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VIRTUAL IMAGE DISPLAY FOR FLIGHT SIMULATION

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16. Abstract

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SYMBOLS

d	separation between two lenses
d_1	camera diagonal frame size
d_2	lens diameter
f	focal length
f_{eq}	equivalent focal length
f_i	focal length of television camera lens system
F	focal point
L	eye-to-lens distance (includes thickness of lens)
L_1	distance from pilot's eye to first surface of lens
M_a	angular magnification
n	index of refraction
R_1, R_2	radius of curvature of first and second lens surface
S	object distance
S'	image distance
X	lens thickness, normally called sagittal height
Y	radius of lens
Z	viewing width of television monitor or picture width
α	angular field of view of television camera
δ	horizontal field of view when the object is positioned at the focal point of the lens
θ	horizontal half-angle of object
θ'	horizontal half-angle of image

VIRTUAL IMAGE DISPLAY FOR FLIGHT SIMULATION

Bruce C. Ganzler

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SUMMARY

Simple uncorrected plastic lenses were used to provide a virtual image of a flight scene for use in a flight simulator. A virtual image display provides a realistic impression to the simulator pilot because the image seems to be a substantial distance from the simulator. A number of pilots made landings and takeoffs in a flight simulator to evaluate subjectively a virtual image display. The display consisted of a Schmidt color projector, rear projection screen and a large diameter, long focal length, plano-convex plastic lens. Another virtual image display utilizing a color television monitor and two plano-convex plastic lenses was evaluated without formal pilot comment. Various lens parameters were studied to determine their effect on the flight scene. The conclusion was that simple lenses could be used, with certain limitations, to obtain a usable virtual image of a flight scene with either a Schmidt projection system or a television monitor.

INTRODUCTION

A visual out-the-window flight scene observed by a pilot in a flight simulator should represent the real world. In the real world, the pilot generally sees objects at a distance of 30 m (100 ft) or more which, in optical terms, is infinity. A realistic simulated flight scene cannot be obtained if the scene is viewed from a short distance. Closed-circuit television-monitor and projection-screen displays require close viewing, usually less than 3 m (10 ft).

When the flight scene image is more than 12 m (40 ft) distant, a pilot's eye is focused at infinity. A change of view from the outside visual scene to the instrument panel requires refocusing the eyes, a process known as accommodation. The change from an unaccommodated to an accommodated state, and vice versa, is how a pilot's eyes react in the real world.

Highly complex and sophisticated virtual image systems have been made, especially for space flight simulators, at great expense. Single lenses, or for some cases two lenses in combination, can be employed in a flight simulator to increase the realism by providing a feeling of depth to the flight scene viewed by the simulator pilot.

The lenses can be plastic (acrylic). Plastic lenses are relatively inexpensive compared to glass lenses and can be made in a short time.

The purpose of this study was to determine the pilot opinion of a virtual image display for flight simulation and the requirements for selecting the correct lens. This study was concerned with image formation, lens focal length, magnification, image and object distances, perspective, field of view, lens aberrations, and their effects on a visual flight scene.

SYSTEM CONFIGURATION

The design of a virtual image display for a particular simulator must consider visual presentation of flight data, cab and room geometry, and weights and moments of inertia of equipment which may have to be mounted on a motion simulator. Two systems were used for this study. The first system consisted of a fixed-base simulator, rear projection screen, Schmidt color projector, and a single lens with a focal length of 216 cm (85 in.) and a diameter of 83.8 cm (33 in.). The second system consisted of a motion simulator, color television monitor, and a double-lens combination with an equivalent focal length of 61 cm (24 in.) and a diameter of 63.5 cm (25 in.). The image generator was a Plumbicon color camera that viewed a three-dimensional scale model of terrain and runway. Flight dynamics were provided with a general purpose analog computer.

SUBJECTIVE EVALUATION

The first virtual image display was designed so the pilot would observe a flight scene having the same picture perspective as the image generator. Three pilots flew a DC-8 aircraft landing and takeoff problem a number of times in the simulator. They were asked to write their comments on a prepared questionnaire (table 1).

TABLE 1.– SUBJECTIVE EVALUATION OF VIRTUAL IMAGE FLIGHT SCENE

QUESTIONS	ANSWERS		
	Pilot 1	Pilot 2	Pilot 3
1. Did you notice any color distortions and, if so, how objectionable were they?	NO	NO	Looks good
2. Did you notice any line distortions (curve or wavy lines) and, if so, how objectionable were they?	NO	NO	Looks good
3. Were there any head restrictions (laterally and vertically)?	None serious	NO	Not within the normal head area
4. Were you conscious of the fact that you were looking through a lens?	NO	NO	Only when moving the head from side console to forward view
5. Did the overall scene appear realistic (feeling that the scene was out a great distance)?	YES	YES, not sure of distance	Looked good
6. Do you feel the virtual image of the flight scene is an improvement over previous systems?	YES	YES, seems to be easier on eyes	At least as good
7. Additional comments?	None	You have to avoid lights in the cab which might reflect off the lens surface	Everything satisfactory

VIRTUAL IMAGE LENS PARAMETERS

Virtual Images

With a positive lens virtual images (fig. 1) at infinity are formed when the object is positioned at the focal point of the lens. Each point on the object acts like a point light source which results in collimated bundles of rays emerging through the lens system. Any photographs taken looking into this system will require the camera to be focused at infinity. A virtual image cannot be focused onto a projection screen as a real image can and one must look through a lens to locate the image. A virtual, magnified, upright image, not necessarily at infinity, will always be obtained with a positive lens when the object distance does not exceed the focal length of the lens. When the image is viewed through the lens, the iris of the eye will act as the aperture stop of the system, regardless of the viewing position. For the present systems, the pupil of the eye is the common receptor of light ray bundles coming from various parts of the image and, therefore, is the exit pupil of the system. The edge of the lens or frame around the lens acts as a field stop and therefore limits the total field of view.

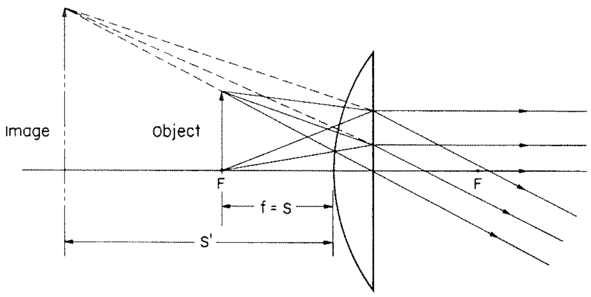


Figure 1.- Virtual image formation.

Plastic Lens Characteristics

Plastic lenses have a high light transmission capability, approximately 92 percent for a 6.35 cm (0.25 in.) thickness in the visible region of the spectrum. For each inch of additional thickness, there is about a 4 percent loss in light transmission. Lenses can be supplied in thicknesses up to 30.5 cm (12 in.). Large plastic lenses are lightweight, cost much less than glass lenses, and are equal to or better than grade B optical glass, which exhibits only light and scattered striae. This material can be sawed, machined, drilled, and adapted to various mounting configurations. The main disadvantage in using plastics is that they become scratched very readily.

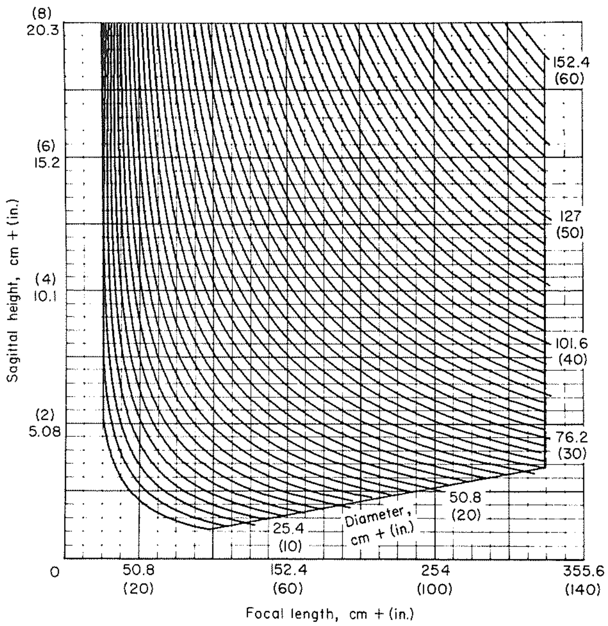


Figure 2.- Lens diameter, focal length, and sagittal height (thickness); n = 1.49.

Lens Diameter, Focal Length, and Thickness

Figure 2 shows the relationship between lens diameter, focal length, and thickness as determined by

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \tag{1}$$

where n = 1.49. Since the present study involved plano-convex lenses, the radius of curvature of the second lens surface is infinity. Therefore, the above equation will reduce to:

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1}\right) \tag{2}$$

or

$$R_1 = f(n - 1) \tag{3}$$

The relationship between lens diameter, thickness, and radius of curvature is illustrated in figure 3 and defined by equation (4). From figure 3,

$$R_1{}^2 = Y^2 + (R_1 - x)^2 \tag{4}$$

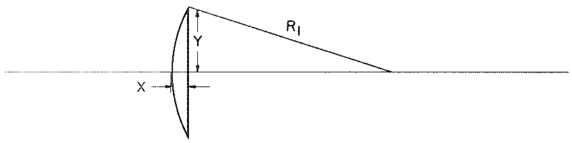


Figure 3.- Relationship between lens diameter, thickness, and radius of curvature.

From equation (3), the radius of curvature can be found for a lens of any focal length. When these values are substituted into the above equation, the lens thickness can then be determined for various lens diameters by use of the quadratic formula. Figure 2 shows that a slight increase in lens diameter causes a substantial increase in focal length. Figure 2 indicates that if a single lens is to be used for a virtual image display and a large lens diameter is required, then a long focal length lens will have to be incorporated into the display system. Systems requiring short focal lengths and large lens diameters can employ two lenses in combination. The equivalent focal length for two thin lenses in combination is

$$f_{eq} = \frac{f_1 f_2}{f_1 + f_2} - \frac{d}{f_1 f_2} \tag{5}$$

When the separation (d) between the two lenses is small, equation (5) reduces to

$$f_{eq} = \frac{f_1 f_2}{f_1 + f_2} \tag{6}$$

If

$$f_1 = f_2$$

then

$$f_{eq} = \frac{f_1}{2} \tag{7}$$

Since the focal length of f_1 will be twice that of f_{eq}, a larger diameter lens can be used (fig. 2) as compared to a single lens having a focal length equal to f_{eq}.

Thin Lens Equation

The thin lens equation,

$$\frac{1}{f} = \frac{1}{S} + \frac{1}{S'} \tag{8}$$

establishes the relationship between object and image distance and focal length of a lens. For a lens of a particular focal length, equation (8) shows that, as the object distance approaches the focal point of the lens, the image distance increases rapidly. Figure 4 shows this effect graphically for various focal length lenses. It is possible to change the image distance by hundreds of feet by moving the object only a few inches from the focal point of the lens. The object is always positioned between the lens and the focal point. If the object is positioned beyond the focal point, the light rays will start to converge. The light rays of a virtual image system for flight simulation should consist of diverging collimated ray bundles (fig. 1). When the object is moved closer to the lens, the image will move in the same direction.

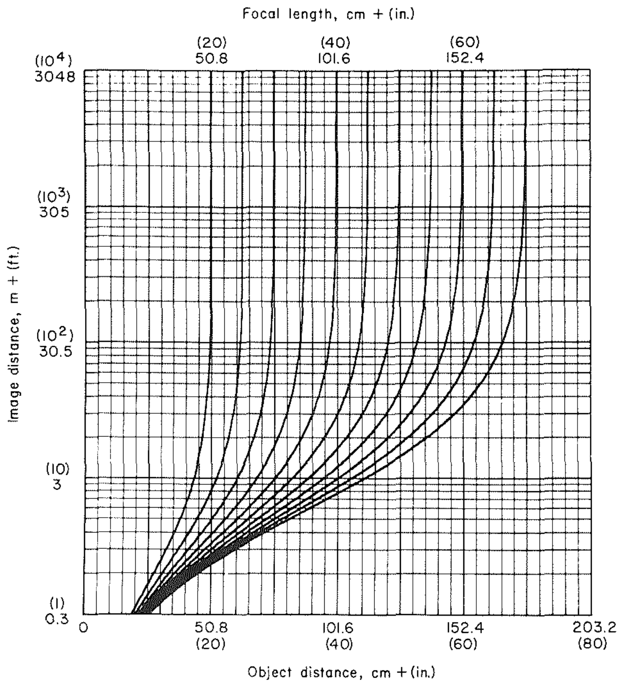


Figure 4.- Relationship between object and image distance and focal length.

Angular Magnification

For the present kinds of applications a virtual image lens system requires relatively low magnification. The angular magnification of the lens system (appendix A) is the ratio of the angular size of the image seen through the lens to the angular size of the object seen with the unaided eye from the same position. Equation (9) gives the angular magnification (M_a):

$$M_a = \frac{\tan \theta'}{\tan \theta} \tag{9}$$

The angular magnification can also be expressed in terms of focal length, object distance, and eye-to-lens distance,

$$M_a = \frac{1 + (L/S)}{1 - L[(1/f) - (1/S)]} \tag{10}$$

Figures 5 and 6 are plots of equation (10) showing how the angular magnification varies with eye-to-lens distances and for different object distances for lenses having focal lengths of 61 and 216 cm. If the object is positioned at the focal point of the lens, equation (10) reduces to

$$M_a = \frac{f + L}{f} \tag{11}$$

For this case, if the position of the eye does not exceed the back focal point of the lens, an observer will see any part of the image as the same size, regardless of the eye location on the optical axis, because the lens angular magnification will vary the image size in the correct proportion to keep the subtended angle of the image a constant (fig. 7).

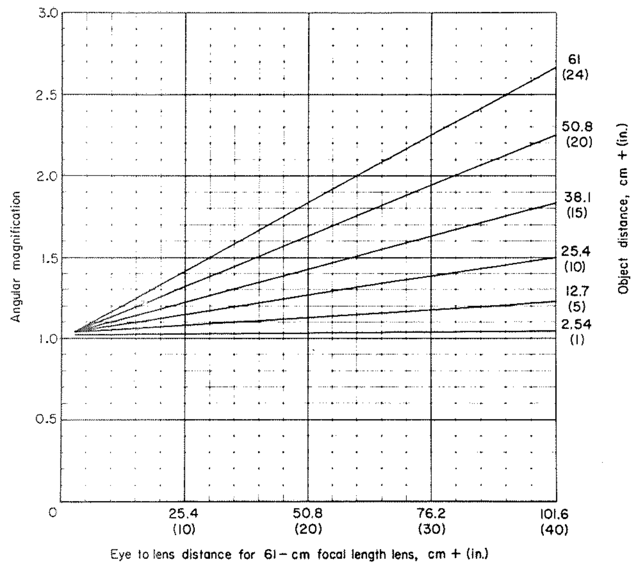


Figure 5.- Relationship between angular magnification, object distance, and eye-to-lens distance for a 61-cm focal length lens.

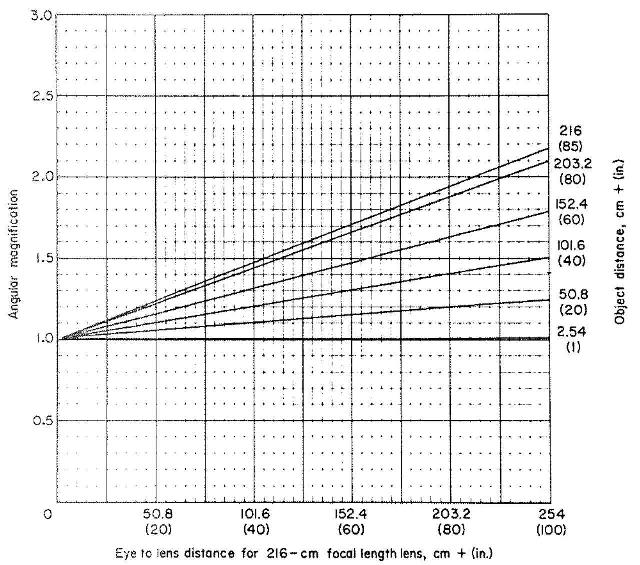


Figure 6.- Relationship between angular magnification, object distance, and eye-to-lens distance for a 216-cm focal length lens.

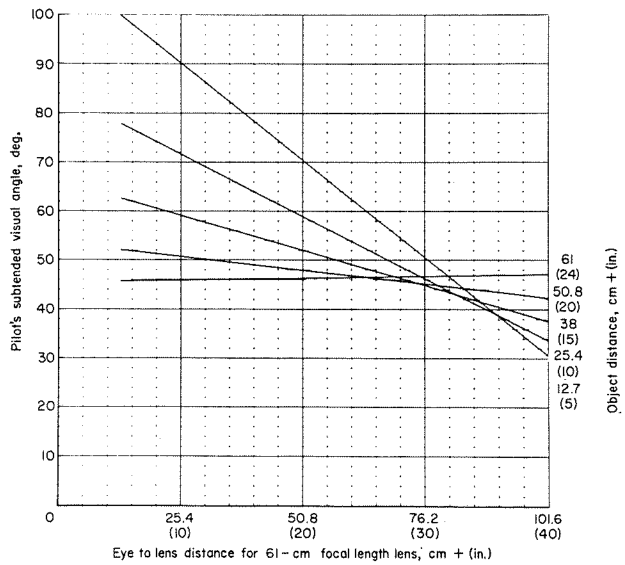


Figure 7.- Relationship between pilot's subtended visual angle, object distance, and eye-to-lens distance for a 61-cm focal length lens.

Perspective and Field of View

Perspective in a flight display should be the same for the pilot as it is for the camera viewing the scene. Perspective of the picture, at any instance, is determined by the view point (object-to-lens distance) at the camera. The image size changes proportionately with respect to a change in the object-to-camera-lens distance. The angular field of view of the image generator (α), in this case the television camera, is limited by the camera frame size (d_1) and focal length of its lens system (f_i) and is related by

$$\alpha = \frac{2 \tan^{-1} d_1}{2 f_i} \tag{12}$$

The camera used in this study provided a maximum diagonal angular field of view of 56°, while the horizontal field was 46° and the vertical field was 34.5°. The ideal situation would be for the pilot to have the same maximum field of view as the camera but this is generally impossible because of the limitation of lens diameters and long eye-relief distances. The pilot's field of view may be less, but the picture perspective for both pilot and camera will be the same since perspective depends strictly on the size relationships or subtended angles at the eye and camera for various parts of the image. The pilot's field of view can be determined from equation (9) where

$$\tan \theta' = M_a \tan \theta \tag{13}$$

The subtended angle of the object is

$$\tan \theta = \frac{Z}{2 (L + S)} \tag{14}$$

Substituting equation (14) into (13) we have

$$\tan \theta' = M_a \frac{Z}{2(L + S)} \tag{15}$$

From equation (10) we can substitute for the angular magnification; thus

$$\tan \theta' = \frac{Z}{2 (L + S)} \left\{ \frac{1 + (L/S)}{1 - L \; [(1/f) - (1/S)]} \right\} \tag{16}$$

For the total horizontal field of view at the pilot's eye

$$2\theta' = 2 \tan^{-1} \frac{Z}{2 (L + S)} \left\{ \frac{1 + (L/S)}{1 - L \; [(1/f) - (1/S)]} \right\} \tag{17}$$

and, if $f = S$, equation (17) reduces to

$$2\theta' = 2 \tan^{-1} \frac{Z}{2f} \tag{18}$$

Figure 7 uses equation (17) to show how the visual angle varies for various eye-to-lens and object distances for a 61 cm focal length lens. For the special case of $f = S$, the visual angle of 46° can be considered constant for various eye-to-lens distances.

Focal Length Determination

Figures 8 and 9 show the physical relationship for single and double virtual-image lens systems, respectively. When the object is positioned at the focal point of the lens, the angle (δ), which is the maximum horizontal field of view from the lens position, is equal to the total horizontal field of view of the image from the pilot's eye position. From equation (18) we have

$$\delta = 2\theta' \tag{19}$$

It is obvious from equation (18) that the focal length of the required simulator lens can be determined if the horizontal field of view and object size are known. The equation for the focal length (f) based on equations (18) and (19) can be written

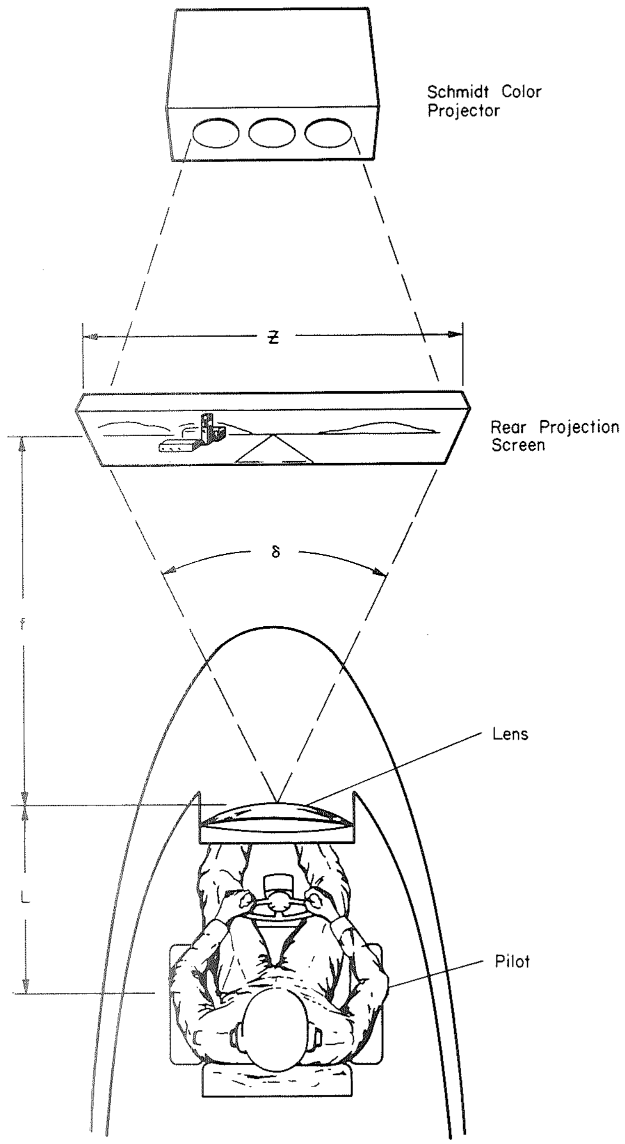


Figure 8.- Single lens virtual image system.

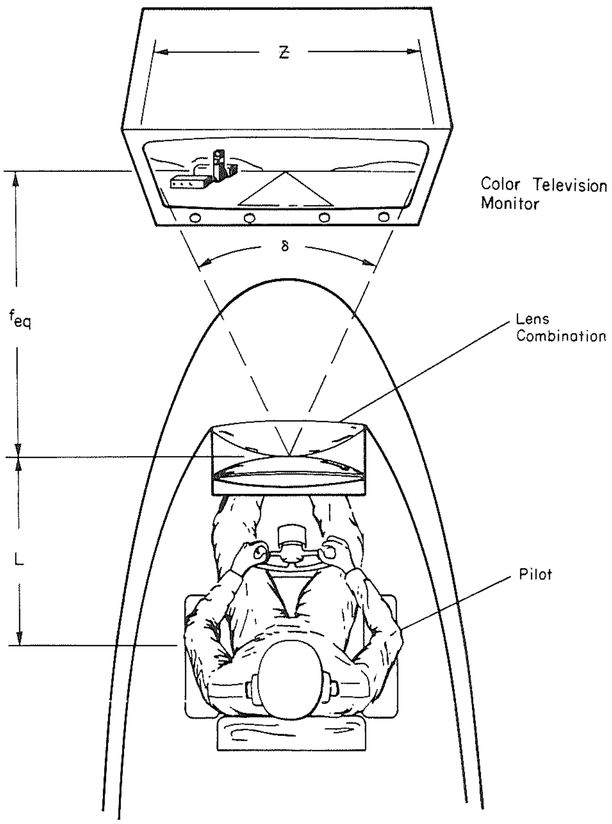


Figure 9.- Double lens virtual image system.

$$f = \frac{\not{Z}}{2 \tan (\delta/2)} \tag{20}$$

If the object is positioned at a point between the lens and focal point, the focal length of the required lens will have to be calculated from equation (17). For this case, the pilot's angular field of view angle is not constant for various eye positions; therefore, the distance (L), from the pilot's eye to the lens, must be accounted for. In this study, the focal length of the required lens was calculated on the basis that the object would be positioned at the focal point of the lens. For a closed-circuit television monitor, the size of its viewing screen determines the object size. For the Schmidt projection system, the object size will be the size of the projected real image. The focal lengths of the two virtual image lens systems studied were determined as follows:

Schmidt projection system and single lens:

$$\not{Z} = 183 \text{ cm } (72 \text{ in.})$$

$$\delta = 46^\circ$$

$$f = \frac{183 \text{ cm}}{2 \tan (46^\circ/2)} \approx 216 \text{ cm } (85 \text{ in.})$$

Television monitor and double-lens combination:

$$\not{Z} \approx 51.8 \text{ cm } (20.4 \text{ in.})$$

$$\delta = 46^\circ$$

$$f = \frac{51.8 \text{ cm}}{2 \tan (46^\circ/2)} \approx 61 \text{ cm } (24 \text{ in.})$$

A combination of two 122 cm (48 in.) focal length lenses will give an equivalent focal length of 61 cm. A single lens could not be used with the television monitor since a 61 cm (24 in.) focal length lens could only be obtained in diameters up to 43 cm (17 in.) (fig. 2) and a maximum lens thickness of 10 cm was desired; lens thicknesses of 10 cm were chosen since lenses thicker than this generally show more material defects. A lens diameter of 43 cm is too small to provide sufficient head motion for the pilot. The lens diameter was increased to 64 cm when two 122 cm focal length lenses were used in combination to provide a system focal length of 61 cm. This increase in lens diameter provided adequate head motion for the pilot.

The location of a pilot's eye behind the lens should be considered when the lens diameter is determined. Generally, the eye-to-lens distance will vary from 51 to 91 cm, depending on the particular simulator cockpit configuration and assuming that the lens is positioned at the windshield of the simulator. When the field-of-view requirement and the exact eye-to-lens distance are known the necessary lens diameter for a maximum fleld of view can be calculated from

$$d_2 = 2 L_1 \tan \theta' \tag{21}$$

When possible, it is desirable for the lens diameter to be larger than required for the maximum field of view since the lens may have to be cut for mounting and masked to simulate the framework of the cockpit windshield.

IMAGE DEFECTS AND OPTICAL CONSTRAINTS

Simple, uncorrected lenses exhibit many aberrations that affect the quality of the image. Coma and spherical aberrations vary with the square of the aperture while astigmatism and curvature of image vary with the square of the image height. Coma and lateral color vary directly with the image height, while distortion varies with the cube of the image height.

Moving the object closer to the lens will minimize many lens aberrations but changing the object distance will depend on the required field of view and image distance. Moving the object closer to the lens, then, results in less angular magnification and significantly reduced image distance. Also, the image size is less because of the reduced angular magnification; consequently, some of the above-mentioned aberrations will be reduced.

When single plano-convex lenses are used, the convex surface should face the object since this will minimize spherical aberrations (i.e., refraction of light rays in the outer portion of the lens compared to rays near the optical axis will be less). Longer focal length lenses have to be used with a color Schmidt projector since the projector requires at least 335 cm (11 ft) "throw distance" to properly converge and register the colors from its three cathode ray tubes. Picture size is thus much larger than that produced by a TV monitor and, in order to maintain the proper TV camera perspective, long focal length lenses have to be used so the projection screen can be positioned the necessary distance from the pilot's eyes.

For the double lens system, the convex sides of the two lenses should face each other. Pincushion distortion and lateral color are problems with this system.

Nevertheless, the resulting image from each of the systems studied here did provide an adequate flight scene for simulator aircraft landing and takeoff. The central area of the virtual image (approximately one-third of the lens diameter) appeared to be in sharp focus. The remaining portion of the image became progressively worse out to the edge of the lens. Normally, the runway area is approximately centered on the central area of the lens. More peripheral details, such as trees, shrubs, and mountains, are generally in the area that is slightly out of focus. Various pilots who have flown the simulators with the virtual image display have not complained of this condition, and from all indications it has not affected their landing and takeoff performances.

Table 2 shows some of the advantages and disadvantages between the two display systems used for this study.

TABLE 2.- SINGLE LENS SCHMIDT VERSUS DOUBLE LENS TV MONITOR COLOR DISPLAY

Schmidt – single lens – projection screen

1. Lens system shows less aberrations (not bothered as much by pincushion distortion and lateral color)
2. Larger lens diameters are available (head motion, without image shift, much greater)
3. Higher TV resolution (approximately 30 to 50 TV lines)
4. Absence of shadow mask CRT tube structure that contributes to the degradation of the image

TV monitor – double lens

1. Higher contrast
2. Easier to register colors and maintain registration
3. Cost from 10 to 25 times less than various Schmidt color projectors
4. Higher reliability – easier to maintain
5. Less weight – especially attractive for motion simulators
6. Separate displays as well as side windows can be provided for both pilot and copilot
7. Higher brightness – cabin lights can be left on to simulate a daytime condition inside the simulator
8. Setup time is negligible compared to a Schmidt

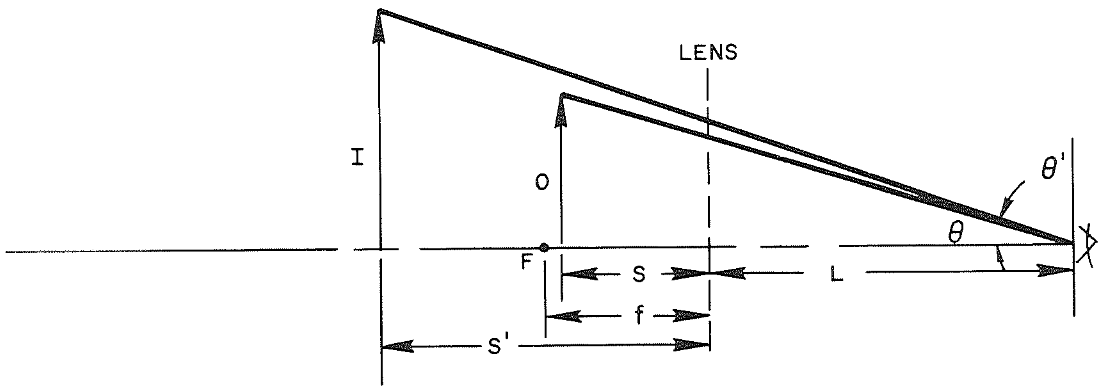
CONCLUSIONS

A virtual image system employing simple uncorrected plastic lenses can be utilized in a satisfactory manner in simulating a realistic flight scene. Various lens parameters must be closely scrutinized, however, in order to obtain an optimized virtual image lens system for a particular flight simulator. A virtual image of a flight scene using television monitors requires two lenses so that large diameters can be used to allow the pilot adequate head motion. If separate virtual image systems are desired for both pilot and copilot, then television monitors become attractive because of their small size and relative ease in simultaneous control.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, April 1, 1971

APPENDIX A

DERIVATION OF THE ANGULAR MAGNIFICATION



From the above diagram:

$$\tan\theta = \frac{0}{S + L} \qquad \tan\theta' = \frac{I}{-S' + L}$$

(minus sign for the image distance based on standard sign convention)

The angular magnification is

$$M_a = \frac{\tan\theta'}{\tan\theta} = \frac{I}{0}\left(\frac{S + L}{-S' + L}\right)$$

The lateral magnification can be defined as

$$M_L = \frac{I}{0} = \frac{-S'}{S}$$

Substituting M_L into M_a,

$$M_a = \frac{-S'}{S}\left(\frac{S + L}{-S' + L}\right) = \frac{1 + (L/S)}{1 - (L/S')}$$

Since

$$\frac{1}{S'} = \frac{1}{f} - \frac{1}{S}$$

then

$$M_a = \frac{1 + (L/S)}{1 - L[(1/f) - (1/S)]}$$

If $f = S$ then

$$M_a = \frac{f + L}{f}$$

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