Development of a Powerful but Inexpensive Helicopter Flight Simulator

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ABSTRACT

This paper describes the design, development, and sample applications of a cost-effective, but powerful helicopter flight simulator. The Pilot/Rotorcraft Intelligent Symbology Management Simulator (PRISMS) has been developed to provide many of the features of simulators costing hundreds of times as much. An immersive, virtual reality approach has been used so that the pilot can turn his head to observe the aircraft or terrain in any direction. PRISMS offers head-tracked HMD symbology in screen-fixed, aircraft-fixed, and earth-fixed frames of reference, overlaying a gaming area of realistic terrain. PRISMS facilitates "quick-look" demonstrations, formal experiments, and training applications. The flight symbology, aircraft handling, and other characteristics are easily changed to suit the needs of the investigator. The system is portable for research or training in the field. This paper also describes the results of recent research conducted with 14 AH-64 Apache pilots in the evaluation of virtual waypoint and engagement area symbols as well as five other useful new HMD symbols.

PRISMS Design and Development

INTRODUCTION

The Need for an Inexpensive Simulator

During the conduct of an extensive study of intelligent helmet-mounted display (HMD) symbology management (Rogers, S.P., and Asbury, C.N., 1999), it became apparent that it was nearly impossible to evaluate potential new symbols without a sophisticated simulator; expert pilots could not effectively envision symbol behaviors and utility without "flying" them. It is extremely difficult to appreciate the complex dynamics and interactions of HMD symbols without observing them in action while moving both the aircraft and the head to different angles and attitudes. Furthermore, the results of symbology discussions with pilots are vastly more fruitful given the opportunity for both of the discussants to simultaneously observe and comment upon the symbology set in action.

For this reason, in the second phase of the project, the objectives were extended to include the provision of a sophisticated flight simulator that could be used in the evaluation of candidate HMD symbols. Such a simulator could permit the observation of symbology mode changes during a variety of flight maneuvers. The use of a sophisticated simulator can greatly enhance the quality of symbology studies and can aid in: integrating knowledge from the research, engineering, and pilot communities; demonstrating established problems and their candidate solutions; and applying the range of research tools in the most meaningful ways.

The advantages of such powerful simulators, however, are accompanied by well-known disadvantages. In general, they are extremely expensive to construct and maintain, require a team of specialized technical support personnel, are time-consuming to reprogram for new applications, and are certainly not portable to other locations where expert pilots might be permanently or temporarily located. These simulators are also in great demand for major research projects, such as the LHX studies of past years and the current Air Warrior research efforts. Despite the surge of interest in HMD display systems, it is extremely difficult for most research groups to obtain access to these costly and tightly scheduled simulators.

It was apparent that the only solution to these problems was in the development of a sophisticated, but relatively low-cost HMD research simulator, taking advantage of the most recent advances in technology. Such a system would be so inexpensive as to cost only 1% of current high-end simulators. It would be easy to reprogram, with a point-and-click graphical user interface. It would require no advanced programming training to design and conduct studies in a timely manner. It would be easily transportable for use at field sites. Finally, because of its revolutionary cost-performance ratio, it would provide a much broader segment of the research community with the simulation capabilities necessary for the experimentation so urgently needed for the development of new flight systems.

The following pages provide an overview of the Pilot-Rotorcraft Intelligent Symbology Management Simulator (PRISMS) design and development process, followed by the results of experimental and subjective evaluations of seven new HMD symbols.

PRISMS DESIGN ANALYSES

One of the goals of the development was to make the simulation as realistic as possible, incorporating "virtual reality" techniques such that the experience would include an "inside-out" perspective of self-directed flight through terrain landforms and full head movement for exploration and examination of surrounding features.

Different techniques for inducing virtual reality may be judged on the degree of "immersion" or sense of "presence" each provides. Although these are subjective aspects of the experience and there is no single metric of "immersion," many of the contributing factors have been identified, as shown in Figure 1. As indicated by the checked items at the right of the figure, it was determined that PRISMS could and should incorporate nearly all of the key features necessary for providing a fully immersive experience.

Despite its low cost, it was determined that PRISMS had to provide the capabilities necessary to show HMD symbology in screen-fixed, aircraft-fixed, and earth-fixed frames of reference (described below), along with facilities for symbology demonstration, knowledge acquisition, experimental control, and extensive data recording. In addition, and within cost constraints, many high-end features were to be included, such as a gaming area of realistic terrain, multiple moving targets, photo-textured objects, 3D sound, and voice synthesis and recognition.

In addition to the helicopter cyclic, collective, and pedal controls for full flight control by experienced pilots, it was deemed valuable to permit flight by non-pilots, such as offering flight along a pre-determined path, as if on an "invisible rail," for demonstrations or experiments not requiring aircraft control inputs. Between these two extremes, any level of error constraint could be invoked, such as flight within an "invisible tube" of experimenter-controlled diameter for use in studies employing beginning or intermediate-level pilots.

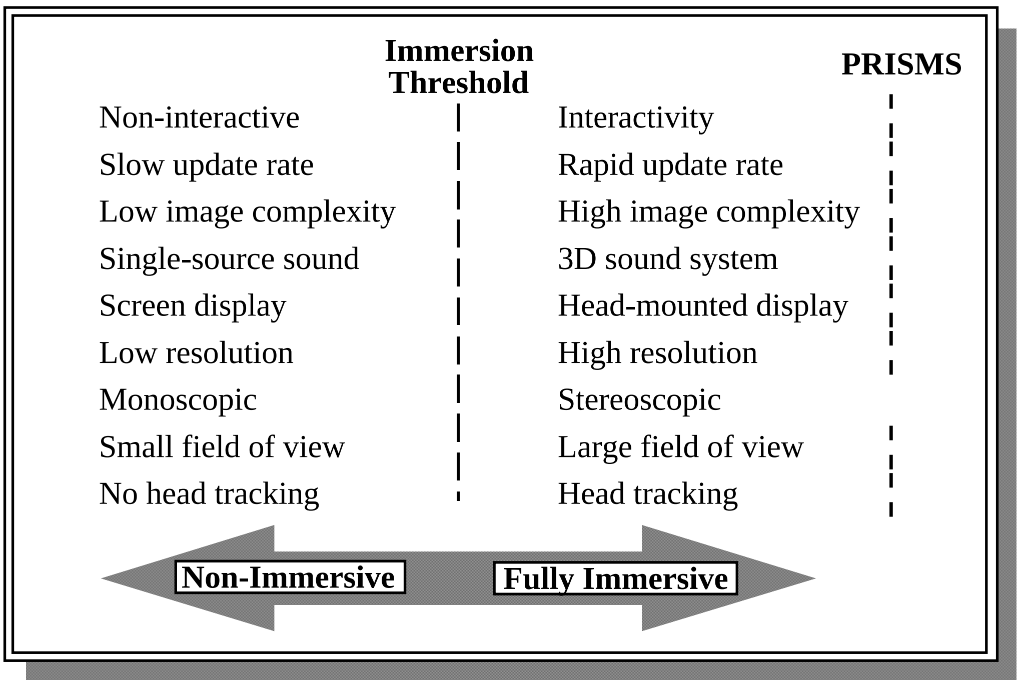

Figure 1. Factors influencing the degree of virtual reality immersion with checkmarks indicating PRISMS capabilities (adapted from Pimentel & Teixeira, 1993).

Desired Capabilities

Over the course of the project, sets of sample experimental scenarios were continually expanded and fleshed out in order to clarify the PRISMS design requirements. The primary requirements categories included (1) a set of selectable simulated flight capabilities ranging from fully automatic to partially constrained, to fully pilot controlled, (2) selectable HMD symbology elements of a broad number of types, behaviors, and moding structures, grouped and arranged as desired, (3) selectable capabilities for conducting experiments and demonstrations such as "head-down" views of horizontal situation displays or other data, (4) environmental controls (sun, moon, wind, haze, etc.), and (5) target appearance and weaponry applications for use in evaluating situation awareness.

PHYSICAL CONFIGURATION

Major Components

As shown in Figure 2, the two PRISMS shipping cases contain a cockpit station, an experimenter's station, and an electronics station. The cockpit station includes the pilot's seat, full flight controls, HMD with headphone and microphone, and head-tracking system. The experimenter's station includes a large-screen monitor (with a second monitor optional), keyboard and mouse, four-axis flight control, headphone and microphone, and the

Figure 2. The PRISMS system, nearing completion.

symbology management system. The electronics station includes two dual-CPU NT workstations, three OpenGL graphics accelerators, a six-channel audio mixer, a four channel audio amplifier, a full matrix video switching system, and a VGA to NTSC/PAL converter for video recording of PRISMS sessions.

Anthropometric Study

In planning the simulator physical configuration, an anthropometric study was completed to identify the range of dimensions necessary to accommodate test subject pilots and to meet typical control locations relative to human body dimensions. The control positions were adapted from MIL-STD-1333A, Aircrew Station Geometry for Military Aircraft. Although this document assumes seat adjustability, PRISMS was designed to use pedal position adjustability to provide the same anthropometric dimensional range at much lower cost and weight. The reach envelopes for all controls are within the comfortable zones for 5% through 95% male operators.

Packaging and Transportability

Cockpit design efforts focused on providing a realistic and effective control location geometry for the cyclic, collective, and pedals, while permitting the system to be rapidly packed or unpacked and set up. The design objectives included the use of shipping cases that permit quick access to seat and control mechanisms and storage for the HMD, CPUs, hard disks, and the associated computer components. The test subject's seat itself serves as a storage area in order to save weight and space. The total weight of the two packed cases is only seven hundred pounds. This weight allows for reasonably convenient transport to conferences, military facilities, and other meeting sites for clearly communicating symbology behavior and conducting knowledge acquisition sessions with subject-matter experts (SMEs).

Flight Controls

To reduce costs, high-quality gaming system hardware was selected for PRISMS controls. Two ThrustMaster controls were purchased including the F-16 FLCS Limited Edition control stick and the Rudder Control System (RCS). These served respectively as the cyclic and pedals of the PRISMS simulator. The FLCS was found to be quite satisfactory except for the high displacement force requirements, which were modified to reduce the forces to levels more representative of helicopter controls. A sturdy Flight Link control with a stainless steel arm served as the PRISMS collective.

Helmet-Mounted Display Selection

The selection of an HMD for PRISMS use was one of the more difficult issues. First of all, helmets vary across a broad range of parameters including horizontal and vertical field of view, brightness, color capabilities, video formats, pixel size and number, weight, and many other factors. Secondly, the range of costs is quite broad; roughly $1,000 to $120,000. After extensive deliberation, the Visette Pro, manufactured by Virtuality was selected. The Visette Pro is very sturdy and reliable, incorporates its own Polhemus InsideTrak system and provides a 60° by 47° field of view.

Since then, three of the nVision HMD systems have been used with good effect, including the Datavisor VGA, the Datavisor VGA/HiRes (up to a 78° field of view), and the DatavisorLCD (with a 60° diagonal field of view). The Virtual Research VR8 (also with a 60° diagonal field of view) has also been used with PRISMS. Given the rapid technological and cost changes occurring in the HMD field, PRISMS was designed to accommodate the use of any HMD, simply by entering the correct field of view.

Figure 3. The Virtuality Visette Pro helmet.

Head-Tracking

One of the PRISMS goals was to offer an "immersive" approach, providing an effective virtual reality experience for more realistic representation of military rotorcraft tasks. In response to the pilot's control inputs, the PRISMS aircraft altitude, attitude, heading, and speed change as they would in a real helicopter. An accurate head tracker was required so that symbology positioning and behavior is appropriately slaved to the user's head movements. The addition of an opaque visor on the HMD and accurate head-tracking fully involves the pilot in the simulation. As the pilot turns his head and shoulders, the field of view moves through the full-surround field of regard and additional portions of the aircraft or the terrain come into view. The effect of being fully surrounded by simulated terrain is enormously more realistic and immersive than peering at a monitor on a desktop.

The head-tracker also provides a look-down capability for the HMD imagery, presenting images in the cockpit area when the pilot rotates his head downward, as if to look at the console or his lap. As shown in Figure 4, maps, horizontal situation displays (HSDs), other avionics displays, or kneeboard data may be presented to the pilot in this manner. The head-down capability adds realism to

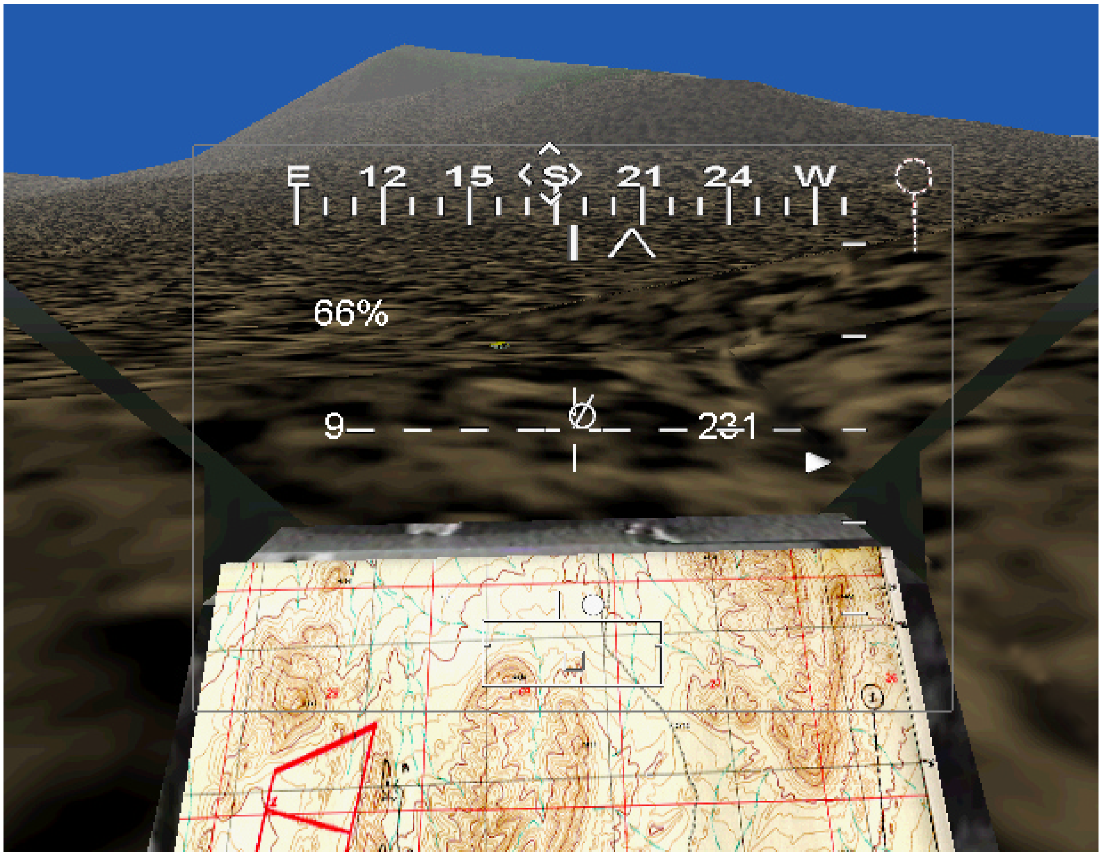

Figure 4. The PRISMS HMD view of a map on the aircraft console.

the situation awareness, navigation, or other experimental tasks performable in the simulator. If desired, and appropriate scaling and rectification values are entered, an aircraft present position "bug" could be also be shown on the pilot's map, simulating a digital map system. The Polhemus InsideTrak head tracker was evaluated and found to be quite suitable for PRISMS. PRISMS was also designed to use other head-tracking systems such as the Ascension Flock of Birds.

Experimenter Station

As the pilot flies, the experimenter or trainer is able to view several different movable and resizable windows on his monitor. As shown in Figures 5 and 6, the experimenter can simultaneously observe the pilot's HMD view, maps in various scales with present position indicators, and dialog windows designed for controlling session settings, events, or recordings. This context is similar to flying with the pilot in a test aircraft without the cost or safety concerns usually associated with test flights, and permits discussions of flight symbology during realistic, representative flight operations.

A present position "bug" can be displayed on the experimenter's station map, an invaluable aid for monitoring the pilot's progress through the terrain and his current heading and position.

The provision of a second aircraft, controlled with a joystick from the experimenter's station, was undertaken to lend additional realism to an already immersive environment. The second aircraft can be used as a wingman or an enemy aircraft, or simply as another "eye position" to view the exterior of the pilot's aircraft. Object and attribute passing using inter-process communication was implemented to allow each of the two helicopters to update the other's position.

The experimenter or trainer can stop the action, query the pilot on his actions or impressions, and replay a flight sequence after introducing a change in symbology. A series of scenarios can be predefined and linked together to permit a broad variety of tactical situations, aircraft maneuver requirements, and pilot activities in a brief time period. PRISMS is designed for flexibility of application so that individual researchers will find it easy to incorporate and demonstrate a wide variety of symbology ideas and easy to prepare for more formally designed experiments, demonstrations, "quick-look" evaluations, or training sessions.

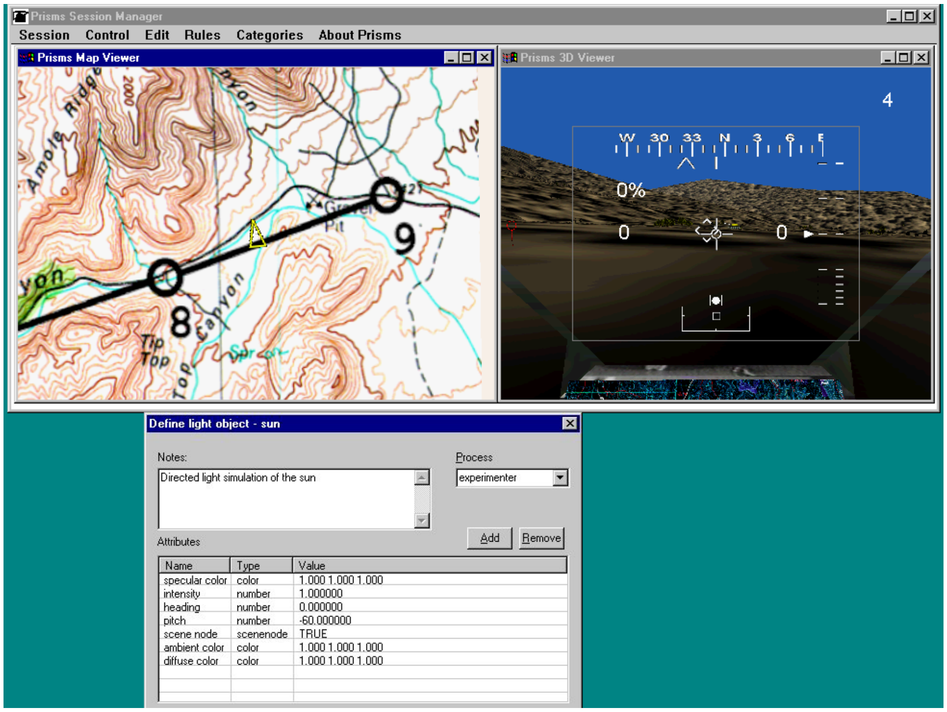

Figure 5. An example of windows available on the experimenter's monitor.

Figure 6. A view of the PRISMS experimenter's station.

Workstation Processors

PRISMS incorporates two dual CPU NT workstations. Depending upon the terrain models visible and the density of the vegetation texture, the frame rate ranges as high as 70 Hz. Frames rates are dependent upon a number of factors such as the extent of terrain visible (number of model areas depicted), the types of vegetation codes presented, and the number of symbol elements shown.

Any system can be "brought to its knees" by increasing the density of the presentation until frame rates fall below acceptable levels. For this reason, the PRISMS interface permits the experimenter to make the appropriate trade-offs. For example, a linear symbol "draping" algorithm was devised giving the experimenter indirect control over the number of points used to describe lines drawn on the terrain, trading off line precision against acceptable frame rate.

SOFTWARE

Flight Model

Although various flight models are commercially available, a unique model was deveoped for PRISMS because it permitted maintaining control over the model's complexity and the resulting impact on video frame rate. Furthermore, it assured direct control over variables such as thrust, power, mass, velocity, drag, torque, angular velocities and moments of inertia, relative wind moments, and trim adjustments,. Iterative qualitative evaluations of aircraft handling during flight through the New Mexico database were conducted by the authors, as well as Army helicopter pilots with very satisfying results and continual improvements to the fidelity of the aerodynamic simulation.

An Apache SME provided interim evaluations of the PRISMS simulator handling and helped to maximize the similarity of the PRISMS handling to that of the AH-64. In enhancing the PRISMS flight model based on the SME's suggestions, improvements to the handling qualities were made as quickly as possible, so that several iterations could be completed in the time available. In conducting these activities, the payoff of having of developed the flight model was most evident. SME comments about handling qualities could usually be directly related to factors such as mass or drag and corrections could be made accordingly.

A view of the SME in the PRISMS cockpit station is shown in Figure 7. The cyclic and pedal controls are visible, as is the HMD and head tracker. Components of the experimenter's station are shown in the background.

Although PRISMS currently is configured to have flight handling characteristics similar to the AH-64 Apache, it is important to recognize that the flexible flight model easily permits simulation of other helicopters. Fixed-wing simulation or ground vehicle simulation are also possible with relatively few changes.

Figure 7. Apache pilot testing the PRISMS flight model.

Symbology and Frames of Reference

Because Apache pilots form the available pool of attack helicopter SMEs, a complete set of symbols from the AH-64 Integrated Helmet and Display Sighting System (IHADSS) was constructed as a baseline to which other symbols may be added. In addition, PRISMS provides a set of tools for easily defining new symbols and their appearances, behaviors, and the rules for their presentation or removal from the current symbol set. PRISMS is also designed to permit the use of any of three different "frames of reference," as described below.

In order to effectively describe and control the behavior of HMD symbols, three different frames of reference must be considered. First, symbols may be "screen-fixed," as if painted on the helmet visor, so that they are always in the same position relative to the pilot's field of view. Nearly all of the Apache symbols are of this sort. Second, other symbols may be "aircraft-fixed," in that the symbol is moved or rotated to compensate for head movements and stay in the same position relative to the aircraft itself. The Apache has one (diamond-shaped) symbol that behaves in this manner. It is called the "head-tracker" and is used to show the relative position of the aircraft nose.

Third, symbols may be "earth-fixed," in that the symbol is moved or rotated to compensate for both pilot head motion and aircraft motion, so that the symbols appear to be located on or above positions in the real-world terrain. No earth-fixed symbols are currently included in the Apache. Flight simulator studies of these earth-fixed, or "conformal" HMD symbols have rarely been published in the open literature. One such study is that of Haworth and Seery (1992). Because the earth-fixed symbols are likely to have a major role in the next generation of HMD symbology, PRISMS was specifically designed to support their simulation.

Digital Terrain Data Availability

PRISMS uses the South West USA (SWUSA) database constructed by the Data Base Generation System (DBGS) group of Lockheed-Martin. The PRISMS geographic location mechanisms employed with the SWUSA data base were designed to include both latitude-longitude and UTM coordinate systems. These mechanisms permit the selection of flight areas during an experimental session, the definition of specific positions such as waypoints, and the scoring of flight performance precision. The accuracies of the mechanisms were repeatedly evaluated through analytical comparisons with USGS paper map coordinate and elevation data. The coordinates of prominent terrain features in mountainous portions of the New Mexico terrain were identified from USGS 1:24,000-scale paper maps. The coordinates were input to PRISMS and the accuracy of the generation of resulting views were evaluated through map-terrain analysis.

Metrics

In recognition of the broad range of potential applications of the PRISMS simulator, a concerted effort was made to include all of the tools the research community might require. A literature review was undertaken to identify the most important experimental methods and metrics, so that the necessary tools for each type of research would be made available. A primary objective of the interface design effort has been to permit the experimenter to choose and implement sophisticated metrics in the dialog without any requirement for additional software programming.

PRISMS was designed to incorporate a range of selectable performance measurements including: (1) root mean square error (RMSE) from a designated flight path, altitude, or airspeed, (2) accuracy of HMD reticle placement on a specified feature in the terrain, (3) response time for target detection and accuracy of target engagement, (4) total time of intervisibility with a known enemy position, (5) waypoint crossing accuracy, (6) precise position landing accuracy, and (7) evaluating pilot skills with aircraft maneuvers such as the Aeronautical Design Standard (ADS-33) "pirouette" with measures of altitude, heading, and distance errors.

In addition to these built-in measurement options, provisions have been made to ensure the ease of creating new metrics as needed by the experimenter or trainer. For example, some new PRISMS metrics were needed to support an experiment conducted with the Apache pilots. The dialog structure, with its provisions for creating rules, expressions, and operations, was used to construct rules that would start and stop timers for measuring head azimuth dwell times in nine segments of the forward 180°.

User Interface

A large portion of the system design activities was directed at user interface development. One of the primary objectives for PRISMS was that this powerful system be easily operable without need for sophisticated programming skills. Because the system is very versatile and the potential users may have countless ideas for demonstrations and experiments, great flexibility was required of the dialog. The challenge was in devising a dialog that could provide this flexibility without adversely impacting its ease of use. The design philosophy has attempted to balance an almost open-ended range of PRISMS capabilities with easy-to-use features for constructing and conducting experiments and demonstrations.

The initial intent in the development of the PRISMS dialog was to provide a broad range of powerful simulation and experimentation capabilities yet make the interface so intuitive and forgiving that it would require only pointing and clicking on button selectors, check-boxes, and entering a few text and numeric items. However, as the PRISMS system capabilities grew, the number of possible selections made such an interface unwieldy. Finally, with the decision to allow the PRISMS user to construct essentially any type of tasks, conditions, and metrics, the notion of a simple, unchanging graphic interface became wholly inapplicable. Instead, what was required was a more powerful, expandable dialog approach that could nevertheless be quickly mastered by a researcher without formal training in programming.

It also became apparent that the interface should include multiple levels of user interaction. At the highest level, a user-friendly interface should permit the selection of parameters for most experimental requirements, such as choosing the HMD symbols to be included and basic metrics to be employed. A series of pop-up and pull-down menus and screens has been designed to permit the experimenter to define the characteristics of an experiment or demonstration including objects in the terrain, flight plans, lighting, aircraft model constraints, auxiliary displays, HMD symbol types, performance measurement techniques, and a variety of other parameters. For example, Figure 8 shows the pop-up screen used for defining the nature of the simulated sunlight falling on the terrain.

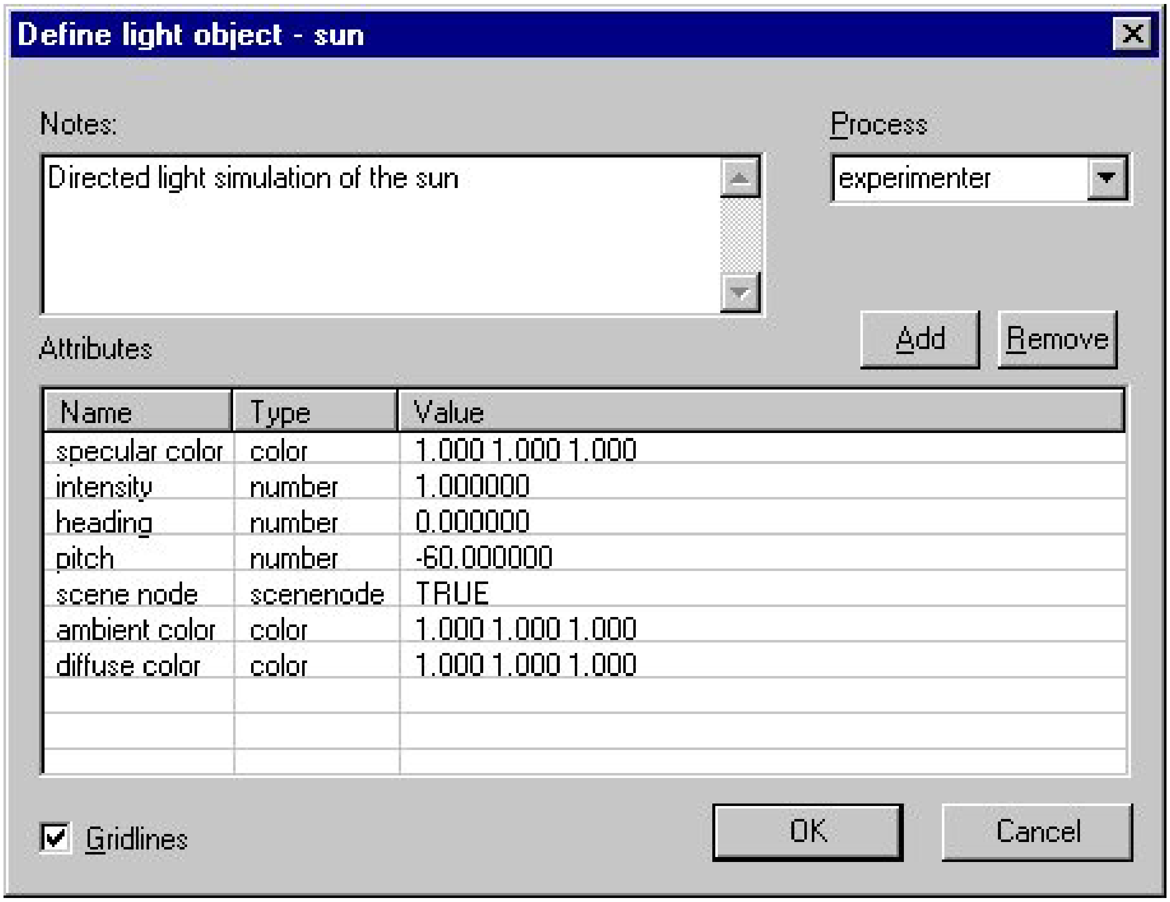

Figure 8. PRISMS dialog page for defining the sun simulation.

Although the authors attempted to create comprehensive high-level interfaces, it was recognized that the research community is an inventive one, and may create entirely new methodologies. To support these advances, a second level of user interaction with a set of "tools" was provided for building new experimental paradigms, metrics, and symbol characteristics without a requirement for programming skills. The result was a rule-based system with which the user specifies that *if* certain conditions exist, *then* certain events will take place.

Formalizing some rule statements is quite easy, and for some it is more challenging. First of all, it is necessary to determine how the knowledge should be described. In the domain of expert systems, things are typically described as belonging to three categories: *objects*, *attributes*, and *values*. For the purposes of this project, objects are usually (but not always) major components such as "the helicopter" and have attributes such as "airspeed" and "altitude" which in turn have values such as "40 knots" and "50 feet".

The objects and attributes already included in the PRISMS system may be all that many users ever need. The addition of new objects and attributes, however, is a straightforward task and is aided by the PRISMS dialog system itself. A dialog page summarizing a few of the hundreds of PRISMS objects is shown in Figure 9. Column 1 presents the object names, Column 2 the attribute name, Column 3 the attribute type, and Column 4 the current attribute value.

The dialog design has attempted to foresee a number of experimenter task requirements and provide assistance through special, user-controlled windows that may be displayed during the construction or conduct of an experiment. For example, the experimenter may wish to observe the changing values of some particular attributes in order to control various events during the simulation (such as the sudden appearance of an enemy vehicle). For such requirements, the PRISMS dialog includes an "Attribute Watch" window, as shown in Figure 10. The experimenter can move the window to a corner of his screen and add as many attributes as desired for monitoring purposes.

Once the necessary objects, attributes, and values have been identified, inferential relationships can be

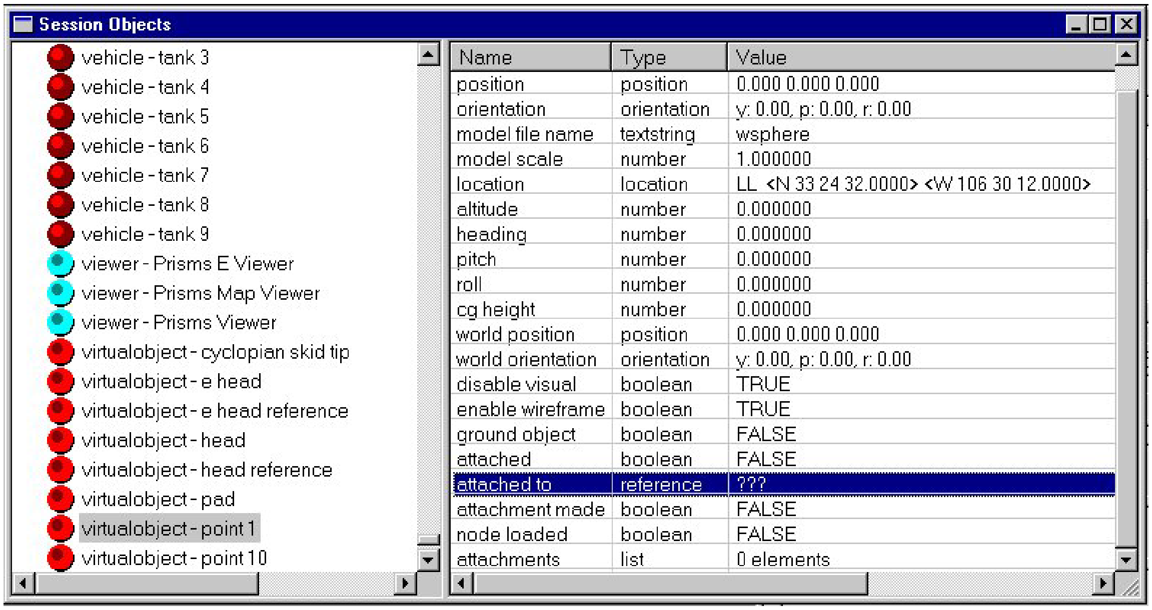

Figure 9. Sample of objects used in one PRISMS test session.

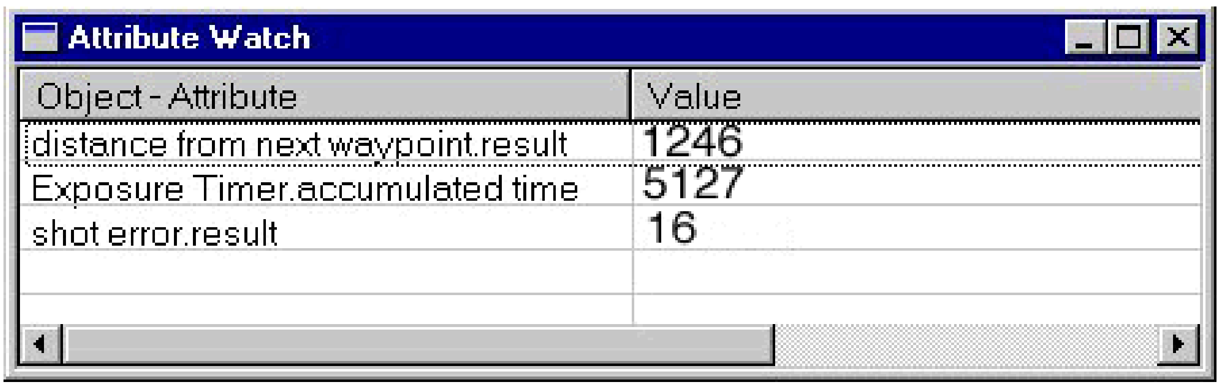

Figure 10. The Attribute Watch window for monitoring changing values.

stated in the form of rules. A rule uses an IF clause to identify one or more conditions that must be satisfied, and a THEN clause to indicate the inference. Both the IF and THEN clauses are stated using a mix of objects, attributes, and values.

Thus, at this second level of user interaction, a unique logical dialog is provided so that the user can easily set up an infinite variety of special task requirements or performance metrics. For example: "record elapsed time between Waypoint 7 crossing and designation of Target 3 unless altitude is greater than 200 ft." This development of this dialog structure was a significant system design achievement and was critical to meeting the project objectives. The third level of interaction is the programming level, required only for major system changes that could not be anticipated.

PRISMS Sound and Video Systems

PRISMS includes a six-channel audio mixer and four-channel audio amplifier for isolated communication between pilot and experimenter, input of helicopter and weapon sounds, 3D sounds, voice synthesis, distribution to NTSC output for video, external speakers. Full matrix video switching and VGA to NTSC/PAL video converter has been provided, permitting routing any of three graphics channels to any of four output channels (experimenter's monitors, subject helmet, and NTSC video).

A 3D sound generation has been implemented making it possible to produce sounds such that they appear to the pilot to be attached to a position in space or on the ground, regardless of the pilot's own head movements. These sounds may be used as desired by future researchers, perhaps evaluating the utility of a wingman “beep,” the positions and actions of enemy weapons systems, or spatial separation of incoming radio messages.

In addition, PRISMS voice recognition and synthesis systems have been implemented, permitting pilots to use voice commands for changing symbology sets or any other purposes. The experimenter may also use voice commands for control of experimental parameters. The voice synthesis system can be used with rule-based methods for use in presenting voice warnings such as used with the APR-39 warning system, or for other cockpit alerts.

PRISMS EXPERIMENT AND DEMONSTRATION APPLICATIONS

PRISMS is broadly applicable to a variety of demonstration, training and research roles. Subsequent to its development, PRISMS was used to compare performances on an attack mission with and without new earth-fixed symbology representing the positions of waypoints, battle positions, and engagement areas. It was also used in knowledge acquisition sessions, demonstrating a series of new concepts in HMD symbology for subjective evaluation by Apache SMEs. The results of these research techniques are described in the following pages.

Although critical to mission success, attempting to maintain situation awareness by identifying tactical positions in the terrain from navigation and map interpretation is extremely difficult. For example, the engagement area (EA) is typically defined by lines drawn on a paper map or transparent overlay and is often subdivided into fire sectors assigned to different friendly units. As described in Field Manual 1-112; Attack Helicopter Operations, EAs are used because it is critically important to correctly distribute and control the fires from available weapons. Attack helicopters must fire only in their assigned sectors in order to prevent fratricide, to avoid target overkill (such as firing 10 missiles at one tank) to avoid target underkill, and to use each weapon system in its best role.

Effective use of EAs depends largely upon the presence of some easily recognizable features in the terrain. Unfortunately, the battlefield area does not always offer obvious, discernible landforms and other terrain features so that finding the EA and the correct sector at night in unfamiliar terrain is an extremely arduous task. Near the battle area, the copilot-gunner’s (CPG’s) primary responsibility is operating the aircraft's complex weapon systems, and he has little time to aid the pilot in navigation tasks.

The pilot must frequently move between battle positions and firing positions in order to deceive the enemy, yet orient the aircraft properly for the CPG’s use of the weapons in the correct firing sector, an area that may be very difficult to identify. The problem is made even more difficult if the planned mission has been changed enroute, due to unforeseen changes in the situation, so that new EA positions and sectors must be assigned by radio.

The Attack Mission Experiment

In structuring these data-gathering techniques, we attempted to make the best trade-off between experimental control and realistic mission relevance, pretesting our methods with expert pilots. We also selected research topics to demonstrate the breadth of PRISMS’ capabilities for symbol development, performance measurement, and flexibility in adding and modifying study session features and characteristics. The experiment is described in detail in Rogers, Asbury, and Haworth (1999) and is only briefly summarized in this paper to indicate the sophistication of PRISMS data gathering capabilities.

Fourteen Apache pilots from the 1st Battalion (Attack), 211th Aviation Regiment, of West Jordan, Utah participated in a series of simulated flights to gather data on the new HMD symbology. The terrain selected for the experiment was located in south-central New Mexico in an area with mixed vertical development ranging from flat desert to low hills to mountains about 3,000 feet above the desert floor. The area selected for the experiment provided nearly ideal landforms for a helicopter attack mission, including cover and concealment along the route, good battle positions (BPs) behind a ridgeline masking the battle positions from the enemy armor column, and a large hill to the rear of the BPs so that the aircraft would not be “sky-lined” during the bob-up maneuver. A copy of a portion of this map is presented in Figure 11.

In the first experimental condition, the pilots were provided with no special symbols (unaided condition). They were instructed to examine a 1:24,000-scale paper map of the area of operations, complete with a attack mission plan overlay and drawing of the engagement area (EA). They were shown the head-down map visible in the helmet and told that it would display a series of overlapping portions of the route shown in the paper map. They were told that they were to overfly all of the waypoints and that the map and the command heading caret in the magnetic heading scale would be their only navigation aids. They were further instructed to maintain 100 feet AGL altitude and a 60 knot airspeed, to detect and fire on targets of opportunity, and to land at the Holding Area (HA) at Waypoint 5.

After landing at the HA, the pilots were instructed to examine the HMD map segment showing the path to the BPs and that they should fly to and land at the center BP, where the command heading marker would lead them. They were instructed to proceed at approximately 40 knots, to maintain masking from the enemy positions to the west, and to land at the BP as accurately as possible. After landing at the BP, the pilots were instructed to look at the HMD map segment showing the EA in its entirety and to observe the three firing sectors. They were told that upon bob-up they would see a column of enemy tanks (16

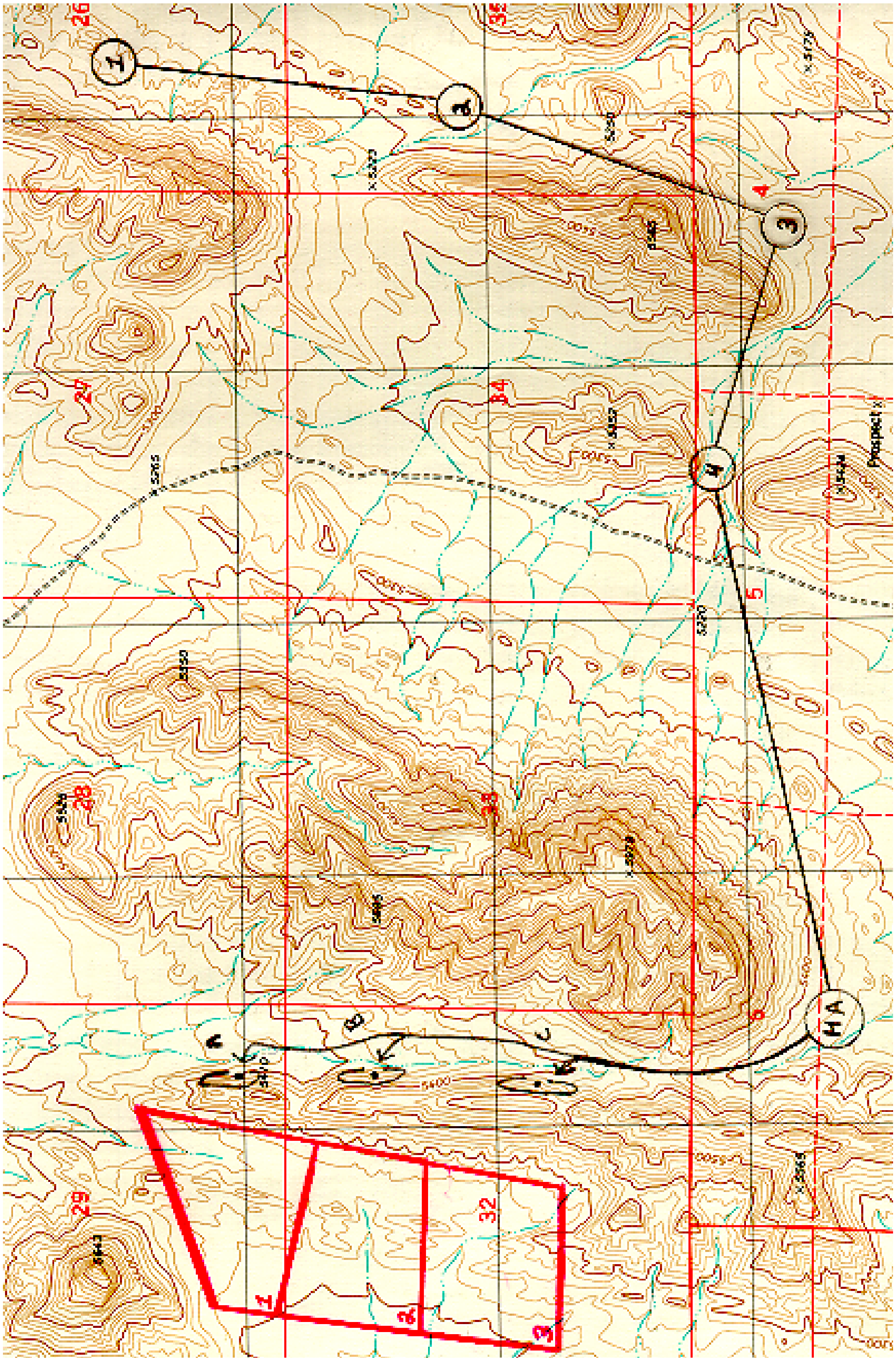

Figure 11. A part of the topographic map of the experimental area.

tanks were visible) and they were to fire on only two tanks: the one closest to the left boundary of the center sector and the one closest to the right boundary of the center sector. They were urged to fire within 15 seconds and then bob down to the BP. The pilots received no feedback regarding their accuracy in performing any of the tasks.

The second condition of the experiment included the presentation of earth-fixed symbols (aided condition). In all cases, the aided tasks were performed after the unaided tasks. After a rest period of about two minutes, the pilots were instructed that the next condition would be the same as the previous one except that they would be aided by virtual waypoint markers, or "lollipops," along the route. They were also told that when they closely approached the waypoints, they would be able to see a 10-foot hemisphere marking the exact spot on the ground, as shown in Figure 12. These hemispheres could be used to aid accurate landings at the HA and the BP, especially if the aircraft had overflown the waypoint and the waypoint marker had jumped to the next waypoint. The rest of the instructions were identical to those of the unaided condition.

at the BP in the aided condition, the pilots received the same instructions as in the unaided condition, except they were told they would be able to see the EA in the terrain and should shoot the two tanks nearest the lines marking the left and right boundaries of the center sector. Figures 13 and 14 show the pilot's view of the EA symbology as it is seen from the BP. Figure 13 shows an example of the dotted lines of the symbol becoming solid as the aircraft rises from a masked position behind the ridgeline. Figure 14 shows the appearance of the assigned central section of the EA viewed from above the BP.

Experimental Design

The single independent variable in the experiment was the presence or absence of the earth-fixed HMD symbology marking the waypoints and the EA boundaries. To control for the very large range of individual differences in performance, a repeated measures design was selected in which each subject flew both the unaided and then the aided conditions. During the first flight through the mission area, the pilots received no feedback from the experimenters regarding the accuracy of their

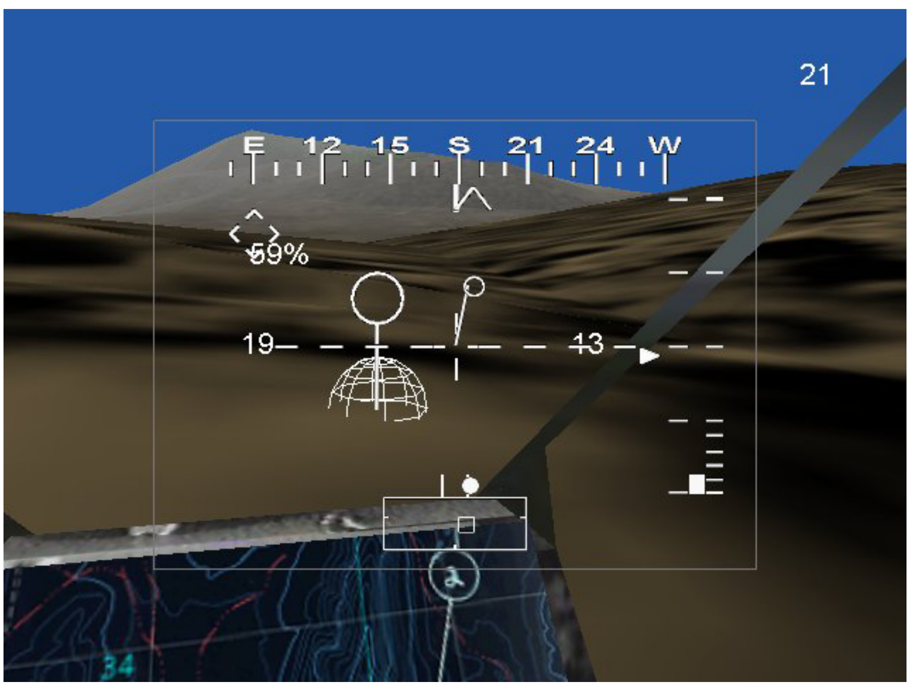

Figure 12. Examples of the "lollipop" and "igloo" waypoint markers.

After landing at the HA in the aided condition, the pilots were instructed that, in addition to the BP marker, they would see the EA marked out with red lines in the terrain and that if the aircraft was masked from the EA, the red lines would appear as dashed lines. Upon landing

waypoint crossings, landings, shots at the EA, or on any of the other performance metrics. During the second flight, the earth fixed symbols provided the pilots with direct feedback on their performance accuracy.

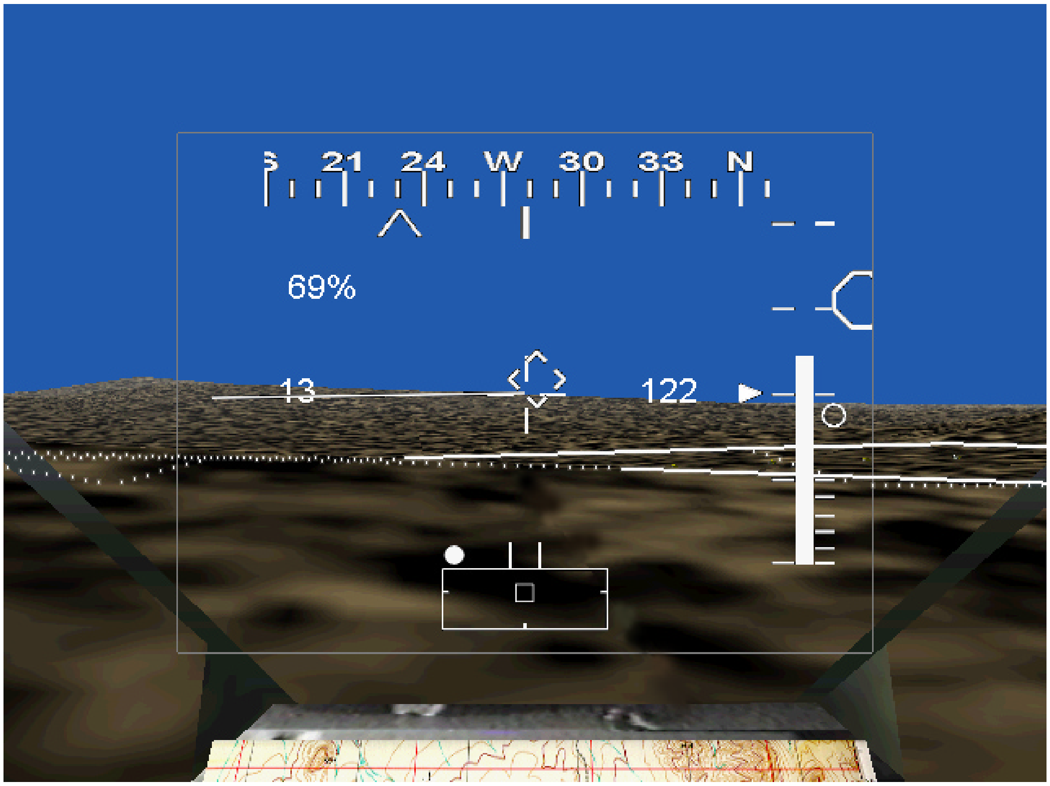

Figure 13. Partially masked view of the EA from the BP.

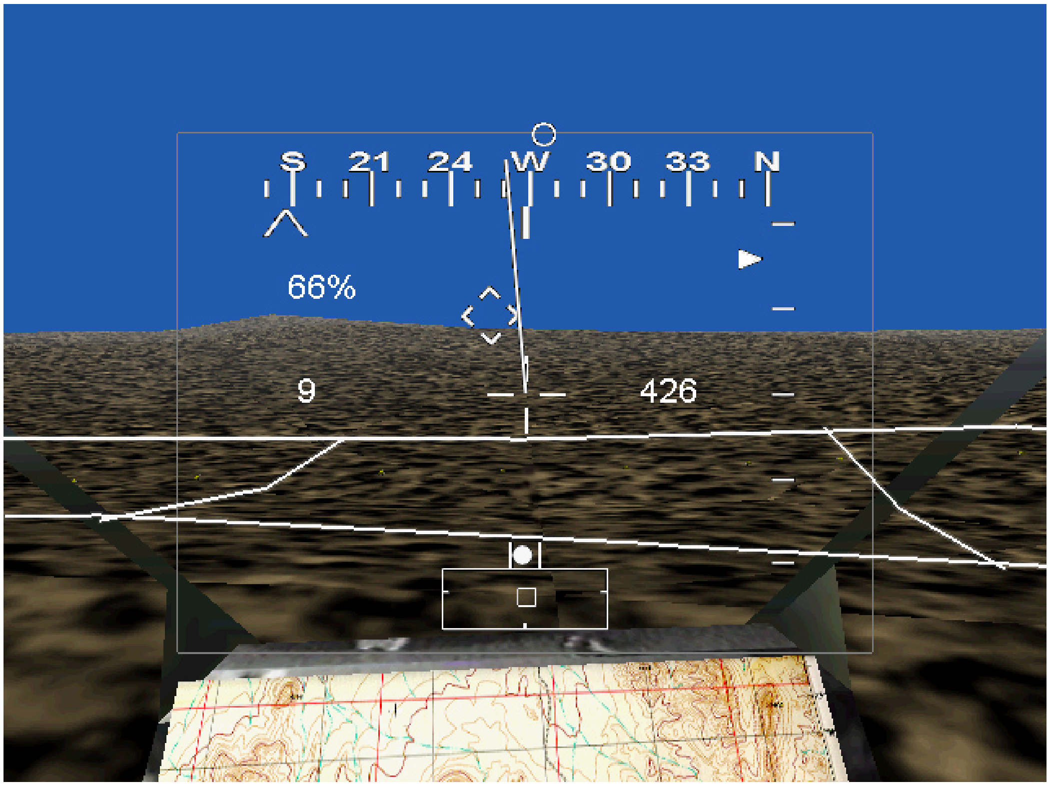

Figure 14. Direct view of the central section of the EA from the BP.

The experiment included ten dependent variables. The earth-fixed symbology was expected to greatly reduce pilot workload in the navigation tasks and increase situation awareness. Because performance measurements are not always clearly related to these improvements, a number of different metrics were employed in attempting to identify enhanced performance. These included the accuracy of waypoint passage (feet), the number of targets of opportunity detected (number fired upon), the landing distances from the HA and BP (feet), the accuracy of altitude maintenance (root-mean-square error, or RMSE feet), the accuracy of airspeed maintenance (RMSE knots), the total exposure time to the EA enroute (seconds), the total number of exposure events, the total exposure time during the bob-up (seconds), and the accuracy of target selection in the EA (feet).

In addition to the objective performance measures described above, after the aided condition was completed, the pilots were requested to estimate the workload reduction percentage resulting from the presence of the waypoint markers and also from the presence of the EA sector lines. As an extension to these estimates, they were queried regarding the perceived utility of the earth-fixed symbols, their suggestions for improving them, and their recommendations for the conditions under which these symbols should appear and disappear from the symbology set.

Results of the Experiment

Accuracy of waypoint passage This metric (the sum of passage distances for Waypoints 1 to 4, the HA, and the BP), was significantly better for the aided group, $t(13) = 7.276$, $p<.001$, with a mean distance of 878 feet (SD = 373) vs. 287 feet (SD = 215) for the total error over six positions. The respective means for an individual position are 146 feet and 48 feet. Every pilot in the study was considerably more accurate with the earth-fixed aids to waypoint recognition than without them. The relative difference between unaided and aided conditions was consistent across all six waypoints.

Landing distances from the HA The distances between the designated position of the HA and the actual landing positions of the aircraft differed significantly, $t(12) = 4.679$, $p<.001$; the mean distance in the unaided condition was 1,130 feet (SD = 588) and the mean distance in the aided condition was 262 feet (SD = 481). All of the pilots but one were closer to the HA with the earth-fixed waypoint markers. Had that pilot's score not been included in the group, the mean distance from the HA for the aided condition would have been halved (131 feet).

Landing distances from the BP. The distances between the designated position of the BP and the actual landing positions of the aircraft differed significantly, $t(11) = 5.458$, $p<.001$, in a manner very similar to that observed with the HA landing distances. The mean distance in the unaided condition was 1,111 feet (SD = 529) and the mean distance in the aided condition was 256 feet (SD = 406). All of the pilots landed closer to the BP with the waypoint markers than without them. Again, however, one of the pilots made a large landing error (1500 feet) even with the waypoint marker. Had his score not been included in the group, the mean distance from the HA for the aided condition would have been much smaller (143 feet).

Mean exposure time to the EA enroute. In both unaided and aided conditions, pilots were advised to maintain masking behind landforms to prevent their detection by enemy forces in the EA. The unaided group accumulated an average of 28.7 seconds of exposure time (SD = 27.0), and the aided group accumulated an average of only 15.8 seconds (SD = 22.2). This difference was significant; $t(13) = 2.234$, $p<.05$.

Mean number of exposure events. The unaided group exposure events ranged from zero (one pilot) to four with a mean of 1.93 events (SD = .997). The aided group exposure events ranged from zero (six pilots) to three with a mean of 1.21 events (SD = 1.188). This difference was also significant; $t(13) = 2.687$, $p<.025$.

Total exposure time during the bob-up. The exposure time during the bob-up maneuver was collected primarily to indicate whether or not the pilots were able to comply with the experiment instructions to complete the maneuver rapidly. The exposure time prior to firing the second shot was 22.7 seconds (SD = 12.3) for the unaided condition and 20.5 seconds (SD = 13.0) for the aided condition. The exposure times from first exposure to remasking after the bob-down were 42.3 seconds (SD =19.7) for the unaided condition and 39 seconds (SD =18.6) for the aided condition. Neither of these differences were statistically significant.

Accuracy of altitude maintenance. The mean RMSE around the 100 foot AGL altitude was 112 feet (SD =48.1) for the unaided condition and 93 feet (SD = 42.7) for the aided condition. This difference was not statistically significant.

Accuracy of airspeed maintenance. The mean RMSE about the 60-knot airspeed was 16 knots (SD = 7.1) for the unaided condition and 22 knots (SD =6.5) for the aided condition. This difference was not statistically significant.

Number of targets of opportunity detected. The average number of targets of opportunity hit, out of a possible 4 was 1.6 for the unaided condition (SD = .73) and 1.7 for the aided condition (SD = 1.43). This difference was not statistically significant.

Accuracy of sector identification in the EA. The utility of the earth-fixed EA symbology was particularly dramatic. The average error (as a sum of the two shots) was 1666 feet (SD = 869) in the unaided condition and 14 feet (SD = 54) in the aided condition. Not surprisingly this difference was statistically significant $t(13) = 7.147$, $p<.01$. In the unaided condition, only 3 of 28 shots were directed at the correct points. In the aided condition, 27 of 28 shots were fired at the tanks on the sector boundaries; one stray shot was directed at a tank 201 feet away from the correct one.

Workload reduction estimates. Although there many techniques have been used to estimate workload and workload reduction, most of these require a substantial investment of time. In attempting to gather as much flight and knowledge data as possible in the 90 minutes available with each pilot, a very simple metric was chosen for workload reduction estimates. The pilots were asked, given the flights with and without the ground-fixed symbols in PRISMS, how much their workload would be reduced for similar operations in the aircraft. The responses were extraordinarily favorable for these symbols. The mean workload reduction attributable to the waypoint symbols was estimated at 55% (SD = 25.4). The mean workload reduction attributable to the EA symbols was estimated at 69% (SD = 24.3). These are certainly impressive votes of confidence for these new symbol types.

Summary. The experiment was most effective in demonstrating the overwhelming advantages of the new earth-fixed symbol types for use with HMDs in military helicopters. The accuracy of position-finding in the terrain improved by approximately 300 to 400 percent with display of the virtual waypoint symbols. The exposure to enemy forces through inadvertent unmasking was reduced by approximately one half. The EA fire sector identification accuracy was improved by about 12,000 percent. In addition to these important findings, the experiment has also demonstrated the relative ease with which PRISMS can be used to construct and edit experimental sessions, add and improve symbology features and behaviors, provide realistic terrain and objects, and provide an extensive range of performance measures—all in two cases that are easily transportable to the field for experiments with, or training of, military pilots.

HMD SYMBOLOGY EVALUATIONS USING PRISMS DEMONSTRATIONS

The following pages provide a summation of pilot subjective data, amplifying the objective data gathered during the experiment, previously described. The first two subsections present the pilots' responses to the waypoint marker symbology and the EA marker symbology. However, because there were many more opportunities for new HMD symbols than could be evaluated in formal experiments in the scope of the project and because PRISMS has been specifically designed for "quick-look" evaluations and knowledge acquisition sessions, symbol demonstration sessions were constructed to show the pilots some of these new concepts.

The five new concepts demonstrated included special new symbology for presenting slope landing data, wind speed and direction, required speed for accurate arrival time, threat weapon direction, and flight path prediction. Each of the demonstration sessions are described in terms of the background and reasons for their development, the instructions given to the pilots before the demonstration, the pilots' overall subjective responses, and specific topics pertinent to each symbol.

WAYPOINT MARKER SYMBOLOGY

Background

Following a planned route at low nap-of-the-earth (NOE) flight altitudes is an extremely demanding task. Other than a rough sketch map on his kneeboard and the command heading caret in the heading scale, the Apache pilot is almost entirely dependent on the copilot-gunner (CPG) for navigation information. As a result, the pilot's situation awareness is often less than optimal. It is usually too dangerous to look down at the sketch map when flying NOE, especially at night. In some cases the pilot may try to memorize the flight legs (the heading and distance to each new waypoint). The CPG currently must help the pilot by "talking him through" the waypoints with the use of a map and avionics in the front cockpit.

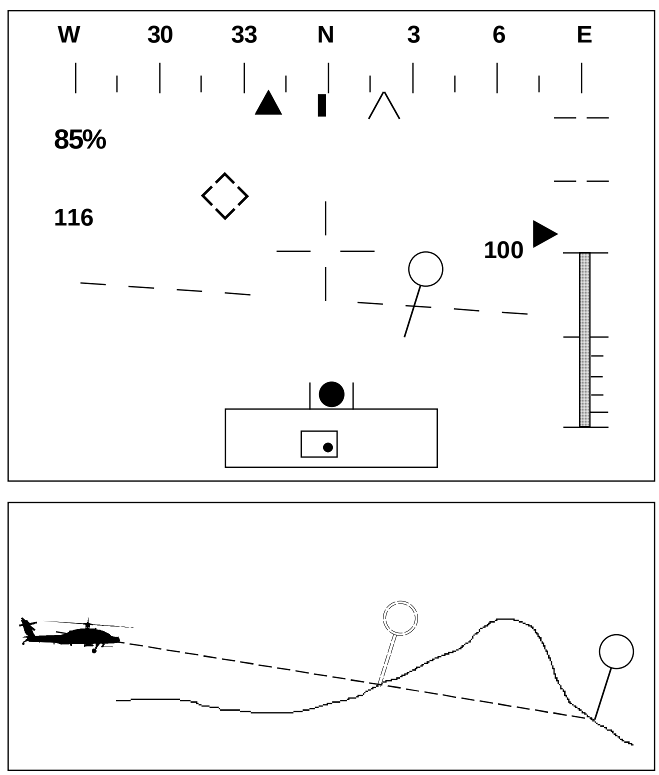

Figure 15. The appearance of the virtual waypoint marker with the other HMD symbology (above) and an explanation of the meaning of the dashed symbol (below) showing a waypoint obscured by intervening terrain.

Because of these known operational difficulties and given our search for high-payoff improvements, the first new symbol to be chosen for experimental evaluation was the virtual waypoint marker, similar in some respects to one of the advanced features planned for the RAH-66 Comanche helicopter. It is an earth-fixed symbol that appears to the pilot to be a giant map-tack or "lollipop" stuck in the real-world terrain to show upcoming waypoints, thus reducing navigational workload.

Instructions to Pilots (Aided Condition)

The pilots were instructed to examine a 1:24,000-scale paper map with a flight plan overlay. "The mission will begin just northeast of Waypoint 1 and continue through Waypoints 2, 3, and 4 to a Holding Area, then on to a Battle Position. Along the route to the Holding Area, try to maintain 60 knots and 100 ft AGL altitude. You need not follow straight flight legs between waypoints, but you must overfly the waypoints. In addition to the Command Heading Caret under the magnetic heading scale at the top of the display, we will add some symbols that point out the waypoints to you. They look like "lollipops" (The SME was shown a drawing of the virtual waypoint symbol). When you cross a waypoint, the symbol will appear over the next waypoint. If the next waypoint is obscured by terrain between it and your position, the symbol is shown by a red, dashed outline."

In addition, another figure was shown to the pilots to depict an additional cue to waypoint and landing positions. The cue had the appearance of a small "igloo" 10 feet in diameter. This symbol, unlike the waypoint symbol, did not disappear (jump to the next waypoint) as the aircraft passed the waypoint position. Thus, it could be used as a continuing reference point which was particularly useful for landings.

Overall Response

Without exception, the pilots praised the virtual way-point marker utility. Comments included "lots of merit," "definitely a workload reduction," "I love it," "excellent," "very useful," "boy, I like that," "Nice," "definitely going to help you," and "very valuable." They noted that the markers were much better than following the heading cursor because it was unnecessary to fly a straight line between waypoints. With the waypoint markers, the pilot could follow a frequently changing course offering the best cover and concealment between waypoints.

During planning, the pilots attempt to select easily identifiable features like road intersections or mountain peaks as good check features, but such features are not always available, or may be difficult to see in the actual terrain. As another pilot put it, the "where am I?" kinds of questions "happen constantly." and the waypoint markers would "really help situation awareness."

They observed that in some cases the pilot doesn't always "have tons of work to do if the guy in front is navigating," but if the CPG gets "task-overloaded" or makes some mistakes, "things become much tougher." The front-seater is particularly busy working on navigation, continuously figuring the heading and distance to waypoints, using a strip map and the Doppler system. He is head-down most of the time, and verbally relays course and speed information to the pilot, attempting to bring the aircraft to the waypoints accurately and on time.

Under this pressure he sometimes makes Doppler input mistakes and "the pilot must always anticipate where his directions should take you" and tell the CPG when he must be wrong. The navigation task is "especially tough if you are the lead aircraft -- knowing where the next waypoint is, is much more significant with people following you."

The waypoint markers would "definitely reduce workload" for both men, letting them concentrate on other tasks. They would let the CPG "hunt for targets" and let the pilot make better use the terrain and look for targets of opportunity.

Additional Information Recommended

Nearly all of the pilots believed that the waypoint marker information should be augmented to include waypoint distance from the aircraft, in kilometers. As one pilot explained, "The waypoint symbol gives an intuitive sense of direction, but not distance. I want the range so I can use the terrain to advantage." The range of the waypoint is currently obtained from the Doppler by the CPG and passed to the pilot. The range data can become especially important when trying to make accurate passage times, "such as FLOT passage times."

Several pilots suggested that the waypoint should be specifically identified by number. Some sort of coding should permit easily matching a waypoint on the map to the waypoint symbol seen in the HMD. The pilots cautioned that the Doppler numbers are not the same as the waypoint numbers. For example, Doppler Number 5 could be Waypoint Number 17, which tends to be confusing. One pilot said he uses the taxonomy of "waypoint" to be equivalent of Doppler number, and "air control point" (ACP) to be the number on the mission plan and another term such as FARP to describe the nature of the position. In any case, the waypoint number on the mission plan is the one that should be shown with the symbol.

Some of the pilots also thought that letters, shape codes, or color codes should be used to identify the earth fixed symbols. "You could use T for a target, H for holding area, F for FARP, A for ACP," and so forth. This could save a lot of time since the pilot is "always asking the front seater what's where." Another code might be used when using the laser to "store points for targets that the aircraft could attack on the egress route." Using conformal markers this way could permit designation of many more targets for the second pass through the same route.

The pilots were divided on where to show the distance and waypoint identifier. Most believed that it should be inside the waypoint marker circle, or adjacent to it, but others were concerned about its readability if small enough or the clutter it would introduce if large enough. Two of the pilots mentioned that their unit was about to receive the Embedded GPS Integration (EGI) retrofit. When a waypoint is selected, this unit will display the range to the waypoint in the right side of the High Action Display (HAD). The EGI display may thus provide the necessary distance information without additional clutter to the center of the waypoint symbol.

ENGAGEMENT AREA SYMBOLOGY

Background

This new symbol (shown in Figures 13 and 14) belongs to a class of more complex, earth-fixed markers ("augmented reality") proposed after the authors' prior interviews with expert Apache pilots (Rogers, Spiker, & Asbury, 1996). This class of symbols would aid the pilot by pointing out critical tactical demarcations and zones on the ground such as phase lines, planned artillery fires, international or unit boundaries, holding areas, battle positions, and target engagement areas. Such markers are presently defined on transparent operations overlays superimposed on paper topographic maps that are very difficult to use in the cockpit. If they were instead presented with HMD symbology in an earth-fixed frame of reference so as to appear "painted" on the ground, the benefits could include reduced navigational workload, improved tactical situation awareness, and diminished risk of fratricide (destruction of friendly forces).

Instructions to Pilots (Aided Condition)

When the pilot had reached the BP, he was directed to look downward to view the map and its tactical overlay data showing the EA. "As you can see on the map, the EA is divided into three firing sectors. Your team has been assigned the center sector. On my command, you will bob up to an altitude sufficient to view the EA sectors drawn out on the terrain and observe a column of enemy tanks. You are to fire on only two tanks: the one closest to the left boundary of the center sector and the one closest to the right boundary of the center sector. Both shots must be completed within 15 seconds after the bob-up, then bob down to land at the BP."

Overall Response

The pilots were perhaps even more enthusiastic about the EA symbology than the waypoint symbols. Comments included "huge utility," "worth their weight in gold," "enormously easier," "I love that symbol," "awesome," "so much easier," and "tremendous workload reduction."

All of the pilots confirmed the difficulty of the fire control and distribution process. "Units spend a lot of valuable time at the BP trying to get this right." Pilots can't tell where the targets are without good target reference points, and these are rarely available. Currently, in the operational setting, "dicing up the EA is always a challenge." Even though there may be roads and streams in the area, actually seeing them at night "can be quite challenging." The EA symbol would "save time, ordnance, confusion, and money," and avoid the problems of fratricide and "hitting the same target many times." The EA symbol would lead to "a marked increase in the economy of ammunition used." Without these symbols, "it's a stab in the dark." None of the pilots characterized the experimental task as unrealistically difficult.

Information Distribution

Two pilots observed that it's important that both the pilot and the CPG have the EA symbols for situation awareness and coordination. A very experienced pilot stated that the fire control sectors in the EA should be identified during mission planning, using the AMPS, and this information should somehow be directly routed to the HMD symbology generator. The same pilot noted, however, that sometimes when the unit arrives at the BP, the tactical situation has shifted and in such cases it would be extremely valuable for the battalion commander to be able to "data-burst" new fire sectors to the companies. Two pilots suggested that "you should show battalion, company, and fire team sectors," and some suggested the use of color codes for identifying the various sectors.

Use as a Masking Cue

The use of the dashed EA lines as a cue to masking from the enemy positions received mixed reviews. Many found the broken red line masking cue to be very valuable. One pilot, for example, stated that "the use of the dotted lines as you're moving in to get to the BP helps a lot." Another said "I can't believe how much better I flew this" (section of the route) because of the dashed line cue to masking. Some who praised the solid lines nevertheless found the dashed lines "potentially confusing" because of their unfamiliar perspective. The confusion might disappear with more exposure to the dashed line symbol. As one pilot said, "with more experience" he would "learn to use the solid and broken lines more effectively."

SLOPE LANDING SYMBOLOGY DEMONSTRATION

Background

Although pilots would always prefer to land on flat terrain, sometimes landing on a slope is unavoidable. The Apache slope landing limits are 10° of roll, 7° nose-up, and 12° nose-down. Unfortunately, no clinometer is provided in the aircraft for determining the steepness of slopes. For example, with a lateral slope, the pilot contacts the slope with the upper wheel, then gently lowers the downhill wheel toward the ground by lowering collective, while attempting to judge whether the limit is about to be exceeded from the trim ball and out-the-window visual cues.

Instructions to Pilots

"Apache pilots know that the slope landing limits for the AH-64 are 10° of roll, 7° nose-up, and 12° nose-down. However, judging the actual slope of terrain is difficult. The next symbol we want to show you is the Slope Landing Aid, or inclinometer. (the pilot was shown an illustration similar to Figure 16 as the symbology function was explained).

When one wheel touches the ground, four tic marks appear in the HMD. The two marks in the center are used with the horizon line to show nose-up and nose-down limits. The two tics toward the right sight show the left and right roll limits.

We'll start by looking at the symbology in an aircraft that has already landed on a fairly steep hillside. If you do a slow pedal turn on the ground you can see how the horizon line changes with respect to the tic marks as the direction of slope changes.

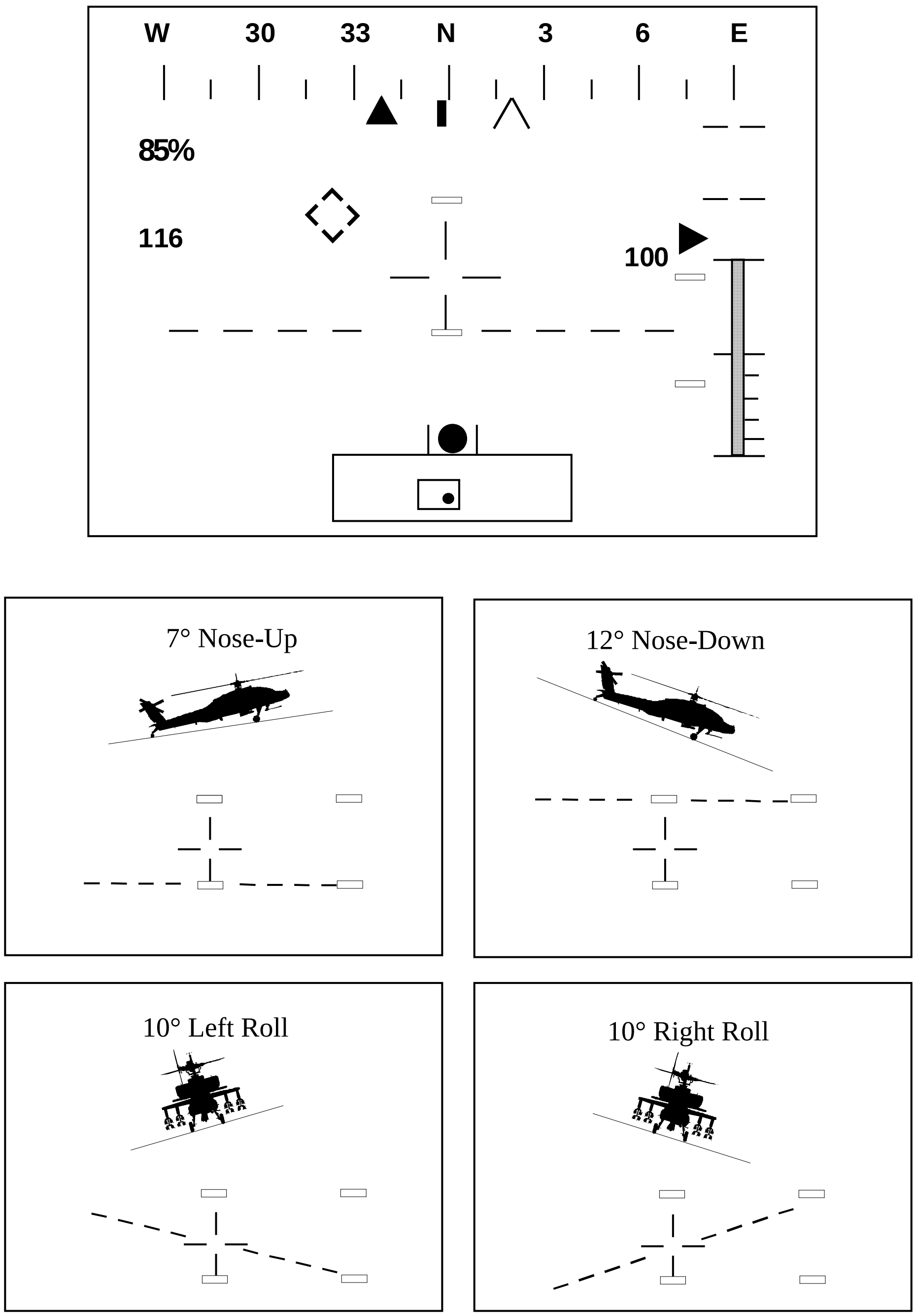

Figure 16. The four tic marks used with the horizon line for slope landing.

Now try gently picking the aircraft up and landing to see how the symbols change and go on and off. As you lower the collective, you can watch the horizon line and the tick marks to see if the slope is acceptable for a landing."

Overall Response

Five Apache pilots evaluated the Slope Landing Aid, and all agreed that it would be a very useful addition. Additional comments included "I like it," "It's easy to understand," "It would be good for any kind of landing," "very helpful," and "I can work with this easy."

Typical Slope Landings

The pilots stated that it is very hard to tell how steep the slope is, especially at night. As a result, they currently avoid slope landings at night unless they are absolutely required. In addition, at night a landing spot may appear to be flat when in fact it is not. After initial touchdown, there is about 6 inches of compression of the strut, then some expected additional compression of the snow or dirt. Then surprises may happen. Day or night, slight slopes can suddenly become much greater when a wheel slips over a ledge, sinks into a gopher hole, or settles deeper into the snow.

To counter these surprises, Apache pilots carefully "feel" their way down, to make sure they do not exceed the angular limits of 10° left or right roll, 7° nose-up, and 12° nose down. Currently, their only instrumentation cue for slope landings is the trim ball. The trim ball "rolls" along the top of the field of regard box, and when it reaches the point at which it is centered on the edge of the box, the aircraft is approximately at a 10° roll angle. The ball stops at the edge of the box, so pilots can't actually tell if the 10° roll angle has been exceeded. Of course, the trim ball is not a useful cue for nose-up or nose-down landings, and it's "especially hard to tell for nose-up and nose-down conditions" whether the slope limits are being exceeded.

Symbol Activation Suggestions

Pilots agreed that the use of the wheel touch-down would be a good way to make the slope landing symbol appear. One noted that "it's good to know that event anyway;" that is, the symbol appearance would be useful in indicating a touchdown. "You can't trust the altitude sensor for indicating your touchdown."

Unfortunately, the Apache "squat switch" is currently implemented only on the left side of the aircraft. This could cause a problem when aircraft on the ground are aligned in "herringbone or wagon-wheel patterns." Two of the pilots suggested that a second squat switch could probably be added at minimal cost. Another approach would be to use an accurate "ground proximity switch." If a ground proximity approach were to be available, "you could simply use the last four feet of altitude" (to turn on the symbol) because below that is the "limit of hovering flight," an Army standard.

Three of the pilots pointed out that in addition to use during slope landings, it was "nice to land and get the horizon line" without having to go back to the transition mode from the hover mode through actuating the thumb switch.

One pilot pointed out that the symbol would not have to be visible whenever the aircraft was on the ground, but would only be needed upon landing, and not at takeoff. So, "if the aircraft systems were turned on while the aircraft was on the ground, the tic marks and horizon line would not be there, but would appear just on landing," an easy rule to implement.

WIND INDICATOR CUE SYMBOLOGY DEMONSTRATION

Background

The Apache airspeed symbol in the HMD does not currently show the relative direction of the wind, although it does show a speed even if the helicopter is not moving. Prior interviews, Apache pilots had told us that wind velocity and direction data could be helpful in certain situations such as "cranking or shutting down, takeoff with a tail wind, or descending into trees with a tail wind that might push you into trouble." In addition, wind data could be valuable for "rocket engagements," "hover taxi," "restricted area landings," "bob-ups," "landing at unfamiliar fields," and "hovering at night in the trees." Head winds and tail winds are the most difficult to detect, since no aircraft attitude changes are available as a cue. Knowledge of wind direction can also be important for aircraft recovery maneuvers, such as after loss of an engine, when flying into the wind may be particularly desirable.

Instructions to Pilots

"The next symbol we want to show you is a wind indicator. As you know, the Apache true airspeed readout does not show the direction of the wind, although it does show a speed even if the helicopter is not moving over the ground. We've been told that a symbol showing the wind speed and direction relative to the aircraft could be useful (The pilot was shown a drawing similar to Figure 17 illustrating the wind symbol).

This symbol, shown in the lower left corner of the display, shows the windspeed numerically. It uses a rounded pointer to show the direction of the wind with respect to the aircraft. This illustration shows how the symbol would indicate a 15 knot wind from about 7 o'clock. (the pilot then donned the helmet).

First, orient the aircraft to the north and do a bob-up maneuver to about 10 feet. (a 15 knot wind from 270° was detected as the aircraft left the ground).

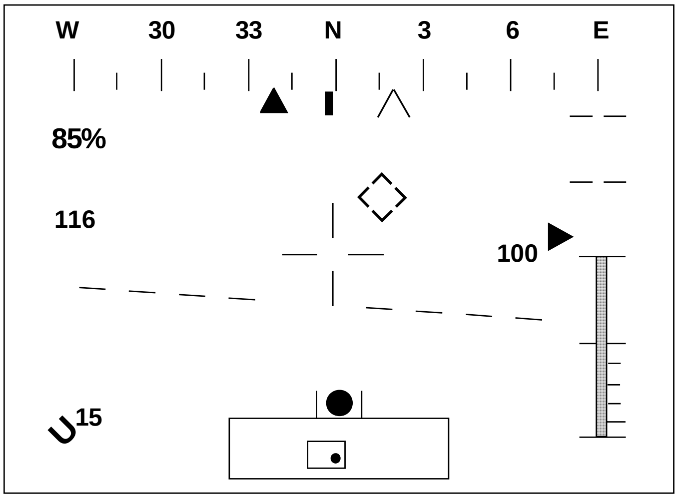

Figure 17. The wind indicator cue (lower left).

As you see, there is a wind active in the area. Touch down and we'll turn on the wind indicator symbol. Now you can bob-up again knowing which way and how hard the wind is blowing."

Overall Response

All of the five pilots who tried the wind indicator cue found it to be "useful" or "very useful." Other comments included "immediately understandable," "I like it," "would be handy," "would save you time," and "it can only help."

Application with Weapon Engagements

The pilots offered a range of applications for the wind symbol based on their operational requirements. Three of the pilots noted that wind direction "is important for rocket shots." There is a "zero-knot limit for tail winds for firing of rockets, and there's another limit for Hellfire missiles, so this would be useful for weapon engagements." One of the pilots stated that "the rocket ADS ballistic solutions do, in fact, include wind calculations; however they are not shown to the pilot." He also observed that even though it's undesirable, "sometimes you still have to shoot with the wind up your tail." When firing rockets, knowing the winds would also "be handy for using Kentucky windage."

Application in Mountain Operations

Two of the pilots stressed that in mountain operations "it's very important to understand the winds for pinnacle or ridge line operations." These pilots "do a lot of power management work at 6,000'+ altitudes, up to 7500', so winds are critical in hovering and landing." Pilots must be sure to fly into the wind for pinnacle approaches. They currently perform a "high recon," flying a circular pattern around a position to determine the direction and strength of the winds. The wind symbol "would save a lot of workload in determining the best approach," and, "since at airspeeds of greater than 35 knots you don't make such landings, it would be nice to know that figure, as well."

Applications in Other Operational Requirements

The pilots described a number of other situations in which the wind indicator cue would be valuable. "If you're shooting an approach, you want to see if there's a tail wind. It's hard to tell unless you're very experienced." "When you perform health indicator checks for the engines, you must orient the aircraft into the wind." "It would also be useful for roll on landings to unimproved areas. That way you could both put the aircraft into the wind, and by flying into the wind, keep the dust behind you when you land." The symbol would be useful "particularly on cranking or shutting down." "It would also be very useful if you had a single engine out." "You want to land into the wind when you're at the FARP, so it would be useful for that." "It would enhance situation awareness such as hovering at night near trees." "It is also useful for showing which way the dust and snow will blow." "A lot of times I wish I knew what the windspeed was, especially on take-off from the FARP or the holding area. I currently use dust to figure out which way the wind is blowing."

SPEED-TO-FLY SYMBOLOGY DEMONSTRATION

Background

Accuracy in arrival times at certain waypoints or other tactical positions can be critical to mission success and aircraft survival. For example, inbound and outbound Passage Point arrival times must be very accurate (± 30 seconds accuracy is allowable) to avoid risking "friendly fire." The existing airspeed display is, by definition, influenced by winds and does not provide ground speed unless the pilot "fails" the Air Data Sensor (ADS). As an alternative, the CPG can be further burdened with a request to repeatedly calculate GS and tell the pilot to "speed up or slow down a little." Given the current speed, the Doppler system alone can be used to determine the ETA at a waypoint. However, the system does not "know" whether the aircraft is on time, or by how much it is ahead or behind schedule. Some kind of cue to determining correct time of arrival could be a significant workload reducer for both the pilot and the CPG.

Instructions to Pilots

"The next new symbol we want to show you is called the Speed-to-Fly Cue. Pilots have told us that hitting certain waypoints on time can be important, such as at passage points. The Doppler system can calculate ground speed and ETA at a waypoint, but does not 'know' if the aircraft is ahead or behind schedule.

We can compare the ETA with the required waypoint time and display a symbol that looks like this next to the regular airspeed indicator (the pilot was shown an illustration similar to Figure 18).

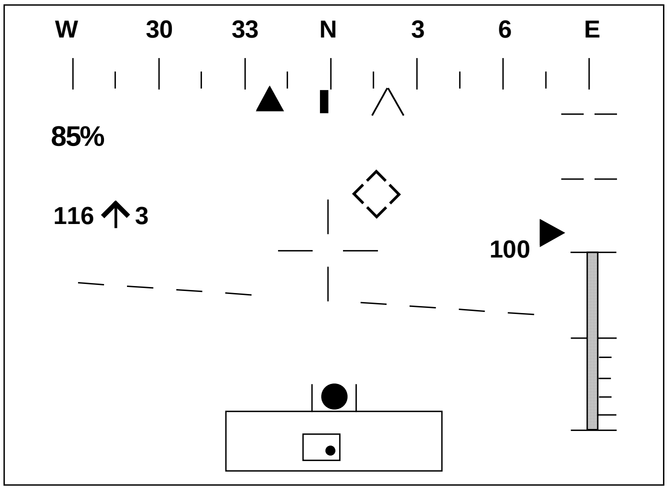

Figure 18. The speed-to-fly cue next to the 116 knot airspeed symbol.

The ‘up’ or ‘down’ direction of the little arrow next to the airspeed tells the pilot whether to increase or decrease airspeed, and the number to the right how much to change it for accurate arrival time at the next waypoint. We’ll begin near Waypoint 1 and fly to the HA.”

Overall Response

All of the five pilots that tried this symbol found it to be very useful. Other comments included “definitely a useful addition,” “much faster,” “more accurate,” “could relate to time easily,” “would reduce workload,” and “its location and appearance are just perfect.”

Improvement Over Current Operations

The specific waypoint times derive from the planning process. “You back-plan from the FLOT time or other critical position, and then set the times for each point, given the ground speed and the distance.” Pilots usually “fudge for the winds,” and do a Doppler check along the way. Enroute, the pilot "can turn the ADS off and get the ground speed. But most pilots prefer to leave the ADS on for use with waypoints.

The pilots were adamant regarding the necessity of accurate waypoint arrival times. One said that “Timing is really important, especially in and out of the passage point, the cross FLOT times must be within plus or minus 30 seconds. It’s critical.” Another stated that waypoint times are “nearly always important, but are critical with SEAD (suppression of enemy air defense) missions when there are artillery barrage times” to be considered. “To be either early or late over these points is dangerous.”

For accurate data, the pilot has to ask the CPG for time-distance information. The CPG must use the Doppler (which provides ground speed in knots) and do “a lot of calculations.” He determines the necessary true airspeed for the aircraft to deliver the proper ground speed for each leg, then relays the information to the pilot, suggesting that he increase or decrease current airspeed to make the waypoint time.

The pilots noted that with the speed-to-fly symbol, all this calculation and communication would be unnecessary. “It would also prevent a lot of speed fluctuations between waypoints.” Every one of the pilots considered the speed-to-fly cue to be a very useful addition.

One pilot observed that it would be possible to use the speed-to-fly cue as an indicant of “when to transition to the start point on the egress route.” For example, if the crew had 15 minutes station time plus 2 minutes to get to the start point, “in your setup you could enter 17 minutes to the start point from the BP arrival time.” Then “you would just wait until the display says it’s time to leave.” That is, the symbol would appear with an up arrow and a speed increase (such as “80 knots”). Or, if the aircraft left the BP late for some reason, “it would give you the needed speed to make that start point at the egress route.”

THREAT CUE SYMBOLOGY DEMONSTRATION

Background

Although the APR-39 radar warning device in the AH-64A provides voice warnings of threat activity and their relative direction, such as “Searching - 2 o’clock,” Apache pilots previously interviewed by the authors had indicated that HMD symbology might provide a better situation awareness cue. In order to permit rapid masking of the aircraft, instead of receiving just a numerical bearing to the threat, it was suggested that the HMD present an enemy weapon symbol in the field of regard, perhaps supplemented with a 3-D audio cue, to more naturalistically represent the weapon’s position in space.

Since the APR-39 does not provide distance-to-weapon information, the symbol could not be used to identify a specific position on the ground, but would have to show the azimuth to the weapon. Pilots have indicated that the HMD symbology could give a spatially superior indicant of direction with a line or some other marker so that the pilot could either orient the aircraft appropriately for use of the gun, jammer, chaff, or flares, or prepare to deploy to cover. Unlike a spoken warning, a visible line provides a continuous indicant of the direction of the threat, even as the pilot changes his heading to respond to the threat.

Instructions to Pilots

“The next symbol is an improvement for the APR-39. In addition to the voice warning of the rough direction of threat activity, a Threat Cue Symbol could be presented in the HMD, to point out the direction of the threat. The symbol we will show you is a pair of vertical lines. The target will be found between them. This symbol is used if no good target range data is available.

(A figure similar to Figure 19, depicting the symbol was shown to the pilots) Let’s fly through part of the waypoints from the first experiment and see how the

Threat Cue Symbol would point out the threat positions. A 3D sound cue will help to indicate the direction of the threat. Fire on the targets then continue route at low altitude."

of sight to the helmet line of sight," but using the new Threat Cue symbol is much faster, assuming both the front and the back seat have it. One pilot said that "using it for air-to-air would be great, too."

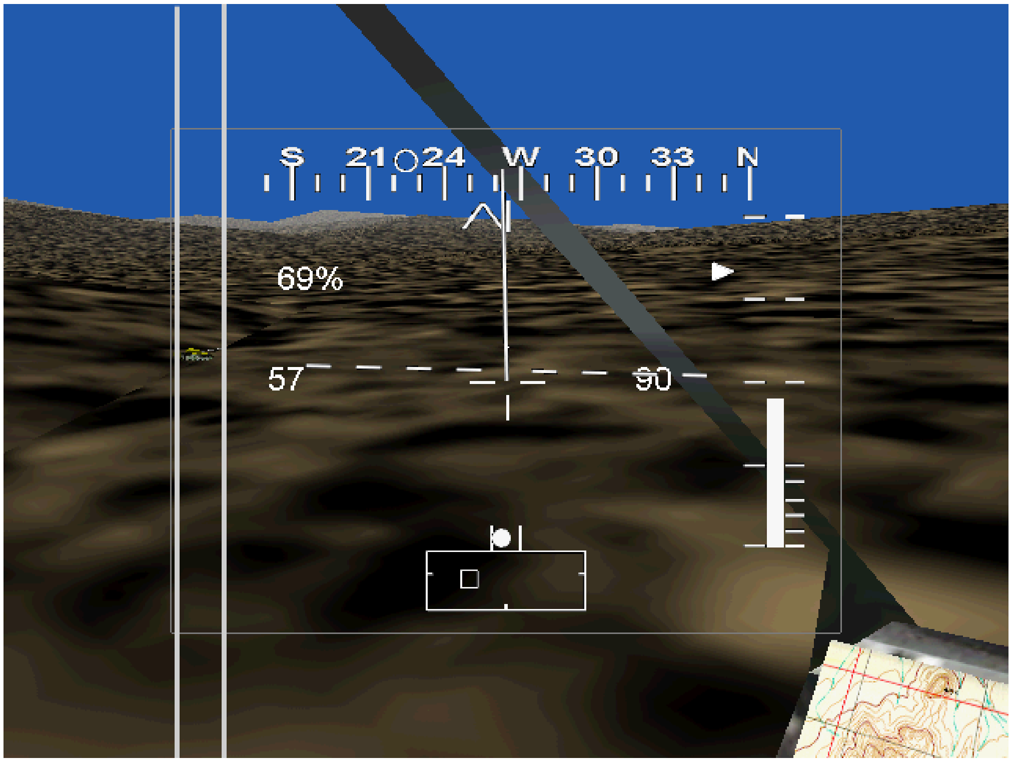

Figure 19. The Threat Cue Symbol indicating a target azimuth.

Overall Response

All five of the pilots who tried the Threat Cue symbol were very favorably impressed. Comments included "I like it a lot," "this would be great," "pretty neat," "absolutely a useful addition," "this is a novel, good thought," and "it sure beats looking down at that stupid thing" (the APR-39). It is noteworthy that during their previous two PRISMS flights through the same area these five pilots detected and fired upon an average of 1.2 semi-hidden targets of opportunity per flight. With the Threat Cue symbol, of course, all four of the targets were easily found.

Improvement Over Current Operations

The current APR-39 gives a verbal message such as "ZSU 11 o-clock tracking" and presents "a quick strobe on the head-down display." But "the strobe disappears right away and you may miss it entirely." The pilot doesn't always see the APR-39 strobe line and "a clock position is useless if you're maneuvering too late to figure out the real direction of the strobe." In addition, "this information must be relayed from the pilot to the front seater." The front seater "has to ask the back seat where the strobes are coming from so that he can effectively slew the weapons." Alternatively, "he can slew his TADS line

Use of 3D Sound

The 3D sound is "great' because it "tells you where to look immediately." Otherwise, "it's hard to figure out with the current APR-39." Some pilots felt that a simple buzzer sound such as used in the demonstration would be adequate because "knowing it's there is more important than getting an idea of the specific threat." Two pilots thought the buzzer sounded too much like "an engine-out warning."

Other pilots pointed out that the current APR 39 uses a voice message to indicate the type of weapon of the threat and that the type of weapon is still important information, suggesting that the auditory portion of the cue should perhaps use the name of the weapon instead of a simple tone. "A woman's voice would be okay." The other words of the APR-39 message, such as "tracking, acquisition, launch, or lock broken," should also be included, but done in 3D sound.

Symbol Appearance

Most of the pilots indicated that the symbol appearance was "good," or "appropriate," and were not particularly concerned about the clutter the two lines would add at this point in the mission. As one of the pilots put it,. “Don’t worry about having two lines--clutter is not a big issue in this case. When the target comes up, it’s the most important thing.” Two of the pilots liked the two-line approach, but suggested that they be in a color unlike that of the other symbology or the target itself.

Target Prioritization

Several of the pilots suggested some form of additional information be added, for example, something akin to that currently used with the voice warnings of the APR-39. One pilot suggested that it might be good to prioritize pairs of lines for multiple targets by using shape codes for our lines.

“You might want to be able to discriminate between tracking or lock or launch so that the first priority would be launch, the second lock, the third tracking, with some kind of shape code.” he suggested dotted lines for tracking and solid for acquisition, “or color codes if they are possible.” He also noted that the APR-39 currently shows small symbols indicating the type of enemy weapon, so these could be considered for the head-up application as well.

FLIGHT PATH MARKER SYMBOLOGY DEMONSTRATION

Background

The flight path marker symbol shows the continuously computed velocity vector of the aircraft. The Apache symbology currently includes a velocity vector that is a “top-down” view useful for hover control. The flight path marker symbol, however, is an “out-the-window” view along the axis of the velocity vector, showing where the aircraft will fly or contact the ground if no changes are made to the controls. Thus, the most obvious virtue of the flight path marker symbol is for avoidance of controlled flight into terrain (CFIT) accidents. The knowledge of the aircraft’s velocity vector can be useful in many other ways as well, including terrain following, turn coordination, and precision landings.

Instructions to Pilots

“The next symbol we want to show you is called the Flight Path Marker. It shows the continuously computed velocity vector of the aircraft. You can use it to see exactly where the aircraft will fly or contact the ground if control inputs do not change. (A drawing similar to Figure 20 was shown to the pilots). We have it set up so that the symbol “grows” in size as the impact point becomes nearer to the aircraft, and will begin flashing at 3 seconds to impact.

First, let’s compare landing at a specific position without and with the Flight Path Marker. From about 500 feet, land at the pad. Next, we’ll try it with the Flight Path Marker on. Just keep the Flight Path Marker positioned on your desired landing point.

(Later, after landing exercises)

Now let’s try it out first flying low and fast. Observe how it moves with your control inputs and how it changes size. See if you can get the flashing warning of 3 seconds to ground impact.”

Overall Response

All of the five pilots who evaluated the flight path marker symbol were strongly in favor of its addition to the symbol set. Comments included “a really good addition,” “it would be great,” “very useful,” “excellent,” “pretty nice,” “it’s a good tool,” “especially useful at night,” “a precise power manager,” and “it could save your life.”

Utility in Tactical Flight

All of the pilots agreed that “this would be a really good addition for low-level flight,” especially in for terrain following and terrain avoidance.” Accurately clearing ridgelines without “ballooning to 400 feet” is another requirement that would be aided by the flight path marker. One pilot observed that “it’s good for night flight, especially, because it’s hard to see the terrain then.” Another pilot tried it with aggressive turns and pronounced it “great for sharp turns while you’re losing altitude.”

Utility for Landings

Pilots also agreed that “it’s good for setting up landings,” because it’s not necessary to “look inside the cockpit for information” during the landing. One stated that it was “great for shooting approaches” because the pilot doesn’t “have to check several different things.” Another said “I like it. Especially for roll on landings.” It provides a “good rate of descent cue,” and the landing position can be fine-tuned, using the symbol as a “precise power manager,” keeping the symbol over the intended landing spot. It would also be useful for autorotations, setting the aircraft attitude to produce an 80-knot airspeed and putting the symbol on a desired landing area.

Utility with Weapons

One pilot was particularly interested in the use of the flight path marker with rocket fire, suggesting that the symbol might indicate “both the aircraft’s and the rocket’s point of impact in the terrain.” when using direct fire methods. Another pilot noted that the symbol would be valuable in “determining the pull-up point for diving fire” with the gun or rockets.

Utility in Flight Instruction

An instructor-pilot indicated that as a safety cue, flashing the flight path marker symbol would “be excellent for flight with students. At low level, high speed, you really need to detect descent in a hurry.” He and another pilot suggested that an auditory warning message such as “Pull up” be added to correspond with the flashing

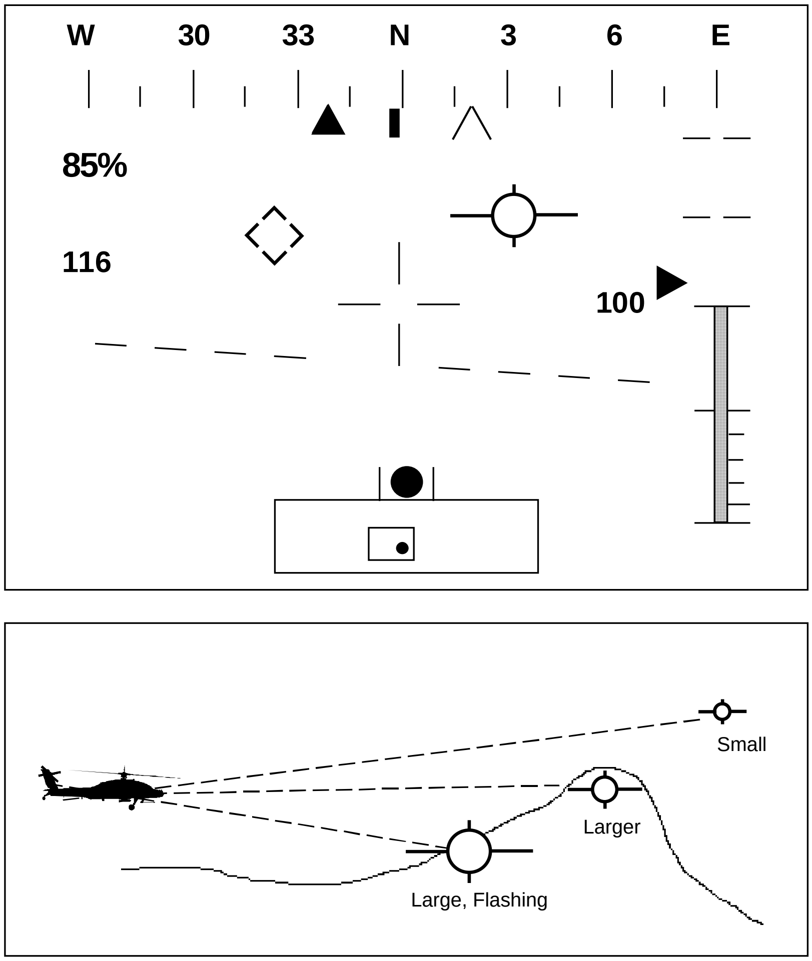

Figure 20. Appearance of the flight path marker with the other HMD symbols (upper) and example of the flight path marker changing size (lower).

flight path marker. Pilots were very much in favor of the flashing symbol indicating imminent ground impact, one saying “it could be what saves you,” and another saying “it will help you survive in flight.”

Concluding Remarks

The PRISMS experiment was most effective in demonstrating the overwhelming advantages of the new earth-fixed symbol types. The accuracy of position-finding in the terrain and engagement area fire sector identification were enormously improved through the display of virtual waypoint and engagement area symbols.

In addition, the knowledge acquisition sessions conducted with the Apache pilots immediately following the experiments were particularly effective in that PRISMS permitted the pilots to fully appreciate the complex dynamics and interactions of the new HMD symbols after observing them in action while moving both the aircraft and the head to different angles and attitudes. The new symbols for presenting slope landing data, wind speed and direction, required speed for accurate arrival time, threat weapon direction, and flight path prediction were all judged to be very valuable.

Finally, the project has also demonstrated the relative ease with which the PRISMS simulator can be used to construct and edit experimental sessions, add and improve symbology features and behaviors, provide realistic terrain and objects, and create an extensive range of performance measures—all in a package that is easily transportable to the field. PRISMS has not only fulfilled its immediate project objectives, but will continue to provide a powerful but inexpensive simulator for research and training for many years to come.

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