
Characteristics of Flight Simulator Visual Systems

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PREFACE

The Flight Mechanics Panel (FMP) of the Advisory Group for Aerospace Research and Development has maintained a continuing involvement in assessing the fidelity of aircraft simulation. In keeping with this continuing interest and in recognition of the need for a common method of assessing motion system characteristics, the FMP, in October 1976, established Working Group 07 on "The Dynamic Characteristics of Flight Simulator Motion Systems." That Working Group was charged with defining and determining metrics of the hardware-delivered performance of the various degrees of freedom of the motion system; its report (Ref. 1) was issued in September 1979.

As a follow-on activity to FMP WG-07, FMP WG-10 was established in March 1979 to consider "The Characteristics of Flight Simulator Visual Systems." This Working Group was charged with identifying and defining the physical parameters of the flight simulator visual display that characterize it and determine its fidelity. At its first meeting on 26-27 April 1979 at the British Ministry of Defense, London, the Working Group reviewed the terms of reference, defined in more detail its projected scope, and agreed upon three broad categories within which all of the parameters could be identified. At its second meeting at the Hochschule der Bundeswehr, Neubiberg, Germany, on 30-31 August 1979, the members reviewed the identification and definitions of the engineering parameters, agreed upon a format for their presentations, and initiated the study of the importance of these parameters to the performance of a flight task and the degree to which this importance is known. The third meeting of the Group took place on 21-23 April 1980 at the Ames Research Center, NASA, Moffett Field, California. At that meeting, the results of the study efforts of the members were discussed and put into formal context as definitive characteristics. Problems of measurement were discussed and alternatives were reviewed. Tentative agreements were reached on statements regarding the relative importance of the parameters. All members were asked to consider the unknowns in this area and to recommend, prior to the next meeting, the research needed. At its final meeting on 24-26 September 1980 at AGARD Headquarters, Paris, the draft of the Group's final report was reviewed and approved.

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Special appreciation is extended to Mr. Trevor Wilcock, Executive, FMP, AGARD NATO, Paris, France, for his excellent assistance during the entire course of the Working Group's activities.

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LIST OF SYMBOLS AND ABBREVIATIONS

a_x	output velocity amplitude = $\sqrt{2} \sigma_f \omega_t$
A_p	peak value of noise
B	photometric luminance $\equiv L_v$, cd/m ²
C	number of luminance transitions
CIE	Commission Internationale d'Éclairage
CGI	computer-generated imagery
C_m	modulation contrast = $\frac{B_1 - B_2}{B_1 + B_2}$
CRT	cathode-ray tube
d	diameter of aperture, m
D	luminance transition density, deg ⁻²
DFT	discrete Fourier transform
E	illuminance $\equiv$ luminous flux incident per unit area, lm/m ² (or lux)
f	relative aperture of the optical system
F	focal length, m
$H(k_i)$	describing function = $\frac{x_o(k_i)}{x_i(k_i)}$ for a sinusoidal input signal
I	intensity of the source, cd
k_i	ith frequency, sec ⁻¹
L_b	background luminance, cd/m ²
LCLV	liquid-crystal light valve
L_t	target luminance, cd/m ²
L_v	photopic luminance for 2° field, cd/m ²
L'_v	scotopic luminance, cd/m ²
MTF	modulation transfer function
MTFA	modulation transfer function area
$r_{\Delta n}$	low-frequency nonlinearity ratio = $\frac{\sigma_{\Delta n}}{\sigma_f}$ (see Sec. 4.2.3)
r_n	noise ratio = $\frac{\sigma_n}{\sigma_f}$
r_p	peak ratio = $\frac{A_p}{\sqrt{2} \sigma_f}$
T	transmission efficiency
v	spatial frequency, m ⁻¹
V.A.	visual acuity
$V(\lambda)$	spectral luminosity coefficient for photopic vision (for a 2° field)
$V'(\lambda)$	spectral luminosity coefficient for scotopic vision
$\bar{x}, \bar{y}, \bar{z}$	standardized primary colors in the CIE system
X, Y, Z	tristimulus values in the CIE system
$X_o(k_i)$	DFT coefficients for the ith frequency of the output signal
$X_i(k_i)$	DFT coefficients for the ith frequency of the input signal

$Y_{10}(\lambda)$	spectral luminosity coefficient for photopic vision (for a 10° field)
γ	system gamma; $B_{out} = K B_{in}^\gamma$
$\Delta\omega$	differential angular velocity threshold, sec^{-1}
θ	angle subtended by radius of a circular field shape
$\theta_{1,2}$	angles equivalent to the north and south bounding latitudes, respectively, of the field of view
λ	wavelength of light, m
σ_f	rms of the fundamental signal output $\equiv \sigma^2(k_\lambda)$
σ_n	rms of the acceleration noise $= \sum_{i=1}^m \sigma^2(k_i) - \sigma_f^2$ (see Sec. 4.2.3)
ψ	angle between the bounding meridians of the field of view
ω	angular speed, sec^{-1}
ω_i	fundamental frequency of input signal, sec^{-1}
ω_t	differential angular velocity threshold for monocular parallax, sec^{-1}

6. FUTURE HARDWARE TRENDS

The primary limitation in satisfying the more demanding visual simulation requirements is in the visual display. Computer image generators can provide full field-of-view imagery at relatively high resolution in color. The limitation on the image generator is more economic than technological. However, display technology is severely limited in terms of being able to provide high resolution simultaneously with wide fields of view. Color at relatively high brightness levels for wide fields of view is also beyond the state of the art. Another display limitation is the inability to provide a relatively wide field-of-view imagery to two or three crewmembers who are several feet apart without parallax or positional errors.

Developments are currently under way to provide improved visual display capability for the single-viewer fighter/attack and the multiviewer transport/bomber aircraft simulators. Several television projector development efforts are directed toward providing high-resolution, high-brightness, color-display input devices. These projectors have application to both the single and multiviewer displays for both real-image and infinity-display types. There are four basic types of projectors currently under development: CRT, liquid-crystal light-valve, Tifus light-valve, and laser. Also, improvements are continually being made to the oil-film type of light-valve projector. Some development efforts in CRTs and CRT displays are currently being pursued. Miniature high-resolution monochrome and color beam-penetration CRTs are being developed for helmet-mounted displays and a full-color calligraphic display has recently been developed that uses a high-resolution, shadow-mask CRT.

6.1 Projectors

One CRT projector under development utilizes a unique arrangement of three CRTs mounted on three vertical sides of a cube containing dichroic beam splitters and a special optical matching and cooling liquid.

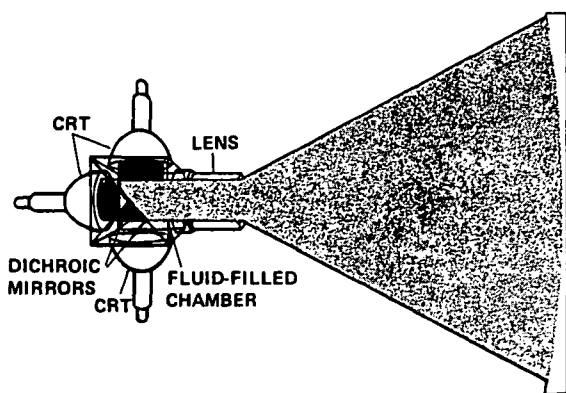


Fig. 59 Aquabeam color CRT projector

A sketch of the projector is shown in Figure 59. The projector combines the imagery from the three primary color tubes and projects it through a single acrylic lens. A 1023-TV-line version of this projector is being developed by the Electronics Systems Products Company for the U.S. Air Force. Through cooling of the faceplates by the liquid-filled cube, light output of the order of 500 μ m should be possible. Higher resolution should be possible with some reduction in light output. This projector is attractive from the standpoint of its simplicity, small size, and low cost.

The liquid-crystal light-valve (LCLV) projector was developed by the Hughes Aircraft Company during the late 1970's. It uses a projection lamp to supply luminous flux, and accomplishes projector light modulation by means of a liquid-crystal device, which itself is modulated by a source of "writing light." For simulation application, the writing light is supplied by a small CRT, which is fiber-optic coupled to the liquid crystal and modulated by a video signal. The principle of operation of this projector is shown in Figure 60; the fundamental function of the LCLV is illustrated in

Figure 61. Full-color operation can be achieved by field-sequential operation or by using red, green, and blue "channels," each consisting of a CRT and LCLV which are optically superimposed by means of dichroic mirrors. This projector has the potential for great flexibility in operational characteristics, such as brightness and resolution, since a proper combination of illumination lamp, liquid-crystal material, photoconductor, and CRT can theoretically be achieved for any desired application. A 1023-TV-line color LCLV projector was recently developed for the U.S. Air Force which provides a 820 cd/m^2 polarized light output. A follow-on version is being developed which is to have a 1360-TV-line background resolution with an equivalent 2700-TV-line inset raster resolution capability.

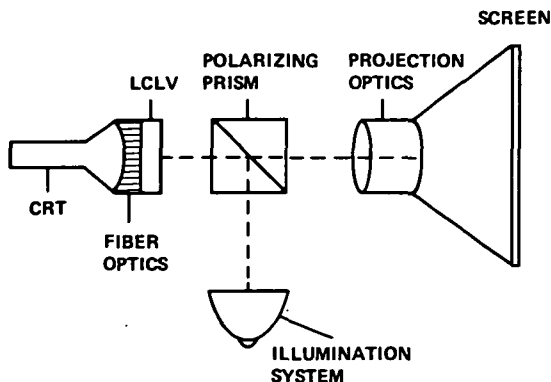


Fig. 60 Principle of operation, LCLV projector

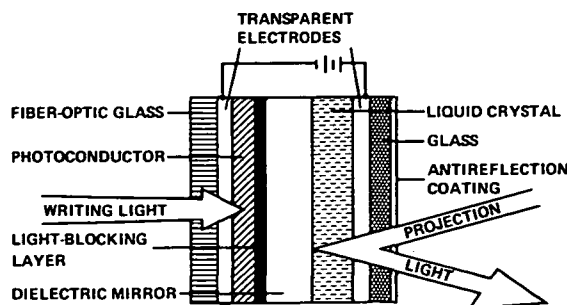


Fig. 61 LCLV fundamental functions

The Titus tube light-valve projector was developed by SODERN (France) in the mid-1970's. Its principle of operation, as shown in Figure 62, is similar to that of the LCLV projector in that it utilizes an external projection lamp, a polarizing/analyzer prism, and a device that accomplishes projector light modulation. Instead of an LCLV, a Titus tube is used to modulate projector light. The Titus tube is an electron-beam-addressed Pockels-effect imaging device using a KD_2PO_4 plate operated just above its Curie temperature in the reflection mode. The Titus light-valve operates on the basis of the variation in birefringence in a crystal when an electrical field is applied through the crystal in the same direction as the light propagation. The Titus-tube light-valve projector is capable of high luminous output, exhibits no raster line structure or flicker, possesses random-access image-writing capability, and has the capability to compensate for distortion. A Titus-tube color projector is currently being built by SODERN for the U.S. Air Force for simulation application. It is to provide a 1080-TV-line resolution capability with a polarized light output of 2700 μm .

Oil-film light-valve projectors, developed in the late 1950's and early 1960's, have been used in numerous simulator visual systems. Improvements in resolution and light output have been made in this type of projector over the years. A color, 1023-TV-line version available from General Electric will provide a light output of 650 μm .

The laser projector utilizes neither a kinescope phosphor nor a projection lamp to supply luminous flux. Instead, a laser supplies luminous flux in the form of a very bright beam. The laser beam is deflected in the vertical and horizontal directions by means of optomechanical or electrooptical scanning devices to write out a raster on a screen. At the same time, the laser beam is amplitude-modulated by video information in synchronism with the deflected beam's position within the raster, thus producing a bright projected image. If full color is desired, multiple lasers of different color can each be individually amplitude-modulated to produce red, green, and blue information, and the multiple laser beams can then be deflected by a common scanning system. Prototype projectors utilizing this principle of operation have been built with limited success since the late 1960's. A recent development program conducted by the American Airlines/Redifon Simulation, Ltd., under joint sponsorship of the U.S. Army, Air Force, and Navy has resulted in the development and successful demonstration of a very promising prototype two-color scanned-laser projector. A laser camera scanning a model-board is used to generate the imagery. This system provides a continuous 180° horizontal by a 60° vertical field of view. A scanned laser display is shown representatively in Figure 63. A similar scanned-laser visual system has been developed by Singer Librascope. It provides a narrower field of view, but is a full three-color system. Although scanned-laser projectors must be further developed before they can be put into production, they offer great promise for fulfilling relatively wide field of view requirements with a single projector. Because of the size and location of the scanner, significant increases in the vertical field of view do not appear feasible.

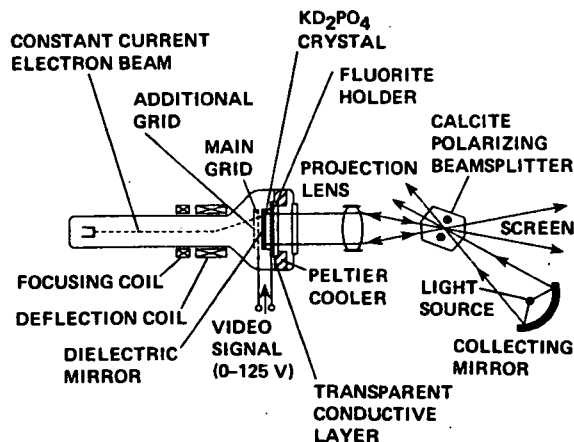


Fig. 62 Principle of operation, Titus tube-light valve projector

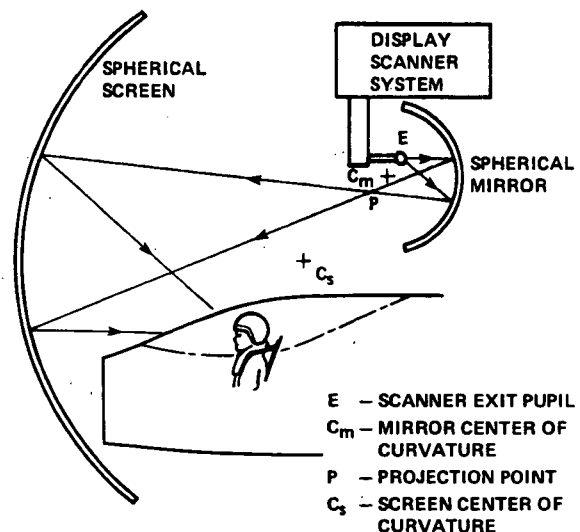


Fig. 63 Visual simulation display utilizing scanned laser projector

6.2 CRTs

Visual simulation has stimulated the development of CRTs of extreme sizes. The world's largest CRT, 36 in. in diameter, was developed during the early 1970's for mosaicked in-line infinity displays used on the Advanced Simulator for Undergraduate Pilot Training. At the other extreme, small high-resolution CRTs, approximately 1 in. in diameter, have been developed for helmet-mounted displays.

A metal-funnel version of the large 36-in. CRT is currently under development; its development was undertaken primarily to reduce costs. The cost of the metal-funnel version is estimated to be less than one-half that of an all-glass version. There is also a side benefit of safety — the metal-funnel CRTs are much safer to handle during manufacture as well as during installation and replacement. These CRTs are being developed by Thomas Electronics under U.S. Air Force sponsorship. The intended application is in tactical air-combat visual simulation systems.

A high-resolution, high brightness, 1-in. CRT for use in helmet-mounted displays is also being developed. This CRT is to be capable of 1200-2000 TV-line operation while producing 1000-1400 cd/m^2 highlight

brightness. This resolution and brightness capability is the result of improvements in high-efficiency, small-grain phosphor and improved electron-gun and deflection-coil design. It is to be used with wide-angle, binocular helmet-mounted display optics providing a field of view of approximately 60° vertical by 135° horizontal. The CRT is being developed by Thomas Electronics with the participation of several other vendors under U.S. Air Force sponsorship.

A small, beam-penetration CRT is also under development for providing a color capability for helmet displays. The CRT is two-color, red and green, and is of the layered phosphor type.

High-resolution shadow-mask CRTs are being used to achieve higher resolution, full-color presentations, both raster scan and calligraphic. A recent development by Evans and Sutherland has provided a shadow-mask-type CRT display that can be driven calligraphically. This capability is the result of new developments in drive electronics, in particular deflection circuitry, and the use of existing high-resolution shadow-mask CRTs.

6.3 Area of Interest

Since the straightforward or brute-force approach to improving the resolution throughout the total field of view is apt to require significant advances in the state of the art and to result in very expensive systems, other more innovative approaches have been considered, some of which are under development. Some of these techniques, such as raster inset or target superposition, typically called area-of-interest techniques, are intended to provide image resolution and detail only where required in the scene, with lower resolution throughout the background area. There are three basic approaches to achieving this, and there are several variations of each. The first, called target slaving, has the high-resolution area depicting the target controlled by the location of the target itself. The second, called head slaving, takes advantage of the instantaneous field of view (i.e., the field of view with the head stationary) being less than aircraft field of view. This approach requires head-position sensing. Fairly reliable head-position sensors are currently available. The third, called eye slaving, takes advantage of the falloff in resolution capability of the eye as a function of angle off the visual axis of the eye. In this approach, the visual system resolution would attempt to match the performance of the eye — a demanding task only in matching the eye's performance over the relatively small foveal area. This approach requires information concerning the line of sight of the eye, in order to appropriately position the high-resolution part of the scene where the pilot is looking. This presents other challenges with respect to eye trackers and head-position sensors. Since eye trackers will require significant improvement before they can be made operational, the approach of target-controlled, high-resolution areas with head-position sensing to eliminate the requirement to generate imagery that falls outside the instantaneous field of view may be the most promising approach for the near future.

6.4 Display Optics

Improvement in optical design techniques and the development of techniques for producing both large refractive and reflective plastic optics are resulting in improved display performance and reduced display weight and cost. Plastic mirrors have recently been developed by the McDonnell Douglas Electronics Company for classical mirror-beam-splitter infinity optics systems which reduce weight and offer potential for larger continuous field of view. Techniques are being developed by Redifon of England, under U.S. Air Force sponsorship, for producing 5-m-radius, plastic spherical mirrors. These mirrors are to be used in a multiviewer display for the transport/bomber-type of aircraft simulator. If successful, this development will provide the technology to produce an infinity display with a continuous field of view of 60° vertical by 180° horizontal with a viewing volume 1.5-m wide, 1-m fore and aft, and 0.5-m deep. An approach to providing a multiviewer display, using improved large plastic refractive lenses, is being pursued by the Electronics Systems Products under U.S. Air Force sponsorship. This approach offers potential for a more compact and less expensive multiviewer display.

More exotic approaches to using Fresnel refractive and holographic reflective optical elements have been pursued recently. The large Fresnel experimental lens is still under development, having been delayed by the unavailability of diamond turning machines able to handle 1-1.25-m plastic blanks. The principal advantage of the Fresnel lens is its projected lower cost and weight. The holographic reflective optics also offer very significant cost and weight advantages. Good quality 81-cm monochrome holographic lens analogs have been developed recently. However, going to the larger 122-cm and 152-cm holographic optics required for mosaicked in-line infinity displays requires a significant investment in new facilities to handle the larger holograms, and the necessary funding has not been available.

Fiber-optics cables are being considered for use as coupling elements in several types of visual systems. They are used in the scanned-laser visual systems just described to couple laser light to the projection system scanner. The U.S. Naval Training Equipment Center is developing a visual system that is essentially a helmet-mounted projector. It is to use a laser as a light source; the light is modulated and deflected horizontally off the helmet. The light is then coupled to the helmet, through a fiber-optics ribbon, where it is deflected by a small vertical scanner mounted on the helmet. This produces a scanned-laser image on a high-gain dome screen whose location is a function of head position. One significant advantage of this approach, which results from using fairly low light levels and high-gain screen material, is that the projected light striking the cockpit and instruments is so dim that it does not need to be masked.

A color multiplexing technique, using fiber optics developed by American Optical Corporation, has been considered for helmet displays that use image-input devices off the helmet. This technique uses a wedge-shaped prism at the input end of the fiber bundle to spread each picture element over many fibers. An achromatic image is formed at the output end, using an identical prism. This technique not only removes the fiber structure from the image, but increases the limiting resolution by as much as a factor of 2 over the same size cable without color multiplexing. Another interesting property of this technique is that the resolution of the cable is no longer a function of the number of fibers in the cable, but depends instead on the ratio of the individual fiber diameter to the overall cable size.

6.5 Helmet-Mounted Displays

The ideal visual system as envisioned by many over the past decade is one that is small and light enough to be carried on the pilot's helmet. Helmet sights, using small CRTs and optics, are in operational use; several efforts are under way to extend this technology to provide a limited capability helmet-mounted visual display. These devices typically utilize 1-in. CRTs as image input devices which are viewed through optics that collimate the imagery and superimpose it over the cockpit scene. A 1-in. two-color beam-penetration CRT has recently been developed for McDonnell Douglas Electronics by Thomas Electronics to provide a limited color capability for such a display. These displays are limited in both field of view and resolution.

Designs have been developed by Farrand Optical under U.S. Air Force sponsorship for optics to provide a larger field-of-view binocular helmet display. These optics provide a field of view of about 60° vertical by 135° horizontal. Such optics, used with small CRTs, will provide a medium display resolution satisfactory for only a limited number of flight tasks, such as takeoff and landing, formation flight, and aerial refueling. Other concepts have been proposed that would couple imagery to the display optics via fiber optics rather than being limited to input CRTs mounted on the helmet, thus offering potential for improved resolution and brightness as well as full color. Multiple-level resolution display inputs with eye tracking have also been proposed in order to provide a display resolution that conforms approximately to the static resolution of the eye. An eye tracker would enable the highest resolution part of the display to be continually positioned according to the line of sight.

6.6 Outlook for Displays

Through the development of various projector devices, higher resolution and higher brightness color displays will be available in the future. These devices, used in conjunction with mosaicked infinity optics and real-image domes will be able to provide wide fields of view with improved resolution and brightness as well as color. The cost of such displays will be rather high, which will continue to stimulate the development of area-of-interest approaches. The target-slaved approach, with head sensing to reduce the instantaneous field of view, seems to hold the most promise for the near future.

The development of wider field-of-view optics as well as the proposed use of fiber optics input has greatly improved the potential of helmet-mounted displays. Such displays can be expected to be utilized in a variety of simulator applications including ground-based, air-combat, part-task trainers as well as both ground-based and airborne engineering research simulators.

At a still later date, it seems plausible that displays that are able to utilize digital information directly from a computer image generator will be developed. Such displays would be attractive from the standpoint of eliminating the video link and the problems associated with broadbanded high-power video equipment. Such displays could take the form of large arrays of display elements or some type of matrix-addressed light-valve projector.

It might be noted that the direction of display developments will be influenced by their potential use in the entertainment industries.

6.7 Computer Image Generation

The capabilities of both calligraphic and raster-scan CGI systems have improved dramatically during the past 5 years. Calligraphic systems, since their introduction during the early 1970's, have evolved from point-light, night-only systems to night/dusk and recently to night/dusk/daylight systems. The recently developed night/dusk/daylight systems are essentially hybrid calligraphic, with surfaces being generated and displayed with a full field-of-view calligraphic raster and lights being handled in the conventional manner. The principal breakthrough that permitted this step into the daylight CGI world was the development of a high-resolution, "full" color, shadow-mask calligraphic display. A calligraphic color projector has also been developed recently that will allow further exploitation of the calligraphic technology for various simulator applications. Future trends seem to be toward increased surface generation capability and improved displays with brighter imagery in full color and more flexibility for various simulator applications.

Current generation raster-scan CGI systems offer many advantages over other previous image-generation techniques, such as being able to handle large fields of view, providing relatively high resolution, allowing flexibility in changing the environment or data base, allowing flexibility in viewpoints and view windows, and providing infinite depth of field. The primary limitations have been in the ability to generate image detail and to eliminate artifacts associated with the generation process. However, the many advantages have apparently outweighed these limitations and have led to the rapid acceptance of CGI and its recent exploitation for virtually all types of visual simulation applications. The limitations are very salient and have stimulated considerable development directed toward increasing image detail and content and reducing spurious information and artifacts in the imagery. Some vendors have concentrated on increasing image-generator capacity and others have concentrated on improving image quality.

The straightforward approach to providing greater image detail through building higher-edge-capacity systems has been pursued by most vendors. Systems with capacities of the order of 8,000 edges or several thousand surfaces are currently available, and some vendors are discussing or developing systems that reportedly will have capacities of the order of 100,000 edges. Figure 64 (from Ref. 66) indicates the increase in system edge capacity over the past 15 years and the projected rapid increase in the future. Advances in very large-scale integration promise rapid advances in hardware performance and reductions in cost.

Another technique that has been incorporated in most current systems and used effectively to increase detail and improve the efficiency of CGI systems is level-of-detail (LOD) control. LOD control essentially attempts to keep the number of processed edges at a high level near the upper capacity of the system. More detail in the form of edges is added to the part of the scene being approached by the viewpoint and is removed

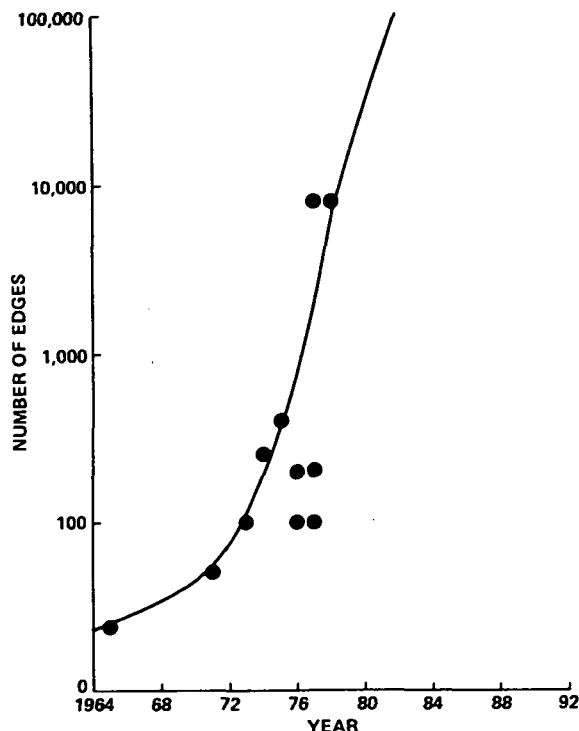


Fig. 64 Future CGI system capacity

from the part of the scene that is receding from the viewpoint or falling outside the field of view. Although these techniques have been used effectively in current systems, there are times when the LOD changes at distances from the viewpoint where it is quite noticeable and causes a distracting "pop in" and "pop out" of detail. Improved level-of-detail management techniques can be expected in the future to minimize some of these distracting effects. In addition, techniques are being developed by some vendors to blend intensity gradually between levels of detail to eliminate distracting instantaneous changes.

Area-of-interest approaches are compatible with CGI techniques and can be expected to be used extensively in future tactical air-combat simulator applications. Techniques are being developed that will provide changing level of detail and resolution as a function of target, head, or eye position.

Another technique that is being pursued by most vendors to increase image detail without resorting to ever-increasing edge-generation capacities is texture generation. Several texturing approaches have been or are being developed; they range from rather stylized patterns to texture that is very characteristic of natural and man-made cultural objects. More advanced three-dimensional texturing techniques, which will provide parallax among features of and objects within the texture, are currently under development.

Progress is being made in improving image quality through the development of improved antialiasing techniques. Most current schemes essentially compute individual pixel intensities on the basis of averaging the intensities of all surfaces within the pixel. This usually involves the computation of subscan-lines and subpixels. Although these techniques work reasonably

well, they do not completely eliminate all aliasing problems, especially in dynamic imagery. In addition, although these techniques are fairly straightforward conceptually, they are costly in computation. The improved techniques involve spatial filtering at the pixel level and result in images that have high subjective resolution and sharpness, with the higher spatial frequencies appropriately attenuated. Further details on the spatial filtering techniques are available in References 57 and 58. It is expected that these techniques will be used in many future systems.

Future military simulation requirements for both tactical and strategic missions involve the simulation of a high percentage of natural terrain over extremely large gaming areas. Edge and planar surface techniques are not optimally suited for representing most types of natural terrain. The large gaming areas require enormous amounts of digitized source data, which is being provided or will be provided by the U.S. Defense Mapping Agency (DMA). To produce the on-line CGI system data bases from these source data requires the use of highly automated transformation programs because of the enormous amount of data involved. Even though the process is highly automated, it is very time-consuming and does not usually result in a completely satisfactory on-line data base without some manual rework. The above future requirements and the associated simulation problems have stimulated interest in the development of CGI approaches that are better suited for simulating natural terrain and that are amenable to more direct use of DMA source data. At least two companies, Honeywell and Grumman, are pursuing such approaches. Some of these approaches involve the generation of curved surface fits to the terrain data, using bicubic patches or quadric surfaces. These approaches are also compatible with texture mapping. Although there may be some simple nonedge-based systems in the field within the near future, the more sophisticated nonedge-based systems are only in the preliminary development phases and may not be available until the late 1980's.

7. RECOMMENDATIONS FOR RESEARCH

Current and foreseeable technology will not produce images of the outside world that represent, in all aspects, the visual scene observed by pilots. Faithful reproduction of the real world is not only technologically unfeasible but would be prohibitively expensive even if it were feasible. Moreover, experience with the use of existing simulators indicates that considerably less than duplication of the real world has been satisfactory for many simulator applications. However, in the absence of firm data on requirements, the tendency has been to strive for higher fidelity and, possibly, to err on the side of overrealism. Past approaches to establishing simulator requirements typically have tended toward duplicating the flight vehicle and its environment. These approaches have led to more and more sophisticated and costly simulators. Consequently, the most pressing need for research in all areas of simulation, and especially visual simulation, is research that will lead to a better definition of requirements. Little objective data exist on precisely what is required for training or researching various flight tasks and vehicle performance in a simulator.

The problem is to identify the visual cues used for a particular task and then to translate from functional definitions, such as orientation or speed cues, to the characteristics of the visual simulation system, such as scene content, luminance, texture, contrast, and color.

The question "What cues do pilots use?" seems to be asked in one form or another at every simulation conference, but it is unlikely that a strictly theoretical approach will provide the answer. The enormity of this question becomes more and more apparent as one reads about the extensive research being performed currently in the area of vision and visual perception. The only promising approach for evaluating the usefulness and necessity of the various visual stimuli available to the pilot would seem to be through transfer-of-training experiments and performance-evaluation experiments in real aircraft. These may be initiated by simulator engineers and users but should be performed with the participation of experienced experimental psychologists to ensure that the results will be valid.

One of the lower-priority objectives of the Working Group was to relate the physical visual system parameters to the visual perception of the observer. The problem was frequently discussed, but it became evident that any major effort in this direction would detract from the primary objective. It now seems appropriate, however, having analyzed the physical parameters of visual simulation systems, to attempt this task. Certain relatively simple control tasks that require visual inputs seem to lend themselves to mathematical analysis and experimental verification. A control model might be formulated that would make it possible to predict a pilot's performance in a simulator and to compare it with his performance in a real aircraft. The pilot may not need to use the same visual inputs or cues in the simulator as he does in the aircraft, but a basic assumption would be that he needs to be able to control the simulator with the same degree of precision and with the same control strategy as he controls the aircraft, using visual cues as the only source of information regarding the velocity and orientation of the aircraft. This assumption would seem to be reasonable for both training and research simulators. The analysis of simple control tasks would not only be useful in itself but would provide insight into how the more complex visual tasks could be analyzed.

Some of the more successful simulators have been based on requirements determined from thorough analyses of the tasks to be trained or researched in the simulator and the information necessary to perform the tasks. Some of these requirements have been determined from observing what the pilot must do in the aircraft to perform the task successfully, for example, the field of view used in executing an approach and landing or the typical acquisition distances for targets in an air-combat engagement. A variation of this approach involves reducing the fidelity of the information received by the pilot in an actual flight situation to the point of being able to determine where his performance is adversely affected. For example, special glasses that reduce the effective resolution of the real-world visual scene as viewed by a pilot could be used to determine what minimum resolution is required by a skilled pilot to perform a particular flight task successfully. This same approach could be used to determine requirements for color, field of view, brightness, and, possibly, image detail for future simulators.

Another type of information that has not been fully exploited in the design of simulators and the determination of fidelity requirements is psychophysical data on human sensation and perception. Such data have been used in the past to make decisions on television refresh rates, interlace techniques and color approaches, and these decisions have been universally accepted. Other simulator visual system issues, such as brightness, contrast, resolution, detail or scene content, and area-of-interest approaches, can perhaps be resolved to a high degree of confidence through further use of psychophysical experimental data.

Not very much is known about motion perception although many manifestations of the phenomenon are observed. Motion perception is so sensitive in humans that many variables affect it: whether the eyes are moving or stationary, whether the motion occurs on a textured or plain background, and the duration of observation are examples of factors that affect the measurements. In addition, many of the variables, such as content, are resistant to being dimensionalized and others, such as viewing distance, have an uncertain status. A variety of experiments, including those by Bouman and van den Brink (Ref. 67), Pollock (Ref. 68), Liebowitz (Ref. 69), Mashhour (Ref. 70) and Kolers and Pomerantz (Ref. 71), have not yet succeeded in explaining completely the perception of motion. The literature on temporal aspects of perception raises two fundamental questions. The first is, Does the human visual system ever note velocity directly? The data suggest, to the contrary, that some of the constituents of velocity, such as time, distance, and intermittency, are more important to the judgment than is velocity itself. The second question is, Does the human visual system process spatially separated and contiguous flashes in different ways? The data suggest that the human visual system constructs the two perceptions of motion quite differently. The immediate need is to know the spatial-temporal range over which the perception of continuous motion in visual simulation systems is acceptable. These data also indicate a need to examine the perception of motion in the context of man moving through space as well as objects moving past a stationary man.

In CGI systems, more study is required of the effect on visual perception of the various sporadic phenomena in the display scene, classified under the general term "aliasing." In camera/model-board systems, distortion of the video image and a reduction in contrast at the edges of objects occur as a result of the time taken in producing a complete video frame. The magnitude of these effects is a function of the velocity