initial field evaluation results. Particular emphasis was placed on practical display technology issues, since this was the highest priority of the controller cadre.

The 1.0 prototype re-used software that was originally intended for human factors laboratory-based experiments. The 2.0 prototype completely discarded this 're-used' code and replaced it with new software that was designed specifically for ARTT applications. One of the first design decisions was to use open source software and packages whenever practical in an effort to reduce development costs and increase options for collaborations and technology transfer.

Many of the suggestions made by the controllers during the evaluation of ARTT 1.0 involved speculations on possible decision support tools. Several of these tools required real-time 3-D animation techniques. In order to implement and experiment with such speculative tools and interfaces the ARTT 2.0 software architecture was designed to support a wide range of 3-D graphics functionalities. The software was written with Open Scene Graph, an open-source graphics software package.

**Figure 7. Augmented Reality Tower Tool (ARTT) version 2.0 uses head-tracking sensors to determine an observer's field-of-view and superimposes 3-D simulated images over the actual views of the airfield.**

The introduction of the 3-D database to represent the airport background was a major departure from the ARTT 1.0 design. A 3-D visual database of Moffett Field and adjacent Ames Research Center, usually called 'Virtual Ames,' became a component of ARTT 2.0, just as the DFW visual database had been a component of SAVE in the previous decade. This visual database was developed with techniques used to build out-the-window displays for flight simulators. 'Virtual Ames' was used to overlay the actual see-through views of Moffett Field. As described above, the 300+ FAA-certified Level-D visual databases of the world's major airports may provide the basis for inexpensively adapting ARTT to any of these locations.

As illustrated in Figure 7, the graphical representation of the airport overlays the actual objects that are seen from the Moffett Tower cab. Hangar One, a familiar landmark, is clearly visible in the background. The photo above (featuring Hangar One) was taken through the Lumus PD-10[‡‡] see-through display. The 3-D CGI of Hangar One is in the foreground, overlaying the actual building. ARTT 2.0 uses head-tracking sensors to determine an observer's field-of-view, and superimposes 3-D simulated images over the actual views of the airfield. The trucks, tarmac, tower-cab window seam, and others features are not created by CGI; they are see-through optical images of the 'real' world.

The ARTT 2.0 prototype, like its predecessor, uses NCT radar data as the primary data source for the display of aircraft position and flight data block information. The baseline flight data block is similar to the format used in the first prototype, though alternative formats can be easily composed.

[‡‡] Lumus Ltd.,_2 Bergman St., Rabin Science Park, Rehovot 76705, Israel


**Figure 8. Photo was taken though an ARTT 2.0 'see-through' display at Moffett ATC Tower. The lights and optical image of the aircraft (ASA301) are framed by the CGI red circle and labeled by the adjacent data block.**

The image in Figure 8 is a detail from a photograph taken through an ARTT 2.0 ‘see-through’ head mounted display (in this case, a LiteEye LE-500[§§]). The display shows a 2-degree diameter circle indicating the position of an actual aircraft (ASA301), which can be seen next to the ‘A.’ The flight data block indicates the aircraft is 4.42 nautical miles from the tower, and that it is flying at approximately 2100 ft. altitude. The foreground (bottom) is computer-generated imagery (CGI) of a 3-D visual database of Moffett Field, which covers the corresponding 'real' area. Note the relative coincidence of actual and CGI runways and other features. The display is optically transparent above the CGI horizon. In this photo the buildings, tree line, and hills on the horizon are optical images of the actual features; not CGI. The actual lights of flight ASA301 are visible inside the CGI red circle, to the left of the 'A' in the first line of the flight data block. In this case the width of the circle is two degrees. The first line of the flight data block identifies the aircraft, the second line displays the aircraft’s distance from the tower, and the third line displays the aircraft’s altitude.

The prototype does not always capture the aircraft within a two-degree circle. Consistently accurate performance is degraded by projection surface orientation uncertainty, magnetic effects on the compass, and the sensor-eye relative orientation errors.

The most glaring deficiencies in the ARTT prototypes involve performance of see-through display hardware. This is a problem that confronts almost all AR projects; a completely acceptable see-through HMD is not yet available. The principal problem with all existing AR systems is that they all (to varying degrees) impair the observer’s vision. The FAA regulations reasonably prohibit tower controllers from wearing optical equipment that impairs vision. New optical technologies (such a light-guide optical elements[22]) promise practical solutions in the near future, though it not possible to accurately and confidently predict the date when these solutions will be perfected, mass-produced, and commercially available. The current ARTT 2.0 activities include integration and evaluation of different display hardware technologies.

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[§§] Liteye Systems, Inc., 7330 S. Alton Way, Bldg. 12, Suite C, Centennial, CO 80112

## V. Concluding Remarks

Augmented Reality tools may improve air traffic control tower efficiency and safety during adverse visibility, and also contribute to development of Virtual Tower facilities. This paper presents motivations, an approach for researching usability requirements, and a basic design for future augmented reality tower tools. This design may be summarized as using head-tracking sensors to determine the controllers' field of view, and contextually overlaying that view with computer generated information derived from air traffic control systems.

This paper does not present a finished design for a tool ready for implementation. There are still many problems that must be addressed by more research and technology maturity. The controllers' evaluations confirm that the prototypes are not acceptable for operational use. They also indicate enthusiasm for ARTT technology as an aid for tower operations, providing the technology matures sufficiently. Although many fundamental problems must be understood and solved, there is ample reason to believe that eventually an ARTT may become operational.

There are many valid approaches that may move ARTT from an intriguing concept to a practical tool fit for operational use. The approach described in this paper focuses on iterative engineering prototype build-evaluation cycles. This approach is greatly influenced by contemporary management practices for mitigating design uncertainties. These methods have proven effective in developing requirements, specifications, and designs for a variety of cutting edge products. This is particularly true when the finished product is not completely defined and also requires technology that is not mature, available, practical or (as in the case of augmented reality tools for air traffic control towers) where the unresolved fundamental research issues challenge the development of satisfactory designs.

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