THE TECHNICAL CONTRIBUTIONS OF THE TACTICAL COMBAT TRAINER DEVELOPMENT PROGRAM

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ABSTRACT

Project 2360, the Tactical Combat Trainer (TCT), was an Air Force Engineering Development Program to develop two prototype Weapon System Trainers (WST) for training A-10, F-15, and F-16 pilots for combat. Each prototype was to consist of two visual simulation systems integrated with two previously manufactured Operational Flight Trainers (OFT) to form a single WST. The two separate cockpit stations would permit two pilots to "fly" mutual support missions or as opponents in air-to-air combat. The WST was designed to provide full mission training for air-to-air and air-to-surface combat tasks. The TCT prototypes were being developed under contract by the General Electric Company and the Singer Company for a "fly off" to select a production contractor. Approximately two years into the program, these contracts were terminated due to USAF budget problems. Before termination, however, important studies and developments were completed in the visual simulation area by each contractor. Both Singer and GE proposed an Area-of-Interest (AOI) visual system and used Computer Image Generation (CIG). The General Electric approach was based upon a head-slaved AOI infinity image display. The Singer-Link approach was based upon an eye-slaved AOI projected on a dome.

TCT PROGRAM

The Tactical Combat Trainer (TCT) program was to develop a full mission Weapon System Trainer (WST) to train A-10, F-15, and F-16 pilots in combat skills. The WST was to create an environment where the pilot could (1) coalesce all his training from separate sources, (2) experience the heavy task loading of combat, and (3) experience aspects of combat which cannot be trained in the air in peacetime, such as SAM launch, acquisition, and defensive maneuvers or low altitude air-to-air combat. The full mission capability of the WST was to include takeoff, formation (close, route, and tactical), aerial refueling, low altitude tactical navigation, air-to-air or air-to-surface combat, return to base and landing.

Project 2360 was a head-to-head competitive Engineering Development Program to develop two prototype TCT systems, each by a different contractor. These prototypes were then to be evaluated in a "fly off" to select a production contractor to build an additional twenty-six units. Each TCT was to consist of two Government Furnished Operational Flight Trainers (OFT), a visual display for each OFT, an image generation system for each display, modified OFT Instructor/Operator Stations (IOS) and modified OFT Electronic Warfare (EW) simulation systems.

The TCT prototypes were to be designed to be integrated with A-10 OFTs manufactured by Reflectone, Incorporated. The production WSTs would be integrated with F-15 and F-16 OFTs manufactured by the Goodyear Aerospace Company and the Singer Company, respectively. The prototype development contracts consisted primarily of developing the visual simulation system, integration with OFTs, modifying the Instructor/Operator Stations (IOS) and modifying the Electronic Warfare (EW) simulation system. The OFTs, along with their respective visual systems, were to be integrated to permit either two aircraft mutual support missons or flying as opposing aircraft. The IOS was to be designed for a single instructor to monitor and control the simulation for both pilots during integrated operations. Contracts to develop the TCT prototypes were awarded to the General Electric Company, Simulation and Control Systems Department, and the Singer Company, Link Flight Simulation Division, in September of 1978. Just prior to the completion of the Critical Design Review in December 1980, these contracts were terminated due to the USAF funding problems. The termination included residual tasks to complete selected development efforts and the documentation of all studies and developments.

The TCT was designed to permit combat training including evasive flight in a high threat (surface and air) environment; target detection, recognition and identification; and weapon delivery against either air or surface targets. A tactical fighter pilot primarily relies on his vision for target acquisition and tracking, detecting and avoiding threats, maintaining contact with his wingman, and controlling his own aircraft. Thus, the major thrust of the TCT was to provide all the visual cues that the pilot needs to fly combat tasks.

From the inception of Project 2360, it was evident that the visual display portion of the visual system placed the highest demand on technology. Due to the high risk involved, both contractors developed breadboards of the display system to confirm projected performance and to establish subsystem requirements. In addition, many tests and emulations were performed to establish system performance. Prior to termination, both contractors were able to complete the development of specific display components.

Since Project 2360 was a competitive program, information concerning the technical aspects of the program was not published. Due to the termination of the contracts, this information can now be presented. This paper will describe the TCT requirements, the technical approaches, design performance, and results of the development efforts. Although many developments and analyses were completed, this paper will primarily address the visual simulation developments with emphasis on the visual display.

TCT REQUIREMENTS

The requirements for the TCT evolved from the combined visual system requirements of the Required Operational Capabilities (ROCs) for the A-10 (Nov 76) and F-15 (Jul 76) and the requirements letter for the F-16 (Aug 74). Each of these documents required a full mission WST which consisted to two OFTs with full (same as the aircraft) field of view (FOV) visual simulation. Each WST was to be capable of independent (individual) or integrated (mutual support or opposing) flight for all tactical fighter training and tactical (combat) roles of the aircraft. These roles included takeoff and landing, formation flight, air refueling, low altitude tactical navigation, air-to-air combat and tactical air-to-surface tasks.

Separate research visual systems had been developed and had successfully trained air-to-air combat at medium altitude, takeoff and landing, and limited formation tasks, but no systems existed to support low altitude tactical navigation, tactical air-to-surface tasks, or low altitude air-to-air combat.

Project 2235 (PE 64227F), the Air-to-Ground Visual Simulation Demonstration, was initiated by the Deputy for Simulators in 1975 to evaluate visual simulation technologies potentially applicable to air-to-surface weapons delivery training. The evaluation of three somewhat modified visual systems by tactical fighter pilots performing both training and tactical tasks showed that indeed more capability existed than was previously thought. The demonstration included both camera model and CIG image generators, optical mosaic and dome displays, and the feasibility of both head slaved and target slaved areas of interest (AOIs). The demonstration included both subjective evaluation and objective measurement of the technical characteristics of each device. The basic recommendations of Project 2235 were twofold: first, begin procurement of a production prototype of a CIG/Optical Mosaic visual system, and second, pursue research and development of a CIG/Dome visual system including further definition of area of interest requirements. In addition, the demonstration pointed out the need for further development to meet the Tactical Air Command (TAC) requirements.

Further evaluation of the technical visual system requirements in the two primary task areas, tactical air-to-air and air-to-surface combat tasks, revealed that the requirements were so similar that a single device was the preferred approach. The display resolution requirements for air-to-air combat against a MIG-21 size target are essentially the same as the resolution requirements for a tank size target for air-to-surface weapons delivery. Also, when the highly likely scenario of offensive or defensive air-to-air combat at low altitude is considered (a scenario not practiced in the aircraft for safety reasons) the visual cues required are also very similar. All three aircraft, the F-15, F-16, and the A-10 can expect to engage or to be engaged in low altitude air-to-air combat. A thorough analysis of training and tactical (combat) tasks and the accompanying technical requirements for a visual system strongly support the development of a single visual system for training in both task areas.

Armed with the stated user requirements, demonstrated air-to-air simulation capabilities, and the results of Project 2235; work was begun in 1977 on the specification and statement of work for what became Project 2360 (PE 64227F), the Fighter/Attack Simulator Visual System (F/ASVS), later known as the Tactical Combat Trainer (TCT) program.

A functional specification was developed for Project 2360 to encourage the competing contractors to use their skills and to be innovative to meet the training requirements of the user. Special care was taken not to preclude a particular technology if it appeared to have any potential to meet the training requirements. The technical requirements for the visual display specified a minimum FOV and some limited optical and alignment characteristics based upon previous work. Image alignment requirements were based upon training task requirements, the most stringent alignment in front of the Heads Up Display (HUD), where it is more critical. A CIG system was required as an image source because of its inherent flexibility and the ability to permit a large gaming area. Imagery requirements were related to task requirements.

To supplement the technical and performance requirements for the visual system a set of four annexes to the specification were developed. These annexes described the planned use of the TCT system. These annexes were:

Annex A: Representative Task List and Generalized Scene Content

Annex B: Concept of Training

Annex C: Prototype Visual Data Base

Annex D: Maintenance Concept

The annexes were developed in concert with TAC to provide a thorough orientation and a ready reference for the contractor to use throughout the program. Annex A contains a comprehensive discussion in layman's language of each task to be trained, how each task is performed, and the visual references used to perform the tasks. All tasks and discussions were oriented toward tactical (combat) tasks as opposed to the normal orientation toward initial qualification training. Most of the TAC training requirements are continuation (recurring) training for mission ready tactical fighter pilots which consist primarily of tactical tasks. These tactical tasks have a significant impact on the visual system requirements.

To document his particular approach, each contractor was required to prepare a Contractor Prepared Prime Item Development Specification

(CPIDS) which was put on contract and updated as his design became better defined. Annexes A through D were included as part of the CPIDS.

The technical requirements imposed upon the competing contractors fell into two basic categories: (1) Training Task Requirements and (2) System Design and Performance Requirements. The primary drivers were the training tasks and the contractors were encouraged to be innovative making system performance tradeoffs to meet the training task requirements.

The training task requirements included 102 tasks which may be grouped into six basic task sets. These basic task sets are: Air-to-Air, Air-to-Surface, Formation, Low Altitude Tactical Navigation, Aerial Refueling, and Takeoff and Landing. Table 1 lists the basic task sets and representative tasks within each set.

TABLE 1 TRAINING TASK REQUIREMENTS SUMMARY

- Air-to-Air
  - Basic Fighter Maneuvers
  - Basic Counteroffensive Maneuvers
  - Gun Tracking
  - Missile Employment
  - Air Combat Tactics
  - Low Altitude Intercepts/Engagement
  - Visual Missile Trace Use
  - AAA/SAM/AI Detection/Avoidance
- Air-to-Surface
  - Scorable Range
    - Box Pattern
      - Bomb, Strafe, Rockets
  - Armed Reconnaisance
  - Forward Air Controller Operations
  - Tactical Deliveries
    - Pop-up
    - Random Attack
    - Tactical Bombing
  - Moving Target Attack
  - Guided Weapons
  - AAA/SAM/AI Detection/Avoidance
- Formation
  - Takeoff, Landing (Lead/Wing)
  - Close, Route, Trail
  - Tactical
    - Air-to-Air
    - Air-to-Surface
- Low Altitude Tactical Navigation
  - Target Acquisition
- Aerial Refueling
  - Tanker Rendezvous
  - Observation Position
  - Precontact Position
  - Contact Position
- Takeoff and Landing
  - Single Ship
  - Overhead Traffic Pattern
  - Closed Traffic Pattern
  - Circling Approach

Air Force system design and performance requirements were primarily written in terms of performance of the training tasks rather than implementation and design specification. The only implementation directed was the use of a CIG system as an image source. Special precautions were taken to avoid precluding potential technologies. Table 2 lists examples of the basic requirements grouped into categories. The requirements were later specialized by each of the two contractors to define their particular approach to solving the training problem.

After contract award, unique methods were employed to insure that both the contractors and the users fully understood the significance of the system requirements throughout the program. Starting during the second month of the contract, Contractor Orientation Visits were made to operational bases. These visits included opportunities to look at, photograph and measure the aircraft and weapons; to discuss tasks and visual cues with pilots; to see films and video tapes of tasks being performed; and to ask questions of the pilots until the contractors understood the tasks. No questions were too trivial to ask. Orientation visits were held with A-10, F-4, F-15, and F-16 pilots and Tactical Fighter Weapon Center Penetration Aids Instructors to cover all aspects of the planned use of the TCT system. The contractors

TABLE 2 TCT TECHNICAL REQUIREMENTS/GOALS SUMMARY

- System Requirements
  - Independent/Interactive
  - Correlated In-Cockpit/Visual Cues
  - Object/Pattern/Light Size, Position
  - AOI (If Proposed) Position
  - HUD to Visual Alignment
  - Geometric Distortion
  - Moving Vehicles
  - Visual Effects
  - Monochrome (Color-Goal)
  - AGM-65B Maverick
  - Channel Misalignment
  - Transport Delay
  - Safety
  - Instructor Operator Station
  - Availability/R&M Goals
  - Computational System Requirements
- CIG Requirements
  - Basic Image Content
    - Expanded in Annex C
    - DMA Terrain, Cultural Data
    - Model to Meet Training Requirement
  - Performance
  - Accuracy
  - Special Effects (Haze, Clouds, etc.)
- Display Requirements
  - Field of View
  - Collimation
  - Head Motion Evelope (Minimum)

NOTE: Contractors were encouraged to be innovative and to make tradeoffs to meet training requirements.

showed extensive learning with these visits and developed a strong operational orientation. This had a very positive impact on both system analysis and design, and the morale of the persons assigned to the program. A true mission orientation developed. The questions became more incisive during subsequent visits and caused the pilots to really look at how and why they performed each task. Pilots attended each design review to continue the operational inputs. Data base visits were also conducted at bases to be modeled. Data base modelers were able to discuss the significance of features with pilots, to look at and photograph features, and to collect drawings of airfield layouts. Reconnaisance photography of gunnery ranges and low altitude tactical navigation routes was also provided.

The orientation and data base visits made major contributions to a thorough understanding of the requirements and to the development of a sense of mission on the part of contractor personnel. Design tradeoffs were then made after an analysis of the effect on mission performance instead of on strictly cost or technical considerations.

GENERAL ELECTRIC'S APPROACH

General Electric's approach to the TCT visual system was based upon an expanded and modernized Advanced Simulator for Pilot Training (ASPT) display. The expansions included increasing the field-of-view (FOV) to provide coverage essentially limited only by aircraft structure and the addition of a High Resolution Area (HRA) inset into the lower resolution backgroud. Figure 1 is an artist's concept of the TCT WST as designed by GE.

The visual system was to use a common approach to generate and display all imagery. A CIG system would produce eight channels of video which were to be displayed to the pilot on ten CRTs and viewed through a dodecahedron arrangement of ten pentagonal Pancake Window(R) virtual-image optical units. The image presented to the pilot would consist of a helmet-slaved high resolution area (HRA) centered within a large high detail background area of interest (AOI) and a low detail background/horizon filling out the remainder of the display as shown in Figure 2. With the Maverick missile selected, one channel of video would be dedicated to the Maverick monitor and the remaining seven channels allocated to the visual display. The two or three channels which did not contain CIG imagery would be behind the pilot and would have a horizon display to provide a peripheral horizon and illumination in the cockpit.

The insetting of the HRA was to be accomplished electronically by sequentially scanning alternate fields of the full raster and a miniraster. The miniraster consisted of 600 scan lines and 600 pixels per scan line. The full channel raster consisted to 888 scan lines with 888 pixels per scan line. The field-of-view (FOV) of the HRA is 15 degrees, circular, providing a resolution of 1.5 arc minutes. The average resolution of the full channel raster (for both high detail AOI and background) is 6 arc minutes. Both the HRA and high detail AOI display the same high detail scene content and provide most of the visual cues to the pilot. The low detail background scene contains the terrain outline, horizon and representative alerting cues such as a SAM launch, wingman or an air interceptor. The high detail AOI FOV is 120-

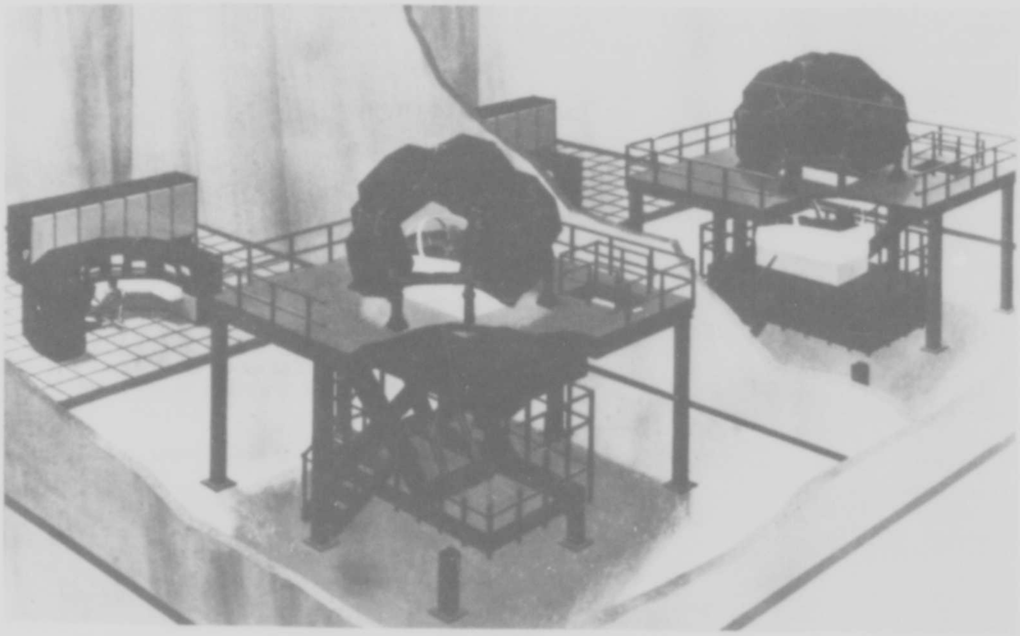

FIGURE 1 Artist's Concept of General Electric's Approach to the TCT WST

degrees, horizontal, and 80-degrees, vertical. This AOI FOV is based upon an AFHRL air-to-surface weapon system delivery study that evaluated pilot performance for various FOVs. The HRA remains centered in the high detail AOI and both are directed about the total FOV of the display by a Helmet Mounted Sensor (HMS). Thus, the highest scene content will be displayed to the pilot in the direction his head is pointed with the high resolution area for target acquisition centered within the area of the highest scene content. Blending is provided in the HRA to minimize the effects of a distracting boundary with the background imagery. This all electronic AOI approach requires no electromechanical servo mechanisms. This display approach has no constraints on the number of high resolution aircraft or ground targets which may be simultaneously displayed to the pilot, since the target will appear at high resolution whenever the pilot places the target in the HRA.

While the helmet-slaved AOI approach was adopted to avoid false "searchlight" cues which would pinpoint the targets, there was operational pilot concern that, because the HRA is centered about the helmet line of sight, the HRA could not be directed to the "6 o'clock" position and that unnatural visual scan patterns would be necessary in the simulator since the head must be moved to control the HRA to acquire targets. It should be noted that the General Electric visual system could also position the HRA along the pilot's line of sight (LOS) by using both eye and head position measuring devices.

The CRTs, developed by Thomas Electronics for General Electric, are 36-inch diameter metal funnel CRTs with a dispenser cathode electron gun. It was necessary to develop the metal funnel CRT technology in order to reduce significant schedule risks and cost associated with the use of glass funnel tubes in the TCT production phase (as well as for safety considerations during manufacturing). The CRT developed for the TCT program is the largest metal funnel CRT ever developed. This technology is presently being used to fabricate replacement CRTs for both ASPT and Simulator for Air-to-Air Combat. Figure 3 is a photograph of the metal funnel CRT in process before application of the phosphor screen.

To drive the CRTs, the display electronics accept the video signals generated by the CIG system and produce signals for driving each CRT in such a manner that the proper view is provided to the pilot. The geometric distortion requirements placed upon the system required that the CRT sweep signals be very accurate. The display electronics subsystem designed and breadboarded by GE was capable of providing these sweeps, including the compensations for CRT to image plane mapping and Pancake Window(R) mapping functions. The magnitude of the compensations, the need for inset raster capability, and the accuracy requirements led to an approach using linear feedback deflection amplifiers to track precorrected sweep signals.

Breadboard CRT electronics were fabricated and tested which sequentially scan a full channel raster field, a mini-raster field, a full channel raster interlaced field and mini-raster interlaced field. In addition to the dual scanning format, the electronics would position any part or all of the inset anywhere within the channel FOV. Figure 4 is a photograph of the 36-inch CRT with the mini-raster overwriting the full channel raster using breadboard CRT electronics. The mini-raster is scanned in a square format as shown in the figure. The blanking for the round format and the insetting and boundary blending is

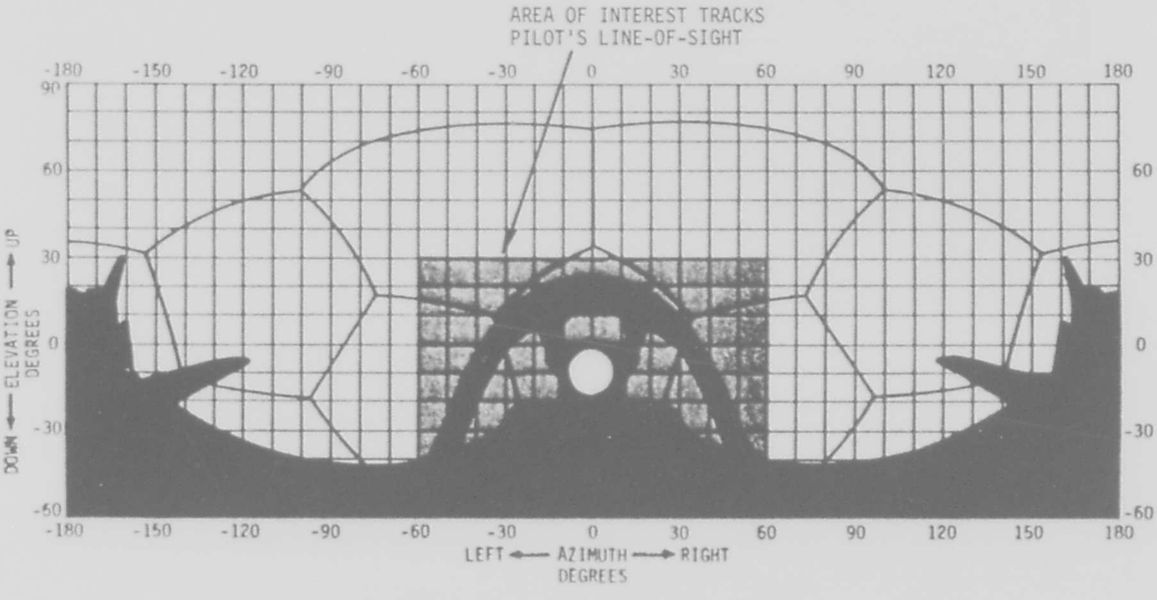

FIGURE 2 The Field-of-View of General Electric's Visual Display and Area-of-Interest (The white circle represents the HRA)

generated by a CIG system. Since the CIG system generates a scene with a "Tan θ" mapping and the Pancake Window(R) is true angle mapping, the CRT electronics must compensate the raster format on the CRT to display an undistorted image to the pilot. This compensation also requires that the circular HRA be scanned as an elipse on the CRT as the HRA moves from the center of the channel. Tests were conducted which showed that the registration error on the HRA to the full channel raster was less than 0.40 degrees within the total FOV, less than 0.15 degrees within the instantaneous FOV and was much less near the center of the channel. Overall, the breadboard CRT electronics met all the TCT distortion specifications except in a few areas at the edge of the CRT. In addition, the breadboard CRT electronics, operating with a 36-inch CRT, met or exceeded the resolution and MTF requirements without considering the effects of the Pancake Window(R). This was a significant advance in the state-of-the-art of display technology.

The In Line Infinity Optical System (ILIOS) consisted of ten Farrand Optical Company Pancake Windows(R) and a dodecahedron shaped support structure. Each optical unit has a 24-inch focal length and is pentagonally shaped. When juxtaposed in the dodecahedron, the ten windows provide a continuous field of view from the pilot's eye reference point. The designed and manufactured ILIOS is similar to the ASPT system with two significant differences:

a. Although the dimensions of the individual Pancake Window(R) and dodecahedron are the same as the ASPT system, the orientation of the ILIOS relative to the cockpit is different in order to accommodate three additional channels and, therefore, a larger FOV.

b. Improved Pancake Window(R) fabrication techniques resulted in reduced defects and imperfections in the optical elements.

The overall specified performance on the General Electric visual system is summarized in Table 3. Before termination of the contract, GE had completed and tested a breadboard of the CRT electronics with a glass funnel CRT. These breadboards met or exceeded all TCT specifications. A 36-inch metal funnel CRT, the largest ever built, was developed, fabricated, and tested. When tested this CRT met all requirements except for the resolution of the HRA raster. This lower resolution was attributed to the newly designed electron gun used for the test. With these developments, the overall technical risk of the General Electric concept was significantly reduced. However, the training risk of the helmet-slaved HRA remains and requires further evaluation with a pilot in the loop. Currently, no such effort has been funded to resolve this question.

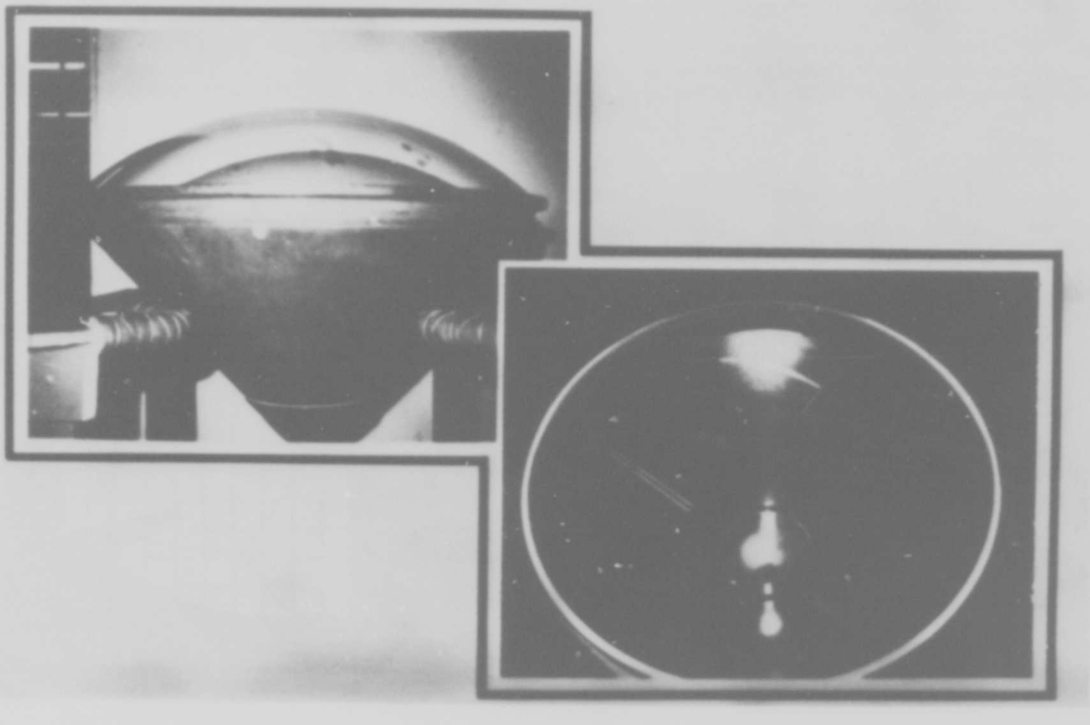

FIGURE 3 Thirty-six Inch Metal Funnel CRT
in Process Before Phosphor Application

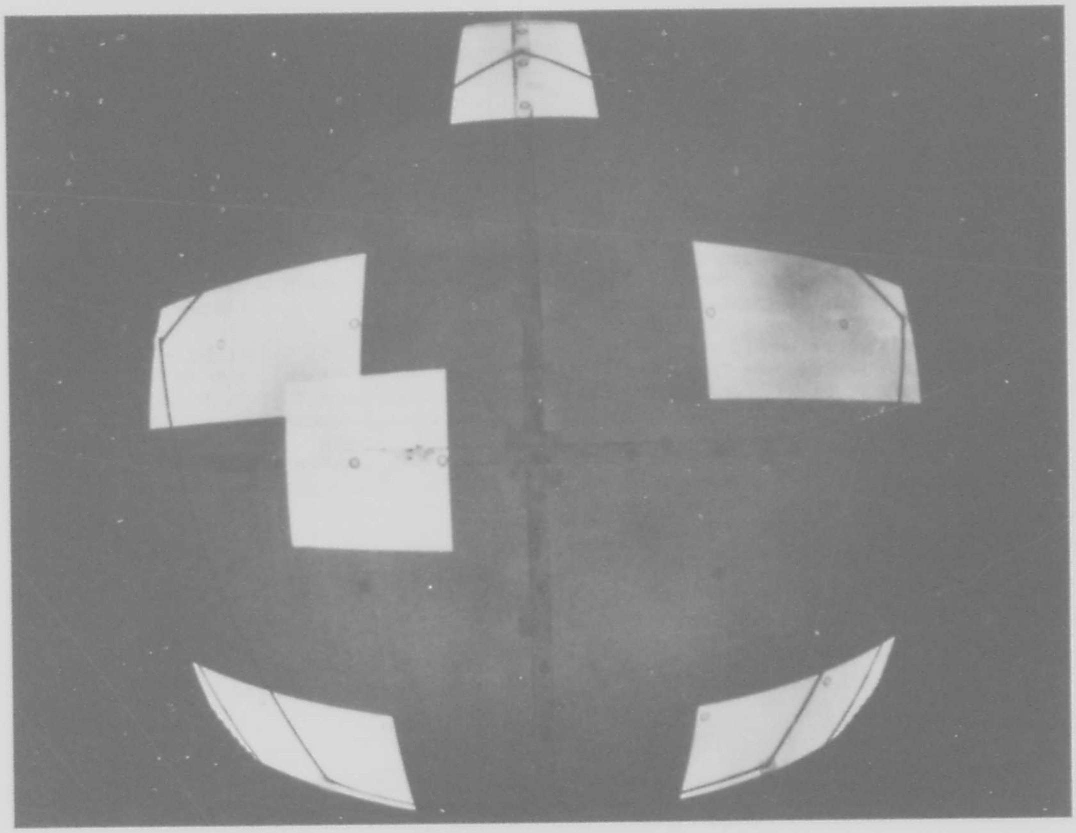

FIGURE 4 The High Resolution Mini-Raster (Off Center) Shown Inset Into the Background Raster, Visual Display

TABLE 3 GE TCT PERFORMANCE PARAMETERS

Total Field of View:	Essentially same as aircraft
High Detail Area of Interest:	120 degrees Horizontal, 80 degrees Vertical
High Resolution Area:	15 degrees Circular
Full Channel Resolution:	6 Arc Minutes, Average
High Resolution Area (HRA) Resolution:	1.5 Arc Minutes
Brightness:	6 Footlamberts, Highlight
Contrast Ratio:	15:1 Minimum, 25:1 Nominal
Number of Edges:	4000
Number of Point Features:	4000
Number of Circular Features:	1000
Video Raster Lines:	888 Background, 600 Mini Raster
Edge Crossing/System Line:	400 Background, 220 Mini Raster
Edge Crossing/Channel Raster Line:	256 Background, 220 Mini Raster
Moving Model Types:	Airborne, 10 Types Ground, 50 Types
Environment:	Full Weather, Time of Day Effects
Scene Enhancement:	Articulated Parts, Curved Surface Shading
Surface Texturing:	Circular Features, Curved Surface Shading, Point Features, Gray Shade Variations
Visual Data Base:	Both Transformed DMA and Hand Models
Gaming Area:	1380 NM x 1380 NM

SINGER-LINK'S APPROACH

The Singer-Link approach to TCT exploited the fact that the high-resolution viewing area of the eye is relatively small. This high-resolution area is the fovea of the eye, which is the only area where small details may be perceived.

Surrounding the fovea is a peripheral area where the resolution of detail is low but, because of the way human vision operates, there is a high sensitivity to movement. The psychophysics of human vision creates an image in the "mind's eye" of building a total high-resolution image of the real-world scene from a series of small high-resolution "snapshots", each of which is surrounded by lower-resolution information. If this situation is emulated in the visual system, the FOV requirement for instantaneous high resolution and high detail is greatly reduced. Thus, the capacity of the image generator can be concentrated where it will be used and the number of image display channels may be reduced.

In the visual system, the pilot's line of sight (LOS) is monitored and a high-resolution, high-detail area; surrounded by a large low-resolution, low-detail area; is displayed along this LOS. When the eye's LOS changes, this is sensed and the high-resolution area is moved accordingly, matching the eye's ability to discern high detail in only a small area of the total scene at any one time. The net result is the impression that there is high-resolution, high detail imagery everywhere.

The TCT eye-directed AOI visual system provides the pilot with high resolution and high detailed imagery anywhere within the pilot's FOV. This is accomplished by projecting a 20 degree monochrome image on a 35 ft diameter dome wherever the pilot looks out the cockpit. This 20 degree foveal image is directed along the pilot's LOS using servo driven foveal projectors. This foveal image is inset into a lower resolution and lower detailed monochrome peripheral image that is projected onto the dome through fixed wide angle peripheral projectors. Figure 5 shows the layout for the projectors coupled to an A-10 OFT. It requires four foveal and four peripheral projectors to provide an unobstructed FOV to the pilot. The four peripheral projectors are located at the four corners of the simulator (45 degrees to the cockpit axis system) and are optically merged to form a continuous 360 degree image to the pilot. However, the CIG instantaneous field of view is limited to 180 degrees azimuth and 120 degrees elevation along the pilot's LOS to concentrate the scene detail capability of

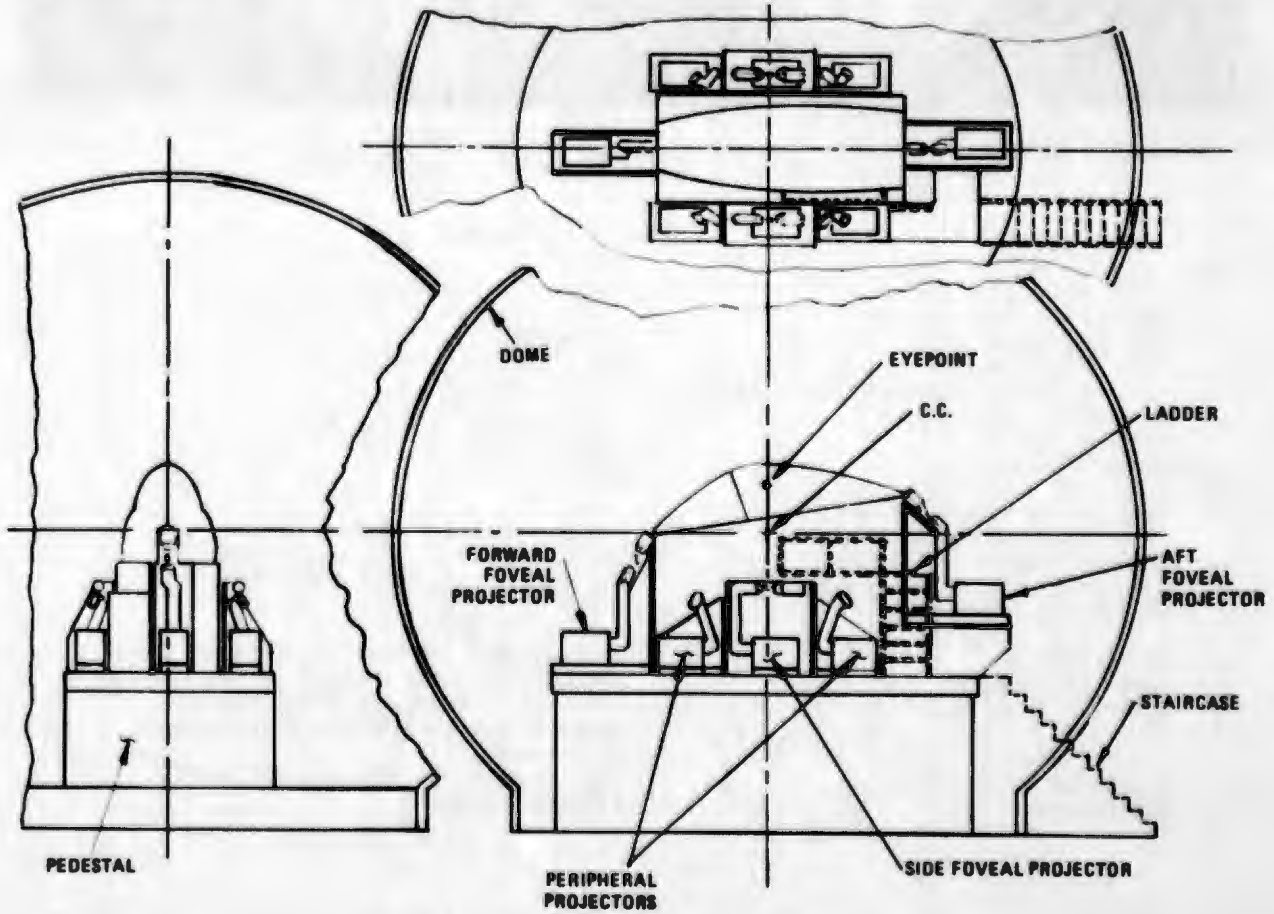

FIGURE 5 The Layout of Singer's Visual Display Approach on an A-10 OFT

the CIG. The four foveal projectors located on the cockpit axis system (forward, aft, left and right) have overlap on the dome to permit the switching of foveal projectors without loss of imagery. Therefore, only one foveal projector is required at any instand to provide the foveal image along the pilot's LOS. The imagery for both the foveal and peripheral projection systems is generated by a single five channel CIG that supplies 874 active lines with 922 pixels per line. This provides better than 1.4 arc minute resolution everywhere within the total simulated aircraft field-of-view. In addition, two very important visual cues, head motion compensation and realistic G-dimming, are inherent in the eye-directed approach.

In real-image displays, there is an inherent problem of image placement as a function of head motion. In previous dome displays as the pilot moved his head, the simulated imagery would appear to be located on the projection screen. The eye-directed system solves this problem by using the helmet positional information to move the imagery in response to the pilot head motion. This results in correct image motion so that objects located in infinity move as if they were at infinity and objects at, say, 5 feet move as if they were at 5 feet. This is accomplished by providing to the CIG eyepoint position and projector/screen/eyepoint geometry data. The result is imagery that moves as it should relative to the pilot changing viewpoint not only with respect to the data base but also with respect to the projection geometry.

The visual cue associated with pullint G's is a familiar visual effect used by experienced pilots of high performance aircraft. As the pilot pulls higher G's over given periods, his FOV will normally start to collapse, and if the G-level is sustained, the FOV will eventually collapse to zero. This collapse could be fully simulated in the TCT visual system. The initial collapse down to 10 degrees from the foveal is handled by the peripheral hardware with the collapse from there to zero being handled in the foveal merge hardware. In an air-to-air mission, the TCT visual system will allow pilots to "fly the tunnel" when engaging another aircraft at short range. In this maneuver the pilot attempts to keep the target within the fovea while maintaining sufficient G's to provide an almost but not totally collapsed FOV.

EYE PSYCHOPHYSICAL REVIEW

The human vision system provides highly detailed information about the relative positions, reflectances, and visible emissions of very small elements in the visual world. It also senses changes and rates of change in scene element positions, and supports the examination and tracking of these elements.

Highly detailed vision is maximized in a relatively small area in the center of the eye, approximately 5 degrees in diameter, known as the fovea. The eye is sensitive to light as far out as 90 degrees from the fovea. But, in the area beyond 10 degrees, the functions are primarily to alert the person to the presence and general activity of the scene elements. Figure 6 depicts the resolution falloff of the eye as a function of angle from the fovea.

The movement of the eye is called a saccade. These saccades are the eye's way of moving new elements into the fovea for detailed examination. Saccadic motions are typical of voluntary shifts of attention from one scene element to another and take place at relatively high speeds and accelerations. The speed of a saccade depends on the distance to be scanned. Experiments indicate that the eye tends to maintain fixation on a scene element for a minimum of about 250 milliseconds, moving to new scene elements with peak velocities of 700 degrees per second with accelerations of about 50,000 degrees per second squared.

During these high-speed eye movements, scene information is passing very rapidly across the fovea and is not apparent to the observer. This visual suppression process precedes the start of a saccade, continues on through the saccade with perception not fully returning until some time after the cessation of eye motion. For example, one is unable to see one's own eye movements in a mirror when looking from one eye to the other.

The previous discussion was for static scenes only. In the dynamic scene situation, the eye can smoothly maintain points of interest within the fovea for objects moving up to about 100 degrees per second. During these tracking motions, the scene elements of interest remain relatively fixed to the fovea and thus there is no need for visual suppression. Even so, visual acuity does decrease as the tracking velocity increases. At high velocities, up to 200 degrees per second, the eye uses a combination of saccadic motions and tracking motions to maintain the object within the fovea.

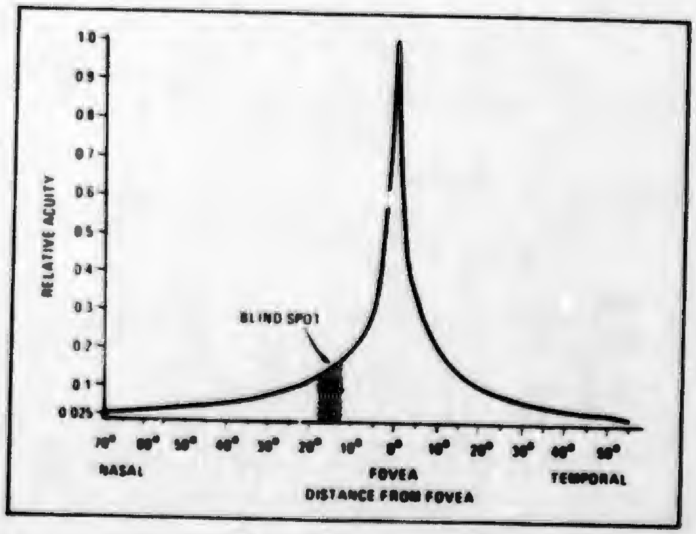

FIGURE 6 Relative Visual Acuity as a Function of Angle from Fovea

The smooth eye motion used to track moving objects cannot be voluntarily induced without the presence of moving imagery. It is difficult to prevent one's eye from following images that fill a large portion of an observer's field of view. As an example, one can observe someone trying to move his eyes smoothly down a typed page. It cannot be done without the aid of a pointer smoothly moving down that page. Also, if the observer "focuses" on a page and the page is moved smoothly, the eyes will track the page's motion.

DISPLAY SYSTEM

The design of the TCT visual display system was based on these two characteristics:

(1) Visual acuity as a function of angular distance from the fovea, and

(2) Suppression of visual perception during eye motion.

The first characteristic permits the concentration of image detail and resolution in the region where the eye is looking. Figure 6 suggests that high resolution and detail in the peripheral regions are unnecessary. The suppression of visual perception before, during, and after a saccade, provides the key to the feasibility of a visual design which is optimized on the eye's angular acuity falloff. Without the period of visual perception loss associated with a saccade, the bandwidth requirements to position the foveal image would be well beyond the state-of-the-art.

The eye-director AOI display approach for TCT was developed around five major hardware systems.

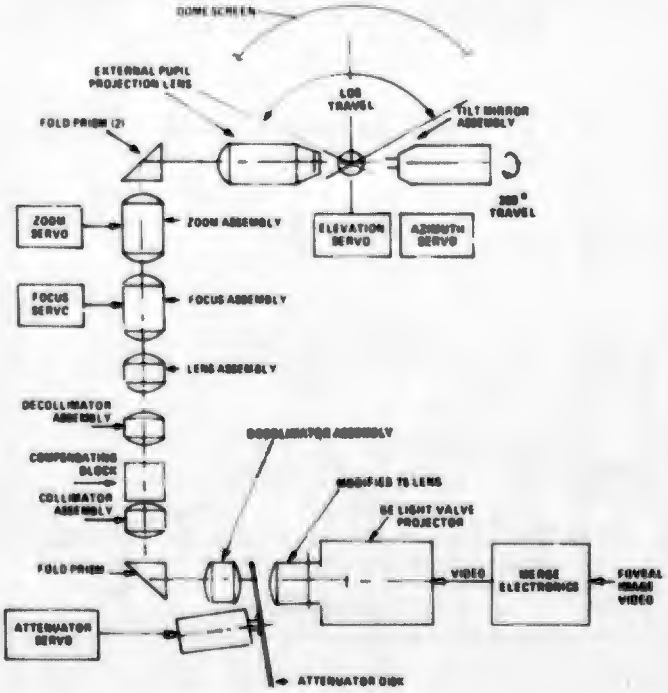

FIGURE 7 Foveal Projector Diagram

(1) Foveal projection system

(2) Peripheral projection systems

(3) Helmet mounted oculometer system

(4) Dome display screen

(5) CIG

FOVEAL PROJECTION SYSTEM

Figure 7 shows the components of a single foveal projector from video input to the dome screen.

The foveal projection lens has an external pupil and is approximately telecentric. The external pupil allows the servoed mirror to be made small by imaging the pupil on it. The first advantage is obvious: the servos used to drive the mirror can be made smaller as the load size is made smaller. The second advantage is an increase in excursion without vignetting as compared to a system without an external pupil.

As shown in Figure 7 there are five servos in the foveal projector; two control LOS, two control size and focus, and one controls brightness. The servo rates and accelerations are designed to be consistent with the requirements of an eye-directed AOI. Link has breadboarded a complete foveal projector that fulfills these requirements. The azimuth/elevation servos control the LOS of the foveal image. This image can be pointed anywhere except where occulted by the projection lens or azimuth/elevation servos. By the nature of this system, the image must be derolled as the azimuth servo rotates; this function is accomplished in the image generator. The zoom/focus servos control the size and focus of the projected foveal image. Due to the geometry of the display system, the throw distance and apparent AOI FOV size to the pilot will vary as a function of his LOS. In order to maintain a constant AOI FOV size to the pilot, the projected FOV must be varied as a function of the pilot LOS. In addition, the image must be refocused as the projection throw distance varies. Both these functions are controlled by zoom and focus. The attenuator servo controls the brightness of the projected image. Because of the geometry, the brightness of the imagery before reaching the screen must be varied as a function of the pilot LOS in order to maintain a constant apparent brightness to the pilot. The main contributing factors to the variance are (1) screen gain, (2) angle of incidence and reflectance with respect to the pilot, and (3) projected FOV. The brightness of the output image is controlled by rotating a variable-density disk located within the optical path.

The light source for the foveal projector will be provided by a GE light valve projector (PJ7150). This light valve provides a light output of 1,000 lumens with a minimum resolution of 800 by 750 TV lines per picture height resolution. The light valve will be modified to a 1:1 format rather than the standard 4:3 format, to reduce the losses in foveal image circular FOV. The modifications will result in a usable light output of 750 lumens and a resolution of 800 TV lines horizontal and 750 TV lines vertical.

The brightness of the outside 3 degrees of the foveal image is reduced to blend/merge the foveal image into the peripheral imagery. This blending is accomplished by electronically feathering that area of the foveal system as a function of angular subtense to the pilot eyepoint. The reverse is done in the peripheral merge electronics.

PERIPHERAL PROJECTION SYSTEM

Figure 8 shows one of the four peripheral projection systems from video input to the dome screen.

The system utilized a wide angle lens in each peripheral projector to provide information in the peripheral FOV. The output is a 210 degree (relative to the lens) circular field projected onto the dome surface. Within the optical chain of the peripheral projector, a variable-density (spatial only) filter will be used to provide two functions. The first is the flattening of the field brightness as seen by the pilot. This comparison is required due to lens falloff, light valve falloff, screen gain, and varying bend angles. The second use is the feathering of the peripheral image at the boundary between two peripheral projectors. The roll assembly is used to orient the 4:3 aspect ratio of the light valve within the circular optical FOV.

The light source for the peripheral projector will be provided by a GE light valve projector (PJ7155). The light valve provides a light output of 2,000 lumens with a minimum resolution of 800 by 750 TV lines per picture height resolution.

As mentioned in the foveal projector description, the outside 3 degrees of the foveal image is used to blend/merge the foveal image into the peripheral imagery. The blending is accomplished by electronically feathering that area of the peripheral as a function of angular subtense to the pilot LOS. In addition, the area inside the blend/merge region is electronically blanked within the peripheral to provide a blank hole for insertion of the foveal image.

The projection/screen/eyepoint geometry along with the wide-angle lens, would provide a distorted image to the pilot if left uncorrected. TCT utilizes two methods of correction in order to reduce the complexity of the system. The first approach is software mapping within the image generator. This removes the basic distortion introduced due to the projector/eyepoint geometry. The second method of correction is provided by a scan converter. The scan converter compensates for the remaining distortion caused by the wide-angle optics and spherical screen.

HELMET MOUNTED OCULOMETER SYSTEM

The measurement of the pilot's eye LOS utilizes a Helmet-Mounted Oculometer System (HMOS) developed by Honeywell Avionics Division under a sub-contract to Singer. The eye LOS relative to the cockpit is continuously measured by the HMOS in two stages: (1) A standard Honeywell Helmet-Mounted Sight (HMS) measures helmet position and LOS relative to the cockpit, and (2) a recently developed Honeywell Helmet-Mounted Oculometer (HMO) measures eye LOS relative to the helmet. The two LOS are then summed to obtain the eye LOS with respect to the cockpit. The resultant eye LOS and helmet position is then provided to the display computer to control the position of the foveal image. This same data is provided to the CIG for the generation of the foveal and peripheral image. Figure 9 depicts the components mounted on the helmet.

The HMS subsystem utilizes a magnetic field established by a transmitter located behind and above the pilot's head. The magnetic field components are detected by a receiver mounted in the helmet as shown in Figure 9. The amplitudes of the field components are then transformed into helmet position and LOS.

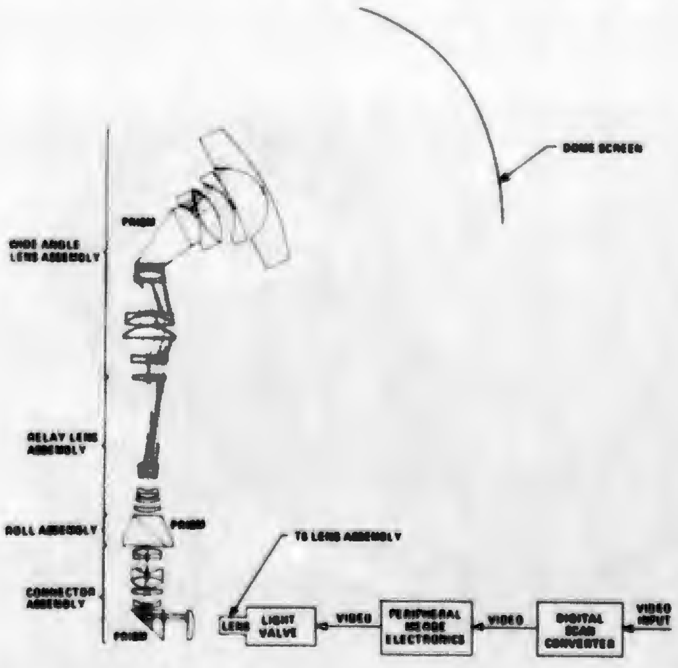

FIGURE 8 Peripheral Projector Diagram

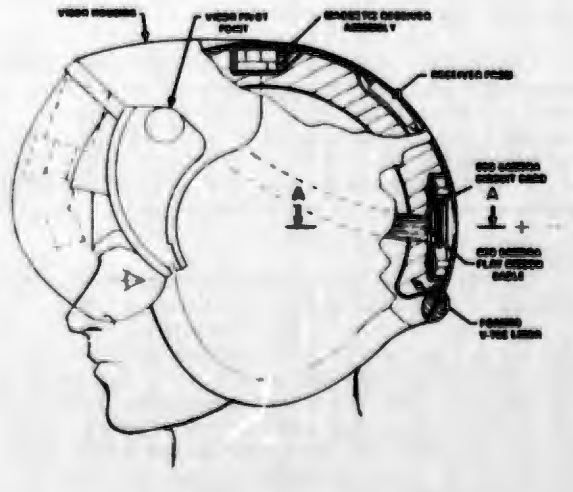

FIGURE 9 Helmet System Layout
Mounted Oculometer

The HMO main component is a charge coupled device (CCD) camera that views the pilot's eye from a mounted position on the helmet, Figure 10. The pilot's eye is illuminated by a low intensity IR lamp that shares the same optical path with the camera through a beam splitter. The CCD picks up the illuminator's reflection off of the pilot's cornea along with the pilot's pupil image. Using this information, the HMO system determines the pilot's eye LOS with respect to the helmet. The HMO computational system then combines the HMS helmet LOS with the HMO eye LOS into a combined pilot's eye LOS with respect to the cockpit.

DOME DISPLAY SCREEN

The display screen is constructed of three basic fiberglass panels and rib structures. The panels below the equator are 22.5 degrees x 46.7 degrees; above the equator the panels are 22.5 degrees x 62 degrees; and the cap panels are 22.5 degrees x 28 degrees. The screen finish, a patented Link process, provides a variable gain function in order to provide compensation for brightness falloff due to the projector and observer locations. The screen gain is four above +55 degrees elevation and two below +10 degrees elevation. The gain varies linearly from two to four with elevation angles between +10 degrees and +55 degrees. The dome construction process entails assembling the rib structure then laying in the panels. The panels are riveted and epoxied in place. The seams between panels are filled to the dome radius before the multiprocess screen coating is applied.

COMPUTER IMAGE GENERATOR

A single five channel CIG system drives the four peripheral projectors and four foveal projectors.

Four image channels are continuously projected on the dome screen to provide the peripheral image. The scene content is allocated between channels based upon the eye LOS. The fifth image generator channel is switched between the four foveal projectors as a function of the pilot LOS outside the cockpit. In addition, the foveal image channel is used for the Maverick cockpit display monitor when the pilot's LOS is directed toward the monitor.

The foveal image channel can process 3,000 potentially visible edges at a rate of sixty times a second; the four peripheral image channels can process a total of 6,000 potentially visible edges at a rate of thirty times a second in an instantaneous FOV of 180 degrees x 120 degrees about the pilot's foveal LOS.

STUDIES

During the TCT contract, Singer conducted several studies to define critical system parameters. The test arrangement consisted of viewing a rear projection screen with an eye directed, high resolution AOI in a low resolution background. The image was generated by two television cameras viewing test imagery. One camera operated at full resolution while the second camera was operated at approximately one-fifth resolution. A bench mounted oculometer detected eye position and directed the position of a variable size and blend/merge of the AOI (from the first television camera) inset into the background (from the second camera). A GE light valve then projected the image on the screen for viewing.

The AOI FOV was variable from 10 to 24 degrees. The blend region, within the AOI, was adjustable for zero blend and variable from 1.4 to 6.7 degrees.

In these studies, a blend region of 3 to 4 degrees within the AOI provided the best viewing. With this blend region, the effects of image mismatch, brightness and resolution differences were minimized. A high resolution area of 12 degrees, exclusive of blends, provided the best viewing. This value maybe decreased as the eye tracking accuracy improves. Thus, the final AOI design was a 14 degree FOV of high resolution imagery surrounded by a blending ring of 3 degrees for a total AOI FOV of 20 degrees.

An additional benefit of these studies was the unstructured subjective evaluation of the eye directed AOI concept. As the observer moved his eyes throughout the scene, it did appear to be completely high resolution. However, when the AOI was not eye directed, the difference between AOI and background resolution was easily seen. This provided additional confidence that this concept would be successful.

Prior to the termination of the contract, Singer completed the fabrication and test of the HMOS, Figure 10. Two units were built and both met or exceeded the TCT requirements. In addition, a breadboard of the foveal projector was fabricated but not tested, Figures 11 and 12. This breadboard was tested on a subsequent contract, Project EDIT, described below. These tests indicated that all TCT requirements were met, except for the peak velocity of the azimuth servo requirement. Corrections to this problem have been designed and will be incorporated in the future. The performance of the Singer eye-directed AOI approach is summarized in Table 4.

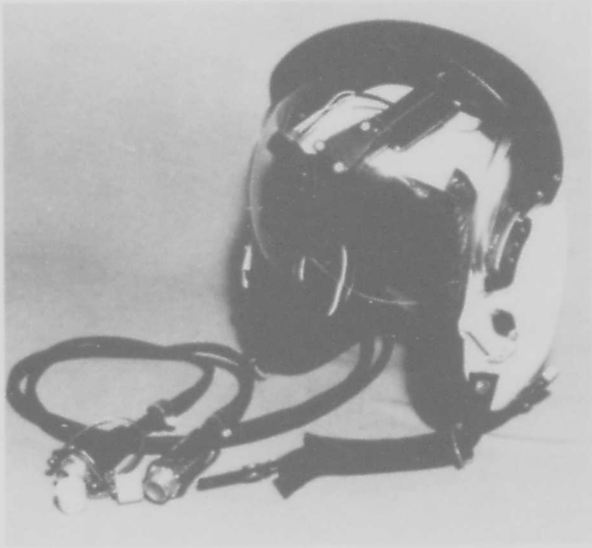

FIGURE 10 Helmet-Mounted Oculometer System

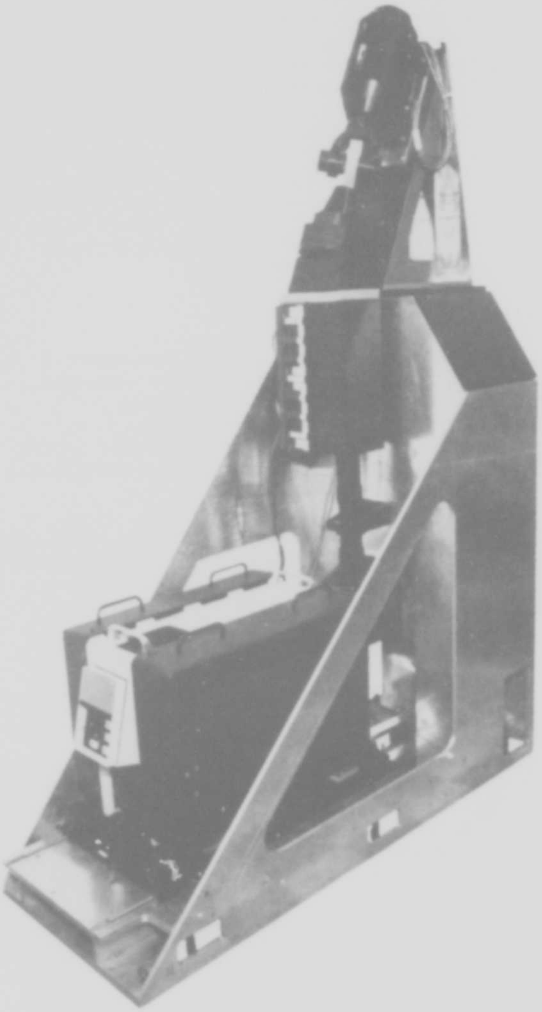

FIGURE 11 Foveal Image Projector

PROJECT EDIT

Project EDIT (Eye-Slaved Display Integration and Test) is a cooperative Air Force and Navy continuation of the Singer eye-directed AOI development started on TCT. The Air Force is providing residual TCT contract equipment and funding. The Navy is providing funds, equipment, facilities, and contract administration. Project EDIT is a multiphased effort which will lead to pilot evaluation of the TCT eye-directed AOI technology on the Visual Technology Research Simulator (VTRS) located at the Naval Training Equipment Center.

Phase I has been recently completed where the HMOS and servos were integrated with the central computer and dynamically tested; and the video electronics checked out and dynamically tested. Phase II started in August 1982. During this phase, all the subsystems will be integrated and tested end-to-end. This will include using an artificial eye to provide known inputs to the HMOS and measuring the response of the projector servos. Preliminary plans are that Phase III will integrate the breadboard eye-directed AOI equipment on the VTRS for pilot evaluation. The exact plan and schedule for Phase III will depend upon available funding and success during the various stages of integration.

The Air Force goal for Project EDIT is to determine the feasibility of the eye-directed AOI concept for tactical combat training. If successful, data from Project EDIT will be used to establish system performance specifications for future procurements. The eye-directed AOI approach has the potential of meeting most of the tactical training requirements.

CONCLUSIONS

Although the TCT contracts were terminated, several developments were successfully completed, such as the 36-inch metal funnel CRT and the Helmet Mounted Oculometer System. These equipments are currently being used in laboratories

TABLE 4 SINGER TCT PERFORMANCE PARAMETERS

Field of View:	Total aircraft FOV including head motion
Resolution:	1.4 arc minutes
Contrast Ratio:	14:1
Brightness:	1.5 foot Lamberts
Foveal FOV:	20 degrees diameter with 3 degrees merge
Peripheral FOV:	360 degrees H, +90 degrees, -60 degrees V except where occulted by cockpit
Number of Edges:	1 foveal channel, 3,000 edges @ 60 Hz 4 peripheral channels, 6,000 edges @ 30 Hz
Texture:	Surface (16 unique patterns)
Moving Model Types:	Airborne, 10; Ground, 50
Environment:	Full weather, time of day effects
Gaming Area:	1,000 x 1,000 nautical miles
Scene Enhancement:	Articulated parts, light point features
Visual Data Base:	Transformed DMA, Hand modelled
Special Effects:	Head Motion Compensation G-Dimming

to perform much needed research. In addition, the feasibility of other developments were demonstrated such as the inset mini-raster on a CRT and the foveal projector. It is hoped that work will continue to complete and evaluate these developments.

On the TCT program, there was a continuing evaluation of the Technical and Training Risks of fielding a successful WST. It is our belief that the work accomplished on these contracts and described in this paper have significantly reduced the Technical Risk of these two approaches. However, continued effort is needed to reduce these Technical Risks for a production procurement. Additionally, the Training Risks have not been significantly reduced. A simulator environment for flying combat tasks is needed to permit task-loading the pilot to predict the training performance of the visual system. Continued efforts, such as Project EDIT and other similar work, are needed to reduce the Training Risks.

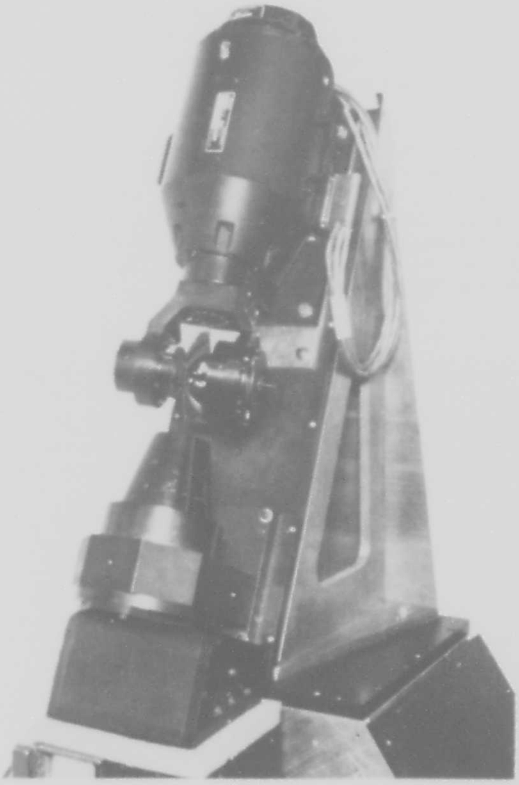

FIGURE 12 Closeup of Azimuth/Elevation Servo Assembly

Another contribution of the TCT program, although not strictly technical, is demonstrating the importance of thoroughly communicating to the design engineers the pilot's tasks, visual references and how such visual references are used. The Air Force, General Electric and Singer-Link agree that the orientation trips and the continued dialogue between designers and pilots during the TCT program was extremely useful in designing the TCT system and determining design and performance tradeoffs. It is hoped that these effective communication techniques will be used on future programs.

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Mr Robert A. Fisher is a Visual Systems Program Engineer with Singer Link, Flight Simulation Division. He is currently Principal Investigator for the Wide Angle Tactical Visual Program and Program Engineer on the Eye-Slaved Integration and Test Program. He has over twenty-two years experience in display system technology. Mr Fisher has a B.S.E.E. degree from Syracuse University.