DESIGN OF AN OPTICAL SIMULATOR VISUAL SYSTEM

Ralph W. Fisher
Principle Technical Specialist, Flight Simulation Technology
McDonnell Aircraft Company
P.O. Box 516
St. Louis, MO 63166
Dept. 251, Bldg. 65, Level 2E, Rm 269
Phone 341-234-3403

ABSTRACT

This paper describes the design of a truly optimal simulator visual system, i.e., one that fully satisfies human visual requirements with minimum information processing and display equipment.

The concept is based on the fact that only 130,000 visual resolution elements or pixels can be observed by the eye at any instant in time. This, coupled with the inability of the human to distinguish intermittent visual occurrences if they occur at moderate rates (30 per second) leads to the conclusion that one should be able to generate a wide field high resolution display with no more information processing requirement than those of a conventional 525 line television system. The impact of this is very great. Current wide field visual systems require several 1000 line image generation and display systems to produce resolutions significantly poorer than the desired one minute of arc human capability.

The concept takes advantage of the variable acuity nature of human vision by utilizing non-linear projection optics to redistribute pixels on a linear light valve format in the correct geometric pattern on the viewing screen so the eyes' requirement is met in both field of view and resolution. The optical system is then slaved to the observers' viewpoint by an eye position sensor and closed loop control system.

This paper describes the 10 years of development on this and related concepts conducted by MCAIR and supported by the Navy, NASA, and USAF. It concludes with design and performance details of a demonstration system being constructed for the USAF (HRL), Williams AFB, AZ.

INTRODUCTION

The state of the art in Flight Simulator Visual Systems has made significant advances in the last few years. Figure 1 is an example of the 1000 by 1000 element image that was generated in real time. While one cannot help but be impressed with the amount of detail present in this image we must keep in mind the total requirement of human vision. This is illustrated in Figure 2. Human vision can resolve about 1 arc minute detail and has an angular field of view exceeding a hemisphere. The large circle of Figure 2 shows the number of resolvable picture elements (pixels) required to meet these requirements if one minute of arc detail is produced over the entire hemisphere.

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Figure 1. Computer Generated Image

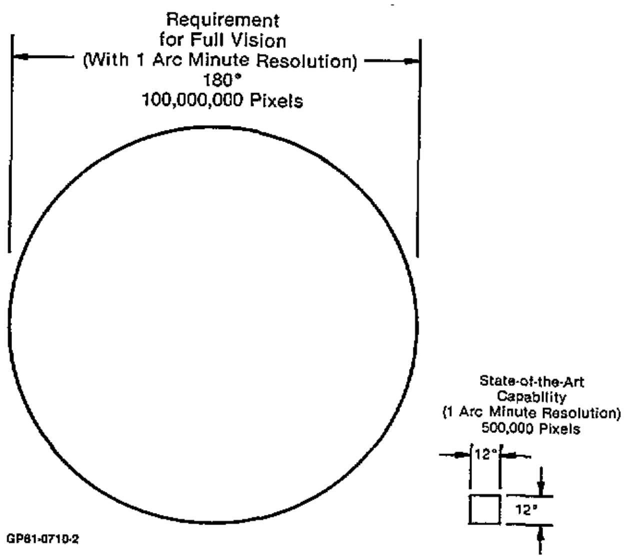


Figure 2. The Simulator Visual System Problem

The small square shows the total one arc minute pixels contained in Figure 1. When one considers the volume of equipment required to generate this image, Figure 3, it is clear that it is not practical to simply add more channels of equipment. Todays visual systems are forced to accept either lower resolution, small field of view or a combination of both. The result is simulators that are restricted in capability to specific missions.

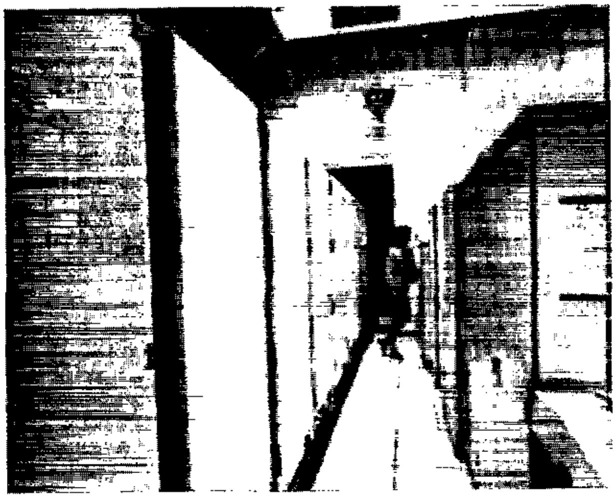


Figure 3. Typical Image Generator Hardware

The solution to the above problem lies in the nature of the human vision. The human breaks his visual field up into pixels of variable angular size as shown in Figure 4. Only about 130,000 pixels can be seen at any instant of time. When this is compared to the one million that exist in a display such as Figure 1 it would seem that such a display has more than enough capability to fully support human vision if the pixels are made of have variable angular subtense and a pointing system is provided that is capable of positioning the high acuity region along the eyes' foveal axis.

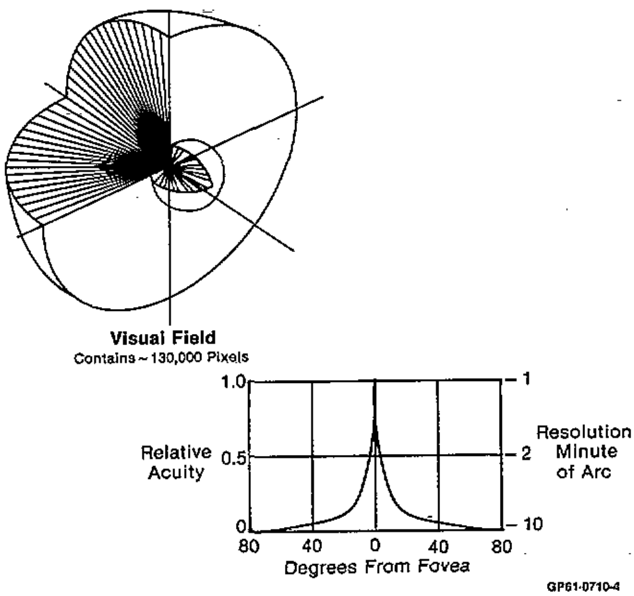


Figure 4. Human Eye Acuity

Almost 10 years ago MCAIR began studying ways of generating a variable acuity display as a bandwidth reduction technique for remotely piloted vehicles. This effort concluded that the best way was to use non-linear optics to convert a linear distribution of pixels in an image plane into variable size angular increments in the object field as shown in Figure 5. Such an optical system has a long focal length on-axis (like a telephoto lens) and a very short focal length at its field edge (like a wide angle lens). The focal length is made to vary in the same function as human visual acuity. Figure 6b is a photo made with such an optical system. It is compared to a fisheye lens image of the same scene, Figure 6a, which is the only other lens system that can cover a hemispherical field. Note that detail covered in the central 10% of the fisheye format occupies over 50% of the non-linear lens format. One minute of arc detail appears as

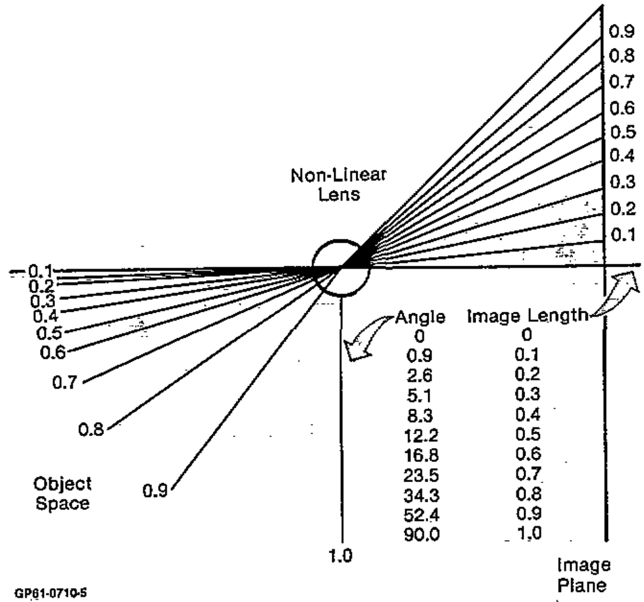
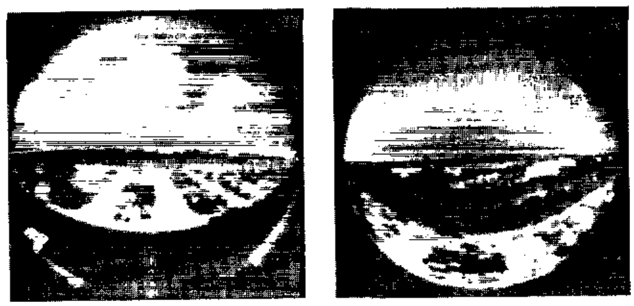


Figure 5. Non-Linear Lens
Transfer Characteristics



(a) Fisheye Image

(b) Non-Linear Lens Image

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Figure 6. Wide Angle Lens Comparison

1/1000 of the picture diameter in the non-linear lens image compared to 1/10000 on the fisheye image. When the non-linear optical system is used to project a simulator display the computer image generator must produce a geometrically distorted but constant resolution image at the source raster plane. When projected, this optical system produces an undistorted display with variable resolution. Figure 7 shows the central portion of a reprojection. Note the high resolution at the photo center and the gradual degradation with distance from the center in any radial direction. When the eye concentrates on this high resolution area, the entire display appears to be high resolution. A closed loop system is required to keep the high resolution area always at the eye's foveal axis. This requires an oculometer to detect eye position and a servo mechanism to point the display. In addition, the eye position and display position must be communicated to the computer image generation equipment in order to generate the correct image position and distortion.

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Figure 7. Reprojection of Figure 6b

Another way of illustrating operation of the variable acuity display can be made with reference to Figure 8. This is a photo of a normal linear raster projection through the non-linear optical system. Note how the raster lines coverage towards the center. The optics also cause scan velocity to reduce towards the center. The result is that of a much higher line content at the display center that can support very high resolution at normal display information rates (bandwidth).

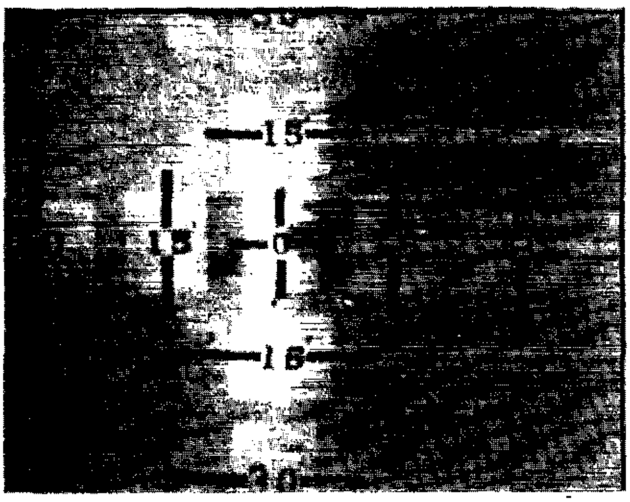

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Figure 8. Linear Raster Reprojection

The first demonstration of a Variable Acuity Display was made by MCAIR in 1978 using brassboard hardware developed under contract to the Navy (ONR). Two non-linear lenses were fabricated during that effort and assembled into a Variable Acuity Remote Viewing System (VARVS). One lens was used on a camera and the other on a projector. The pointing control was by head position and the projection was made in a 10 ft diameter dome. This system demonstrated very good support of human vision with 160 degree field of view and about 2 arc min resolution. This hardware is now at Edwards AFB where NASA (DFRC) has been evaluating it as a viewing link for remotely piloted research vehicles. Some other related efforts supported primarily by the USAF (AVAL) have been development of a virtual image display, a size reduction study, and sensing lens designs for the infrared spectrum.

Experience gained during the above programs led us to the following conclusions. First and most significant - eye control must be used to gain full benefits from the concept. Too much time is spent moving the head to point the system. The other is that a different optical approach is needed for the display. Use of a "taking" or camera lens as a projection lens results in an inherent display brightness falloff with field angle and excessive inertia on the projector platform gimbals.

In 1984 the USAF (HRL), Williams AFB, AZ became interested in the concept for a simulator visual display system. Their interest is in the enormous potential that the Variable Acuity Display has for cost reduction over current systems because only one projector and computer image generating system is required. Progress on this effort is described below.

SYSTEM DESIGN

There are some very firm bounds on what can and can't be done with variable acuity. These are established by the pixel parametrics which reflect a conservation of pixels, i.e., the number of pixels available from the linear source must exactly equal the number of pixels displayed. This leads to the data of Figure 9. Here the on axis resolution (in arc minutes/line) possible is plotted versus the width of the constant acuity region and resolution capability of the source. A 1000 line TV system can support about 715 pixels over the raster height. Figure 9 shows that this source capability can support 1.5 arc min resolution on axis and out to a field angle of 1 degree (a 2 degree constant acuity region).

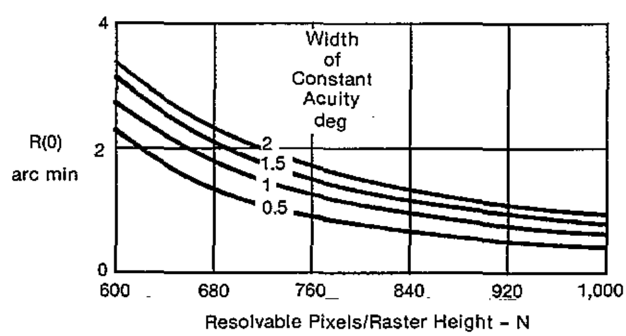

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Figure 9. Pixel Parametrics for a 160° Variable Acuity Projection System

This is the distortion function selected for the Variable Acuity Display. A smaller constant acuity region would be risky from a pointing control standpoint while a larger constant acuity region produces too low an on axis resolution.

OPTICAL DESIGN

The key element in the Variable Acuity Display is the non-linear optical system. A general optical arrangement is shown in Figure 10. It consists of the projection lens which is

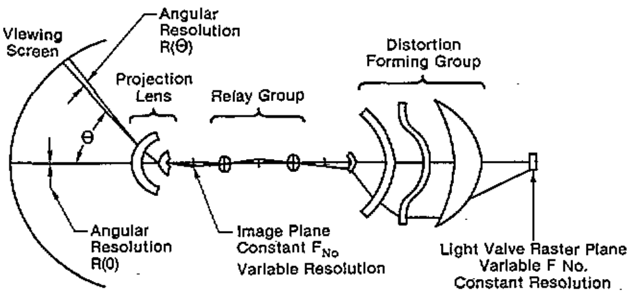

Figure 10. Optical Approach

mounted on the gimballed platform, the optical relay that transmits the image through the gimbal axes to the projection lens, and the distortion forming group that can have varying degrees of non-linearity. As mentioned previously our original design had all the distortion in the projection lens and suffered from extreme display brightness falloff from center to edge. This can be improved by using less distortion in the projection lens and placing it in the distortion group. There are other benefits that occur with lowering the distortion in the projection lens. These are listed in Figure 11. The gimballed mass on the

	Distortion Location		
Tradeoff Parameter	Projection Lens	Both	Relay
• Design Experience	Considerable		None
• Gimballed Mass	High		Low
• Brightness Uniformity	Poor		Good
• Maintainability	Good	Poor	Good
• Cost	Low	High	Moderate
• Relay Requirement	Low		High

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Figure 11. Optical Design Tradeoffs

projection platform can be reduced significantly. Maintainability and cost considerations further influenced our decision to place all the distortion in the distortion group and use a linear lens for the projection lens. This configuration assures the most uniform display brightness possible and the smallest projection system. The distortion parametrics are then as shown in Figure 12. The left half of the figure shows the projection lens characteristics. The image size reflects our choice of a 7.5 mm focal length linear (fisheye) lens. This lens is the smallest in size that can support the resolution and brightness parameters required. The right side of Figure 12 shows the distortion that must exist in the distortion group to match the light valve source height to the projection lens.

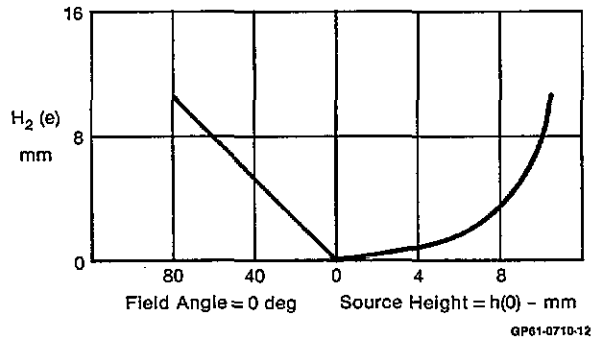

Figure 12. Distortion Parametrics for Linear Projection Lines
7.5 mm Fisheye Projection Lens

The distortion group optics presented the most difficult technical challenge of the design effort. Simultaneously meeting the requirements for distortion, resolution and ray cone geometry (Fnumber) involves a delicate balance of optical aberrations and physical geometry. The design is shown in Figure 13. Ten aspheric surfaces are required. Six of these are imbedded surfaces for color correction. The large elements are almost 7 inches in diameter. This makes the off platform optics quite large.

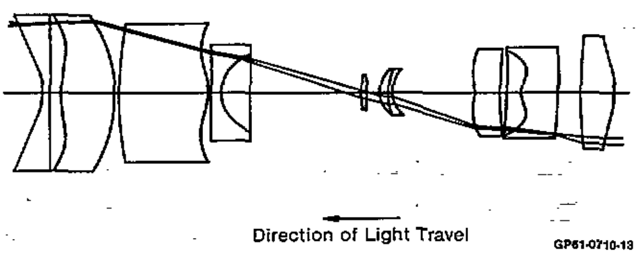

Figure 13. Distortion Group Components

The overall optical layout showing the system installed in a 10 ft diameter dome is shown in Figure 14. Details of the projector are shown in Figure 15. The projectors' location causes very little obscuration to the operators' field of vision. The predicted performance of the optical system is shown in Figures 16 and 17. Figure 16 shows angular resolution of the projected display as a function of optical field angle. Note that the display resolution appears to be better than the eye over the entire 160 degree field of vision. An exception is within .2 degrees of the eyes' foveal axis where the eye resolution peaks at 1 arc minute compared to the 1.5 displayed. The disparity seen between radial and circumferential resolution arises from pixel conservation in the two directions. Display brightness predictions using a 1000 lumen light valve source are shown on Figure 17. The constant brightness out to about 35 degrees

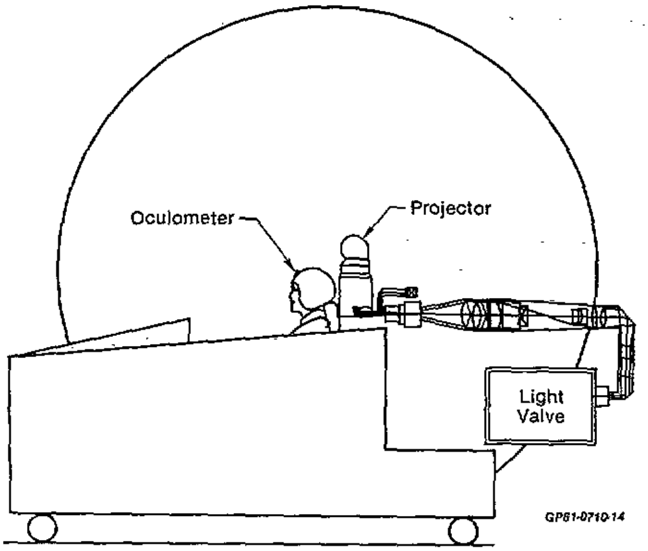

Figure 14. Projector Installation for 10 Ft. Dome

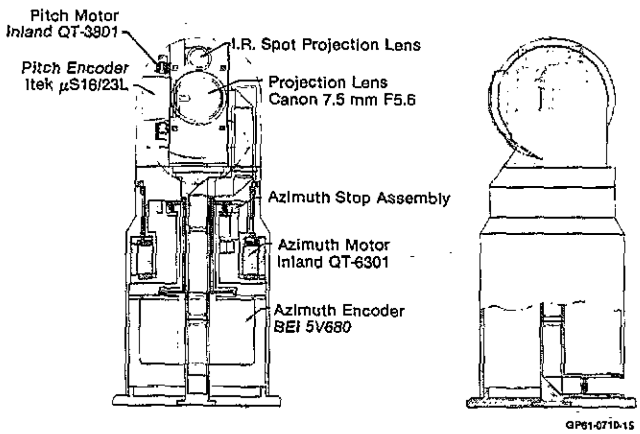

Figure 15. Projector Assembly

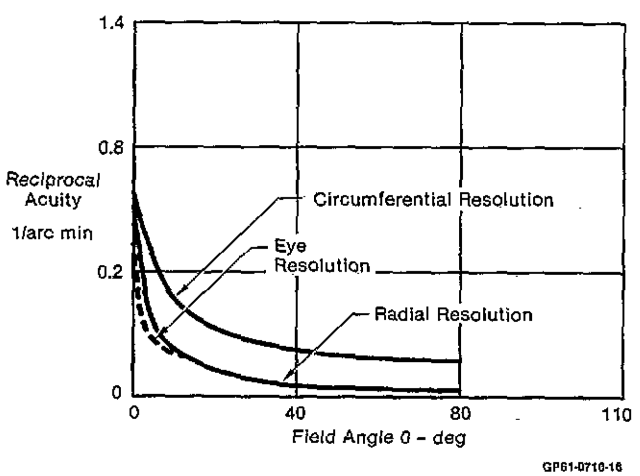

Figure 16. Resolution Parametrics

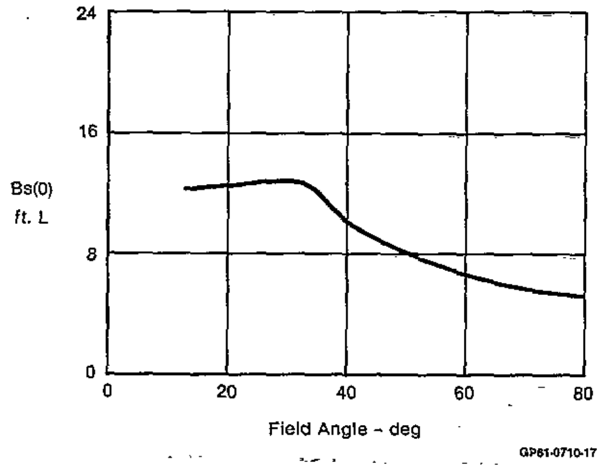

Figure 17. Brightness Parametrics for Linear Projection Lens
7.5 mm, F/5.6 Fisheye Projection Lens

shows that the Fnumber of the projection lens is being fully supported in this region. Beyond this angle some mismatch occurs resulting in about 60% loss at the field edge. While the design can be made to have uniform brightness, that design will have lower on axis brightness. Experience with the NASA equipment which has over 100/1 falloff has convinced us that this design compromise is justified.

CONTROL SYSTEM DESIGN

The control system consists of the oculometer and associated processing and servo drive equipment. Innovative approaches were required in all these areas. Existing oculometers were not considered accurate enough, require excessive calibration for each operator, and have too much delay between measurement and output. Our oculometer approach is shown in Figure 18. It is display referenced rather than head referenced. This is achieved by projecting an infrared spot at the display center which forms the source for the eyes' corneal reflection. The correct display position will, therefore, always result in the same corneal spot location relative to the iris. The system is independent of head motion

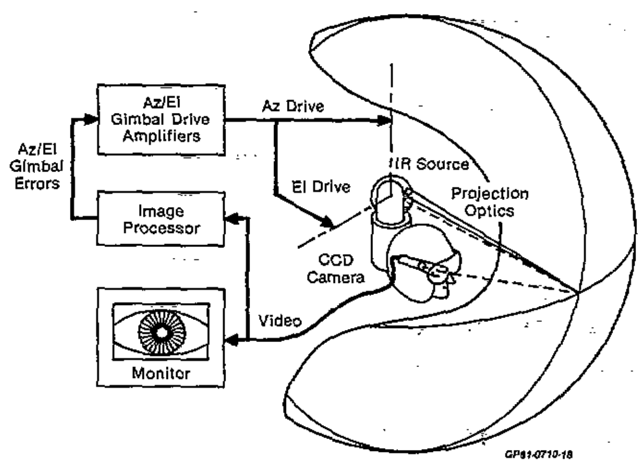

Figure 18. Oculometer Concept

and calibration becomes a second order parameter. The display problem was eliminated by processing the video at line rates rather than frame rates and by using a non interlaced format.

Conventional servo equipment is too slow to support eye rate movements with our projection approach. For this reason we developed the Highly Intelligent Serve System (HISS). It is an off shoot of our Highly Intelligent Servo Controller concept that was developed for high speed mirror drive systems. The HISS concept computes the optimum path required to get the platform from its current position to the desired position in the shortest possible time and drives the motors as required to follow this response. A functional diagram of this system is shown in Figure 19. Analytic simulations show that this system is capable of true acceleration limited performance with zero overshoot and a sightline stability of .5 arc minute (3 sigma).

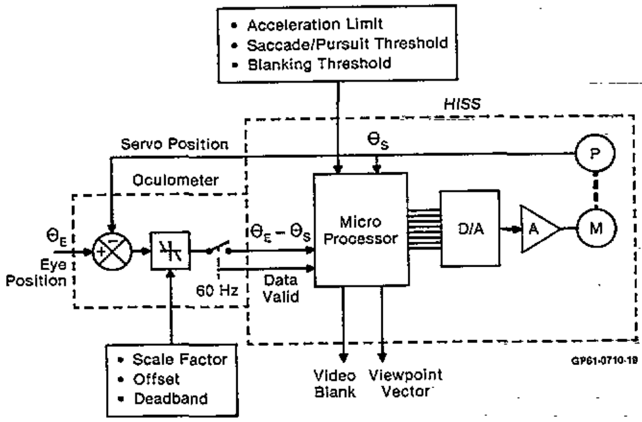

Figure 19. Functional Diagram

COMPUTER IMAGE GENERATION

Computer generation of non-linear images with the degree of distortion required for the Variable Acuity Display has not been accomplished to date although all major vendors think it is feasible. The unique requirements of this effort made a low cost CIG approach possible. They are an earth background representation with a single aircraft target. The background was the most difficult because of the vary large field of view combined with the high resolution required. A ray trace approach was adopted that computes a vector from the scan position on the linear source format in real time and determines its intersection with the earth. A simple 2 dimensional data base is then used to determine the attributes of this intersection point which forms the video for this pixel. This can be done at pixel rates so there is no significant delay in the background presentation.

The maximum angular subtense of the target for our mission is about 3 degrees. A study was made to determine how much distortion exists in this area for all possible locations on the source format. The worst location was found to be near the optical axis. Here a straight line could have a curvature of one pixel or more if its length was greater than about .5 degrees. If polygon edges can be kept this small no curvature should be noticeable. This means conventional image generation techniques can be used to generate the target with the constraint of breaking larger polygons down if necessary. The required distortion can then be achieved by relocating polygon vertices per the distortion function.

The composite video is obtained by mixing the target and background with the target having priority.

CONCLUSIONS

Results of the analysis and preliminary design of the Variable Acuity Display have been very encouraging. No problems have been encountered to date and detailed design and fabrication are proceding as scheduled. The Variable Acuity Projection System should be completed towards the end of 1987. The equipment will be located at Williams AFB, AZ. Those interested in demonstrations of the system should contact the Human Resources Laboratory for details.

ABOUT THE AUTHOR

Mr. Fisher is Senior Systems Technical Specialist in the Flight Simulation Technology Group of the Flight Simulation Laboratory, McDonnell Aircraft Company. He has B.S. and M.S. degrees in electrical engineering from Oklahoma State University and over 32 years experience in design and development of electronic, electro-mechanical, and electro-optical equipment. Mr. Fisher originated the Variable Acuity Display concept over ten years ago and has been responsible for its continuing development.