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Visual-simulation optical systems

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I. Introduction

The story of Visual Simulation as a useful tool in Training and Engineering Design is now over twenty years old. It has expanded to a multi-billion dollar industry and yet not very much is known about the details outside those directly involved in the field.

While much of this paper is concerned with Visual Displays used in Flight Simulation Systems the application of Visual Simulation has not in any way been limited to this purpose. It has been used successfully for such diverse tasks as training in the navigation of Oil Tankers, aiming guns from a Tank and practicing the hookup of a refueling boom with a receiver aircraft.

Many of the subjects I will discuss in general in the course of this paper are discussed in more detail in a number of articles listed in the bibliography at the end of the paper.

II. Some basic principles of Visual Simulation systems

An overall Flight Simulation Train starts with an object surface. This object surface may be:

1) A scale terrain model board.

2) A film with scaled information.

3) A data base.

These objects are viewed from the "entrance pupil" of the Simulation System. Along with the entrance pupil is a defined direction called the optical axis.

Quotation marks surround the words entrance pupil because two of the three types of systems listed above do not use a real entrance pupil.

In a model board system we have a real entrance pupil flying at a scale altitude over a scaled model.

In a film system the correct positions of the principal planes and correct distortion correction provide the proper overall magnification.

In a computer generated image system a computational point and direction in space relative to the data base comprise the entrance pupil and the axis of the system.

Once the image of the object as seen from the entrance pupil is generated, this image is processed by one or more different methods. It is eventually presented to the observer as though he were positioned at the originally defined entrance pupil of the system.

It has become customary to divide Visual Simulation Components into those concerned with image generation and those presenting the final image display.

This paper describes various methods and technologies that have evolved over the past twenty-five years generating a significant industry involved in the field of Visual Simulation.

III. Display system development

My personal involvement in Visual Simulation started in the late Nineteen Fifties with a Display System project.

The basic problem was as follows:

An optical system was required that presented to the observer a wide angle display projected to infinity with a field of view on the order of ninety degrees.

The system was to be dimensioned to permit both eyes to view the whole field of view with a reasonable amount of eye freedom - a four inch diameter exit pupil.

The focal length was to be minimized to require a minimum size object but this focal length was to be consistent with good optical performance.

The eye relief or distance from the first element of the system was to be on the order of four inches.

Such specifications considered in terms of a refracting magnifier would mean a twelve inch diameter first element, obviously leading to a long focal length and large diameters.

Another approach utilizing a reflecting magnifier as shown in Figure 1 would be satisfactory in terms of providing a large horizontal field but could only provide a limited vertical field.

The solution that was found was along the lines of an erecting eyepiece as shown in Figure 2 wherein the overall focal length is equal to the product of the focal length of the eyepiece times the magnification of the erecting system. A field lens is included to image the aperture stop between the erectors to form the exit pupil of the system. The use of the erecting eyepiece afforded the possibility of achieving a shorter focal length but still presented the problem of the large refracting elements.

Utilizing a reflecting type eyepiece as shown in Figure 3 in such an erecting eyepiece we achieved a spectacular improvement in the dimensioning and performance of the wide field display.

We were able to design and build a system that had pupil and field characteristics in accordance with those previously listed as specifications and the overall focal length was four inches!

Other advantages of the system were:

1. The only large diameter element was the mirror which was relatively inexpensive.

2. A convenient dimensioning was achieved when the exit pupil was positioned near the center of curvature of the mirror in that the pupil imagery was achieved without the use of a field lens. This allowed the aerial image of the relay lens to intersect the flat beamsplitter, thus permitting a large vertical field to go along with the previously achieved large horizontal field.

As a further improvement, as shown in Figure 4, the relay system was replaced by a spherical mirror and beamsplitter. In this system the ideal object surface is a sphere. The principles involved herein became the basis for all of the out-of-the-window displays used in the Mercury, Apollo, Gemini and LEM Space Flight Simulators(1).

As a further amplification of the concept, mirrors and beamsplitters were split off from the main path and thus we were able to superimpose multiple inputs of different objects such as the celestial sphere, an orbital image

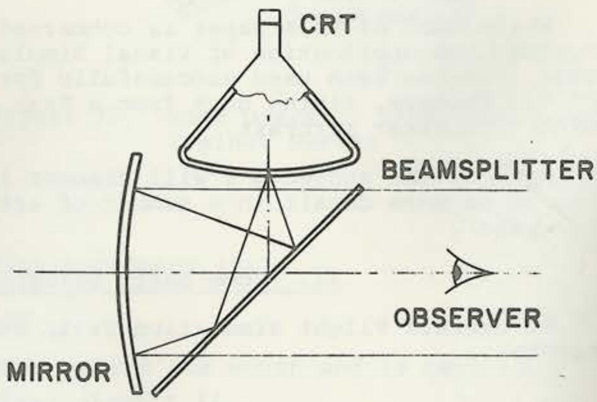

Figure 1. Reflecting Magnifier

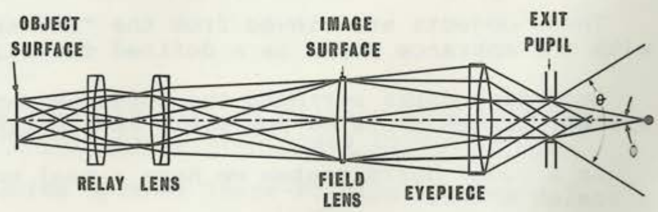

Figure 2. Erecting Eyepiece

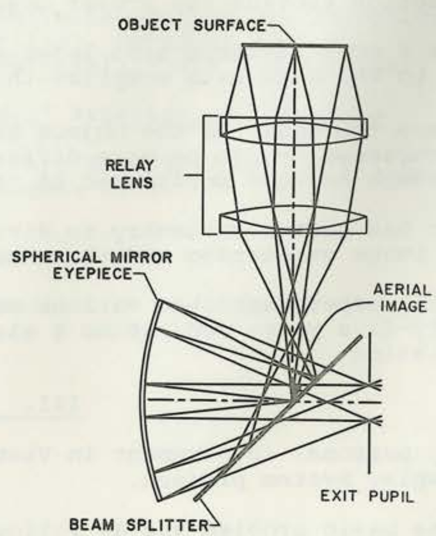

Figure 3. Reflecting Eyepiece Erecting Eyepiece

of the earth or moon plus a separate image generation of a rendezvous vehicle.

These systems all had focal lengths of 13-1/2" with exit pupil diameters of 12" and overall fields of view on the order of 100 degrees. The spherical input surfaces had 13-1/2" radii of curvature equal to the overall system focal lengths.

While these simulators used in the Space Program were really designed and built at a time when the field of optically enhanced visual simulation was in its infancy, they probably represent the most complex and sophisticated simulators ever built. They were also quite expensive.

IV. Commercial flight simulation displays

While this work on the Visual Simulation for the Space Program abated in the late sixties work had started on the introduction of visual systems for commercial airline flight training, particularly in the tasks of take-off and landing at airports throughout the world in various aircrafts.

These display systems in almost all cases reverted to the use of a spherical mirror and beamsplitter for the display, an arrangement which fit the aircraft field of view quite well. The limited vertical field is similar to that available from most commercial aircrafts. To present the display to both the pilot and co-pilot arrangements using two spherical mirrors and two beamsplitters, each having their own CRTs, were used. This is shown in Figure 5a. Another approach uses one larger spherical mirror and beamsplitter with two observers sharing the one system - Figure 5b. Having a longer focal length the input is projected onto one screen. While methods utilizing motion picture film and others utilizing optical scanning probes and model boards were developed, the majority of these systems have utilized computer generated imagery of the runway lights primarily for dusk and nighttime display.

V. Military flight simulator displays

In the field of military aircraft simulators, a number of different simulator systems have evolved. Many military aircraft are similar to commercial aircraft and utilize systems similar to the commercial simulators. Fighter aircraft have much more demanding field of view requirements. Solution of these requirements became possible through the invention of a rather unique system called a PANCAKE WINDOW™(2). As shown in Figure 6, in this invention the basic optical component is a spherical mirror as in the spherical mirror and beamsplitter system previously described. However, in the PANCAKE WINDOW™ system the flat beamsplitter is turned up so that it is normal to the optical axis and the spherical mirror is in the form of a beamsplitter. Thus the object positioned behind the spherical mirror is essentially at its focus. The direct image of the

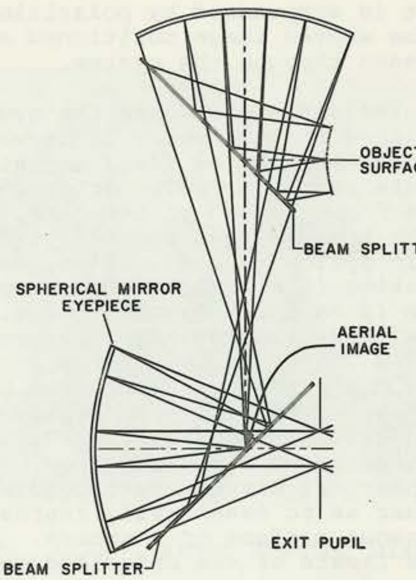

Figure 4. Spherical Mirror Relay Erecting Eyepiece

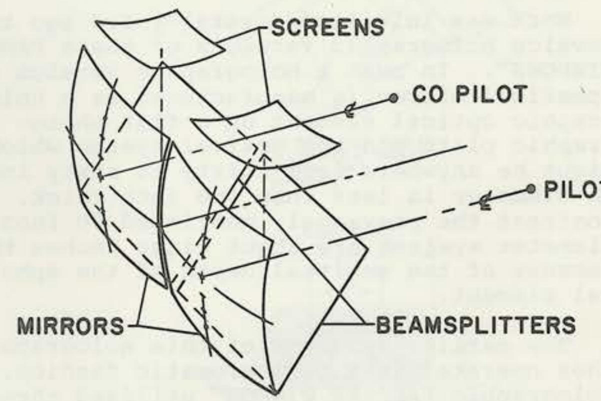

Figure 5a. Two-Mirror, Side-By-Side Display

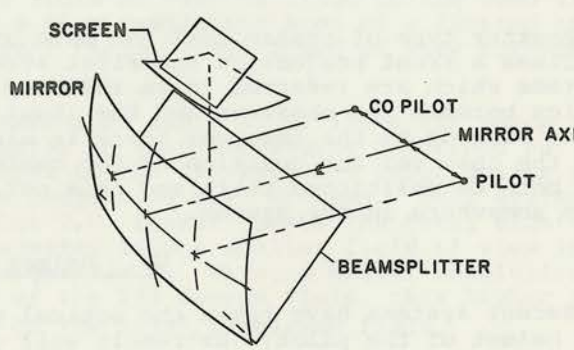

Figure 5b. Single Mirror, Side-By-Side Display

object is suppressed by polarizing elements but the wanted image positioned at infinity is passed through the system.

In the situation where the eyepoint is positioned at the center of curvature of the spherical mirror the ideal object surface is a sphere having a radius of curvature equal to the focal length of the spherical mirror and the basic system operates as a monocentric optical system. Thus, the only aberration is spherical aberration and the system is capable of unlimited fields of view without any additional aberrations.

The manner in which this has been used for a wrap-around visual display is to make the individual PANCAKE WINDOWS™ into pentagonal facets of a dodecahedron, Figure 7. The spherical mirrors butt together in such a manner as to essentially represent the continuous surface of a sphere. Filling all twelve facets of the dodecahedron corresponds to a total sphere surrounding the pilot. In actual systems seven to ten facets have been utilized. Supplying 3 feet of eye relief these pentagonal PANCAKE WINDOWS™ have focal lengths of 24 inches and are cut from 5 foot diameter circular systems.

Work was initiated several years ago to develop holographic versions of these PANCAKE WINDOWS™. In such a holographic version the spherical mirror is manufactured as a holographic optical element on a flat photographic plate and the optical system which might be anywhere from thirty to sixty inches in diameter is less than one inch thick. In contrast the previously mentioned 60 inch diameter systems are about eight inches thick because of the sagittal depth of the spherical element.

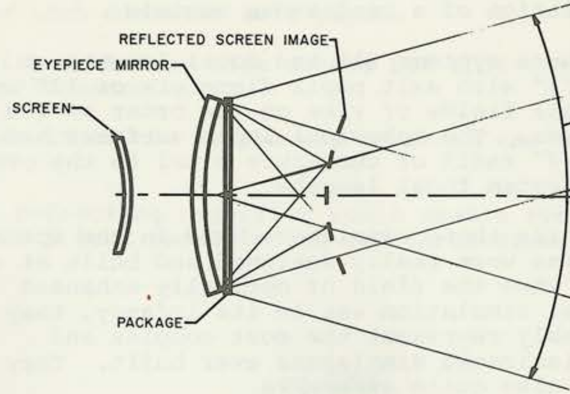

Figure 6. PANCAKE WINDOW™

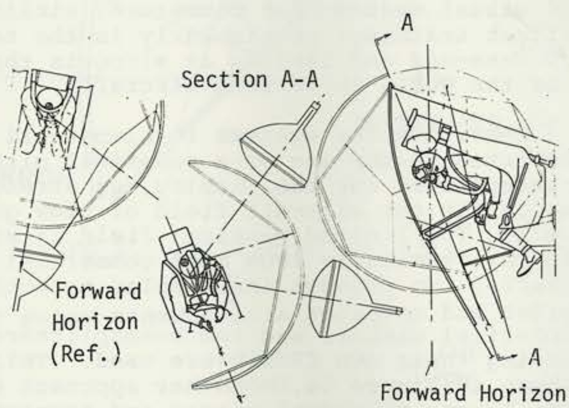

Figure 7. PANCAKE WINDOW™ Dodecahedron

The earlier versions of this holographic window operated with green spike phosphors and thus operated in a monochromatic fashion. Further development called the Trichromatic Holographic PANCAKE WINDOW™ utilized three different holographic spherical mirrors to provide a full color display.

These systems are discussed in detail by Magariños(3).

Other systems have been utilized that mosaicked spherical mirror and beamsplitter systems, but the basic modules with their limited fields of view in the vertical direction have been utilized to generate considerably smaller fields of view than those available with the mosaicked PANCAKE WINDOWS™.

Another type of system that has been utilized to generate sizeable fields of view utilizes a front projection spherical screen or dome. Unlike the previously described systems which are referred to as infinity display systems, these dome systems have no optics between the observer and the input screen. However, with the front projection and front viewing by the observer there is always a competition between the projection system and the observer for position at the center of curvature of the dome. Obviously they cannot both be positioned there and this per force requires an asymmetric distortion correction somewhere in the system.

VI. Helmet mounted displays

Recent systems have taken the optical portion of the display system and mounted it on the helmet of the pilot. Extremely well corrected erecting eyepiece type systems have been developed with fields of view on the order of eighty degrees per eye. While based on the optical design principles of the earlier discussed spherical mirror and beamsplitter erecting eyepieces they actually use the PANCAKE WINDOW™ as the eyepiece of the system affording a long eye relief with an eyepiece mirror of reasonable size.

The earliest of these systems shown in Figure 8 designed and built for the VCASS Program at Aero Medical Research Laboratory, Wright Field, Dayton, Ohio utilized 19mm CRTs as the inputs. The optical systems have an overall focal length of 13mm and an exit pupil 15mm in diameter. Thus they might be described as .55 NA 19X microscopes having fields of view of eighty degrees. The systems are extremely well-corrected so that it is quite feasible to turn out the axes by about 27-1/2 degrees each so that the total presented field is   degrees wide. The fields are shown in Figure 9. It should be noted that the use of these systems in this manner requires an excellent off-axis correction in that the edge of each field is used as the center of the field of the two-eyed display.

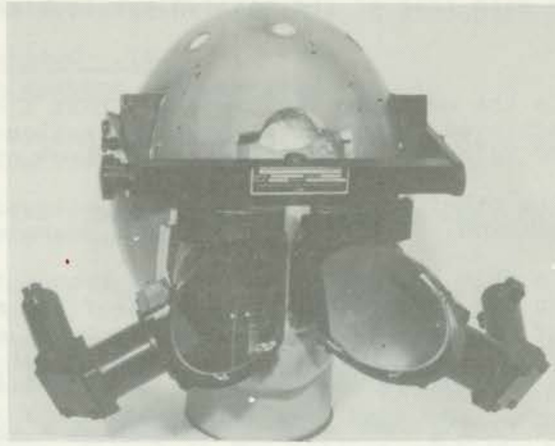

Figure 8. VCASS Helmet Mounted Display

The use of television-type systems to present wide angle scenes in visual simulation displays has always represented a significant limitation in the level of angular

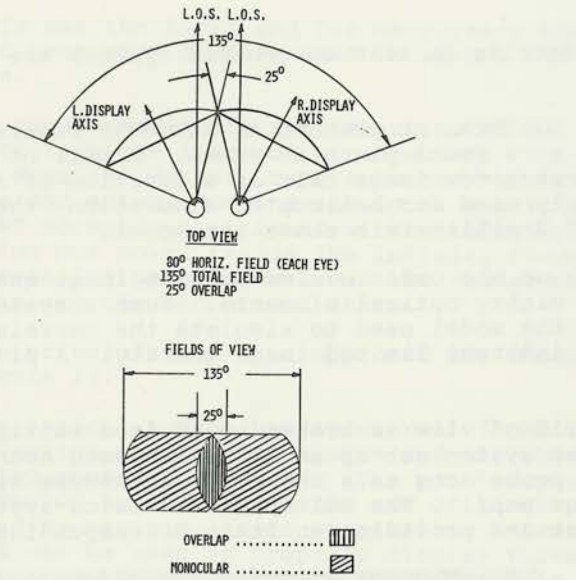

Figure 9. VCASS Helmet Mounted Display Fields of View

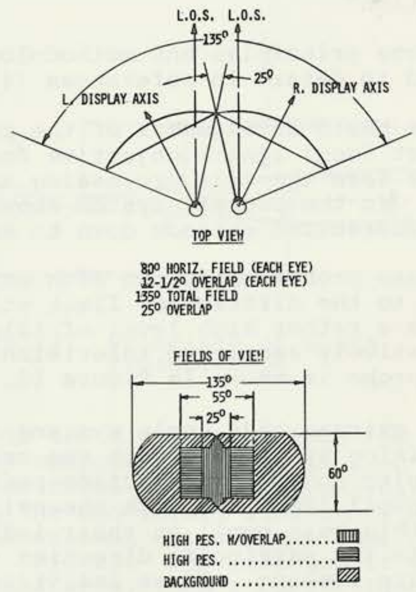

Figure 10. H.R.L. Helmet Mounted Display Fields of View

resolution that can be achieved. For instance, utilizing a high resolution T.V. system for the 80° fields, a cutoff resolution on the order of 8 arc minutes can be realized. In the helmet mounted display system wherein the field of view is fixed to the head it is possible to present a field to each eye wherein a high resolution area of a limited angular field is positioned in the center of the visual field. This field of view arrangement is shown in Figure 10.

This system presently being built for Human Resources Lab., at Williams Air Force Base in Arizona utilizes a helmet mounted display similar to that previously described but instead of mounting the CRTs on the display the input to the displays are fiber optics ropes upon which images are projected from light valve projection T.V. systems. This system is set up with two input focal surfaces per eye. One T.V. format covers the total eighty degree field of view and the other format is projected into a smaller field of view in the center of the displayed field off-axis in the larger field. Thus, a higher resolution portion of the field is generated at the center of the 135 degree field, this higher resolution field is always positioned at the center of the total displayed field.

The input to this displayed field is generated by CGI and thus the directional position of the head must be tracked quite accurately to insure the observer sees the proper image in the direction in which he is looking. As a further improvement in resolution along these lines is the thought of tracking the eyes of the observer in addition to tracking his head. This can lead to a system living with the basic limitations of television resolution that can present to the observer image quality that has a resolution level comparable with that of the unaided eye looking at the real world.

VII. Optical scanning probes

In the multiple field systems that I have described, the image generation in most cases is achieved by computer image generation wherein a data base is stored and an image computed relative to an eyepoint "flying" over the data base.

The other method that has been extensively utilized, particularly in helicopter flight simulation, is that of an optical scanning probe.

In this technology an optical system "flies" over a scale model of the terrain flying at an eye height that is a scale of the real world altitude. At this scale altitude the probe provides a true perspective point corresponding to the eye of the observer and the orientation of the aircraft. The latter is simulated by three angular motions of the line of sight through motions of internal components of the probe.

In flying over a terrain model at a scale altitude, the line of sight rather than being normal to the object surface is in reality closer to being parallel to it. This gives an image surface that would be tilted relative to the optical axis with a significant variation in focus as a function of vertical field angle. To correct this tilt we have developed an optical processing system based on what we refer to as an "Anti-Scheimpflug Condition".

Probe principles and methodology plus the details of tilt correction systems are discussed in detail in references (4) and (5).

The basic arrangement of the probes we are building at present is shown in Figure 11. A short focal length objective forms an image at a focal plane as shown. A pair of tilt lenses form the tilt processing unit which correct for image tilt as a function of altitude. In the overall system shown, particularly used for helicopter simulation, the image tilt correction extends down to an altitude of 3 millimeters above the model.

These probes operating with entrance pupils on the order of 1mm provide image quality close to the diffraction limit utilizing over eighty optical elements. Such a system requires a rather high level of illumination on the model used to simulate the terrain and a relatively sensitive television system with inherent limited image quality. A picture of a probe is shown in Figure 12.

In extreme wide angle systems the total field of view is broken up to feed multiple television systems through the use of the probe system set up so that the basic scanning, focussing and tilt correction portions of the probe acts as a one-power telescope with an exit pupil identical with the original entrance pupil. The multiple television systems view this exit pupil in their individual directions providing an image corresponding to a view in the particular direction in which they are looking. These individual outputs may now be used to feed individual displays each of them having its own axis. This arrangement is shown in Figure 13.

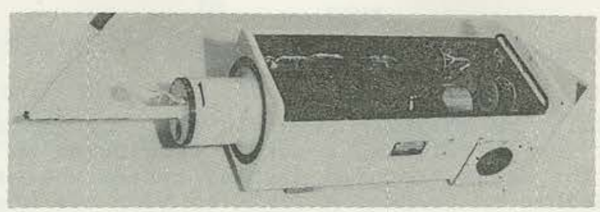

Figure 12. Helicopter Scanning Probe

Another technology utilized to circumvent some of the resolution limitations imposed by television is being reduced to practice by the Singer Company. It utilizes the same helicopter probe but operates in the opposite direction. That is the television pickup

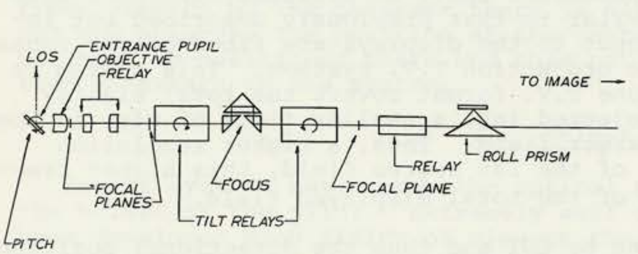

Figure 11. Optical Scanning Probe Optical Arrangement

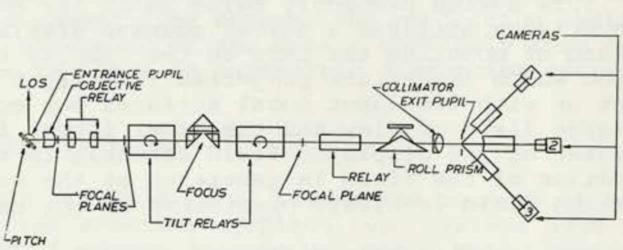

Figure 13. Multiple Output Probe Optical Arrangement (Patent Pending)

tube is replaced by a system of three lasers. With the probe operating in reverse, the laser illumination is focussed on the model and photomultipliers view the model replacing the illumination system previously utilized. The laser scanning probe is discussed in reference (6).

VIII. Direct view simulation systems and parallax

In special cases the requirement for the television type system itself has been eliminated and the simulation system is realized by direct viewing of a model.

The earliest of such systems was realized in the space capsule simulators wherein the celestial heavens were simulated as direct viewing of a model.

The ideal input for the space capsule type display windows was a convex sphere. This convex input took the form of a spherical black globe 27 inches in diameter. Imbedded in its surface were aluminized bearing balls each used as a reflecting negative mirror to simulate an individual star, with the ball diameter decreasing as the star magnitude number increased. The balls were embedded in true right ascension and declination as measured from the center of the sphere. Each ball created a minified image of an arc source. These virtual images all lay on the object surface of the infinity display system. The largest of these images corresponding to the -1 magnitude stars subtended less than one arc minutes at the eye. Thus the stars formed by the smaller balls appeared to be dimmer in proportion to the square of their diameters creating a display quite analagous to the natural celestial sphere.

This was the first and for many years the only direct view display used in visual simulation.

In these spacecraft simulators a CRT was used to form the image of a rendezvous vehicle. When the vehicle came into the shorter ranges and actual docking was to be simulated the CRT normally positioned at the infinity position was moved inside the infinity focus thus creating parallax between the rendezvous vehicle and the background stars.

The principles of this approach are shown in Figure 14.

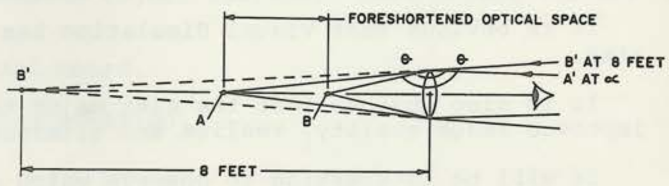

Figure 14. Principle of Depth Presentation

The optical system has an overall focal length equal to the distance between the lens representing the display system and the object A. At the output this point is seen at infinity represented by A'. The point B positioned inside focus has an apparent distance represented by B'. While the use of these principles in the spacecraft simulators were limited to the simulation of parallax between two two-dimensional objects the same principles can be used to properly display three dimensional objects. For instance if we assume that the point A like the point B is also inside infinity, then a finite length of a real object can be displayed between A and B.

The first use of a three-dimensional display system was in a development performed in conjunction with the Aeronautical Systems Division at Wright Patterson Air Force Base for what is referred to as a Part Task Trainer used for training In-Flight Refueling Boom Operators.

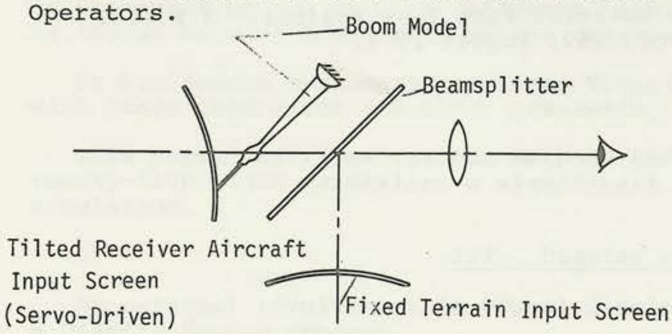

Figure 15. Boom Operator Part Task Trainer Inputs

The underlying goal in the development of this simulator was the aim that true depth and true parallax should be included in the visual scene because these elements provide the cues that are used by the Boom Operators in the real world situation to accomplish their mission.

Figure 15 illustrates the three different inputs that were considered to be important.

Operating in foreshortened object space, an actual boom model was employed which provided true apparent size and true apparent distance for the full envelope of boom operation, which included pitch and yaw of the boom and change of boom length.

Next the receiving aircraft was projected onto a tilted input screen which added depth to the receiver aircraft in terms of the nose and the tail being at different apparent distances especially when in the refueling position. The screen was servo driven so that the distant aircraft image would appear at infinity and as the aircraft grew in size and approached the boom operator the screen with the image of the receiver was driven continuously to the correct apparent distance. The third and final input was a screen used to input the background terrain and clouds which were fixed at infinity.

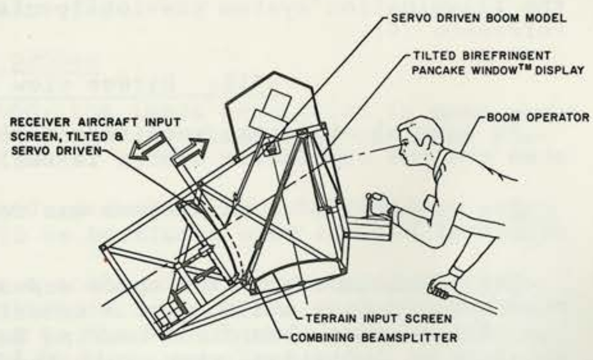

Figure 16. Boom Operator Part Task Trainer System

The system was set up as shown in Figure 16.

Further discussions of this system are included in reference (7).

IX. Conclusion

It is obvious that Visual Simulation has more than proven its worth and is here to stay.

It is also obvious that the next major thrust in the field is directed towards vastly improved image quality, realism and elimination of field of view limitations.

It will be interesting to observe which of the previously mentioned technologies succeed in achieving the desired results.

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