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A R M S T R O N G

L A B O R A T O R Y

HELMET-MOUNTED AREA-OF-INTEREST DISPLAY

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This report describes the results of a design study for a helmet-mounted display (HMD) for use as an area of interest (AOI) for the Display for Advanced Research and Training (DART). The objective of the research was to investigate alternative optical approaches for building a helmet-mounted area of interest (HMAOI) for the DART and to recommend the optimal approach based on performance and cost tradeoffs. The experiment examined several system design problems: the design of an HMD eyepiece with minimal obtrusiveness, visual blending of the HMD imagery with the projected imagery, and timing and perspective issues relating to the computer-generated imagery presented by both the HMD and the projection display.

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PREFACE

The design study presented in this report was conducted by the University of Dayton Research Institute (UDRI) and its subcontractor Martin Shenker Optical Design, Inc., for the Aircrew Research Training Division of the Armstrong Laboratory (AL/HRA) under Contract No. F33615-90-C-0005, Work Unit 2743-25-17, Flying Training Research Support. Mr. Melvin Thomas was the Task Monitor and Ms. Patricia Spears, the Contract Monitor.

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HELMET-MOUNTED AREA-OF-INTEREST DISPLAY

SUMMARY

This report describes the results of a design study for a helmet-mounted display (HMD) for use as an area of interest (AOI) for the Display for Advanced Research and Training (DART). The objective was to investigate alternative optical approaches for building a helmet-mounted area of interest (HMAOI) for the DART and to recommend the optimal approach based on performance and cost tradeoffs.

The research effort examined both the optical design of the HMAOI as well as system design issues concerning the use of the HMAOI in conjunction with DART. In regard to the optical design, the research focused on the design of the helmet-mounted eyepieces and on the design of a lens system called the relay optics to couple the image produced by high brightness cathode ray tubes (CRTs) to coherent fiber optic bundles.

Two eyepiece designs were studied in depth; the air combiner and the prism combiner. The prism combiner has many advantages over the air combiner such as mechanical stability and comparatively large eye relief. Unfortunately, the prism combiner has a small see-through field of view. This can be rectified, but not without the weight of the prism becoming excessive. For this reason, the air combiner is the recommended eyepiece for the HMAOI.

The study results recommend that the relay optics provide all of the distortion mapping required for the f-theta mapping of the eyepiece. Additionally, the high-resolution AOI for the HMAOI should be combined with the background HMAOI imagery by a cube combiner between the CRTs and the relay optics.

System design issues were also studied in depth including the visual combining or blending of the HMAOI imagery with DART imagery, human factors of the HMAOI, and eye-slaving of an AOI within the HMAOI field of view.

INTRODUCTION

Wide field-of-view display systems for tactical flight simulators represent a significant portion of the total cost of the simulators. In addition, the ability to display a large field of view naturally increases the price of the image generators (IG) needed to drive the display. In many cases the resulting high cost of the visual system is justified because the training of certain tasks such as low-level flight cannot be accomplished without a wide field-of-view display. The conventional wisdom has been to provide a wide instantaneous field of view that is head slaved, so that the required number of IG channels is minimized. High resolution can be obtained by the use of a head- and/or eye-slaved AOI. The Limited Field-of-View Dome (LFOV Dome) and the Fiber Optic Helmet-Mounted Display (FOHMD) are both examples of this approach (Welch et al., 1986). Figure 1 shows the FOHMD.

Since the development of these systems, one of the assumptions upon which they were based has changed; the cost of IG channels no longer outweighs the cost of the display system. It is now economically feasible to use a relatively large number of IG channels (eight or more) to produce a total field-of-view display. This is the design philosophy behind the DART display system developed by the Aircrew Training Research Division of the Armstrong Laboratory (AL/HRA). The DART is a full field-of-view simulator display that consists of 8 rear-projected pentagon screens placed in a dodecahedron frame. The image on each screen or window is projected by a 1,000-line CRT projector. This provides a medium resolution scene (i.e., 4.3 arc-min/pixel addressability) with high contrast over the total out-the-window field of view of a modern fighter aircraft. The DART is also inexpensive ($300,000) when compared with other full field-of-view simulator displays. The main drawback of this system is that it provides only moderate resolution and not the eye-limited resolution required for many tasks. Figures 2 and 3 show the DART display.

AL/HRA has proposed the use of technology developed for the FOHMD to provide a high-resolution AOI for DART. In this approach an HMD would be worn by the pilot within the DART. The HMD would consist of medium- and high-resolution areas optically combined with the lower resolution imagery created by the DART. The display will provide a total field of regard without limiting the pilot's instantaneous field of view, unlike the LFOV Dome or the FOHMD.

THE DESIGN STUDY

The University of Dayton Research Institute (UDRI) initiated a design study by Martin Shenker Optical Design (MSOD), a consulting firm with FOHMD display expertise, to investigate the relative merits of at least two alternative HMD designs. A set of

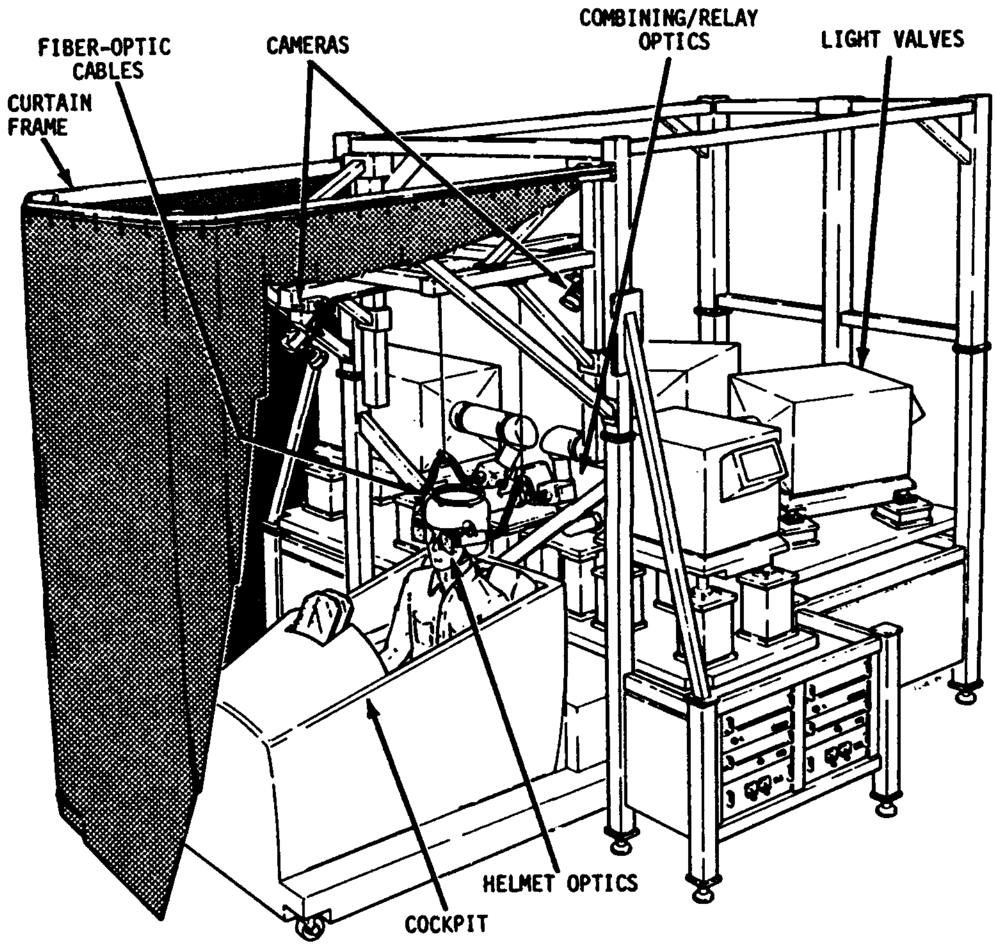

Figure 1
The Fiber Optic Helmet-Mounted Display

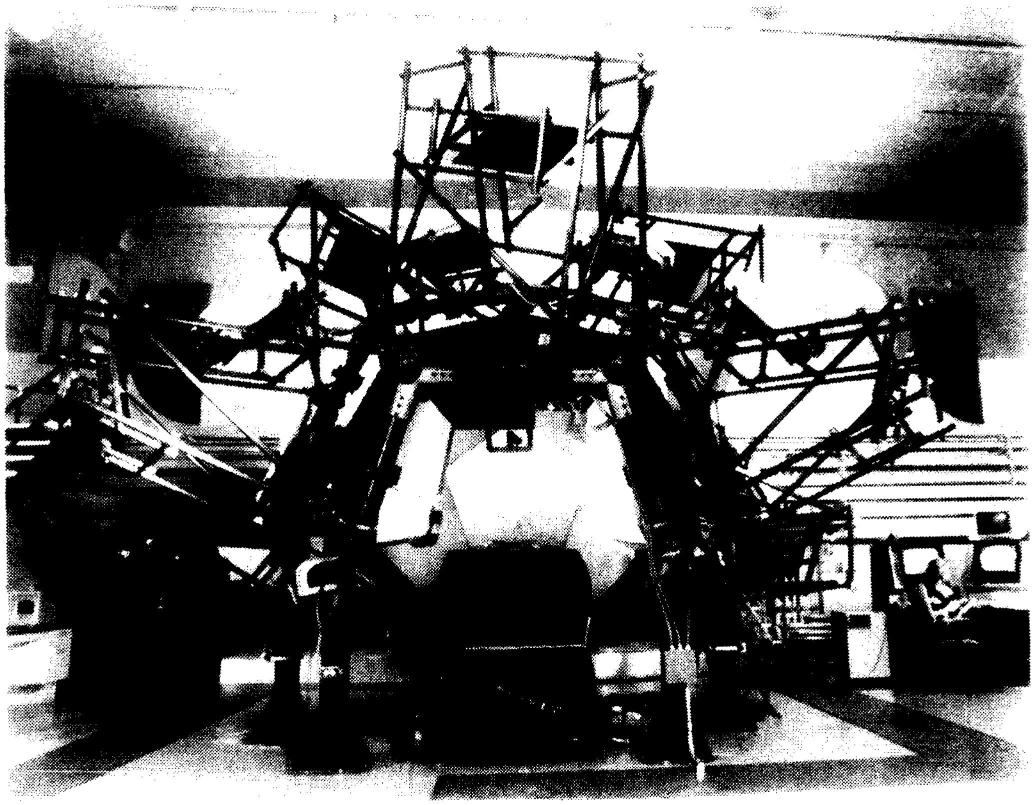

Figure 2
External View of the DART

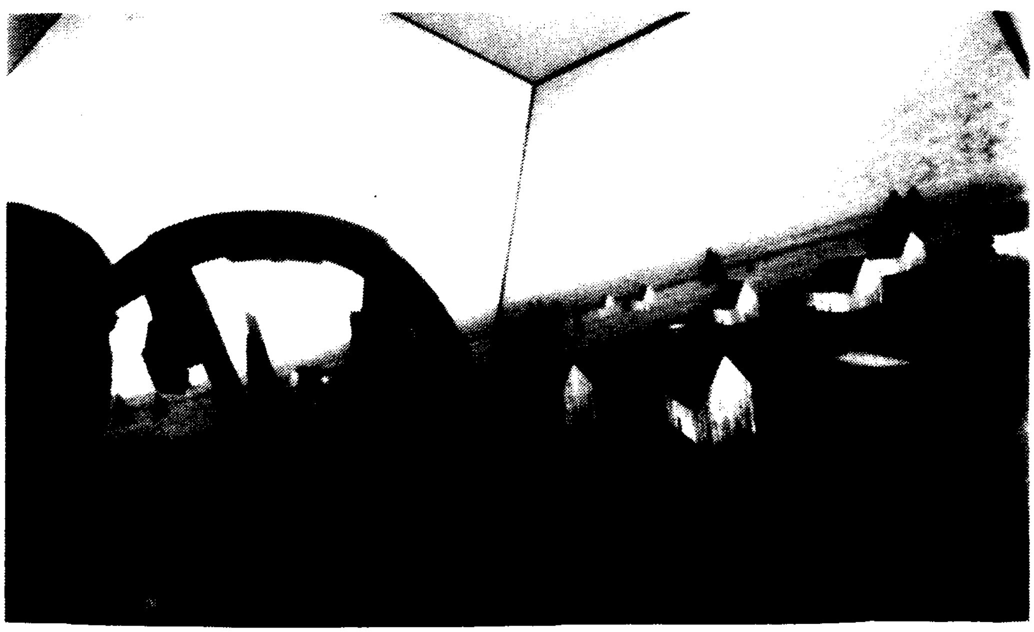

Figure 3
DART Imagery

minimum requirements for all candidate systems was established to ensure that all systems would be evaluated with respect to their utility as a display device used in conjunction with the DART. The final recommendation was based on optical performance, human factors, and production cost, in that relative order of merit.

The primary goal for the HMAOI project is to provide a display device to supplement the DART display system. Fortunately, the HMAOI has the potential to be a useful device independent of the DART. This potential was realized early in the concept development. As a result, the decision was made to design the HMAOI as a broader research tool for use beyond its original DART application. This decision translated into design requirements such as modularity of components and flexibility to accommodate different configurations. Practically, this led to a subsequent decision to build a CRT to a fiber optic bundle relay lens system that would be compatible with a variety of eyepiece designs with different fields of view and which could have either partially or totally overlapping binocular visual fields. Consequently, a new HMAOI configuration was examined for use with the Transportable Visual System (TVS), a low-cost compact transportable simulator visual display system. This added flexibility will increase the complexity and cost of the HMAOI, but will allow its use as a research tool in areas beyond the DART and extend its period of usefulness before obsolescence by permitting the incorporation of new technological advances as they occur.

Design Specifications

A set of minimum specifications for the HMAOI was initially chosen to eliminate from consideration any design that was clearly inadequate either inherently or because it would be incompatible with DART. The minimum specifications were based on previous experience with the FOHMD and other simulator displays. All designs that met the minimum design specifications were then considered candidate designs and examined in the design study.

The preferred specifications were chosen as a means by which the performance of each candidate design could be compared with the other designs. The comparison would ultimately be based on optical performance (in conjunction with the DART), human factors and estimated production costs. The recommended design ideally would provide the maximum performance and have the lowest risk.

Both minimum and preferred specifications are listed in Table 1. The only eyepiece design eliminated by the minimum specifications was the pancake window because its see-through transmission is only 10%. The off-aperture eyepiece was eliminated, not because of the specification, but due to manufacturing difficulties and the subsequent high cost.

Table 1. HMAOI Design Specifications

Specifications	Minimum	Preferred
Horizontal FOV:	40 deg	51 deg
Vertical FOV:	30 deg	38.5 deg
Binocular Overlap:	100% Overlap	Variable
Luminance: (10% Screen Area)	10 fL	20 fL
Contrast:	20:1	30:1
Resolution: (@ 10% Modulation)	3 arc-min/lp	2 arc-min/lp
High Resolution FOV:	11.25 x 15 deg	
Pupil Diameter: (Uniform Illumination)	12 mm	18 mm
Eye Relief:	> 15 mm	19 mm
Helmet Mounting:	FOHMD compatible	USAF flight-helmet compatible
Eyepiece Transmissivity: (Dart Display)	> 50%	80%
Collimation:	1 m to infinity	
Weight:		
Helmet Optics:	< 4 lb	< 3 lb
Fiber Optics:	< 3.5 lb	< 2.5 lb
Fiber Optics Length:	6 ft	

OPTICS

Eyepieces

The research focused on two basic eyepiece designs. Both designs consisted of a semitransparent spherical mirror and a flat combining surface mounted at roughly a 45° angle to the optical axis of the spherical mirror. The fundamental difference between the two systems is that one system has the combiner and spherical mirror separated by an air space while the other system utilizes a combiner immersed in glass or plastic. This combiner is normally identified by the misnomer, "cube beamsplitter." In this report, the air beamsplitter eyepiece will be referred to as an air combiner or air combining eyepiece, while the cube beamsplitter will be referred to as a prism combiner or prism combining eyepiece.

Prism Combiner

The major advantage of the prism combiner is that it effectively allows the lengthening of the optical path, permitting the spherical mirror to be placed in a horizontal position (vertical optical axis) for the vertical fold configuration. This results in the eyepiece having only a single partially reflecting surface (the flat combining surface) to degrade the see-through transmission of the display. The DART imagery is not viewed through the spherical mirror.

The system has the following characteristics:

EFL = 22.8 mm
Exit Pupil = 15 mm
F# = 1.52 Numerical Aperture = 0.33
Exit Pupil Clearance = 20.4 mm
Field of View:

A: Display:

Horizontal	40°	= 16 mm
Vertical	30°	= 12 mm
Diagonal	48.6°	= 19.5 mm

B: See-through (from center of exit pupil)

Horizontal	60°
Vertical	30° Up
	35° Down*

* with the spherical mirror on top of the prism

Table 2 shows both the display and see-through transmission of the prism combiner.

Table 2. See-Through and Display Transmission

Flat combiner reflectivity	Display transmission	"See-through" transmission
50%	25%	50%
40%	24%	60%
30%	21%	70%
20%	16%	80%
10%	9%	90%

The other advantages of the prism combiner system are its inherent mechanical stability and the fact that it has 20 mm of eye relief. The major disadvantages are the intrinsic weight of the prism (even if plastic) and a full-brightness ghost image from the prism face closest to the spherical mirror. This ghost cannot be eliminated by the use of antireflection coatings because it is the result of total internal reflection within the prism itself. While potential solutions exist for reducing or eliminating the ghost, none of these solutions have been proven or even tested and, hence, involve a high risk and higher costs.

The weights of the optical components of this system are shown in Figure 4. It is obvious that the weight of the "combining prism" of 173 g is the dominant weight for this system.

The horizontal dimensioning of this combining prism is approximately 54 mm, which is that required to avoid vignetting in the eyepiece. This corresponds to the $\pm 30^{\circ}$ see-through FOV visible from the center of the exit pupil.

The see-through FOV may be larger than the display FOV. In the vertical direction, the see-through FOV can be increased to 35° down by 30° up by extending the vertical dimension of the block. The extension in the direction of the spherical mirror is also useful in reducing the total internal reflection ghost from that surface.

It should be remembered that all transmission values must be reduced by the standard transmission losses caused by absorption and reflection losses in all of the components in the display system. It should also be noted that the total efficiency of the coatings can be maintained so that transmission plus reflectivity is greater than 95%. Although this can be achieved, it is often quite difficult to hit an exact value for reflectivity. When these values are in the neighborhood of 50%, this is not serious, but when very low reflectivities are required, a small variation in the realized value can represent a large change in the system transmission.

Air Combiner

Figure 5 shows the layout and the ray paths for the Air Combiner Helmet Display. The system has the same characteristics as the prism combiner with the following exceptions:

Exit Pupil Clearance = 18 mm
See-Through FOV (from center of exit pupil)
Horizontal $+/- 27^{\circ}$
Vertical $+/- 22.5^{\circ}$

This system eliminates the ghost problem of the prism combiner previously discussed and is significantly lighter in weight as shown in Figure 6. It provides less eye relief for the same optical distance from the exit pupil to the spherical mirror. However, a clearance of 18 mm from the plane of the nearest point of the combiner to the plane of the exit pupil can be achieved. Its major negative feature is that the spherical mirror must be positioned between the eye and the DART thus reducing the brightness of both the DART and the HMAOI. If any portion of the DART is to be viewed through the HMAOI, then the see-through transmission of the HMAOI should be optimized at the expense of the brightness of the HMAOI.

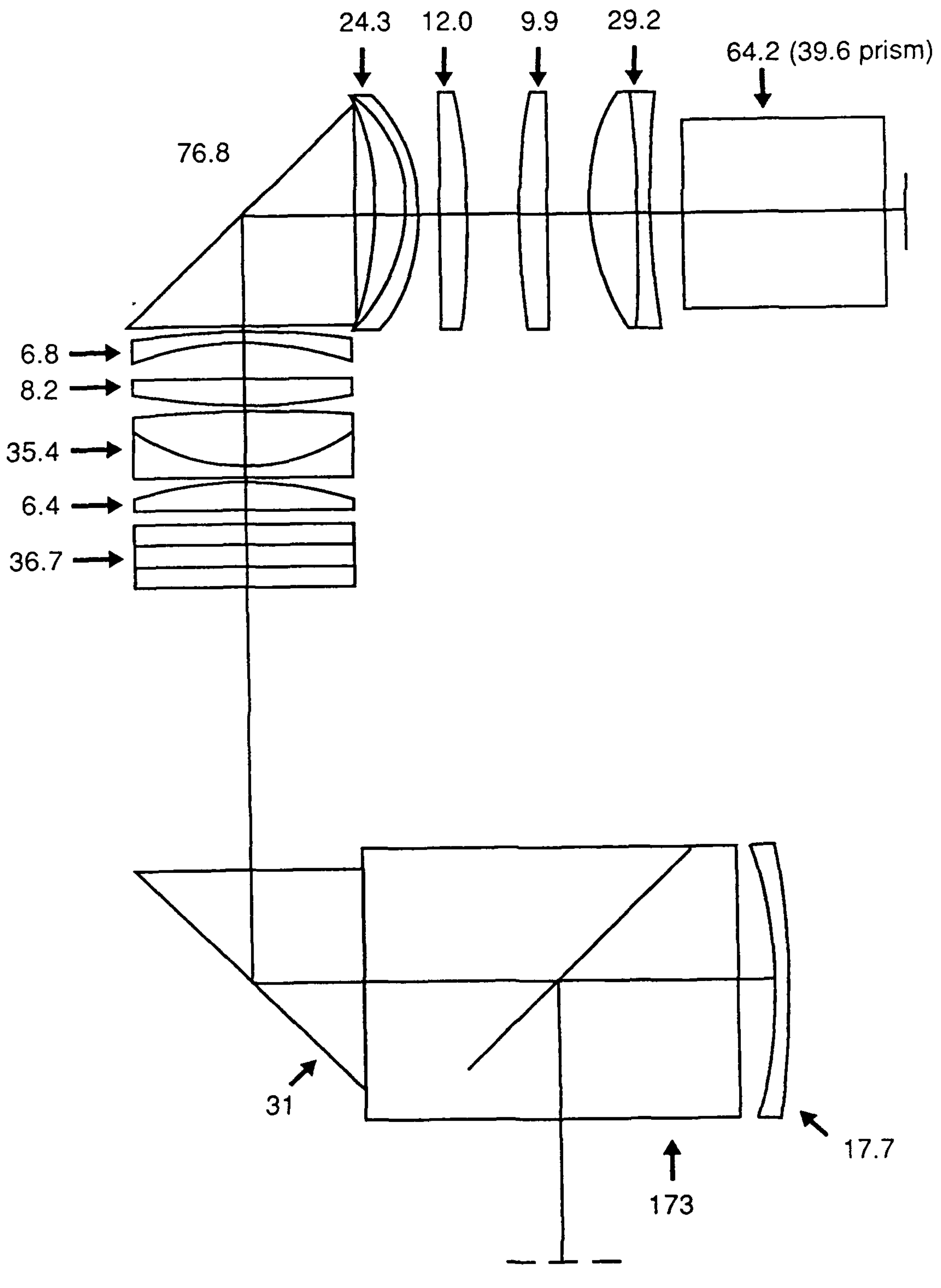

Figure 4
Weights of the Optical Component in the Prism Combiner

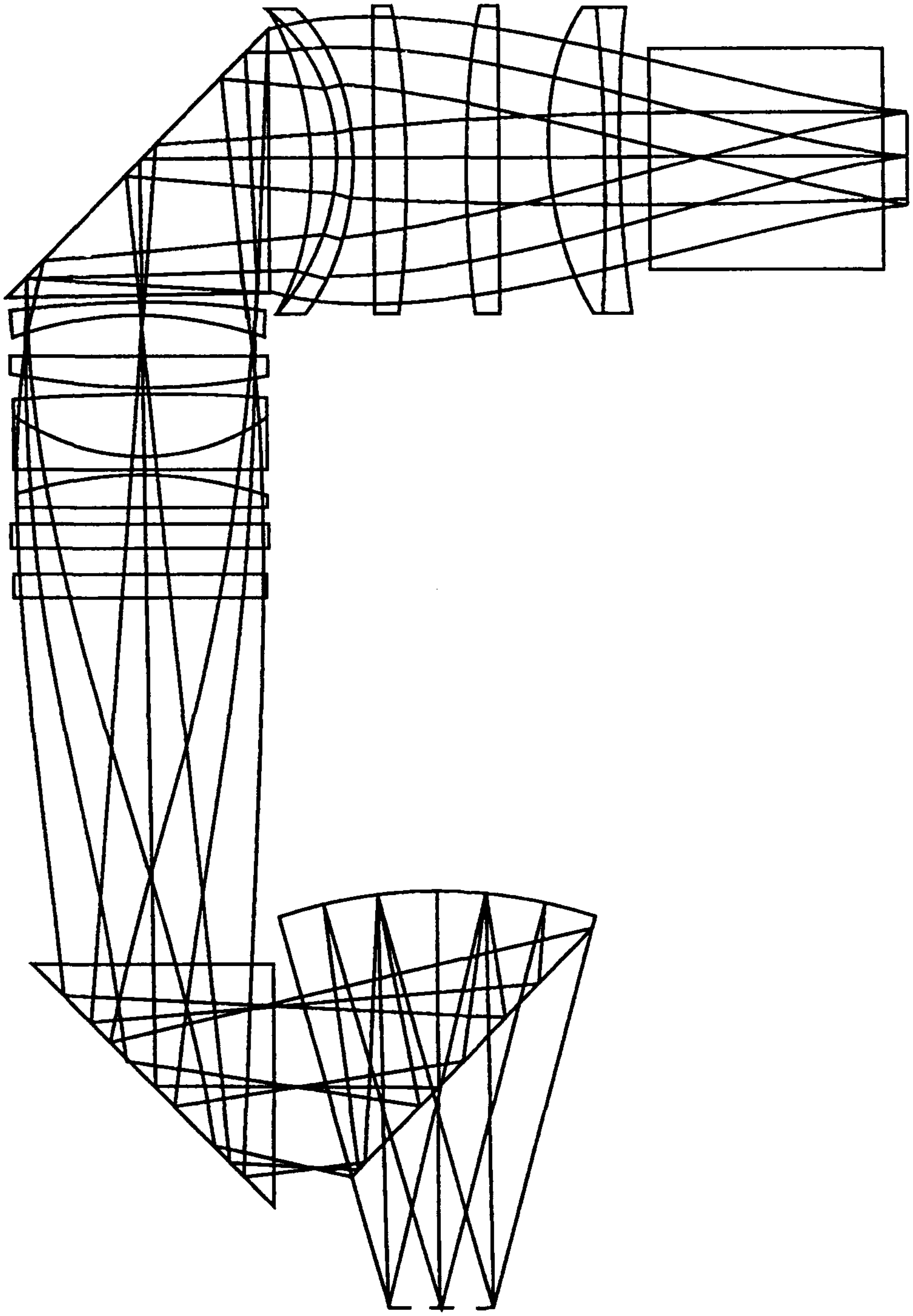

Figure 5
Air Combiner Optical Layout

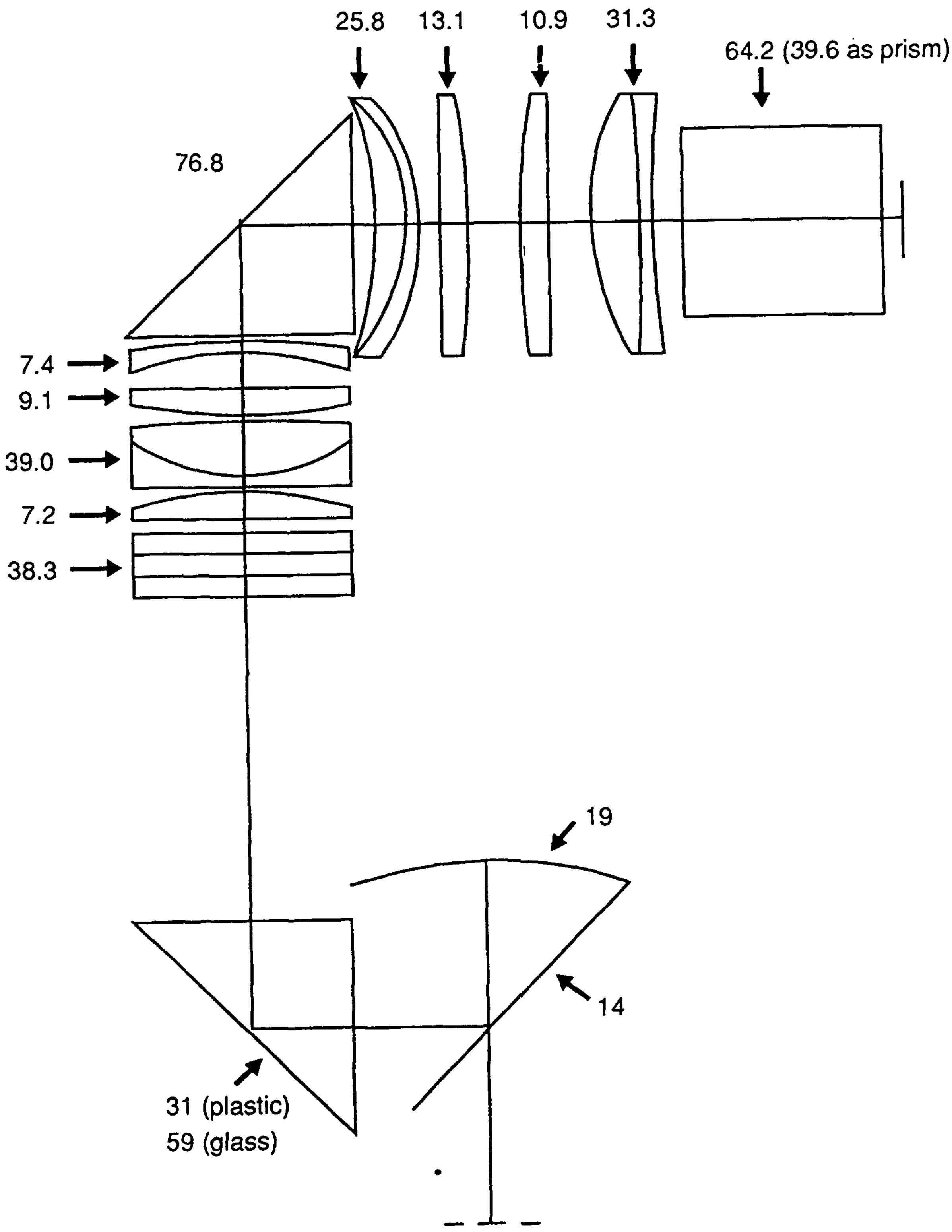

Figure 6
Weights (in Grams) of the Optical Component in the Air Combiner

Display ideal transmission = 25% Reflectivity of Spherical Mirror (RSM)

See-through transmission = Transmission of Tilted Beamsplitter (TBS) x Transmission of Spherical Mirror (TSM)

Table 3. See-Through Transmission Versus Display Transmission

Flat combiner reflectivity	Display transmission	See-through transmission
50%	25% RSM	50% TSM
40%	24% RSM	60% TSM
30%	21% RSM	70% TSM
20%	16% RSM	80% TSM

Note: There is a second surface ghost from the tilted air beamsplitter and the spherical mirror beamsplitter even with the best of antireflection coatings. This reflection is between 0.5% and 0.7%. Thus, for low reflectivities on the spherical mirror and/or the flat beamsplitter, the relative ghost brightness is computed as:

$$\text{Ghost Relative Brightness} = \text{TBSxTBSx.007/RBS}$$

Thus, for RBS = 20% the relative ghost brightness is 2.24%.

Fortunately, the HMAOI will be far brighter than the DART so there is no penalty to be paid for sacrificing HMAOI brightness for increased HMAOI see-through transmission. This trade-off can be accomplished by using low reflection coatings on both the spherical mirror and the flat combiner. There is a limit to how low the reflectance of the spherical mirror and the combiner can be before a ghost image from the second surface of the optical components becomes comparable in brightness to the actual image. The highest efficiency that can be achieved with an antireflection coating is a reflectance on the order of 0.5% to 0.7%. The loss of contrast due to the ghost, as well as the visibility of the ghost images themselves, must be carefully considered when choosing the reflectance of the reflecting surfaces in the eyepiece. As stated, the prism combiner does not exhibit the ghost images.

The see-through FOV is defined by the angular size of the required dimensioning of the spherical mirror as seen from the center of the exit pupil. If it is desired to increase the see-through field to $\pm 30^\circ$ by defining a larger spherical mirror, then the weight of the mirror increases by approximately 10 g; an increase of $\pm 35^\circ$ would increase the weight of the mirror component by approximately 20 g. However, it should be noted that the smaller increase in the horizontal see-through field would increase the required width of the spherical mirror to 61 mm, which would limit the minimum interpupillary distance for the full overlap configuration.

The see-through FOV is also governed by the flat combiner. The flat combiner cannot be lengthened in the vertical direction, but it may be lengthened, if desired, to increase the horizontal size of the combiner.

Discussion

The prism combiner has many characteristics that make it an attractive eyepiece for the HMAOI. Unfortunately, the prism adds too much weight to the helmet-mounted display which makes the display very uncomfortable to wear. A comparison of the weight of the optical components for both the prism and air combiners is shown in Table 4. The air combiner is 156 g lighter than the prism combiner. For this reason the prism combiner is not considered a viable eyepiece for the HMAOI.

Table 4. Helmet-Mounted Display Weight Comparison

	Air combiner	Prism combiner
Spherical Mirror	19 g (54°)	18 g (60°)
Beamsplitter	14 g H. see-through (for Prin. Rays)	173 g H. see-through (for Prin. Rays)
Folding Prism	31 g (plastic) 59 g (glass)	31 g (plastic)
Color Multipl.	38 g	38 g
Lenses	144 g	132 g
Folding Prism	77 g (glass)	77 g (glass)
Slab	64 g (cylinder) 40 g (prism)	64 g (cylinder) 40 g (prism)
Total	363(415) g	519(533) g

Although the air combiner is relatively lightweight, it has some limitations which require consideration before it can be considered a practical eyepiece for the HMAOI. First, the FOV of the air combiner is limited in the fold direction to approximately 40°, and in the direction orthogonal to the fold, to approximately 55°. Further, the nature of the blending of the HMAOI imagery to the DART imagery makes full binocular overlap desirable. Finally, the air combiner requires a mechanical mount, which can maintain the optical alignment of the eyepiece while minimizing both its overall weight and the amount it obstructs the pilot's vision.

The design of the HMAOI eyepiece evolved as each of these constraints was considered. Initially, the full binocular overlap constraint placed a limit on the horizontal FOV by limiting the diameter of the spherical mirror to the minimum interpupillary distance of 58 mm. This in turn limits the horizontal FOV to approximately 40°. Since this is the same FOV as the maximum FOV in the fold direction, it seemed natural to make the HMAOI FOV 40° circular with the fold direction being in the direction which provides an optimal placement of the eyepiece relay optics. Primarily for weight distribution reasons, the optimal fold direction is 40° down from a horizontal fold in the temporal direction. With a second 90° fold at the eyepiece end of the relay optics, the relay optics are then located beside the ear cups of the helmet roughly parallel to the pilot's line of sight. This position is desirable because it lowers the inertia of the helmet primarily for pitch movements, and it also locates the visible portion of the relay optics in an area of the peripheral vision which is not crucial for flying a fixed-wing aircraft.

The final concern was the design of a mechanical mount for such an eyepiece which would meet the above stated constraints. The recommended design is depicted in Figure 7. The mounting frame is essentially a cone with the spherical mirror mounted on the open end of the cone. The cone is then cut along a plane so the flat combiner can be added to the frame. Finally, any material not needed for rigidity is cut away to reduce the weight and to eliminate material that will obstruct the view of the DART from the exit pupil of the display.

Initially, both of the eyepieces were designed for a 40° x 30° FOV (48.6° diagonal FOV). This was based on the use of a fiber optic bundle having a useful format of 16 mm in the horizontal direction and 12 mm in the vertical direction, utilizing 10 micron fibers having 8 micron cores. If the FOV is extended to 51.77° x 40° (62.48° diagonal FOV), then either the format size of the bundle or the magnification of the eyepiece would have to be increased. Since the fiber optic bundle would become too heavy if it were larger than the 16 mm x 12 mm format, the magnification of the eyepiece would have to be increased. The magnification can be increased by shortening the overall focal length of the eyepiece. CAE Electronics, Ltd. has built a display with a 50° FOV using a 16 mm x 12 mm bundle. If this approach is chosen, then the 40° circular FOV eyepiece would use only a 12 mm diameter circular area

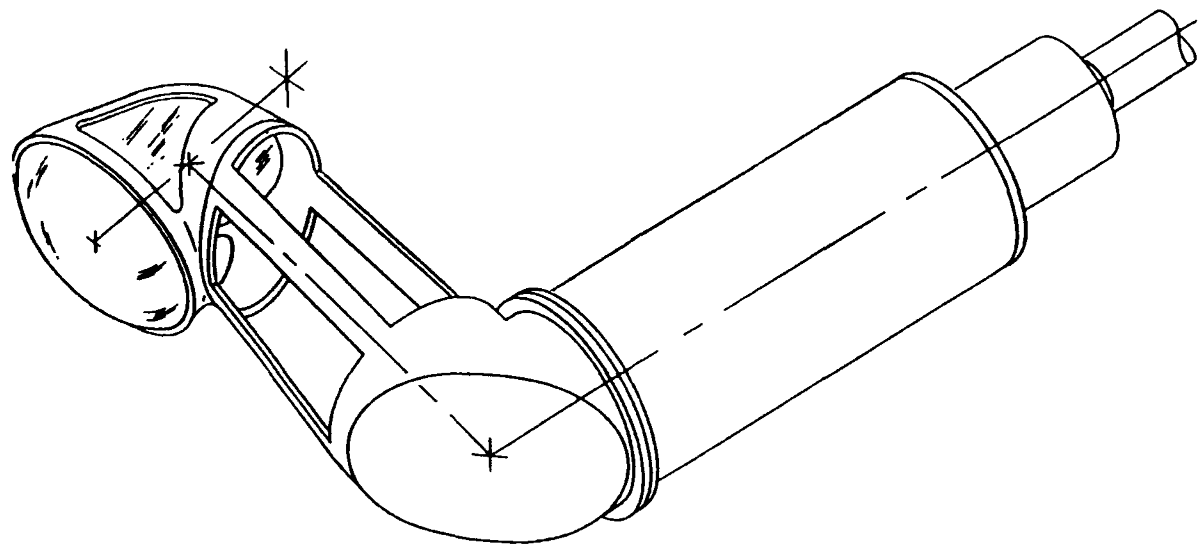

Figure 7
The Air Combiner Eyepiece Mechanical Design

on the fiber optic bundle. Alternatively, a separate hexagonal fiber optic bundle with a minimum cross section of 12 mm could be used. The design which increases the horizontal FOV to the desired 53.3° does so by simply increasing the horizontal sizes of the eyepiece components. However, this must be done judiciously because the size of the aperture of the eyepiece mirror is already 53.5 mm for the full pupil for the 40° FOV while the 53.3° FOV would require a horizontal width of 64 mm if no vignetting was desired. This increase in the horizontal size of the mirror will start limiting the minimum interpupillary distance for the full overlap arrangement. As the width of the mirror increases, there is a corresponding increase in the width of the cube. If the 53.5 mm width for the mirror is maintained, then the 53.3° image would have the outer 6 mm portion of the pupil vignetted for the point in the field of view that is 26.7° off axis in the horizontal direction.

In the vertical field direction, the choice is clearer. Increasing the vertical field above 30° to allow no vignetting will have a basic effect on the size of the eyepiece components and thus on the weights of these components as well as on eye relief. It is recommended that if the definition of the CRT input is changed so that the horizontal format defines a larger field of view, then angular definition of the vertical field of view should be permitted to increase but sizes or arrangement of components in the vertical plane should not be changed.

It should be noted that this increase in the horizontal field can be accomplished without significantly changing the sizes of any of the other elements in the display except for the horizontal folding prism.

As presently designed and dimensioned, the candidate systems achieve all of the minimum requirements of the minimum specifications. It is felt that once a configuration is decided upon, we will be able to significantly reduce the weights of the refracting components without taking recourse to aspheric components which we have not utilized in this system because of the significant recurring costs of such components. We hope that, in either system, we will at least be able to eliminate the rear block if, in fact, we decide that a final fold is not required.

Fiber Optics

The FOHMD systems built by CAE Electronics, Ltd. use skip-wound fiber optic bundles manufactured by Schott Fiber Optics (Welch et al., 1984). These bundles consist of layers of multifibers (5x7 blocks of individual fibers) separated by a spacing material. This approach provides a means of maintaining a large format size (25 mm x 19 mm) using only half as many fibers and, consequently, eliminating half of the weight. In actuality, 55% of the format area can be skip-wound material, thus reducing the weight by up to 55%. Since the weight of a bundle is proportional to the area of the format, it is clear that a 16 mm x 12 mm bundle will inherently be only 40% as heavy as a similarly constructed 25 mm x 19 mm bundle. This reduction allows the use of nonskip-wound or simply skip-wound bundles.

This is fortuitous because the wavelength multiplexing used in the FOHMD to eliminate the visibility of the skips does not work well when the image source is a CRT. This is due to the narrow spectra emitted by CRT phosphors as compared to the wide band spectrum of a GE Talaria light valve projector used on the FOHMD.

Relay Optics

MSOD conducted a preliminary design study of the input relay optics. The most important consideration in the research was the incorporation of distortion correction within the input relay. Distortion correction is required when transforming an F-Tan-Theta input image to an F-Theta image at the input to the fiber optic bundle. In previous systems with larger angular fields of view than the present system, a significant portion of the distortion correction has been achieved through the use of large field lenses near each of the CRTs in addition to correction introduced by small field lenses near the output of the relay near the fiber optics bundle. An additional complication was added by choosing 9-in instead of 7-in CRTs because of the superior resolution available in the 9-in CRTs. With the larger CRTs, it was necessary to investigate whether or not the distortion correction for the required 48.6° diagonal FOV could be achieved through the use of only the small output field lenses on the fiber optic bundle end as opposed to the large field lenses on the CRTs. We discovered that the small field lenses at the output end of the relay provide sufficient correction.

If a larger horizontal FOV and, consequently, a larger diagonal FOV is deemed necessary while maintaining the present 12 mm by 16 mm bundle, it will be necessary to determine if the distortion correction that can be achieved by these lenses will be sufficient.

The relay optics must also combine the HMAOI background imagery with the HMAOI high-resolution inset imagery. In the initial design a different magnification was used for the inset and background CRTs. This complicated the design somewhat because a cube combiner was required within the relay optics.

The design of the relay optics was greatly simplified by the decision to reduce the raster size on the inset CRTs such that the magnification for the inset CRTs would be the same as the magnification for the background CRTs. This resulted in only one relay optics assembly or lens per eye with the inset and background CRTs being optically combined prior to the relay optics. A schematic of the HMAOI display system is shown in Figure 8.

Optical Design Recommendations

Eyepiece Recommendations

After considering the results of the design study, it became apparent that the 40° circular eyepiece, while satisfying the HMAOI eyepiece constraints, would not be very useful as an eyepiece for other HMD applications. Thus we recommend that two eyepieces be designed and built, one for the HMAOI and one for the TVS HMD. The TVS HMD should have a vertical fold so the horizontal FOV can be maximized. The binocular FOV in the horizontal direction can be further increased by employing partial binocular overlap. The recommended FOV for the TVS HMD is 53.3° horizontal by 40° vertical. If the binocular overlap is 30°, the binocular FOV will be 76.6° horizontal by 40° vertical.

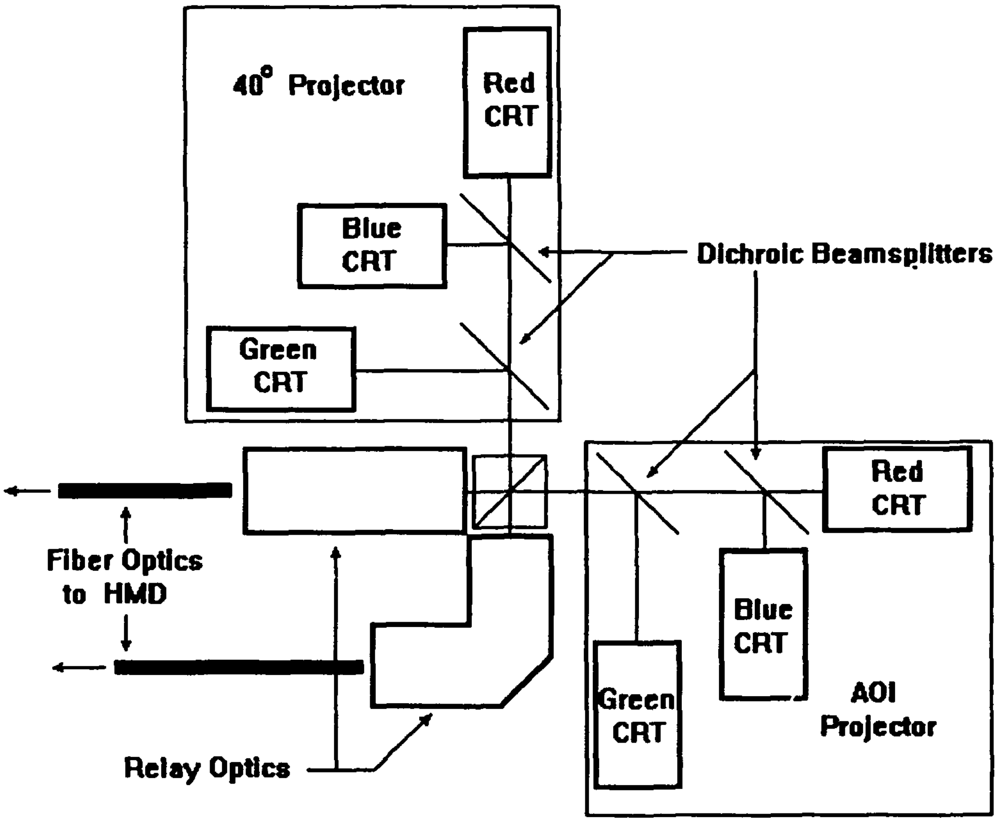

Figure 8
Layout of the Relay Optics

Fiber Optics Recommendations

A 16 mm x 12 mm nonskip-wound bundle is the recommended bundle for the HMAOI. This bundle will support both the 53.3° x 40° FOV and 40° circular FOV. The bundle should be constructed with 5x5 rhomboid multifibers with 10-micron fibers having 8-micron cores. The bundles should also be 6 ft in length. The bundle should be polished on both ends. Similar bundles have a limiting resolution of 120 optical lp/mm if wavelength multiplexing is used. If more resolution is desirable, Schott Fiber Optics is capable of making a similar bundle with a smaller fiber size.

Relay Optics Recommendations

The final relay optics design should perform all of the necessary distortion correction for the eyepiece. This will greatly simplify the daily maintenance of the CRTs by simplifying the convergence procedure. The relay optics should also be designed as a single magnification lens, i.e., the high- and medium-resolution portions of the FOV should be combined optically before the relay optics. The different magnifications for the two different resolution areas should be accomplished by changing the raster sizes of their respective CRTs.

SYSTEM DESIGN

HMAOI/DART Optical Interface

The most difficult aspect in the design of the HMAOI is the visual blending of HMAOI imagery with DART imagery. If the boundary between the two images is too apparent and distracting, the HMAOI/DART display system may be unusable as a training device. Ideally, the pilot should perceive the imagery as one continuous image with changes in resolution with no other perceptible differences. In the eye-slaved AOI version, the change in resolution should not be apparent except when the eye looks outside the FOV in which the eye-slaved AOI moves. Experience with systems with discontinuities in resolution (i.e., FOHMD) has shown that the associated brightness and color discontinuities between the AOI and the background image are extremely difficult to minimize. The blending of the varying resolution images in the HMAOI/DART system is further complicated by two factors. First, the HMAOI image is combined or superimposed on the DART image with an optical combiner mounted on a moving platform, the pilot's helmet. Secondly, the HMAOI image is itself the combination of medium- and high-resolution images.

The HMAOI eyepiece will essentially function as an optical combiner much like that of a head-up display. The image projected by the HMAOI is overlaid on top of the image created by the DART, but unlike HUD symbology, the HMAOI image must fully occlude the DART image. On the other hand, the HMAOI optics cannot block the pilot's view of the cockpit. As a consequence, the HMAOI eyepiece must be transparent. For proper viewing of the instruments, the "see-through" transmission of the eyepiece should be greater than 40% and preferably closer to 70%. Both of these conditions must be satisfied simultaneously. The only way to accomplish this is to blank out the DART image in the area of the DART covered by the HMAOI Instantaneous Field of View (IFOV).

The projection screens in the DART are approximately 1 m from the eyepoint. If the pilot's viewing position is translated parallel to a projection screen, an anomalous parallax error will occur for objects projected on the screen. Distant objects pictured in the scene will appear to move in the direction opposite to the head translation. This parallax error can be eliminated by monitoring the head position in the DART with a head-tracking device and accordingly updating the field of view definitions in the image generator for each projection screen. This solution was not implemented in the DART because the parallax error did not appear to be a serious practical problem.

Although the HMAOI imagery is converged at 1 m, the HMAOI will not have anomalous parallax during head translation because the HMAOI imagery is fixed to the head. This situation will result in a disparity between the position of objects viewed in the DART and objects viewed in the HMAOI. For this reason, dynamic window definitions based on head position are required for the DART when using the HMAOI.

Optical Combining

The primary goal in the design of an HMD eyepiece, which functions as an optical combiner, is to minimize the perception of the eyepiece to the pilot. Both the mechanical structure and the optical components must not distract or hamper performance significantly. Ideally, once involved in the performance of a flight task, the pilot should be unaware of the eyepiece.

The visibility of the eyepiece to the pilot is a complex issue to analyze. Essentially, there are four potential ways the pilot might perceive the presence of the eyepiece.

1. The mechanical structure may be visible or occlude part of the visual field.

2. The eyepiece optics may distort the DART imagery viewed through the eyepiece.

3. The brightness discontinuity between the DART imagery viewed directly and the imagery viewed through the eyepiece may be noticeable.

4. Vignetting of the HMAOI imagery at the edge of the eyepiece exit pupil, if present, may be noticeable.

The mechanical structure must be rigid, lightweight, and unobtrusive. The Pancake Window has the simplest mounting structure, a ring which holds both the spherical combiner and the birefringent sandwich. The cube combiner is also mechanically simple since the cube itself can be used as a structural element. The cube also inherently maintains the optical alignment of the beamsplitter/combiner. The air beamsplitter/combiner eyepieces are difficult to support structurally. The beamsplitter is mounted at roughly a 45° angle to the spherical mirror with its trailing edge being close to the eye. Safety concerns are of utmost importance when designing air beamsplitter eyepieces due to the proximity of the beamsplitter to the eye. Air beamsplitter/combiners also suffer from poor mechanical stability and thus are difficult to align and maintain in alignment.

Optical Blending

There are two potential means of blanking the DART imagery appropriately. The first method is to use a video blending system which blanks out a hole in the background image by operating on the video signal produced by the IG. The second method is to create a model in the IG database which subtends the same FOV as the HMAOI. The latter is simpler to implement than the former because the calculation of the shape of the blanked-out area is inherently calculated in the IG.

If a model in the IG is used, then its position and attitude within the database would be the addition of the ownship and the head-tracker positions and attitudes. The model would consist of a single face which would always remain perpendicular to the helmet and at a fixed distance from the helmet to maintain the proper angular subtend. If the IG has phototexture and transparency capabilities, then the model could be a black texture pattern with edges blended with the scene it is occluding. The HMAOI imagery could be similarly faded either optically, in the IG, or with a video blending system.

Cockpit Visibility

The use of an HMD in a cockpit will, in general, hinder the visibility of cockpit instruments. The cockpit in most instances will be viewed through the HMD eyepiece, but can also be viewed directly by looking around the HMD. When the cockpit is viewed through the HMD, the see-through transmission of the eyepiece must be high enough so that the cockpit instruments remain bright for easy viewing. If the see-through transmission is low, such as the case with a Pancake Window (10%), then cockpit lighting and brightness of CRT displays can both be increased accordingly. This solution can result in a degradation of the contrast of the DART display by increasing the ambient light within the DART. The design of a cockpit lighting system is not a trivial task and can significantly add to the cost of the cockpit.

A further problem arises when there is a large difference in the brightness of the cockpit when viewed through the eyepiece or viewed directly. In certain situations, one of the pilot's eyes will view the cockpit through the eyepiece while the other eye will view the cockpit directly. Eyestrain generally results in such situations if there is a substantial difference in the brightness of the cockpit as seen by each eye.

For these reasons, the minimum design specification for display see-through was set at > 50%. This specification eliminated the Pancake Window as a candidate eyepiece for the HMAOI. Although the same problems exist for the TVS application, the brightness discontinuity problem can be eliminated in this application by using oversized Pancake Windows so that the cockpit is always viewed by both eyes through the Pancake Windows.

As previously discussed, the eyepiece and its mechanical mount must not significantly obstruct the pilot's view of the DART. The same applies for cockpit viewing. Under most flying conditions the pilot will look at the instruments primarily with eye movements and not head movements. This will tend to force the pilot's fixation point towards the edge of the HMAOI FOV. In the case of the 40° circular FOV, the bottom edge of the eyepiece will pass visually through the middle of the instrument panel of most cockpits. The mounting bracket should be designed to minimize its interference with the viewing of cockpit instruments.

A final consideration in cockpit visibility is the blanking of the HMAOI imagery in the FOV which overlaps the cockpit. The image generator must produce a silhouette of the cockpit which remains stable relative to the cockpit during head movements. This is done by having a moving model of the cockpit, known as the cockpit mask, within the IG which is fixed to the ownship position and is colored black. Provided the display is focused at a distance close to the distance of the cockpit from the eyepoint, the binocular image of the cockpit mask will visually align with the cockpit's outline even when stereo imagery is not being generated for the HMAOI by the IG.

Human Factors

Helmet Weight/Inertia

If the helmet weight or inertia is too high, the utility of the HMAOI as a simulator display device will be greatly diminished. Experience with the FOHMD showed that a 5-lb helmet was acceptable to pilots. In general, pilots tend to have stronger neck muscles due to regular subjection to high G forces. The 5-lb weight of the FOHMD was thus not a problem for pilots.

Weight was a problem if the pilot did not use a properly fitting helmet. The center of gravity of the FOHMD is significantly forward of the pivot point of the neck. If the helmet fit loosely, the majority of the helmet weight was supported by the portion of the head just above the forehead. With a properly fitting helmet, the weight is distributed evenly over the whole head.

Inertia of the FOHMD was actually more significant than the weight of the helmet. Inertia slowed both the yaw and pitch accelerations of the head. In addition, deceleration of the head after a rapid movement was difficult resulting in some overshoot at the end of the head movement. The additional force needed to rotate the head resulted in additional muscle fatigue.

The weight of the HMAOI will be approximately the same as the FOHMD. The helmet optics should weigh approximately 500-600 g per eyepiece, of which 300-350 g are glass or plastic and the remaining 200-250 g are the mechanical housing. This weight is very similar to the weight of the FOHMD. An additional weight of 100-150 g per eye is required for mounting the helmet optics to the helmet. The final weight of the optics, excluding the fiber optic bundle but including the bundle ferrule, will be 1.2-1.5 kg or 2.5-3.3 lbs.

The fiber optic bundles for the HMAOI are much smaller than the FOHMD bundles, but are still approximately the same weight. This is due to the choice of nonskip-wound bundles for the HMAOI.

Although the HMAOI will not have a significantly lower weight than the FOHMD, it will have a superior weight distribution and inertia. This is primarily due to the placement of the helmet optics relay close to the helmet along the bottom of the helmet earcup. This will result in a center of gravity which is low and farther back than the FOHMD center of gravity. Inertia will be significantly lower than the FOHMD inertia. Yaw inertia is reduced by placing the relay optics close to the helmet, and the pitch inertia is lowered significantly because the relay optics will be much lower and, thus, closer to the pivot point of the neck.

Exit Pupil Size

The recommended exit pupil diameter for the HMAOI is 15 mm. A particularly attractive feature of the CRT-based FOHMDs, such as the HMAOI, is that the exit pupil is homogeneous in luminance. CRTs provide a diffuse image source which completely fills the numerical aperture of the fiber optics and, consequently, the exit pupil is completely and evenly filled with illumination. FOHMDs employing light valves as image sources suffer because light valves do not produce a diffuse image which fills the numerical aperture of the fiber optic bundle. To correct this, the output end of the bundle is ground to further diffuse the light exiting the bundle. Unfortunately, the grinding of the bundle degrades the MTF of the image and does not sufficiently diffuse the image so that the exit pupil is homogeneous in luminance. The luminance of the image falls off if viewed through the edge of the exit pupil as opposed to the center of the exit pupil.

Experience with the FOHMD showed there was no loss of imagery with a 15 mm inhomogeneous exit pupil if a custom-molded helmet was used. The homogeneous exit pupil of the HMAOI should relax the requirements for a good helmet fit.

Accommodation/Stereopsis

An interesting question arose early in the study; should the HMAOI be collimated at infinity or should it be focused at 1 m, which is the nominal distance of the screen to the eyepoint in the

DART? Since the pilot will foveate primarily on the HMAOI imagery and rarely on DART imagery, it was agreed that the HMAOI could be collimated at 10 m to infinity, effectively making the DART/HMAOI system an infinity display. On the other hand, the HMAOI could be focused at 1 m so that on the rare but inevitable occasion when the pilot's fixation point crosses from the DART/HMAOI FOV's boundary, the pilot's eyes would not have to refocus. An additional benefit of the 1 m focus is that myopic pilots would not require corrective eyeglasses to view the HMAOI imagery. The 1 m focus distance should, in fact, be viewable without eyeglasses by an extremely large population. This is particularly advantageous because it removes the need for a large eye relief which is normally needed if eyeglasses are to be worn in the display. This allows the use of an air combining eyepiece which has an eye relief incompatible with the wearing of eyeglasses. Since the collimation of the HMAOI will be relatively easy to change, both the 1 m and the near-infinity distances will be experimented with to conclusively resolve these issues.

A closely related subject is the relationship between binocular convergence and stereopsis. Binocular convergence is the distance in the space in front of the HMD at which the images in both eyepieces overlap. The FOHMD was typically converged at infinity (i.e., the line of sight of the eyepieces is parallel). In fact, simulator sickness experiments on the FOHMD found that convergence at 6 ft resulted in eyestrain, dizziness and, in one case, slight nausea and imbalance when flying at low levels (Barrette et al., 1990). No symptoms were experienced with 6-ft convergence when flying the simulator at high altitudes. It is likely that these symptoms were not the result of the convergence alone, but were the result of the combination of the convergence with both a collimated HUD and collimated imagery. The eyestrain alone was undoubtedly caused by a double imaging of the HUD which occurs when the pilot's eyes are not parallel. At this time, the available information suggests that the display should be converged at the same distance at which it is focused. The HMAOI will be an excellent testbed for the investigation of the relationship between collimation and convergence.

Binocular HMDs can provide stereo imagery. The utility of stereo imagery in flight simulators in general has yet to be determined. For fixed-wing aircraft simulators, a simple analysis of stereo imagery shows that there are few objects which will ever be close enough to the ownship to have any perceptible binocular disparity. For fixed-wing aircraft, the only flying tasks which could possibly benefit from stereo imagery are formation flying, air refueling and, possibly, landing. Although stereo imagery may be advantageous for the training of these tasks, the tasks themselves are not significant enough to justify the additional cost of an IG channel required for stereo imagery.

The only other reason for using stereo imagery in the HMAOI would be to ensure that the cockpit mask is perceived to be aligned in three dimensions to the cockpit. Without a stereoscopic cockpit mask in HMDs converged at infinity, the cockpit mask appears to be very large and located a significant distance in front of the aircraft rather than being coincident with the cockpit. If the HMAOI is converged at 1 m as discussed earlier, the cockpit mask will actually appear to be located at that same distance and thus appear to be coincident with the cockpit. If a convergence at 1 m is unacceptable, a stereo cockpit mask may be deemed necessary.

For the DART application, stereo imagery is not necessary or justified. On the other hand, the TVS may be a practical device for training air refueling, in which case stereo imagery may be beneficial. The HMAOI and the TVS have the flexibility to be stereoscopic or nonstereoscopic to facilitate experimentation in this area.

Eye Relief

Eye relief is the distance from the exit pupil to the closest optical element of the eyepiece along the optical axis of the eyepiece. In general, the eye relief should be at least 15 mm so that the eyepiece does not come in contact with the eye or the face. If eyeglasses must be worn, the eye relief should be greater than 30 mm and preferably closer to 40 mm. As stated, it is highly unlikely that a pilot will need to wear glasses if the HMAOI imagery is collimated at 1 m. The eye relief of the air combiner and prism combiner eyepieces is 1 m and 20.4 mm respectively.

Performance Estimates

Brightness

The estimated brightness of the HMAOI can be determined from an estimate of the transmission of each of the components in the optical chain. Table 5 shows the estimated transmissions of the components.

Table 5. Percent Transmission of Optical Components

CRT Combiner/Dichroics	45%
Relay Lens	90%
Fiber Optic	45%
HMD Relay Lens	90%
Eyepiece	16%
Total Efficiency	2.6%

The HMAOI must have at least the same peak brightness as the DART, which has a peak white brightness of 25 fL. Provided the HMAOI brightness efficiency is in fact 2.6%, the combined peak brightness on the RGB CRTs would have to be 961 fL for the HMAOI to have a peak white brightness of 25 fL. The peak white brightness of projection CRTs is typically between 2,000 and 5,000 fL. Clearly, the HMAOI will be at least twice as bright as the DART.

Contrast

The contrast ratio of the FOHMD is typically greater than 50:1. The GE Talaria projectors used on the FOHMD have a contrast ratio as high as 100:1.

Eye Slaving

Eye slaving refers to the positioning of an AOI within the display's IFOV such that the line of sight always falls within the AOI. This requires a continuous knowledge of the eye's line of sight which is obtained with an oculometer. This technique has been demonstrated both in the FOHMD and in CAE-Link's ESPRIT (Eye-Slaved Projected Raster InseT) dome simulator display. Although these systems are inherently different, they both move the AOI by mechanical means. The high rotation rates obtainable by the human eye make mechanical slewing of an AOI technically difficult and thus expensive.

The use of CRTs as image sources in the HMAOI provides the possibility of slewing the AOI by nonmechanical means. In the HMAOI, the slewing of the AOI will be accomplished by moving a raster, which covers only a fraction of the faceplate, to any position on the faceplate by an offset voltage or magnetic field depending on the type of deflection employed in the CRT. With minor modifications to commercial CRT projectors, the raster can be shrunk to approximately 1/3 (1/9 area) of its normal size. This allows the CRTs for the AOI and background to have the same magnification which in turn permits the use of a common relay optics assembly for both CRTs. The ability to slew the AOI with the CRT will greatly simplify eye slaving.

Optical Steering

Optical steering is a technique developed by CAE Electronics to compensate for the transport delay of the IG (Welch et al., 1984). It was originally developed for the breadboard FOHMD but was not continued in subsequent designs because of its mechanical complexity.

Although optical steering was abandoned, it inherently is a better means of compensating for transport delay than prediction, provided that the mechanical complexity can be avoided. In the

HMAOI the optical steering can be accomplished in the same manner as the eye slaving as discussed earlier. If the magnification of the CRT relay optics is designed to be slightly larger than the magnification necessary for the nominal raster size of the CRT, then the raster may be translated to a slightly different position on the face of the CRT. This can be used to implement optical steering without the cost and complexity of the mechanical optical steering.

An additional benefit can be gained by using the optical steering to make a 30 Hz IG update rate to appear to be 60 Hz. In a fixed-wing flight simulator, the maximum rotation rates of the ownship are low enough to permit the use of a 30 Hz update rate. (This should not be confused with a 60 Hz refresh rate which is necessary to avoid flicker.) Although the ownship rotation rates are relatively low, the rotation rates of the pilot's head are substantially higher. As a result, HMDs require a minimum of a 60 Hz update rate if perceptible image stepping is to be avoided. For small head rotations, such as the rotation between frames, the computer-generated scene changes imperceptibly with the exception of translation and rotation. Small yaw or pitch movements result in horizontal or vertical translations respectively, while roll movement results in a rotation of the image. If the IG produces a new scene at 30 Hz, the optical steering could reposition the raster on alternate frames to simulate a 60 Hz update rate. In this way, optical steering would compensate for the lack of a 60 Hz update rate for both yaw and pitch but not roll. Fortunately, the roll rate for head movements is relatively low and most likely will not require any compensation at 30 Hz for small FOV displays such as the HMAOI.

CONCLUSIONS/RECOMMENDATIONS

The result of the design study shows the feasibility of constructing a CRT-based HMD which can meet the minimum design specifications previously outlined. The helmet optics should consist of a 40° circular air combining eyepiece with full binocular overlap. To enhance the future utility of the HMAOI, the optical system should be designed to be compatible with an alternative eyepiece for use in the TVS display system. This eyepiece should have a 53.3° horizontal by 40° vertical FOV and may be either an air combining eyepiece or a pancake window.

A 16 mm x 12 mm nonskip-wound bundle with 5x5 rhomboid multifibers of 10-micron fibers having 8-micron cores is recommended for the HMAOI. The bundles should also be 6 ft in length and polished on both ends.

The relay optics design should perform all of the necessary distortion correction for the eyepiece. To provide the highest possible resolution, a 9-in CRT should be used. The relay magnification should be chosen so that optical steering on the CRTs can be tested.

This research effort has demonstrated the feasibility of the HMAOI concept on a technical basis. The feasibility of the HMAOI as a training device can only be ascertained by building and testing a prototype HMAOI.

GLOSSARY

AOI
Area Of Interest - An area within the FOV which has higher resolution than the rest of the FOV. The AOI may be fixed relative to the IFOV or be eye slaved.

Binocular Overlap
The area of the display's IFOV which is common to both eyepieces of a binocular display.

Coherent Fiber Optics
A bundle of millions of optical fibers in which each fiber occupies the same location at each end of the bundle relative to the other fibers. An image projected on one end of the bundle will be transmitted "coherently" or undistorted to the other end of the bundle. A rigid bundle is referred to as a fiber optic conduit, while a flexible bundle is simply a fiber optic bundle or sometimes a fiber optic rope.

Exit Pupil
An area through which the light exiting an optical system passes. In optical terms, the exit pupil is an image of the aperture stop of a lens system as seen from the optical axis on the rear side of the lens system. The exit pupil of most collimating eyepieces is external to the last element or lens of the eyepiece. In other words the exit pupil is a real image of the aperture stop.

Eye Slaving
The movement of an AOI so that it is always in line with the pilot's line of sight. An oculomotor (eye tracker) is required to determine the location of the AOI at any given moment.

Eye Relief
The eye relief of an eyepiece is the distance from the exit pupil to the closest optical element of the eyepiece along the optical axis of the eyepiece.

FOHMD
Fiber Optic Helmet-Mounted Display - Specifically, the HMD developed by CAE Electronics Ltd. for the USAF.

IFOV
Instantaneous Field Of View - The FOV which the pilot sees at any given moment as opposed to the FOV the pilot can see by rotating his head.

Ownship
The aircraft being simulated. This term is often used to refer to some mathematical parameter of the simulated aircraft as represented in the simulation computer program.

Transport Delay
The time which the IG takes to create one complete frame of video. Although IGs update at 60 Hz (16.7 msec) the transport delay is significantly longer than a single frame time. This is because modern IGs employ a pipeline architecture which can take up to 6 frames (100 msec) from the start to the end of the pipeline.

TVS
Transportable Visual System - An inexpensive, compact display and image generator which is small enough to allow its transportation on commercial ground or air carriers.

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