Augmented Reality Tower Technology Assessment

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    Augmented Reality technology may help improve Air Traffic Control Tower efficiency and safety during low-visibility conditions. This paper presents the assessments of five off-duty controllers who 'shadow-controlled' with an augmented reality prototype in their own facility. Initial studies indicated unanimous agreement that this technology is potentially beneficial, though the prototype used in the study was not adequate for operational use. Some controllers agreed that augmented reality technology improved situational awareness, had potential to benefit clearance, control, and coordination tasks and duties and could be very useful for acquiring aircraft and weather information, particularly aircraft location, heading, and identification. The strongest objections to the prototype used in this study were directed at aircraft registration errors, unacceptable optical transparency, insufficient display performance in sunlight, inadequate representation of the static environment and insufficient symbology.

I. Introduction

    Air traffic control Towers suffer visibility impairments during inclement meteorological conditions that negatively impact airport arrival rates, airport departure rates, terminal-area acceptance rates at en route coordination-fixes, traffic flow management constraints, and surface vehicle accidents, including runway incursions.[1,2,3,4,5] There is no validated method for fully mitigating the operational impact of impaired Tower controller visibility. This technology gap is challenging for both current traffic management operations and the Next Generation Air Traffic System (NextGen)[6,7] requirements for equivalent operational capabilities in all meteorological and visibility conditions.

    Several independent research activities have proposed designs that use head-worn, head-tracked, see-through display sub-systems to enhance Tower controllers' situation awareness.[8,9,10,11,12,13,14,15] Most of these proposals were influenced by previous research in three-dimensional displays developed for display of traffic information to the pilot[16,17], air traffic simulation[18], and flight deck avionics[19,20,21]. Though this previous work had diverse motivations, they had in common a technological approach that required high performance real-time three dimensional graphics computation as a critical element of computer-human interface. In most cases, this work was based on experiments conducted in indoor laboratories, where most conditions (such as lighting) could be conveniently controlled. Although these studies clearly showed that Augmented Reality (AR) offered the potential for improved Tower operations, none actually evaluated the concepts in an operational environment using a research prototype built from available technologies.

    The purpose of the current study was to move the scene of investigation for AR concept exploration out of the laboratory and into the field. The study presented below reports five Tower controllers' assessments of the potential benefit of application of this technology, based on their experience using an augmented reality model prototype during 'shadow control' sessions inside their own operational Tower facilities. This 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 Augmented Reality Tower Technology (ARTT) research prototype used in this study displayed both dynamic real-time air traffic data (e.g., aircraft location, identity, speed, and distance), and computer-generated graphics that correlate to the static environment objects (e.g., horizon line, compass rose), superimposed on the controller's view

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from the Tower of the actual objects. In a previous publication the authors described the design approach of ARTT systems in greater detail, and presented preliminary results of the controller assessments, including responses to 18 of the 139 Likert-scale questions that are analyzed below in the present report.[22] This paper presents a more comprehensive description, reporting, and analysis of a controller's evaluations. A subset of 79 questions addresses the potential of AR technology to benefit well defined Tower tasks and duties, such as clearances and control, non-control activities, and vehicular and inter-facility coordination. Another subset of 26 questions address potential information acquisition benefits, including complementary functionality with the current operational Tower radar display. The research prototype apparatus was evaluated for comfort, aircraft data block display and situation awareness utility, and head mounted display and tracking performance. The controllers were also asked to assess the potential of augmented reality technology to benefit Tower operations, and the acceptability of the prototype implementation used in the field study.

II. Background

A. Low Visibility Tower Operations

Tower controllers are required by FAA regulations to visually observe relevant vehicles and their environment whenever possible. Although a discussion of the Tower controller methodology is beyond the scope of this paper, one essential difference between the Tower and the other ATC domains is that only Tower controllers visually observe the 3-D world, rather than use 2-D plan-view displays as their primary sources of information. Tower staff must also use the several "heads-down" 2-D displays and text-based systems found in the Tower cab. Tower controllers integrate the diverse information to address a well-defined set of tasks and duties. These Air Traffic Control Tower (ATCT) tasks and duties include: issuing ground clearances, approach and over-flight control instructions; addressing runway incursion issues; and providing Tower-to-aircraft coordination under regulatory constraints that are dependent on visibility and weather conditions. In most airports, most ATCT coordination is with surface vehicles, including taxiing aircraft, fuel and baggage, crash fire rescue, grounds keeping and wildlife control. In addition to low (and no) visibility conditions induced by weather, it is also possible for the airport, surrounding airspace, and vehicles to be obscured by architecture, high-glare conditions, and the cover of night.

Previous studies have identified large fuel savings and ancillary economic benefits if a system could be implemented that would insure stable rates of airport capacity in all visibility conditions. Shackleford and Karpe (1996) calculated that a 'Low-Visibility Tower Tool' could facilitate 196M Kg. of aviation fuel savings per year, based on deployment at 42 airports in 2015.[23] The studies concluded that a system capable of maintaining the safety and efficiency of surface operations during adverse visibility would produce a variety of benefits. They also concluded that higher average airport arrival rates would enable more uniform and productive en route and Traffic Flow Management operations. The increased surface capacity reliability would improve metrics for taxi-times, departure queues, ground-delays, ground-holds, and cancellations. Their theoretical low-visibility Tower display was required to provide equivalent situation awareness to a clear 360-degree field of regard, encompassing the airport surface and all approaches and departure areas in the Class-D airspace.

B. Augmented Reality Technologies

There has been increasing interest in using AR technology to enable Tower controllers to operate equivalently under visual and instrument meteorological conditions. The independent design consensus is that head-worn AR systems may potentially fuse relevant data from Tower systems (e.g., air traffic control and surface surveillance radar) and display appropriate information as an overlay on the controller's view of airborne and surface vehicles.

Most apparatus configurations used for research prototype in ARTT studies may be viewed as five (theoretically independent) sub-systems, as illustrated in Fig. 1. These sub-systems are: 3-D visual database, traffic management information, head motion and orientation tracker, computer generated graphics, and see-through display. These five subsystems are required to present a 'virtual' world of digital information that is optically combined with the human controller's view of the 'real' world. In some cases, the subsystem implementations are interchangeable. For example, several different head-tracking technologies or optical combiner displays may be used as interchangeable modules. The paradigmatic configuration includes: see-through head-worn display, head tracking system, and computer-generated graphical representation of the surrounding environment and vehicles.
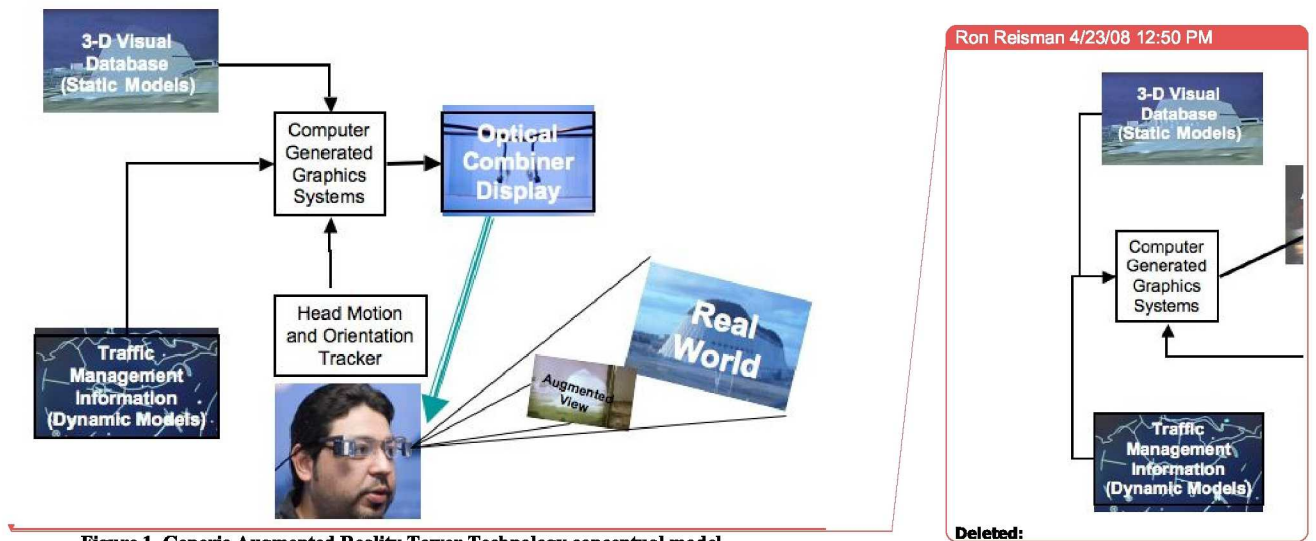
Figure 1. Generic Augmented Reality Tower Technology conceptual model.
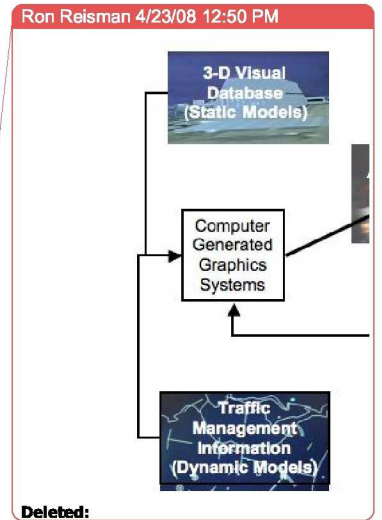
III. ARTT Research Prototype

The apparatus used for this study is illustrated in Fig. 2. The photograph shows a shadow-controller in the Moffett Tower cab, located at Moffett Field, California. The off-duty controllers wore the Sony Glasstron head worn display, with an Intersense InertiaCube head-tracker mounted on the clear plexiglass post (visible directly above the controller's head). The head-tracker enabled determination of observer's field-of-view. The two laptops used in this research prototype are visible to the left of the controller. The first laptop ran NASA's Center TRACON Automation System (CTAS)[24] software to acquire real-time Northern California TRACON (NCT) system and surveillance data. The second laptop used this NCT data as input to the ARTT software that created the 3-D perspective view that is displayed to the controller. The CTAS software ran under the Linux operating system, and the ARTT software ran under Microsoft XP. The subsystems used in the ARTT experimental prototype are described in greater detail below.

A. Computer Software/Hardware

The graphic display system used with ARTT was based on re-used code originally created for use at the NASA Ames Research Center Aerospace Human Factors Laboratory. This code was principally written by Michael Hill under the direction of Stephen Ellis and Bernard Adelstien. The software was written in C++, using the GLUT OpenGL open source libraries, and was used in a variety of human factors studies.[13] The code was modified to read real-time TRACON flight plan and aircraft state data created by CTAS.

This software was used in the ARTT research prototype for the field tests described below. In this study the ARTT software ran on a Dell Laptop configured with an Intel 1.2 GHz Pentium and 1 GB RAM. This system maintained a minimum graphics frame update rate of 30Hz, and was observed to run as fast as 55 Hz.
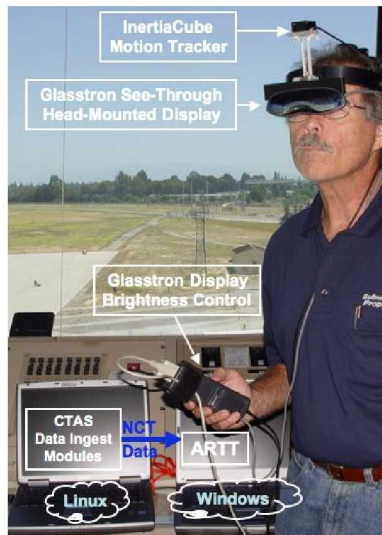
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Figure 2. Augmented Reality Tower Technology research prototype used for assessments by shadow-controllers at Moffett Tower.

B. Prototype Display Symbology

Fig. 3, illustrates the symbology used in the study. Computer generated graphical red circles with 2-degree diameters identified the computed position of each aircraft, based on aircraft surveillance report real-time data. A three-line data block was associated with each of these aircraft marker circles. The first line of the data block contained the aircraft call-sign. The second line contained the horizontal distance (in nautical miles) of the aircraft from the viewer's position in the Tower. This value was derived from evaluating real-time position data reported by the FAA TRACON data, in relation to the position of the viewer. The third line displayed the aircraft's altitude in feet. Ground reference was represented by a computer generated green horizon line, with compass heading markers at 10 degree intervals. Each interval had a vertical line with the compass heading displayed above it. The orientation of the viewer's head was also displayed, expressed as magnetic heading (displayed at the top of the frame), pitch (displayed on the right), and roll (displayed at the bottom of the frame).

C. Optical Combiner ('See-Though') Display

The ARTT research prototype used a Sony Glasstron PLM-S700 head-worn display. This particular display was unanimously assessed to be unacceptable for operational use in a variety of lighting conditions. This is not particularly surprising, considering that the Glasstron was originally designed as a consumer electronics 'personal theater' product, and was not intended for see-through display applications. The 'transparency' of the this display is comparable to dark sunglasses, with the manufacturer specifying 20% transmissivity Consequently it is not optimized for "see-through" performance. In spite of these known limitations the Glasstron has been used in many AR studies.[26, 27]
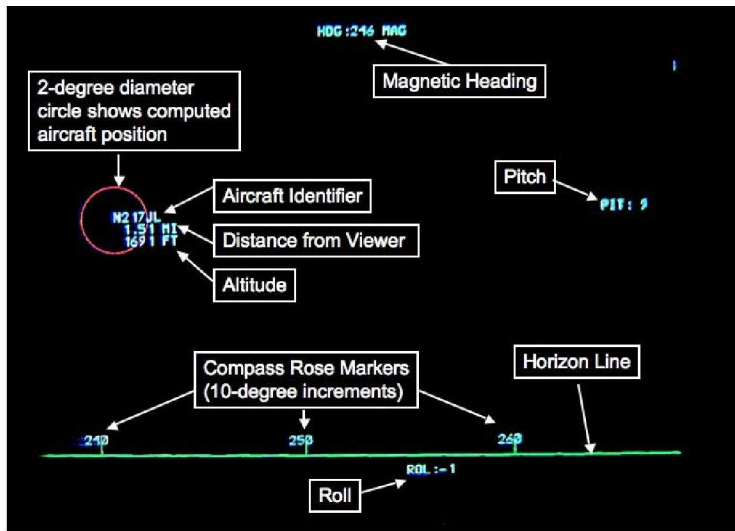
Figure 3. Symbology used in ARTT research prototype display. The callout labels (in white) are illustrative, and are not shown in the actual prototype. The areas that are black in the above illustration are transparent when viewed through a see-through head mounted display.

D. Head Motion and Orientation Tracker

The ARTT prototype used an InterSense InertiaCube2 motion tracking hardware[28] and AuSim AST manager software[29] to determine head orientation data required for viewport and viewpoint calculations. The InertiaCube2 incorporated an accelerometer, an angular rate gyro, and magnetic compass. The AuSim AST software interpreted tracker data, applied appropriate filters, and served the derived orientation data through shared-memory interprocess communication. The ARTT application software accessed head-orientation information via this shared-memory interface.

The Inertiacube2 was selected because it uses inertial tracking, and measures absolute orientation relative to the earth's gravitational and magnetic fields, and therefore does not require a separate external reference. This is convenient for use in areas where it may be inconvenient to erect an external position reference, such as operational ATC facility. Unfortunately this technology is susceptible to interference from environmental metal and electromagnetic interference that create intermittent artifacts, and even under optimal conditions routinely exhibits average orientation errors of two degrees. These limitations and artifacts of the head tracking system are well-understood as a significant source of static and dynamic registration errors[30, 31, 32, 33, 34]

E. Traffic Management Information

The accuracy of the ARTT representation of vehicular position is dependent on the quality of the real-time traffic information, particularly positional information provided by air traffic control surveillance systems. The current operational FAA traffic management system used for Terminal area operations is the Automated Radar Tracking System (ARTS). The ARTS positional state data is based on Airport Surveillance Radar, Model 9 (ASR-9), which has a 4.8 second sweep update rate. In addition to surveillance state data (e.g. aircraft position, vertical and horizontal speed), the ARTS data contains FAA ATC systems data, such as filed flight information (e.g. aircraft type and equipage) and inter-facility messages.

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F. Prototype Limitations

The prototype used in this study had known limitations and was not intended to meet operational requirements. The prototype was primarily used to communicate the characteristics of AR technology to the controllers so that they may imagine how a more capable instantiation may be beneficial for Tower operations. Each of the prototype's subsystems' known deficiencies contributed to the prototype's performance issues.

For instance, the InterSense head-tracking orientation sensor's specified 2-degree orientation accuracy contributes to a potential 2-degree error in overlaying aircraft position symbols over the actual optical image of the aircraft. The InertiaCube's magnetic compass artifacts in this sensor and the resultant excursions would not be acceptable for operational equipment.

The FAA NCT supplied the real-time terminal area data used in these studies. This NCT real-time data infrastructure was originally designed for the FAA ARTCC Traffic Management Advisor (TMA) operational system requirements. The FAA has made this data available to NASA for use in research activities. The Likert test results presented below relied on this current-technology NCT real-time surveillance data. One limitation of the study presented below is the reliance on the current surveillance technology, rather than systems that more realistically model the data quality expected in the NextGen environment. The NCT data's relatively slow update rates (almost 5 seconds) further contributes to registration errors. The Glasstron display's low transmissivity and insufficient display brightness make it unsuitable for use in the Tower's full range of lighting conditions.

IV. Assessments and Evaluations

A. ARTT Field Study Design

The field study presented below were performed using the research prototype discussed in the previous section by five Moffett Field ATCT controllers at the Moffett Tower. Moffett Tower was originally built by the U.S. Navy and is currently operated by the Department of Defense as a contract Tower for NASA. The Moffett Tower is an operational Tower, albeit one that only handles a fraction of the workload it carried when Moffett Field was a Naval Air Station. As a result the Moffett Tower currently often has periods of relatively low activity when research may be prudently pursued without impacting operations. During such periods, non-interference concept exploration studies may be undertaken from the Tower cab, subject to Tower Chief approval. One form of study involves the participation of off-duty Moffett Tower controllers who assess ARTT research prototype and technology concepts while on-duty controllers concurrently perform actual operations. The ARTT protocols required off-duty controllers who engaged in research to maintain a safe separation distance (~6 ft.) from the on-duty controller, and to maintain a non-interference posture at all times, as illustrated in Fig. 4.
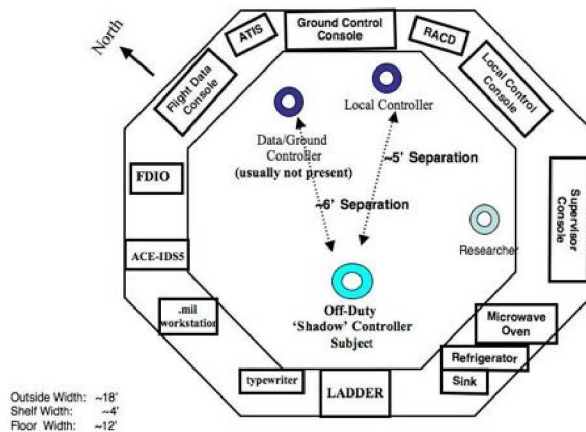

Figure 4. Field study floor-plan at NASA Ames Research Center's Moffett Field Air Traffic Control Tower. The off-duty controller subjects may 'shadow-control', while the on-duty controllers concurrently perform the operational tasks.

In the study described below, the ARTT research prototype was not used to actually control an aircraft. Off-duty controllers assessed the augmented reality prototype in their Tower while on-duty controllers performed normal operations. This type of study is generically referred to as 'shadow-controlling.' The controllers who participated in this study had an average of 13.6 years ATCT experience, with standard deviation of 6 years. They had worked for an average of 4.6 years at Moffett Tower, with standard deviation of 5.5 years amongst the cadre. None of the controllers had any experience with AR technology prior to their exposure during the ARTT assessment studies.[22]

The ARTT engineering prototype was designed to illustrate AR concepts and also identify gaps in practical implementation. The controllers filled out a series of Likert-scale questions after each session as part of the assessment documentation. The range of the Likert scale was five units, representing with ratings of (in descending order): 'Very Useful' (5); 'Useful' (4); 'Neutral' (3); 'Not Very Useful' (2); and 'Useless' (1). The Likert scale questions were divided into five groupings, described below.

The controllers' Likert-scale responses are presented below in 'Box and Whiskers' plot format, also known as 'Tukey Plots.' This is a standardized way of displaying the distribution of data based on the five number summary: minimum, first quartile, median, third quartile, and maximum. In these plots the bottom of the boxes represent the values for the first quartile, the median is the value for the second quartile and is plotted as horizontal bar within each box, and the third quartile value is represented by the top side of the box. The central rectangular box spans the first quartile to the third quartile (i.e. the interquartile range). The 'whiskers' are the lines that typically extend from the boxes, representing the maximum and minimum value by the respective locations of the top and bottom whiskers. [35]

B. Tasks and Duties Applicability Assessment

The first set of 79 questions addressed the potential of augmented reality technology to assist controllers in performing their primary duties. All of the questions in this set were prefaced with: "How useful would ARTT technology be in performing the following tasks:" These questions are grouped into six categories described below: 'Tower Clearances and Control,' 'Inter-Facility Coordination,' 'Air Traffic Coordination,' 'Surface Traffic Coordination,' 'Primary Duties,' and 'Tasks (excluding control).' The context of these questions is therefore the potential benefit of AR, not the actual performance of the particular ARTT research prototype used in the trials. The questions then listed a particular task that each controller rated with the five-level Likert-scale described above. The 'Tasks and Duties' assessment questions were grouped into six categories:

1. Tower Clearances and Control

These 9 questions covered controllers' tasks associated with issuing instructions and clearances to aircraft. Specifically, the controllers were asked to assess the potential usefulness of AR technology for the following duties: ground control, local control, issuing ground clearances, overflight control instructions, arrival control instructions, departure control instructions, flight data processing, clearance delivery, and issuing Instrument Flight Rule (IFR) clearances.

2. Inter-Facility Coordination

This set of 8 questions addressed the potential of AR technology to aid coordination between the Tower and other facilities. These questions referred to both the actual facilities that currently coordinate with the Moffett Tower (e.g. the Palo Alto, San Carlos, and San Jose Towers) and the generalized utility of this technology for genera of coordination (e.g. generalized Tower-to-Tower coordination). Specifically, the controllers were questioned about: Moffett to Palo Alto Tower Coordination, Moffett to San Jose Tower Coordination, Tower-to-Tower Coordination (generalized), Moffett to NCT Coordination, Tower-to-TRACON Coordination (generalized), Moffett to San Carlos Tower Coordination, Moffett to San Francisco Tower Coordination, and Moffett to Oakland Coordination

3. Air Traffic Coordination

This set of 17 questions addressed tasks and duties associated with Tower coordination with aircraft under a variety of visibility conditions. In addition to the normal types of vehicles that would be encountered at most Towers, there were also several questions regarding more specialized vehicular traffic that is controlled by Moffett Tower (e.g. bundle-drops, parachutists, un-crewed aviation vehicles aka UAV). Specifically, the controllers were questioned about coordination with air traffic obscured by architecture or weather during high-glare and IFR conditions; in no-visibility conditions; and in low visibility conditions. Other coordination tasks included: Tower to fixed-wing aircraft coordination, Tower to rotorcraft coordination, Tower to general aviation coordination, Coordination with Air Traffic at night; Coordination with Air Traffic in daylight; Tower coordination with Air Traffic (in general); Coordination with Air Traffic that are clearly visible; Coordination with Air Traffic during VFR Conditions; Tower to bundle-drop coordination; Tower to parachutist coordination, and Tower to UAV coordination

4. Surface Traffic Coordination

This set of 21 questions addressed surface traffic coordination issues. Specifically, the controllers were questioned about coordination with ground vehicles obscured by weather, in no-visibility conditions, obscured by architecture, in

low visibility conditions, during high-glare conditions, during IFR conditions, during VFR conditions, in daylight, at night, and vehicles that are clearly visible. The were also asked 'Tower coordination' questions regarding: Crash Fire Rescue Vehicles, Supervisory Vehicles, Security Vehicles, Fuel Trucks, Runway Sweepers, Electricians and other maintenance staff, Research Project Vehicles, Tow Vehicles, Mowers and with Ground Vehicles in general. They were also questioned about the usefulness of ARTT for addressing runway incursion issues.

5. Primary Duties

This set of 12 questions addressed the primary duties encountered at Moffett Tower. These questions referred to the specific common configurations for the Moffett airspace. Specifically, the controllers were questioned about ATCT duties during West Flow, South East Flow, Memoranda of Agreement (MOA) Amphitheater Extension, MOA Hangar Extension, Left-Hand Pattern Traffic, Right-Hand Pattern Traffic, Designated Border operation, and 40x80 Wind Tunnel operation. The controllers were also asked about the potential usefulness of the technology for cutting ATIS and hourly Weather Observation reports, Watch Supervision, and generalized ATCT duties and tasks.

6. Non-Control Tasks

The last grouping contains 12 questions which address the non-control aspects of Tower 'Tasks and Duties.' The questions concerned systems that are used operationally at Moffett Tower for non-control applications. Specifically, the controllers were questioned about: operations with the Flight Data Information Operation (FDIO), Remote ARTS Color Display (RACD), and Automatic Terminal Information Service (ATIS); evaluating Runway Visual Range (RVR), track proficiency time; evaluating and editing Automated Surface Observing System (ASOS) reports with the ASOS controller equipment display system (ACE IDS); acquiring daily NOAA weather reports and reporting traffic count; and using the Tower status board, the supervisor console, and the Digital Voice Recording System (DVRS).

The 'Box and Whiskers' plot in Fig. 5 summarizes five controllers' responses to these seventy-nine questions, divided into the six categories described above. Each of these categories represents responses to the appropriate subset of questions, described above. The number of questions in each category is indicated within each interquartile box. The common theme of all these questions is the potential applicability of ARTT to Tower tasks and duties, presuming that the various technical deficiencies would be remedied in the future. In all cases the prefix for the questions was: "TASK & DUTIES: How useful would ARTT **technology** be in performing the following tasks:" as part of the larger Likert-scale questionnaire and interview that was given immediately subsequent to each controller performing a 'shadow-controller' session with the ARTT research prototype.
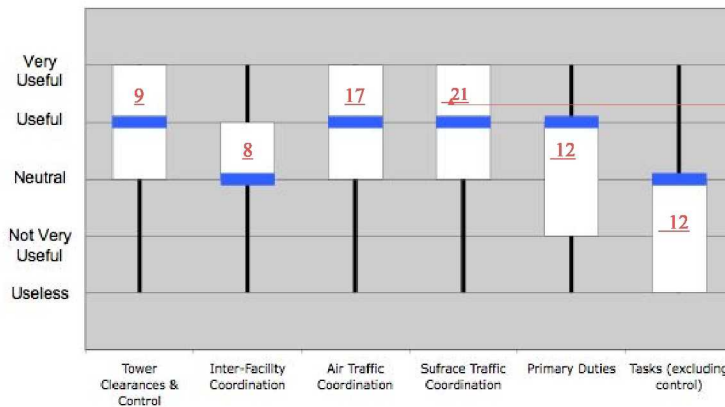

Figure 5. Categorized summary of five controller's responses to 79 'Tasks & Duties' Likert-scale responses to: 'How useful would ARTT technology be in performing the following tasks?'

The context of these questions is therefore the potential benefit of AR, not the actual performance of the particular ARTT research prototype used in the trials. The medians indicate that they found ARTT technology clearly useful for four of these six categories, and neutral for 'Inter-Facility Coordination' and 'Tasks (excluding control)' categories. The 'whiskers' represent the minimum and maximum response to any particular question within a group, and therefore express the full spectrum of ratings, from 'Useless' to 'Very Useful.'

In addition to the 79 'Tasks and Duties' questions described above, there was a final subset of 5 additional questions that addressed the issue of technology preconditions required to use AR technology for Tower applications. These five questions had the form: 'AR technology would be useful in performing the ATCT tasks *only if:*' system-fusion is improved, or computer 'augmented' display is improved, or see-through visibility is improved, or certain features are developed, or procedures are changed. These results are illustrated in Fig. 6, and are consistent with the controllers' assessment of AR technology potential, described below.
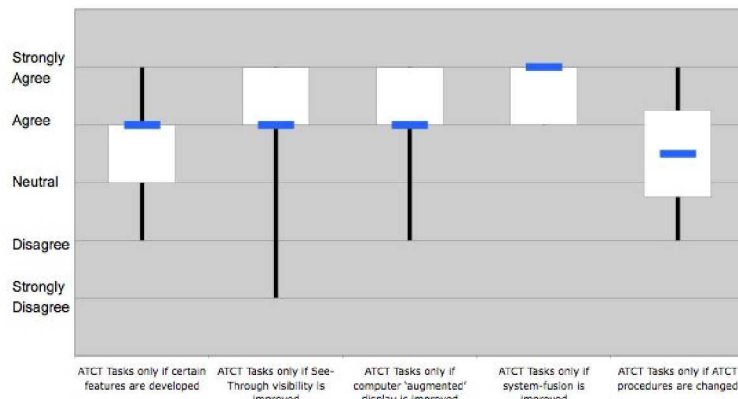
Figure 6. Controller's responses to the five 'only if' questions indicate their assessment that AR technology for Tower applications will require more feature development, improved see-through visibility, and better display performance. They strongly agreed that system and information fusion must be improved.

C. Information Acquisition Technology Assessment

A set of 14 questions addressed the issues of the potential of AR technology to aid in the acquisition of information. These questions had the form: "How useful would ARTT technology be in acquiring the following information?" This set was conceptually divided into two categories, described below.

1. Functional Comparison with Operational Radar Display

A set of six questions compared the potential utility of AR technology with current Tower operational radar system functions. Controllers were asked to assess the capability of ARTT relative to the performance of their primary radar system, the Remote ARTS Color Display (RACD). The ARTT prototype itself did not have display options comparable to the RACD. The controllers were asked to imagine how AR technology could be adapted and deliver data currently provided by the RACD.

In certain specialized cases, such as 'Preview Areas,' 'Tab Lists,' and 'P-Lists,' the potential advantages of ARTT were evaluated as 'Neutral' in comparison to their current system's functionality. The controllers' opinions were particularly strong regarding the potential of ARTT to become more useful than the current RACD plan-view display for 'Aircraft Track and Target Display Options.' Four out of the five controllers responded with the highest rating, 'Very Useful,' and only one disagreed, finding ARTT 'Not Very Useful' for tracking aircraft in comparison with the standard radar display. Though the ARTT prototype could not display the RACD 'Map,' 'Weather,' 'Tab List,' and 'P-list' Display Options, the controllers imagined that using AR technology would add benefit if it could be appropriately modified to display this information. The results for each of the questions associated with the RACD are summarized in Fig. 7.
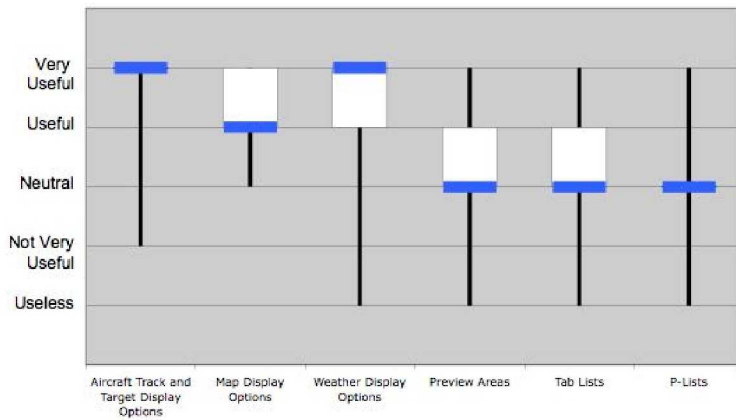
Figure 7. Controllers' assessments of ARTT's potential utility for several display functions. Each of these categories is related to a function of the Remote ARTS Color Display (RACD) System, the primary radar display currently used in Towers.

2. *Information Acquisition*

A set of 8 questions addressed the potential of AR technology for improved acquisition of specific information and situational awareness. The controllers' responses were consistent with their positive response to its potential advantage over the current radar system for tracking aircraft. Fig. 8. summarizes the controllers' responses. In six of the eight questions the controllers consistently (though not unanimously) responded with 'Very Useful' in acquiring information regarding aircraft location, heading, data-block details, and surface vehicle location and situation awareness. The remaining two questions concerned air traffic and Tower situation awareness, the controllers responded that ARTT could be 'Useful.' The controllers generally gave enthusiastic 'Useful' or 'Very Useful' responses to most questions regarding the potential of AR technology to assist in ATCT tasks, duties, particularly regarding information acquisition. The controllers' responses consistently assessed the technology as potentially very useful (though there were a few outliers). There was less agreement about the usefulness for aircraft situation awareness than in other categories.
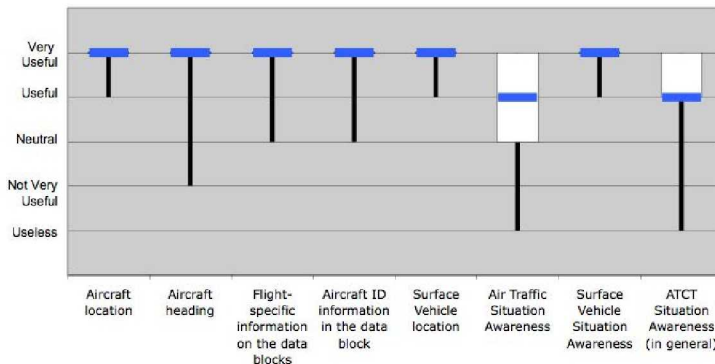
Figure 8. Information Acquisition Question: How useful would ARTT technology be in acquiring the following information?

D. Research Prototype Comfort

The head-mounted display used in the field trials was not acceptably comfortable. The average response to the Likert-scale question "Please rate how comfortable you feel working with the ARTT prototype" was 2.75 (std dev: 0.96), where a 2 represented "not comfortable" and a 3 represented "comfortable." This was consistent with related questions that were included in the evaluation of the research prototype, in which the average head mounted display comfort rating was 2.4 (std dev: 0.89).

The vendor specifies that the Glasstron has an optical transmissivity of 20%, comparable to dark sunglasses, making it unusable during low light conditions. For instance, the controllers were not able to see aircraft lights at night. It is therefore not surprising that the controllers unanimously agreed that the display was unacceptably difficult to use. The controller reactions to this unacceptability evoked a number of spontaneous comments, and they unanimously agreed that an AR display for tower applications required greater optical transparency, and that symbols and text should be readable in all lighting conditions and at all times.

The current head-mounted digital video display technologies, however, constitute a 'vision impairment' as evaluated by current FAA guidelines. The controllers in this study generally consider any see-through displays with less than 50% transmissivity as an unacceptable optical impairment. Several of the controllers complained of visual strain for at least part of the 45 minute trials, and two reported momentary feelings of nausea that they attributed to the disorienting effects of the apparatus.

E. Research Prototype Performance

A set of 26 questions addressed the performance and technical maturity of the research prototype used in the trials. The controllers were instructed to assess the specific prototype used in the trials, rather than assess the potential of AT technology. All questions in this set had the form: "Please rate acceptability of the ARTT **prototype** features and performance." The controllers were asked to constrain their answers to the performance of the as-is apparatus for this section. The 26 questions were conceptually divided into four sub-set categories:

1. Aircraft Data Block Display

This set of 8 questions addressed the acceptability of the data block information presented by the AR research prototype used in the field study. Specifically the controllers were questioned about the display of aircraft identifiers, flight specific information, aircraft altitude, speed, location, heading, and range.

2. Head Mounted Display Performance

This set of 11 questions addressed the performance of the head mounted display (HMD). Specifically the controllers were asked about the acceptability of the HMD's visual transmissivity, the visibility of 'real-world' seen through the HMD, the brightness and clarity of HMD computer-generated text and images, and HMD performance during various lighting conditions, such as typical daylight, night-time, and high-glare situations. There were also summary questions regarding the overall acceptability of the HMD performance and comfort.

3. Situation Awareness

This set of 4 questions addressed situation awareness issues. Specifically the controllers were asked about surface vehicles, specific aircraft, air traffic (multiple aircraft) and overall situation awareness.

4. Head-Tracking and Latency Performance

Three questions addressed the controllers' assessment of head tracking and system latency performance. Many of these perceived latencies apparently due to the TRACON surveillance radar characteristics, such as the 4.8 second update rate. The controllers are not experts in this technology, and their responses were not sought as part of engineering diagnosis and analysis. Instead, they were asked for their perceptions of the engineering prototype's performance and their opinions on the nature of shortcomings. The specific questions addressed perceived latencies apparently due to head-tracking & display processing, and perceived accuracy of head-tracking sensor systems.

The results from these four categories are summarized in Fig. 9. The number of questions in each category is noted in each interquartile box (as in Fig. 5). The exception to this notation convention is 'Head-Tracking & Latency Performance' since there is no visible interquartile box due to the consistent 'Unacceptable' responses by most controllers to all three questions in this category.

The controllers' consensus was that the data block information did not provide any particular benefit over the data blocks currently available from the RACD, and the head-mounted display performance was unacceptable, the overall effect on situation awareness was unacceptable, and the head tracking and perceived latency of the AR system was most unacceptable of any category. Post-session interviews clarified that the controllers' complaints regarding 'latency' appeared to be related to the relatively slow (~5 second) update rate of current Terminal-area surveillance radar systems. They were also dissatisfied with the angular errors attributable to head-orientation tracking anomalies. The controllers were also generally dissatisfied with the apparatus comfort. The general comments were that an

acceptable head mounted display should be no more invasive than standard glasses, with at least 50% optical transmissivity, and with display illumination sufficient to be effective throughout the full range of lighting conditions.
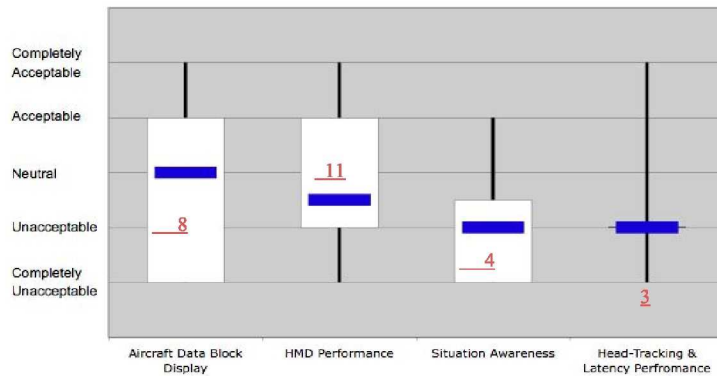

Figure 9. Categorized summary of controllers' responses to 26 questions regarding the performance of the ARTT research prototype.

F. Controller Summations

This set of 12 questions addressed the controllers' summary evaluations of the specific ARTT research prototype used in the study, and the potential of a mature AR technology to benefit Tower operations. These questions had the form of: "Please rate your agreement to the following statements." These 12 questions were divided into two categories, described below.

1. ARTT Research Prototype

This set of 6 questions addressed the controllers' evaluations of the research prototype. Specifically, the statements proposed that the ARTT prototype computer-generated display symbology must be improved, and (conversely) that the symbology is useful; that the displays are perceived adequately; that (conversely) the HMD impairs real-world vision, and that the prototype (as-is) could be useful in an Tower, or that a slightly improved (as opposed to 'completely re-engineered') version of the prototype could be useful. The controllers' responses are summarized in Fig. 10.

The controllers agreed that the prototype HMD constituted a 'vision impairment' rather than a beneficial 'augmentation.' They also agreed that this particular research prototype did not generate acceptable displays, required improved symbology, and generally required extensive improvements before it would be useful for Tower operations.

In post-trial interviews the controllers unanimously voiced concerns about the accuracy and correspondence of the computer-generated information with the actual views from the Tower. The prototype display's static reference was a compass-rose horizon line with 10 degree interval markers. Controllers typically disliked this compass rose display, and unanimously requested more three-dimensional (3-D) representations of visual cues. In post-session interviews they often commented that they do not normally visualize the world as 'points on a compass.' Instead they often used visual landmarks for orientation. During the interviews all mentioned that they would have liked to have seen more representation of static features, such as runways, taxiways, non-moving objects, architecture, terrain, and similar landmarks.

The results of these Likert tests were reinforced by post-trial interviews and by a standard Controller Acceptance Rating Scale (CARS) questionnaire.[36] The controllers unanimously responded negatively to the first CARS decision point, "Is the system safe and comfortable?" and positively to a resultant mandate for improvement.
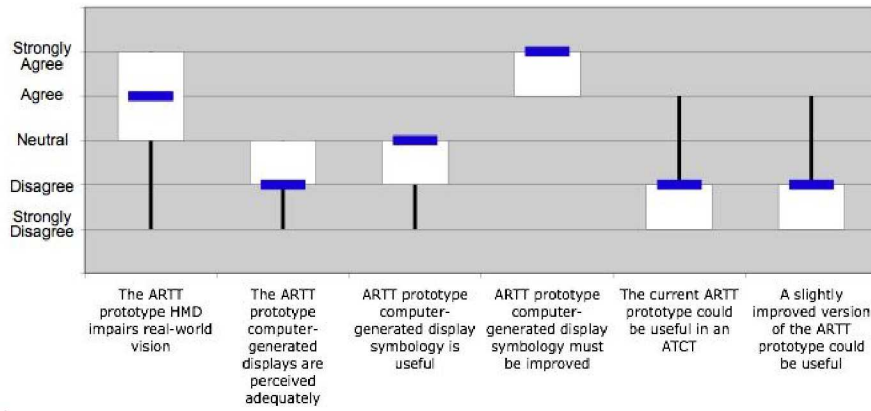
Figure 10. Controllers' assessments of the research prototype used in the ARTT field studies.

2. AR Technology Potential

    This set of 6 questions addressed the controllers' assessment of the potential of a future 'perfected' AR technology to benefit Tower operation. Specifically, the statements proposed that ARTT Technology could be useful for ATCT tasks and systems, or (conversely) that it will never be useful for ATCT tasks and systems; that it requires new aircraft data block information and/or formats, and/or new decision-support-tool operational concepts. The results are illustrated in Fig. 11.
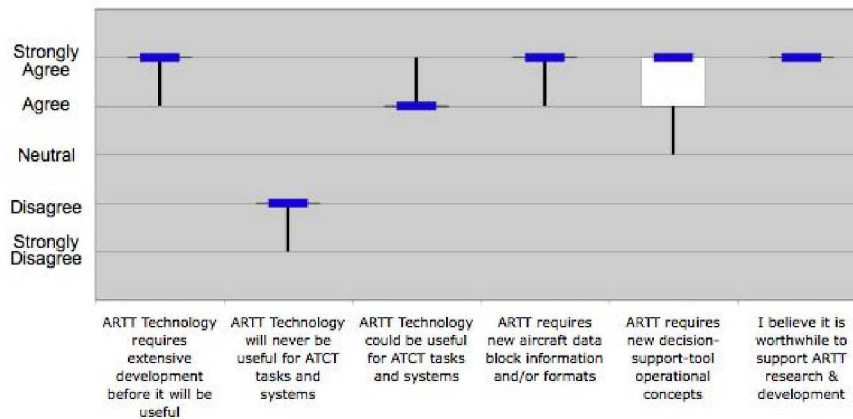
Figure 11. Controllers' summary assessments of AR potential for Tower applications.

    The controllers generally agreed with each other more consistently than with most of the other questions. The most consistency was exhibited in the final question in the series: 'I believe it is worthwhile to support ARTT research & development.' This was the only question (out of 139) in which the controllers unanimously provided the same answer: 'Strongly Agree. In post-trial interviews the controllers often expanded on this last question by advocating further development and expressing their acceptance that AR technology may become very useful for NextGen Tower facilities.

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V. Concluding Remarks

The prototype, though insufficient for operational use, was sufficient for illustrating the potential of AR technology. The controllers strongly agreed on several key areas of the AR technology assessments. Their principal findings were: AR technology is potentially useful for primary ATC Tower tasks and duties. The technology may be particularly useful for clearance and control tasks, and may improve coordination with air and surface vehicles. The controllers strongly agreed that AR technology could complement their current primary surveillance radar systems, particularly for aircraft track and target displays, map display options, and weather displays. They were even more consistent in their agreement on AR's potential to improve information acquisition of aircraft location, heading, identification, surface location, and awareness of vehicle and traffic situation. Even though there were variations in the controllers' assessments of ARTT's potential benefit for these tasks and duties, the controllers were very consistent in their positive evaluation of the over-all potential of AR technology to benefit Tower operations.

The major concerns the controllers dealt with the research prototype used in the study. The controllers' consistently complained that the Glasstron HMD was uncomfortable, impractical, and constituted an unacceptable visual impairment. The 2-degree nominal errors and magnetic compass excursions contributed to their lack of confidence in the system. Many of the controllers' complaints about the research prototype may be attributable to surveillance uncertainties due to the comparatively long update rates (4.8 sec.) characteristic of the TRACON radar systems.

Based on this study, the major challenge in bringing this technology to fruition will be the successful resolution of these problems and limitations. Improvements in surveillance, see-through display, and head tracking technologies should be explored to address these engineering problems. It is clear that the controllers were enthusiastically supportive of developing AR applications for Tower applications, and that ARTT may provide benefit in low-visibilty conditions once the technology gaps have been adequately addressed.

Acknowledgements

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