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Concepts for Conformal and Body-Axis Attitude Information for Spatial Awareness Presented in a Helmet-Mounted Display

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Abstract

A piloted simulation study has been conducted to evaluate two methods of presenting attitude information in a helmet-mounted display (HMD) for spatial awareness in a fighter airplane. One method, the conformal concept, presented attitude information with respect to the real world. The other method, the body-axis concept, displayed the information relative to the body axis of the airplane. The quantitative results of this study favored the body-axis concept. Although no statistically significant differences were noted for either the pilots' understanding of roll attitude or target position, the pilots made pitch judgment errors three times more often with the conformal display. The subjective results showed the body-axis display did not cause attitude confusion, a prior concern with this display. In the posttest comments, the pilots overwhelmingly selected the body-axis display as the display of choice.

Introduction

The traditional head-up display (HUD) used in most modern fighter airplanes presents attitude information that is both conformal to the outside world and aligned with the body axis of the airplane. The introduction of helmet-mounted display (HMD) technology into simulated and actual flight environments has introduced an interesting issue regarding the presentation of attitude information. This information can be presented conformally or relative to the body axis of the airplane, but not both (except in the special case where the line of sight of the pilot is directly matched with the body axis of the airplane). The question addressed in this study was whether attitude information displayed in an HMD should be presented with respect to the real world (conformally) or to the body axis of the airplane. To answer this question, both conformal and body-axis attitude symbology were compared under simulated air combat situations. This paper describes the attitude display formats and the experimental design in detail. Quantitative and subjective results are also presented.

Simulation Characteristics

Simulation Facility

This study was conducted in the Langley Differential Maneuvering Simulator (DMS) (refs. 1 and 2). The facility is designed to provide a means of simulating two piloted airplanes operating in a differential mode with realistic cockpit environments and wide-angle external visual scenes. The DMS consists of two identical fixed-based, visual flight simulators, each housed in a 12.2-m-diameter (40-ft) projection sphere (fig. 1). A dynamic Earth-and-sky scene is generated in each simulator sphere along with a target airplane image. This outside scene, representing the "real world," is produced by a computer-generated image (CGI) system and provides reference in all six degrees of freedom in a manner that allows unrestricted aircraft motions. When the dual simulator mode is used, the target image presented to each pilot represents the airplane being flown by the pilot in the adjacent sphere. For this study, however, only one sphere was utilized and the target airplane was driven by previously stored data files. This aspect is discussed in more detail in the section, "Experiment Description."

The DMS cockpit contains a wide-angle HUD and three head-down color cathode-ray tube (CRT) displays, each with a 6.5-in-square viewing area. These displays were not used during the data collection portion of this study, however. Kinesthetic cues are provided by means of a *g*-seat system. Pilot controls include a center stick controller, dual throttles, and rudder pedals. The controls were programmed and configured for the F/A-18 airplane.

The airplane simulation used for this study was a nonlinear, six-degree-of-freedom, rigid-body, dynamic model of an F/A-18 high-performance fighter airplane and was hosted on a mainframe computer. The simulation was based on the data included in references 3 and 4.

Helmet-Mounted Display

The primary display device for the experiment was the Langley-developed HMD shown in figure 2. This HMD utilizes wide-field-of-view binocular optics, and holographic optical elements for high

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Figure 1. Artist rendition of the Differential Maneuvering Simulator.

brightness and transmissivity. The image sources are two high-resolution CRT displays. For this test, the optics were fully overlapped and the same image was presented to each eye resulting in a biocular presentation with no stereo cues. The instantaneous field of view was 30° vertical by 40° horizontal. The HMD weighs approximately 6.5 lb and could be worn by most pilots for over an hour without discomfort. The optics were adjusted to suit each individual pilot, with display brightness left to the discretion of the pilot. The HMD was driven by a graphics workstation at a resolution of 1280 picture elements horizontally by 1024 picture elements vertically and updated at a 60-Hz noninterlaced rate. The graphics system received airplane state information from the mainframe computer at 32 Hz and pilot line-of-sight data at 60 Hz from a Polhemus head-tracking system (ref. 5). A single frame delay was experienced as a result of transferring data from the Polhemus head tracker to the graphics workstation; however, it was not noticed by the pilots.

Attitude Display Implementation

The graphics display created for this experiment presented attitude information to the pilot in the HMD. For the purpose of the experiment, no other information (e.g., airspeed, altitude) was presented during the actual data collection. The attitude display consisted of a pitch ladder, velocity vector symbol, and waterline symbol (fig. 3).

With the conformal attitude presentation, the appearance of the displayed information was dependent on the head position of the pilot. The displayed horizon line of the attitude symbology, if it was in view, would always overlay the horizon of the outside scene. If the line of sight of the pilot was not aligned with the body axis of the airplane, the attitude of the airplane (e.g., the position of the nose of the airplane) could not always be easily obtained from the displayed symbology.

With the body-axis concept, no matter which direction the pilot moved his head, the display appeared as if the pilot was looking directly out the front of the airplane. In essence, the body-axis concept was analogous to physically mounting a HUD to the helmet. With this concept, the pilot could always directly determine the attitude of the airplane. However, in situations where the line of sight of the pilot was not aligned with the body axis of the airplane, the displayed horizon line of the attitude symbology, if it was in view, would not overlay the horizon of the outside scene.

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Figure 2. Helmet-mounted display.

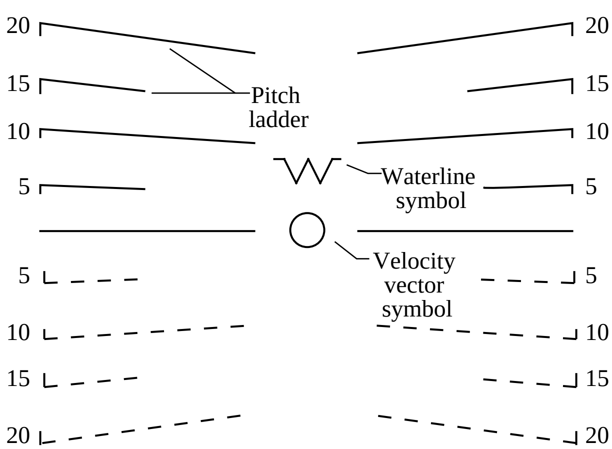


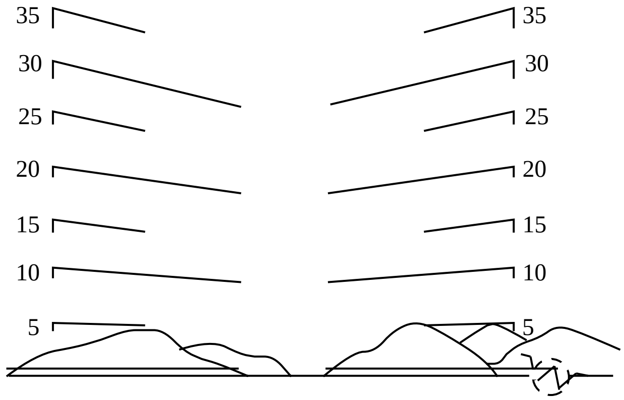
Figure 3. Attitude information display symbology.

Figure 4 gives an example of both display concepts. In the instance depicted, the airplane is in a 20° roll to the right with the pilot looking 90° to the left. Notice that with the body-axis display, it appears as if the pilot is looking directly out the front of the airplane. However, with the conformal display, the horizon element overlays precisely with the horizon of the outside scene. In this figure, the waterline and velocity vector symbols are presented at the right of the display and are dashed to indicate that the nose of the aircraft and the direction in which the aircraft is moving is to the right of where the pilot is looking, that is, out of the field of view of the HMD. Also, notice that the waterline symbol is banked 20° to the right when displayed at the edge of the image to indicate that the plane is in a 20° roll.

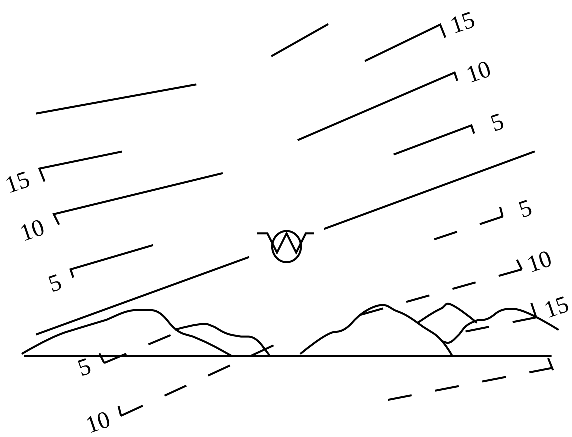
Experiment Description

The concepts for conformal and body-axis attitude display were evaluated with simulated air-to-air intercept tasks. The goal of the flying task was to obtain a gun solution on a maneuvering, but not interactive, target. The target airplane was driven by data recorded from actual flights made by a NASA research pilot. Four different target tapes were made. However, eight target situations were produced for this test by symmetrically "mirroring" each original target tape about the lateral axis. That is, if the target for the task was initially to the right of the piloted aircraft and maneuvered to the left, *then* the target for the mirrored task was initially to the left and maneuvered to the right.

Each simulation run began with a head-on pass in which the target was laterally displaced and was



(a) Conformal display presentation.



(b) Body-axis display presentation.

Figure 4. Conformal and body-axis display concepts.

below the piloted airplane. Prior to each task, the pilot was told the side on which the target airplane would pass. The pilot could begin to maneuver as soon as an audible tone in the cockpit went from a steady tone to an intermittent tone. Until that time, the pilot was to maintain level flight at the initial power setting. The pilot was considered to have obtained a gun solution when the target was within 2000 ft and within a 5° cone about the ownship centerline and had been in that condition for 5 sec. For half of the test cases, the run ended when the pilot obtained a gun solution. The other half of the cases terminated at some predetermined time interval which was unknown to the pilot. Also, as part of the test conditions, the outside scene was presented for only half of the test cases. This was done to determine if the real-world scene had an impact on the manner in which the attitude information was presented.

At the termination of each data run, the simulation would be suspended and the display in the HMD as well as the outside scene and target image would disappear. The pilot was then required to complete a questionnaire to indicate his perception of the ownship airplane's attitude as well as the relative altitude of the target. The questionnaire is shown in the appendix.

Eight U.S. Air Force fighter pilots participated as test subjects for the experiment. Each pilot flew three separate sessions on 3 different days. The first session was for training. The pilot was to first use the HUD during training tasks to become familiar with the characteristics of the simulator as well as the format of the tasks. The training tasks included all parameters that the pilot would encounter during data collection: conformal/body axis, outside scene on/off, and target aircraft on the left/right side. Also, the data tapes used to drive the target for the training runs were different from the tapes used during data collection. The pilots then trained with the conformal and body-axis concepts displayed in the HMD. While using the HMD, the HUD and all head-down displays were turned off. Half of the pilots trained first with the conformal display; the other half trained first with the body-axis display. Eight training tasks were given for each concept.

Following the training session, two sessions were used for data collection, one for each display concept. Data were collected for 16 tasks for each pilot for a total of 128 test cases. The recorded data included information about the state of the piloted airplane and target, as well as the position and orientation of the pilot's head. The test sequence was fully counterbalanced with respect to the target situation, display format, and the availability of the outside scene. The test matrix for this study is shown in table I.

The product of this evaluation was a set of test data from each pilot that included the following: questionnaire results describing the pitch and roll attitude of the airplane as well as the relative altitude of the target for the conditions existing at run termination; questionnaire results describing the usefulness and interpretability of the display symbology; general comments; and quantitative state data of both the piloted airplane and the target, as well as the position and orientation of the pilot's head.

Results and Discussion

Quantitative Results

The primary factor of interest for this study was the assessment and understanding by the pilots of the attitude of the airplane. To evaluate this, the pilots were required to record the attitude state of the airplane at the time the simulation run terminated.

Table I. Pilot Run Test Matrix

[The tasks with astericks (*) are the symmetrical opposite of the tasks without asterisks.]

	Body axis with outside scene—								Conformal with outside scene—							
	On for task—				Off for task—				On for task—				Off for task—			
Pilot	1	2	3	4	1	2	3	4	1*	2*	3*	4*	1*	2*	3*	4*
"Short run" scenarios																
1	1	2					4	7	9	11					14	15
2			1	2	4	7					9	11	14	15		
3		4	7		2			1		14	15		11			9
4	7			4		1	2		15			14		9	11	
5	9	11					14	15	1	2					4	7
6			9	11	14	15					1	2	4	7		
7		14	15		11			9		4	7		2			1
8	15			14		9	11		7			4		1	2	
"Full run" scenarios																
1			6	8	3	5					16	10	12	13		
2	6	8					3	5	16	10					12	13
3	5			3		6	8		13			12		16	10	
4		3	5		8			6		12	13		10			16
5			16	10	12	13					6	8	3	5		
6	16	10					12	13	6	8					3	5
7	13			12		16	10		5			3		6	8	
8		12	13		10			16		3	5		8			6

These judgments of pitch and roll angles were then compared with the actual airplane state for the same time period. In analyzing the results of this comparison, the pilots were deemed (a priori) to have made a correct assessment if their answer was within $\pm 45°$ of the actual state. The value of $\pm 45°$ was selected on the basis that this was twice the size of the selection window used in the questionnaire. This analysis showed that differences in pitch judgment errors were statistically significant at the 95-percent confidence level, with more errors being made with the conformal display. It was also noted that the presence of the outside scene had a significant effect on pitch judgment errors, with more errors occurring when the outside scene was not present. The interaction between the display format and the presence of the outside scene was not significant. The number of judgment errors for both pitch and roll is shown in tables II(a) and (b).

A secondary factor of interest for this study was the assessment by the pilots of the relative altitude of the target airplane. Because a relative altitude judgment is, in effect, an angular estimation between the ownship and the target, the possible responses allowed in the questionnaire were angular. As with the attitude information, the pilots were required to record the relative altitude of the target at the time the simulation run terminated. These judgments were then compared with the actual target position for the same time period. In analyzing the results of this comparison, the pilots were deemed (a priori) to

Table II. Judgment Errors

	Judgment errors with outside scene—	
Display	On	Off
(a) Pitch		
Body axis	1	2
Conformal	2	9
(b) Roll		
Body axis	7	3
Conformal	11	8
(c) Target altitude		
Body axis	2	1
Conformal	1	4

have made a correct assessment if their answer was "above" and the target was at or above the altitude of their airplane, "below" and the target was at or below the altitude of their airplane, or "at" and the target was within a ±45° angle of being at the same vertical level (altitude plane) as their airplane. The analysis of these data showed no statistically significant differences in judgment relative to the displays. The number of errors for target altitude estimation can be seen in table II(c).

Subjective Results

Questionnaire data describing the usefulness and interpretability of the display symbology were obtained immediately after each simulation run. The mean scores for the responses to questions 4 and 5 of the questionnaire are shown in table III. Question 4 was graded on a scale of 1 to 5 (for the 5 possible responses) with a score of 1 equivalent to "no useful information." Question 5 was graded on a scale of 1 to 6 (for the 6 possible responses) with a score of 1 equivalent to "always confused." No statistically significant differences were noted in the analysis.

Following the entire test sequence, the pilots were specifically asked to choose between the two display formats and to provide general comments relative to the evaluation. From the pilot preferences, seven of the eight pilots preferred the body-axis display. Five of these seven pilots stated that the body-axis format provided better information relative to "what the aircraft was doing." Five responses were also noted where the pilots felt that the conformal display was hard to interpret and confusing because of the symbology motion caused by the aircraft and head movements. Fighter pilots use HUD's and are, therefore, more familiar with the information presented in the body-axis format. With more training time available, the conformal display may have been more useful to the pilots.

Table III. Responses on Questionnaire

Display	Responses on Questionnaire with outside scene— On	Off
(a) Question 4		
Body axis	4.1	4.3
Conformal	3.9	4.0
(b) Question 5		
Body axis	4.7	4.2
Conformal	4.5	3.9

Summation of Results

The quantitative results of this study favored the body-axis concept. (See fig. 5.) Although no statistically significant differences were noted for either the pilots' understanding of roll attitude or target position, the pilots made pitch judgment errors three times more often with the conformal display. The subjective results showed the body-axis display did not cause attitude confusion, a prior concern with this display. In the posttest comments, the pilots overwhelmingly selected the body-axis display as the display of choice.

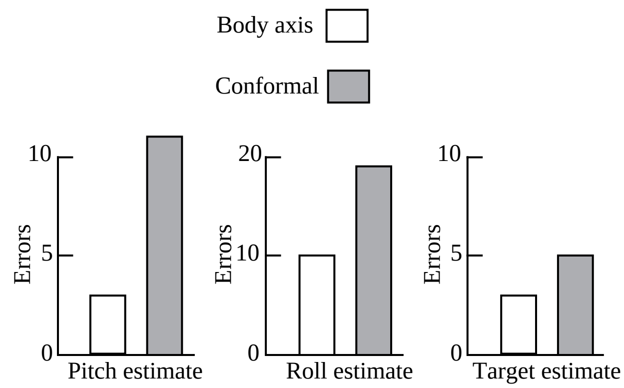


Figure 5. Quantitative results.

Concluding Remarks

This study was conducted to determine if attitude information displayed in a helmet-mounted display should be presented with respect to the real world (conformal) or to the aircraft (body axis). The two display concepts were evaluated by using simulated air-to-air intercept tasks where the pilot was to obtain a gun solution on a maneuvering, but not interactive, target. At the completion of each task, each pilot completed a questionnaire to indicate his perception of the attitude of the ownship airplane as well as the relative altitude of the target for conditions existing at run termination. These responses were compared with quantitative state data recorded for both the ownship and target. The quantitative results favored the body-axis concept because the pilots made one third fewer pitch judgment errors with this display format. The subjective results showed that the body-axis display did not cause attitude confusion, a prior concern with this display. In the posttest comments, the pilots overwhelmingly selected the body-axis display as the display of choice. Pilots stated that the conformal display was hard to interpret and confusing because of the symbology motion caused by the by the aircraft and head movements. However, the pilots commented they were more familiar with the body-axis display format because they use head-up displays. With more training, the conformal display may have been more useful to the pilots.

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Appendix

Questionnaire

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