Real-Time Google Glass Heads-Up Display for Rapid Air-Traffic Detection

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DOI: 10.2514/1.C034362

As airspace becomes increasingly crowded, the need for next-generation traffic-advisory systems for pilots has become more crucial. To this end, a heads-up advisory display is developed within the Google Glass platform to assist pilots in the rapid location and identification of air traffic in their vicinity. The display is conceived as a proposed addition to existing traffic collision advisory systems, and the research seeks to determine if such assistive technology provides advantages in better detecting surrounding air traffic and reducing the risk of a collision. The display features a dynamically updating three-dimensional arrow that continuously guides the pilot’s eye toward oncoming traffic. The arrow updates its orientation in real time based on the relative head motion of the pilot, the motion of the pilot’s aircraft, and the location of the oncoming traffic. Pilot-in-the-loop testing and simulation runs are conducted to gauge the response times of participants tasked with visually acquiring intruding traffic. The results from testing show a significant improvement with the use of the assistive technology, with response-time reductions of over 60% observed in certain cases, notably in conditions in which traffic approaches from peripheral angles and when contaminated against the backdrop of ground clutter.

I. Introduction

In recent years, aircraft have grown larger in size and longer in range, and air traffic has increased in frequency. The notion of maintaining and increasing safety in civil aviation has consequently become a priority in every aspect of air transport. Data from the International Civil Aviation Organization indicated that 2.9 billion people used air transport for purposes of business and pleasure in 2012, an increase of 5% from the previous year. This figure is projected to reach over 6 billion by 2030 [1]. Given this, it follows that airspace will grow increasingly crowded with denser traffic as time passes, especially in major cities and metropolitan areas.

As a greater number of aircraft occupy the same physical airspace, the potential for two or more aircraft to mistakenly enter on a collision path also increases. Even so, thanks to modern technology and near-miss reporting systems institutionalized over the last several decades [such as the Federal Aviation Administration’s (FAA) Aviation Safety Reporting System], the occurrence of accidents has continually and rapidly fallen.

One example of a highly effective technology used to assist pilots in avoiding potential midair collisions is the traffic collision avoidance system (TCAS). In its current form, the TCAS provides pilots with visual and auditory alerts to oncoming traffic intruding into their airspace. If an intruding aircraft is within a certain range, visual and auditory advisories are given to pilots to warn them of the intruding traffic, or to take certain forms of evasive action. Typically, a visual advisory is superimposed on the pilot’s instrument display as a blip, to show the location of the intruding aircraft, along with an accompanying auditory alert.

Upon being presented with such an alert, a pilot would typically turn his or her attention downward to the instrument panel, to determine the relative direction from which the intruding aircraft is approaching. Then, knowing this, the pilot would turn his or her attention out of the cockpit windows to commence a scan to gain a visual sighting of the intruding aircraft. Under certain conditions, this may greatly increase the pilot’s workload. Factors, such as low visibility or a high concentration of clouds, may hinder the pilot’s ability to quickly and effectively locate the intruding aircraft. At other times, the intruding aircraft may blend well into the background, effectively being “camouflaged” against the backdrop of the ground or sky. Research involving tracking eye movements has shown that, in the event of a TCAS alert, pilots may spend half of the total time taken to locate the intruding aircraft on the task of looking at the instrument panel [2].

In recent years, research has been carried out to improve upon existing traffic collision warning systems. One early effort [3] attempted to decrease the time taken to gain a visual sighting of the intruding aircraft using three-dimensional (3-D) audio presentation, and demonstrated an improvement of almost 2.2 s. Another effort by Cleveland et al. [4] had proposed certain additions to the existing TCAS display, to provide pilots information on the intruding aircraft’s velocity track and trajectory. Haberkorn et al. [5] described the need for a TCAS-like system for pilots operating under visual flight rules, the most common mode of operation for general aviation (GA) pilots (who do not typically have TCAS), so as to alleviate their workload and assist with improved decision making in potential

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conflict scenarios. To this extent, the General Aviation Flight Laboratory (GAFL) at Wichita State University (WSU) has developed an air-traffic locator and collision advisory heads-up display (HUD), using 3-D graphics, to assist in the rapid locating of oncoming traffic in the pilot’s vicinity.

Whereas heads-up assistive technologies have seen various implementations in commercial [6–8] and military [9–11] aerospace applications, the recent proliferation of augmented reality (AR) technologies [12–14] has opened up a new array of possibilities for portable heads-up assistive technologies to be introduced into more cockpits. Portable devices, such as Google Glass™ or Microsoft HoloLens™, have opened up opportunities for AR technologies to be used as assistive devices in many fields and industries. Subgroups, such as GA, for which such HUD systems are less commonly available, would benefit from the potential availability of such systems that function to improve safety in aviation. Studies conducted in the past have shown the benefits of HUD systems for GA use [15,16], notably the potential safety improvements they bring, as well as improved pilot performance when using such displays.

With this in mind, the software developed at the WSU was conceived as an extension to existing TCASs, and functions as a visual aid meant to run on wearable AR technologies, such as Google Glass or Microsoft HoloLens. Such wearables provide the user with a clear view of the surrounding environment, while superimposing digital moving images or graphics over that same environment. The prototype software presents the pilot with a visual cue in the form of a 3-D arrow vector that progressively guides his or her vision toward the oncoming traffic. The vector dynamically updates its orientation based on the relative head motion of the pilot, the motion of the pilot’s aircraft, and the location of the oncoming traffic.

This paper details the conception, development, and simulated flight testing of this software. Section II provides a brief overview of existing TCASs and how the software was designed to parallel TCAS alerting protocols, and Sec. III introduces the Google Glass platform. Details of the top-level system architecture and software–hardware workflow are presented in Sec. IV, whereas Sec. V describes the software’s algorithms and logic. Section VI documents the testing process used to validate the concept’s effectiveness, and Sec. VII presents the results from the pilot-in-the-loop simulated flight testing. Finally, Sec. VIII draws some conclusions and suggestions for future work.

II. TCAS Operational Concept

As of the time of this research, the most current version of TCAS is the Traffic Collision Avoidance System II version 7.1 (TCAS II) [17]. TCAS II provides two levels of alerting: the traffic advisory (TA) and the resolution advisory (RA). A TA is an initial alert that notifies the pilot that another aircraft is in close proximity, and allows the pilot to commence a visual search for the intruding traffic. If both aircraft remain on a course that brings them into closer proximity, an RA may then be triggered, which typically entails some form of evasive action. An RA provides a vertical command to the pilot. Complying with the RA is mandatory, unless doing so would jeopardize flight safety, or the pilot can definitively maintain visual separation. Figure 1 provides an illustration of the alerting thresholds in TCAS II.

Inside the cockpit, the pilot will be provided with a visual advisory superimposed as a blip on the multifunction display (MFD). The blip is typically shaded in yellow or red depending upon proximity, and shows the intruding aircraft’s position and azimuth with respect to the pilot’s aircraft. It also contains information on the vertical motion of the intruding aircraft. An accompanying auditory alert upon initial entry into the TA zone typically takes on the form of “traffic—traffic.” An illustration of the visual advisory is shown in Fig. 2.

To maintain the fidelity of the software’s alerting mechanism, traffic alerts given by the WSU’s HUD software were designed to closely approximate the alerts a pilot would experience with an operational TCAS, so far as the timing at which a TA is given. A TA alert is triggered within the software when oncoming traffic is at a 30 s proximity from the pilot’s aircraft. At this point, the software will present the pilot with a visual cue in the form of a 3-D vector, as well as an auditory alert in the form of a traffic–traffic callout.

III. Overview of Google Glass

Google Glass is a wearable head-mounted display unit developed by Google Inc., and runs a special version of the popular Android mobile operating system. It resembles a pair of eyeglasses, but instead of optical lenses, features a clear prism located on the right side of the unit. The prism sits slightly above the wearer’s right eye, and serves as the device’s screen. Figure 3 shows the specific Google Glass device used in this research.
When the unit is powered off, the prism is transparent, and the user is able to see objects behind the prism. When the unit is powered on, high-resolution images, either still or moving, are projected onto the prism. Depending on the color of the image, projections can be made to appear translucent, and thus the user is still able to view objects located behind the prism. This important feature of Google Glass is a key to the function of the software, as it allows digital images to be superimposed over the physical objects that the user sees around him or her—along the lines of an AR environment.

Google Glass has been used by various companies and developers for the creation of user-centric interactive applications. It has also been used for medicine [18], and has functioned as a tool in academic research [19]. One example includes research into the benefits of using Google Glass as an HUD while driving (as a means of keeping the driver’s attention on the road) [20], and another recent study has used its onboard sensors to detect and quantify operator drowsiness, as a means of improving driving safety [21].

The software’s modules and accompanying computations (detailed subsequently) were run in real time onboard the Google Glass hardware. Data from the onboard orientation sensor was used to determine the participant’s head rotations and angles, and this information was used to update the orientation of the 3-D arrow as the participant tilted/rotated his or her head. An illustration of this arrow being projected onto Google Glass prism display is shown in Fig. 4.

IV. System Architecture and Software–Hardware Interaction

A modular approach was used in the design of the software. The native language used for programming for the Google Glass/Android platform is Java. As is common when conducting a research study of this nature, in which the software has to be tested in a confined experimental setup and not in its intended usage environment, the workflow and architecture of the software differ for both scenarios. The authors thus distinguish between the conceptual workflow (software A) and the experimental workflow (software B). Whereas the conceptual workflow represented the ideal, intended way the software would have functioned, were it to be deployed in its intended usage environment, the experimental workflow incorporated the necessary changes made to the conceptual workflow that allowed the software to be evaluated in an experimental, simulated environment.

A. Conceptual Workflow

In the intended usage scenario, software A is run entirely within the Google Glass platform. The inputs to the software would come from the aircraft systems. In this particular case, that system would be the aircraft’s TCAS. Figure 5 provides an overview of the architecture and interaction between software and hardware in the conceptual scenario.

Position information from the aircraft would first be sent to Google Glass, which would then calculate the separation distance through the distance-resolution module (DRM), and the separation time through the collision-advisory-trigger module (CATM). Based on this information, a decision would be made as to whether an alert should be given to the pilot. If an alert is required, the vector is generated through the visual-cue module (VCM), and the accompanying auditory alert is given. The details and inner workings of the specific software modules are discussed in Sec. V.

B. Experimental Workflow

To properly evaluate the software and its effectiveness, various changes were made to the software to allow it to function within the experimental environment. Software B was thus developed as a modification of software A. Figure 6 provides a brief overview of the architecture and interaction between software and hardware in the experimental case.

In the experimental setup, certain modules that would run onboard Google Glass in the intended usage scenario were instead moved to the simulation computer. The primary reason for this was to facilitate better timekeeping, by moving the modules dependent on time tracking to the same computer (ground-station computer), thereby minimizing communication latency. This allowed for a more accurate measurement of the participants’ response times. The programming code in both cases remained functionally identical.

The ground-station computer performed various tasks. Through the use of MATLAB/Simulink®️, the traffic-generator module (TGM) was responsible for generating artificial intruding traffic and inserting them into the simulation environment. Position information about the intruding aircraft from the TGM was also sent to the DRM. The DRM, together with the position information about the piloted aircraft from the simulation computer, was then able to calculate the separation distance between both aircraft. Based on this information, the CATM would determine the separation timing between the aircraft. If an alert was warranted, a signal was sent wirelessly to Google Glass to trigger the VCM to output the visual and auditory alerts.

In addition to generating the simulation environment, the flight-simulation computer was also responsible for registering inputs from the participant when the intruding traffic was visually acquired (through button presses on the flight control yoke). These inputs were recorded by the ground-station computer.
V. Software Modules

The theory behind the software modules outlined in Sec. IV is described next. Although each software module functioned as a separate entity, all were required components to produce the software’s output.

A. Traffic-Generator Module

For the purposes of simulated flight testing, the TGM created virtual instances of intruding aircraft, and then inserted them into the simulation environment. The TGM received information from the simulation computer about the position of the piloted aircraft, and calculated an initial position and trajectory for the intruding aircraft, positioning it at some location ahead of the piloted aircraft. This location was specified based on an initial separation time, azimuth, and delta elevation with respect to the piloted aircraft.

The trajectory of the intruding aircraft deliberately placed it on a collision course with the piloted aircraft. In other words, the trajectory was calculated such that the intruding aircraft would always home in on the piloted aircraft. This trajectory was always the same for a given azimuth/elevation combination, allowing for consistency across every participant.

For the study carried out in this research, 21 approach combinations were set up. Seven azimuth angles placed the intruding aircraft on a heading between −90 to +90 deg with respect to the piloted aircraft, at 30 deg intervals. Three elevations placed the intruding aircraft at initial delta altitudes of −800, −1200, and −1600 ft below the piloted aircraft. These delta altitudes were reduced in a linear fashion as a function of time, such that the delta altitude at the point of collision was zero. The three initial elevations were chosen to place the intruding aircraft above, along, and below the horizon, with respect to the pilot’s viewpoint. This is illustrated in Fig. 7.

Peripheral azimuths aimed to measure if the participants’ response times would be greater than for central azimuths, because the intruding aircraft would appear less obvious. Likewise, lower elevations placed the intruding aircraft against the backdrop of the ground environment, making them more difficult to detect. This is discussed further in Sec. VI.

B. Distance-Resolution Module

The DRM continuously calculated the straight-line distance between the piloted and intruding aircraft. A schematic of its operation is illustrated in Fig. 8.

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Fig. 6 Schematic of experimental architecture and software/hardware interaction.

Fig. 7 Azimuth/elevation approach combinations.

Fig. 8 Azimuth/elevation approach combinations.
In the conceptual case, the input to the DRM would come from systems aboard the actual piloted aircraft, such as the TCAS. In the case of the prototype software, X-Plane® (a commercially available flight-simulation package) was used to substitute for the actual aircraft. Given the latitude, longitude, and altitude of both the piloted and intruding aircraft, the module used the equations specified in 47 CFR 73.208 [22] to determine the distance between the two points. The component distances were calculated according to Eqs. (1–3):

$$\text{DIST}_x = K_1(\text{LAT}_{\text{source}} - \text{LAT}_{\text{target}})$$  \hspace{1cm} (1)

$$\text{DIST}_y = K_2(\text{LONG}_{\text{source}} - \text{LONG}_{\text{target}})$$  \hspace{1cm} (2)

$$\text{DIST}_z = \text{ALT}_{\text{source}} - \text{ALT}_{\text{target}}$$  \hspace{1cm} (3)

in which the coefficients $K_1$ and $K_2$ are defined in [22], and, respectively, represent the number of kilometers per degree latitude/longitude difference. Finally, the straight-line distance between the piloted and intruding aircraft was calculated according to

$$\text{DIST}_{3,D} = \sqrt{(\text{DIST}_x)^2 + (\text{DIST}_y)^2 + (\text{DIST}_z)^2}$$  \hspace{1cm} (4)

This method assumed an ellipsoidal Earth model projected on a plane, and is valid for distances not exceeding 295 miles [22]. Considering that the distances that the software would encounter were significantly less than 10 miles, this set of equations was deemed suitable for use.

C. Collision-Advisory-Trigger Module

Using the distance calculated in the DRM, the CATM determined the time to collision (TTC) by first calculating the change of the separation distance with respect to time, as described in Eq. (5):

$$\text{D}IST_{3,D} = \frac{d}{dt}(\text{DIST}_{3,D})$$  \hspace{1cm} (5)

The TTC was then computed through division of the separation distance by $\text{DIST}_{3,D}$, according to Eq. (6). This provided information about the separation time of both aircraft, assuming that they continued at their current velocities.

$$\text{if } \text{TTC} = \frac{\text{DIST}_{3,D}}{\text{DIST}_{3,D} \leq 30 \text{ s } \Rightarrow \text{alert on}}$$  \hspace{1cm} (6)

If the TTC was found to be 30 s or less, an audible alert (traffic–traffic) was output through the sound transducers aboard Google Glass. At the same time, the VCM was also triggered to display the 3-D vector.

D. Visual Cue Module

The VCM was called up when the CATM detected that the intruding traffic was less than 30 s away from the piloted aircraft. The VCM displayed a 3-D vector that, at any given time for any given head-rotation angle, pointed directly toward the intruding aircraft. As the participant used the arrow to progressively guide his/her vision toward the location of the intruding aircraft, the vector updated its orientation to continually point toward the intruding traffic.

As an example, consider an intruding aircraft at 10 o’clock with an elevation of 10 deg above the horizon, with respect to the pilot in the piloted aircraft. The pilot is currently looking straight ahead at the 12 o’clock direction. As the alert is triggered, the vector is presented to the pilot as pointing slightly upward and toward the left, as pictured in Fig. 9.

As the pilot turns his/her head to the left and upward, the vector progressively updates itself, as the pilot turns his/her head to face the traffic. This is seen in the illustrations in Fig. 10.

Finally, as the pilot’s view faces the traffic, the 3-D vector points directly at the intruding aircraft. This is illustrated in Fig. 11.

Often, in a real-world flight situation, several factors can hinder the pilot’s ability to locate surrounding traffic factors. These factors may include weather conditions that could bring poor visibility, such as rain, cloudiness, fog, or haze. At other times, the intruding traffic may blend in with the colors of the background environment, such as objects or foliage on the ground. The primary goal of the visual cue is to reduce the amount of time it takes for the pilot to obtain a visual sighting of the surrounding traffic, especially in such conditions.

An improved means of visually acquiring the intruding traffic responsible for generating a TA would give the pilot an opportunity to visually locate the traffic sooner, complementing the TCAS’s function and enabling the pilot to comply with his or her responsibility to see and avoid traffic.

Fig. 9 Illustration of pilot’s view of visual cue upon initial alert.

Fig. 10 Pilot’s view of visual cue as vision is progressively guided toward traffic.
VI. Concept Validation Through Simulated Flight Test

A. Single-Large-Surface Panoramic Flight-Simulation Platform

A simulated flight testing was conducted using the single-large-surface (SLS) flight simulator at the GAFL at the WSU. Figures 12 and 13 depict the simulator.

The simulator consists of five large-surface liquid-crystal display monitors, combined to form a single large display, giving the pilot a full 180 deg panoramic view of the environment.

Designed and built in-house in 2014, the simulator has control yokes and pedals for a pilot and copilot, as well as a functional center console. A touch-screen panel above the center console serves as the aircraft’s instrument panel. The simulator is driven using X-Plane® flight-simulation software, and is powered by three computers: the first drives the instrument panel and flight dynamics, the second drives the exterior visuals, and the third serves as a ground/instructor station.

B. Participant Selection and Census

Two groups of participants were chosen to take part in the simulated flight test. One group consisted of certified pilots, whereas the other group consisted of individuals with no prior real-world flight experience. Eight pilots were selected to participate in the study. Their highest rating and approximate hours logged as of this research are summarized in Table 1.

For every pilot taking part in the study, a nonpilot was also selected to participate. The nonpilot participant was selected based on the demographics of each particular pilot. Efforts were taken to find closely matching nonpilot participants, as availability permitted. All participants were given a survey to collect demographic information. The anonymity of the participants was maintained on the survey. The information from the survey allowed for a comparison of educational and occupational background (technical vs nontechnical).

C. Test Procedure

1. Overview

The selected participants were asked to participate in a simulated flight test using the software on the Google Glass device. In the recording of data, anonymity was maintained. Adequate briefing and practice were provided to both pilots and nonpilots, to ensure basic familiarity with the required tasks and with the usage of Google Glass.

Two types of testing were performed. The baseline category required the participants to visually acquire the intruding traffic without assistance from the 3-D vector, whereas the assisted category required the participants to visually acquire traffic with assistance from the 3-D vector. In the baseline case, the participants were allowed to use the onboard TCAS on the instrument panel to help with locating the intruding aircraft. Both categories had identical alert timings and auditory signals, with the only difference being that the baseline category did not feature the Google Glass visual cue.

2. Simulated Workload

The flight test involved having the participants sit behind the controls of the piloted aircraft, with the aircraft in level flight and maintaining a set course and altitude using the autopilot. No tasks in the study required either group of participants to manually fly the aircraft. To simulate a level of workload, however, the participants were given a specific secondary task to perform while the aircraft was in flight. This task was unrelated to the primary task of detecting the intruding traffic. To maintain consistency in the study, it was decided that the chosen task had to be the same for both the pilot and nonpilot groups, while yet being aviation related. Moreover, the task had to be

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suitable for individuals with and without pilot training. The participants were thus asked to read information from a series of instrument approach plates. The information that the participants were asked to read was circled in red and numbered on the charts, and the participants were asked to cycle through the selected information in sequence. A typical example of the chart used in the study is shown in Fig. 14.

It is important to note that the sole purpose of the secondary task was to simulate an amount of workload representative of a task found in today’s cockpits, and that the information the participants were asked to read would not have given either group a better advantage at visually acquiring the intruding aircraft. The information presented on the charts was of no relation to the actual objective of the study.

3. Insertion of Intruding Traffic

At some point while performing the secondary task, the intruding aircraft on a collision course with the piloted aircraft were inserted into the environment, with only one intruding aircraft present at a given time. To reduce predictability, the initial separation times were varied between 35 and 55 s. However, to recreate an actual scenario, in which the participant would not know traffic was present until the alert, the aircraft were made to be invisible until the alert was actually triggered at the 30 s point. This was done to prevent the pilots from “gaming” the experiment, because they knew traffic was present, which would not be the case in an actual flight. Also, whereas the insertion orders of the azimuth/elevation/separation time combinations were randomized, the insertion order was kept the same for every participant. Table 2 gives the initial separation times for each combination.

4. Administration of Traffic Alert

When the TTC decreased below 30 s, the visual and auditory alerts were triggered, and the participants were asked to obtain a visual sighting of the intruding traffic. In the baseline category, the participants were allowed to use the conventional MFD-based TCAS.
to assist in their scan. In the assisted category, the participants were asked to use the 3-D vector to locate the intruding traffic. When spotted, the participants were tasked to acknowledge that the aircraft was in sight by pressing a specified button on the control yoke, and by calling out “traffic in sight.” The elapsed time between the onset of the alert and the button press was then recorded—this was measured as the response time for that particular run. This process was repeated for each of the 21 approach combinations, for both the baseline category and the assisted category.

### VII. Results

In the analysis of the results, three types of comparisons were made. The first compared the response times of the pilots with and without the assistance of the visual cue, the second compared the response times of the nonpilots with and without the assistance of the visual cue, and the third compared the response times between the pilot and nonpilot groups. In all cases, the response time was defined as the time elapsed between the moment when the auditory/visual alert was triggered and when the participant registered visual sighting of the intruding traffic through the button-press procedure described in Sec. VI.

#### A. Comparison Within Pilot Group: Baseline vs Assisted

Figure 15 compares the average response times for each of the eight pilots, with and without the assistance of the 3-D vector.

Across all pilots, it can be seen that the average response time in the assisted case was less than in the baseline case. These differences ranged from between 0.5 and 3 s. The reader is asked to note that these are aggregated values across all azimuths/elevations for each pilot, and far greater differences were observed when analyzing each specific azimuth/elevation approach combination. These scenarios are detailed subsequently.

Tables 3 and 4 list the average response times for each of the approach combinations for the baseline and assisted categories, respectively. Aggregated across all 21 scenarios, the average response time in the baseline category was 6.3 s, whereas that of the assisted category was 4.6 s.

In the baseline category, a visible increase in response time was seen when the intruding traffic approached from peripheral angles (for example, −90 and +90 deg) and from a lower elevation. At the extreme case of −90 deg / −1600 ft, in particular, the average response time was 17.2 s without assistance from the 3-D vector. Taken from another perspective, this meant that the intruding traffic was 12 s from colliding with the piloted aircraft. With assistance from the 3-D vector, this same scenario saw an average response time of 6.2 s, an improvement of over 60%.

In general, the presence of the 3-D vector allowed for much better consistency in the response times of the pilots. This is illustrated in Figs. 16 and 17.

Considering the average response times aggregated by the azimuth for the assisted category, the quickest time measured was 3.6 s and the slowest time measured was 5.1 s. For the baseline category, the corresponding numbers were 3.7 and 9.8 s, respectively.

Considering the same metrics aggregated by elevation for the assisted category, the quickest time measured was 3.6 s and the slowest time measured was 6.0 s. For the baseline category, the corresponding numbers were 4.5 and 9.6 s, respectively.

This suggests that, without the help of the 3-D vector, the participants were spending more time locating traffic coming from certain difficult approach angles. In the assisted category, the presence of the 3-D vector allowed for the quicker location of the same traffic. One can see a trend of an increase in average response time as the intruding traffic approaches from lower elevations and from peripheral approach angles, and this is more pronounced in the baseline category than in the assisted category.

With the presence of the visual cue, less time is needed to be spent “hunting” for the intruding aircraft. The 3-D vector would instantaneously direct the pilot toward the location from which the intruding aircraft was approaching. Once the pilot’s field of view was centered around the intruding aircraft, visually and mentally registering that the aircraft was in sight became a much quicker process.

Even so, it is equally important to note that there were certain scenarios, in which the 3-D vector provided no measurable advantage over the baseline case. These were the scenarios, in which the intruding traffic was along/above the horizon and directly ahead of the piloted aircraft. These scenarios placed the intruding traffic in clear sight directly in front of the pilot and against the clear backdrop of the sky. In such scenarios, no significant benefit was seen from the presence of the 3-D vector.

#### B. Comparison Within Nonpilot Group: Baseline vs Assisted

In planning the tests used to measure the benefits of the 3-D vector, the performance of the software among individuals without pilot training was also of interest. These tests were done to determine if the visual cue would benefit one demographic more than the other, and also to provide a control measurement when comparing results between the participant groups. Figure 18 compares the average response times among the eight nonpilot participants, with and without the assistance of the 3-D vector.

As seen previously, the average response times in the assisted case were less than in the baseline case across all nonpilots. These differences were more pronounced than with the pilots and ranged from between 1.2 and 5.9 s. Once again, the reader is asked to note that these are aggregated values, and far greater differences were observed when analyzing specific approach combinations, which are detailed subsequently.

Tables 5 and 6 list the average response times for each of the approach combinations for the baseline and assisted categories. Aggregated across all 21 scenarios, the average response time in the baseline category was 7.9 s, whereas that of the assisted category was 5.1 s.

As with the pilot group, greater response times were measured for the intruding aircraft approaching from the peripheral regions and lower elevations. The response times along the lower elevations in the baseline category were consistently higher than with the pilot group. Without assistance from the 3-D vector, at the extreme cases of −90 deg / −1600 ft and +90 deg / +1600 ft, the average
response times were, respectively, 18.3 and 15.4 s, bringing the intruding aircraft less than 12 s from colliding with the piloted aircraft. In the assisted category, these scenarios saw average response times of 6.2 and 8.7 s, which were significant improvements of 66 and 43%, respectively.

As observed with the pilot group, the assistance of the 3-D vector allowed for much more consistent response times across the different approach combinations, and these trends are illustrated in Figs. 19 and 20.

In the baseline category, without the help of the 3-D vector, the participants were observed to have spent much more time locating the intruding traffic appearing from peripheral angles and from lower elevations, and much less time locating the intruding traffic appearing from in front, giving for a wide range of response times. In the assisted category, the distribution of response times across the 21 approach combinations was more uniform and showed less variation.

Considering the average response times aggregated by the azimuth for the assisted category, the quickest time measured was 3.9 s and the slowest time measured was 6.4 s. For the baseline category, the corresponding numbers were 5.9 and 10.4 s, respectively.

Considering the same metrics aggregated by elevation for the assisted category, the quickest time measured was 4.0 s and the slowest time measured was 6.5 s. For the baseline category, the corresponding numbers were 5.2 and 12.0 s, respectively.

From the results seen thus far, for both the pilot and nonpilot groups, there is evidence to support the notion that the use of such a visual cue is able to reduce the amount of time spent in locating traffic, and that the visual cue helps much more in certain cases than in others. These cases are those, in which the intruding traffic appears

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Table 3 Average response time in seconds for the pilot group: baseline category

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Table 4 Average response time in seconds for the pilot group: assisted category

**Fig. 16** Average response time by azimuth with and without assistance (pilot group).

**Fig. 17** Average response time by elevation with and without assistance (pilot group).

**Fig. 18** Average response time by participant with and without assistance (non-pilot group).
from the left and right corners, and from below the piloted aircraft, where they are camouflaged against the backdrop of the ground environment.

C. Comparison of Pilot Group vs Nonpilot Group

The third series of comparisons sought to determine whether the assistance of the visual cue would have provided a greater benefit to a demographic without prior pilot training, or to a demographic with prior pilot training.

Because pilots would have already been trained to detect intruding traffic using conventional visual scan techniques, it was hypothesized that the assistance of the 3-D vector may not have resulted in as great of a reduction in response times for the pilot group as compared to the nonpilot group, which had no prior training in detecting intruding traffic. In other words, the maximum potential of such an assistive technology could perhaps be better quantified by a group of participants whose techniques in detecting intruding traffic were not already influenced by the techniques taught in a formal training regimen. Consequently, these comparisons aimed to establish a base measurement to evaluate the maximum potential of the assistive technology proposed in this study.

Figure 21 compares the average response times between pilots and nonpilots across all 21 scenarios, for the baseline and assisted categories. With the assistance of the 3-D vector, the overall improvement for the nonpilot group was a reduction in the average response time of 2.8 s, whereas that of the pilot group was 1.6 s. The assistance of the visual cue appears to lead to a greater reduction in the average response time for individuals without prior pilot training, as opposed to individuals with prior pilot training.

Although these numbers may not appear much when taken at face value, it is important to remember that visually acquiring intruding traffic several seconds earlier, and then taking corresponding evasive

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Table 5 Average response time in seconds for the pilot group: baseline category

Table 6 Average response time in seconds for the pilot group: assisted category

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Fig. 19 Average response time by azimuth with and without assistance (nonpilot group).

Fig. 20 Average response time by elevation with and without assistance (nonpilot group).

Fig. 21 Average response time comparing nonpilot and pilot groups.
action, could potentially reduce the chances of a collision actually taking place.

It is also interesting to note that, with the assistance of the visual cue, both pilot and nonpilot groups achieved very similar average response times, differing by only 0.4 s. This serves to demonstrate the merits of such an assistive technology, in the sense that individuals with no prior pilot training were able to visually acquire intruding traffic at approximately the same time as individuals with pilot training.

Figure 22 compares the differences in average response times between the baseline and assisted cases, across both the pilot and nonpilot groups, sorted by participant number. The minimum improvement seen within the pilot group was 0.2 s, whereas the maximum improvement was 2.9 s. For the nonpilot group, these were 1.2 and 5.9 s, respectively. The trends suggest that the visual cue provided a greater advantage to the nonpilot group than to the pilot group.

Figure 23 shows the average percentage improvement in response time for each participant, across both demographics, sorted in descending order. For the pilot group, the smallest reduction in average response time was 5%, whereas the greatest reduction was 41%. For the nonpilot group, the smallest reduction was 17%, whereas the greatest reduction was 49%.

Although both groups saw a reduction in the average response time, this percentage improvement was slightly more significant with the nonpilot group than with the pilot group. As suggested previously, this could perhaps be attributed to the fact that pilots are already trained to scan for intruding traffic, and, consequently, the time reduction that could be realized with such an assistive technology might not be as significant. Within a demographic with no prior training at detecting traffic, however, the benefits were more substantial.

**VIII. Conclusions**

In this research, a heads-up advisory display designed to assist pilots in the rapid location and identification of surrounding air traffic was developed on the Google Glass platform. The display was conceived as an extension to the existing traffic collision avoidance system implementation, and the primary goal of the research sought to determine if the presence of such an assistive technology would lead to quicker response times in visually detecting intruding air traffic.

The software featured a dynamically updating 3-D vector that continuously guided the pilot’s vision toward the direction of the intruding aircraft, and updated its orientation based on the relative head motion of the pilot, the motion of the pilot’s aircraft, and the position of the intruding aircraft.

In evaluating the effectiveness of this assistive technology, 16 participants were placed in a simulated flight environment, and tasked to visually acquire intruding aircraft with and without the assistance of the 3-D vector: eight participants had prior piloting experience and the remaining eight participants did not have prior piloting experience. The participants were given 21 aircraft to detect, and these aircraft were set up to approach the piloted aircraft from a wide range of approach angles and elevations.

It was observed that the average time taken to detect intruding traffic without the assistance of the 3-D vector was measurably greater than with the assistance of the 3-D vector. Aggregated across all 21 scenarios, the average response time was 6.3 s without assistance and 4.6 s with assistance for the pilot group. The same values for the nonpilot group were 7.9 and 5.1 s, respectively. The assistance of the 3-D vector helped to greatly reduce the time taken to detect intruding traffic. This was consistently observed across both the pilot group and the nonpilot group.

The differences in average response times with and without assistance varied greatly depending on the participant, approach azimuth angle, and approach elevation. The benefits of the 3-D vector were much greater in cases, in which the intruding aircraft would approach from peripheral angles and from below the piloted aircraft. Qualitatively, these were scenarios, in which the intruding aircraft were obscured against the backdrop of the ground environment—a very common scenario that often occurs in a real flight environment. In such scenarios, an improvement in average response time of over 60% was measured.

Further, it was noted that, without the assistance of the 3-D vector, the average response times of the nonpilots were approximately 30% greater than those of the pilots. With the assistance of the 3-D vector, the average response times of both the pilots and nonpilots were very similar. Among the participants with prior flight training, who were already trained in detecting traffic, the reductions in average response times were slightly less, although still quantitatively significant. It may summarily be said that the maximum potential of such an assistive technology could perhaps be fully realized for student pilots or pilots with less experience.

User type or scenario aside, the benefits of such an assistive technology are indeed very prevalent. Even in its current form—that is, software developed for the purpose of experiment—the assistive technology has already been shown to greatly improve response times in detecting intruding traffic. Quantitative results notwithstanding, the benefits of an assistive technology, with the potential to help pilots avoid air accidents, are innumerable. Further efforts to improve and optimize the aspects of this assistive technology, perhaps toward implementation in a real-world applied environment, could potentially lead to even better results.

**Acknowledgments**

This material was based upon the work supported by the John A. See Research Award. Any opinions, findings, and conclusions or recommendations expressed in this material are solely those of the authors, and do not necessarily reflect the views of the award sponsor(s).
References


