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Technical Memorandum

DEVELOPMENT OF A LOW-COST HELMET MOUNTED
EYE GAZE SENSOR

by

Richard S. Dunn, Ph.D.
Donna L. Haspel

Systems Engineering Test Directorate

27 October 1988

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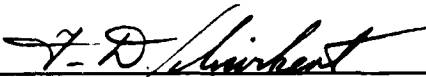
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Improvements in helmet mounted eye gaze point sensor technology are needed for aircrew performance assessment in both simulation and in-flight testing. The task reported in this Technical Memorandum is a design and proof-of-concept effort for development of a low-cost oculometer to meet this need. The work was conducted for NAVAIRSYSCOM under AIRTASK A9303D/053E/7W1812009, Work Unit NATC-3044. Subsequent design refinement is planned; however, this report completes the requirements of the AIRTASK/Work Unit.

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19 ABSTRACT (Continue on reverse if necessary and identify by block number) <i>Visual processing (SBU)</i> This report documents Phase I of a Small Business Innovation Research (SBIR) contract for development of a low-cost helmet mounted eye gaze point sensor. The device, in completed form, is for use in laboratory, simulator, and in-flight studies by NAVAIRTESTCEN in aircraft test and evaluation projects. Numerous other potential applications in behavioral research and development would benefit from use of the device throughout the Department of Defense and in commercial and academic settings. The device produces a time history of eye gaze point information along with pupil diameter and eye-blink data. It has flexibility as a sensor system for many different modes of application. Sentient Systems Technology, Incorporated, completed design, testing, prototype hardware and software development, and functional testing of a prototype unit. The effort constituted a full feasibility demonstration in the multistage SBIR contract cycle format. Success in Phase I is intended to lead to					
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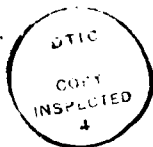
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PUPIL DIAMETER SENSOR
VIDEO IMAGE PROCESSING
VISUAL TASK DEMANDS

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follow-on contracts for engineering development and applications development or production during Phases II and III. Functional demonstrations of the prototype unit with Sun Microsystems computer equipment were convincing and fully successful. A complete prototype with simplified software for operation with an IBM compatible PC system is now being evaluated for in-house applications in a behavioral test and evaluation laboratory setting. The Phase I contract was a 6 month effort completed in March 1988. The full text, in contractor format, of Sentient Systems' Final Report is included in appendix A. Sentient Systems has advanced a Phase II proposal (along with indications of Phase III and commercial applications interest) through the Navy approval cycle and funding for the Phase II contract is now pending. Conclusions are that the technical approach can fully meet the cost, performance, and application goals of the effort. Recommendations are for continuation of this SBIR effort in accordance with the Sentient Systems Technology, Incorporated, Phase II proposal.



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SUMMARY

This report documents Phase I of a Small Business Innovation Research (SBIR) contract for development of a low-cost helmet mounted eye gaze point sensor. The device, in completed form, is for use in laboratory, simulator, and in-flight studies by NAVAIRTESTCEN in aircraft test and evaluation projects. Numerous other potential applications in behavioral research and development would benefit from use of the device throughout the Department of Defense and in commercial and academic settings. The device produces a time history of eye gaze point information along with pupil diameter and eye-blink data. It has flexibility as a sensor system for many different modes of application. Sentient Systems Technology, Incorporated, completed design, testing, prototype hardware and software development, and functional testing of a prototype unit. The effort constituted a full feasibility demonstration in the multistage SBIR contract cycle format. Success in Phase I is intended to lead to follow-on contracts for engineering development and applications development or production during Phases II and III. Functional demonstrations of the prototype unit with Sun Microsystems computer equipment were convincing and fully successful. A complete prototype with simplified software for operation with an IBM compatible PC system is now being evaluated for in-house applications in a behavioral test and evaluation laboratory setting. The Phase I contract was a 6 month effort completed in March 1988. The full text, in contractor format, of Sentient Systems' Final Report is included in appendix A. Sentient Systems has advanced a Phase II proposal (along with indications of Phase III and commercial applications interest) through the Navy approval cycle and funding for the Phase II contract is now pending. Conclusions are that the technical approach can fully meet the cost, performance, and application goals of the effort. Recommendations are for continuation of this SBIR effort in accordance with the Sentient Systems Technology, Incorporated, Phase II proposal.

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INTRODUCTION

1. The Aircrew Systems Department of the Systems Engineering Test Directorate, NAVAIRTESTCEN, initiated and guided a test and evaluation technology development project to obtain eye gaze point monitoring devices. Sentient Systems Technology won a Small Business Innovation Research (SBIR) competition and received a Phase I SBIR contract in 1987 for the development of a low-cost oculometer. Requirements for the device included that it be low-cost, lightweight, self-calibrating, and flightworthy. The Phase I Final Report by Sentient Systems Technology provides a detailed description of their Phase I effort and is presented in appendix A.

2. Some important points of the Department of Defense (DOD) SBIR program are:

- a. Goals are to stimulate technical innovation in the private sector, to enable small business involvement in DOD research and development, and to increase commercial application of DOD-supported research and development results.
- b. Agencies of the DOD identify areas where research and development effort is desired. Selected task descriptions become SBIR contract topics for which small businesses can compete.
- c. The SBIR program consists of three phases. In Phase I, 6 month contracts are awarded to small businesses to determine the technical merit and feasibility of a proposed concept. Phase II awards are made to those companies who show promise in Phase I. This is a research and development effort which takes no more than 2 years. Phase III should involve support from a third party or the private sector and lead to production or application.

RESULTS AND DISCUSSION

3. Phase I of this SBIR project for development of a low-cost helmet mounted oculometer was completed in March 1988 and proved feasibility of the technical concept. Results included a working prototype model which is self-calibrating, lightweight, and extremely low-cost but still works with the required accuracy. Its outputs include precise measurements of eye movement, blinks, and pupil size. Sentient Systems Technology has completed all stated goals of the SBIR Phase I effort and has completed a specific account of the work in the Final Report (appendix A).

4. Sentient Systems Technology provided a full demonstration of the prototype helmet mounted oculometer to the NAVAIRTESTCEN sponsors. The system was controlled by a Sun computer workstation and video outputs of the eye and pupil were monitored. The prototype system functioned as intended in all respects.

5. A Phase II SBIR proposal was received and approved for action pending availability of SBIR funds. An important part of the Phase II process will be iterative NAVAIRTESTCEN participation in testing of the apparatus between modifications as they occur. Three separate stages of design refinement and application testing are planned. Sentient Systems Technology will enhance the prototype hardware for convenient use, such as in all lighting conditions and

with night vision goggles, and also for flightworthiness. Three models will be made for different flight and workload conditions. The optics will also be made modular for use with any helmet. Refinement of the prototype software will occur and will permit eventual integration of the oculometer with a helmet tracker and 3-D computer modeling tools. Application products using the system's computerized outputs are, or will be, gaze point time history, cockpit and field of view scoring, crew performance data, pupillometry derived scores, and task analysis verification.

6. Strong commercial third party interests in this product have been indicated for Phase III of the SBIR program.

CONCLUSIONS

7. Sentient Systems Technology performed all of the tasks called for in the Phase I contract:

- a. The working prototype demonstrated feasibility of the design concept and that it can meet performance and cost objectives. The suitability of the technical approach to the goals of this development effort was fully established.
- b. Use of the working prototype demonstrated that Sentient Systems Technology has command of the required technology and permitted component placement tests which will be the basis for the detail design of a working system.
- c. This project is an exemplary model of the intended operation of the SBIR program.

RECOMMENDATION

8. This effort to develop a low-cost eye gaze point sensor should be continued in accordance with SBIR program procedures and Sentient Systems Technology's Phase II proposal.

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SENTIENT SYSTEMS TECHNOLOGY, INCORPORATED,
SBIR PHASE I FINAL REPORT

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SBIR Phase I Report
Low-Cost, Helmet Mounted Eye Gaze Sensor

April 18, 1988

Gary Kiliany
Dr. Mark B. Friedman

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5001 Baum Boulevard
Pittsburgh, PA 15213
(412) 682-0144

Contract No: N00421-87C-0234
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Naval Air System Command

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Project Summary

During phase I, Sentient Systems Technology (SST) has demonstrated to Navy personnel that application of its low cost, eye gaze sensing technology can result in a practical, low-cost, helmet mounted eye gaze sensing system for use throughout the Department of Defense in human factors, aerospace medicine, and ultimately operational environments. SST has constructed, and demonstrated to Navy personnel, a low cost, helmet mounted, eye gaze sensing testbed. The user wears a flight helmet to which a lightweight, compact, CCD camera has been attached. The camera is connected to proprietary eye image processing electronics which allow the user's point of gaze and pupil diameter to be computed. NATC personnel have used the working phase I system and were extremely pleased with its operation. The testbed has allowed prediction of the ultimate price and performance of a production quality device should it be fully developed in a phase II effort.

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Background and Significance of Problem

In human factors research, there is a tremendous need for determination of an individual's gaze point. Learning to perceptually select those visual cues that are most informative concerning particular combat tasks are an important part of learning to deal with time critical visual workloads. For example, in flight during a roll turn, the visual environment is unusual: the ground surface is seen in near vertical perspective with the oncoming terrain toward the top of the field of view and the visual cues and features that provide major control inputs for initiating, maintaining, modifying, and completing maneuvers must be extracted in conditions of high stress. Rapidly extracting critical information from instrumentation and from the external combat environment may be a matter of life or death. Proper design of instrumentation, based on extensive visual scanning behavior research and simulation, could result in dramatically improved, operational combat effectiveness for the aircraft of intent.

In addition, it is apparent from the effort being expended by all branches of the armed forces on eye gaze control that this technology will move from facilitation of simulation displays to control of operational hardware. The report "Trends Shaping Advanced Aircrew Training Capabilities Through The 1990's" written for the Air Force Human Resources Laboratory states: "In short, the assumption here is that head and eye coupling represents a critical technology, the applications of which, will become increasingly pervasive throughout the decade of the nineties, not only with respect to simulator display technology but also with respect to actual in-flight applications" (AFHRL-TP-84-52). One motivation for this development is that the increasing demands on personnel for vehicle and ordnance control make it desirable to supplement the use of hands and feet, especially for secondary tasks.

Much work being done in Department of Defense medical research labs on visual behavior physiology would also benefit from the use of the low cost, helmet mounted eye gaze sensor. Monitoring point-of-gaze and pupil diameter can tell us a great deal about the fundamental performance limitations of human physiology. As the capabilities of our machines continue to increase, fully understanding the limitations imposed by their human operators will become as important as understanding the laws of physics governing the design of these advanced military systems.

The ultimate cost of a deliverable, production quantity system is one of the primary driving forces motivating this project. In the past, eye gaze monitoring systems were built as one-of-a-kind, high cost (\$50,000-\$100,000) laboratory instrumentation systems and, as a result, the potential of the technology developed for them was never fulfilled. Because SST manufactures low cost, eye gaze controlled systems for the

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price-sensitive commercial market, it approaches the development of eye gaze monitoring systems from a very different perspective. SST and NATC personnel feel that there is a large military and commercial market for a low cost, high performance, eye gaze sensing device that would allow the potential of this exciting technology to finally be fully realized. NATC personnel have indicated that the production quantity price must be under \$10,000. Because of (a) the large production volumes of compact, lightweight, high resolution, CCD cameras and their resulting low cost (under \$500); and (b) the phase I demonstration that the eye image processing hardware for a single camera can be built on a single circuit board; the production quantity cost constraint can be easily attained.

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Technical Objectives of Phase I Work

The primary objective of the phase I effort was to determine if it was feasible to use the low cost, eye gaze sensing technology developed for SST's commercial EyeTyper product line in a low cost, helmet mounted eye gaze sensing system. In addition to simply proving feasibility, it was desired to predict the ultimate performance and price of such a low cost, helmet-mounted, eye gaze sensing system should it be fully developed in a phase II effort.

The desired operational parameters for the low cost, helmet mounted eye gaze device were identified in discussions between SST and Navy personnel during this phase I effort. They are listed below.

- 1) Added helmet weight must be minimized and the center of gravity should not be changed; If the COG is changed it should be shifted low and aft.
- 2) Obstruction to the field of view must be minimized.
- 3) Must be capable of being used with night vision systems.
- 4) Production quantity devices must be deliverable for less than \$10,000 per device.
- 5) Gaze resolution should be a minimum of 2-3 degrees with a horizontal range of plus or minus 20 degrees within the helmet.
- 6) Gaze monitoring speed should be maximized.
- 7) It is desirable to monitor and count blinks.
- 8) Calibration should be easy, fast, and robust.
- 9) Must be easily interfaced to other Navy human factors computer systems. Digital output should be provided with time synchronization.
- 10) A measure of pupil diameter at least once a second.
- 11) Packaging should be rugged enough to demonstrate that flight worthiness could be attained with further development.
- 12) The helmet-mounted camera packaging should provide for easy attachment to, and detachment from, multiple helmets.

Because combat aircraft normally undergo high rates of acceleration, there is a real need to minimize the helmet weight. In simulator and human factors applications, g-loading is not a problem but the helmet weight must be kept realistic. An ultimate limit on operational helmet weight is related to crash survivability. A helmet-mounted visual display, together with the eye position sensing system, must not significantly increase the weight of the helmet. Increasing the size of the helmet is also unacceptable in the limited area of the cockpit. In military aircraft, the primary function of the flight helmet is protection. Since this is not the case in simulators, there are fewer constraints on mounting additional hardware or modifying the helmet in order to reduce the weight.

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If the eye position sensor does add any significant weight to the helmet, it would be most desirable to mount the system as close to the center of gravity of the head/helmet as possible. If this is not done, there is a danger of rotational torques induced by head motion causing the helmet to rotate relative to the pilot's head. For these same reasons, any cabling attached to the helmet must not increase the weight, inertia, and rotational torque induced by head motion.

Another design specification for this system is the number of distinct points that need to be resolved within this total field of view, i.e., the gaze resolution. The minimum number of points required will vary widely from application to application however, all applications undoubtedly desire as large a number of points, resulting in the highest eye gaze point resolution, as is technically possible. NATC personnel have indicated that a minimum gaze resolution of 2-3 degrees is acceptable with a 40 degree total horizontal range.

A major constraint in the design of a helmet mounted eye position sensor is that the distance from the front of the eye to a helmet mounted display, helmet visor, night vision goggles, or other visual enhancement/protection devices is very small. This "eye relief" distance is typically about 39 mm. This makes fabrication of the eye imaging optics one of the more important problems to be surmounted.

In addition to eye gaze location monitoring, it may be desirable in many applications to also monitor pupil dilation. Pupil dilation may be an essential component of measuring workload and emotional stress, especially when combined with other workload/stress measuring techniques.

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Phase I Work and Results

We will now describe the phase I, technical feasibility, development effort which resulted in the construction and evaluation of a low cost, helmet mounted eye gaze sensing testbed.

Initially, the desired price-performance goals of a fully developed system needed to be determined in discussions with Navy personnel. These discussions resulted in a detailed specifications list that was described previously in this report. SST personnel then began designing and building a low cost, helmet mounted eye gaze sensing testbed which would allow: 1) demonstration of the technical feasibility of using technology developed for SST's EyeTyper products in a helmet mounted system; and 2) exploration of the helmet mounted eye gaze sensing system design space to allow prediction of the ultimate performance and price of such a low cost, helmet-mounted, eye gaze sensing system should it be fully developed in a phase II effort.

All eye gaze sensing approaches require some sort of light sensor that registers what the eye looks like, and a microcomputer that computes exactly where someone is gazing based on the eye image. SST's EyeTyper model 100 uses a bulky video camera connected to a powerful microprocessor. The EyeTyper 300 uses an inexpensive and compact solid state light sensor connected to the same microprocessor. Over several years, SST's personnel have developed many algorithms that result in the accurate determination of gaze position given the appearance of an eye. In addition, several proprietary electronic circuits have been developed which greatly assist the cost effective incorporation of eye gaze sensing technology into products.

The low cost, helmet mounted eye gaze sensing system can be broken down into five areas:

- 1) Eye imaging.
- 2) Microprocessor hardware
- 3) Real time, eye image processing hardware.
- 4) Eye image processing software.
- 5) Packaging.

A discussion of the results obtained from evaluation of the prototype system will follow this description of each area as it applies to the working phase I testbed.

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EYE IMAGING

The eye is composed of several components: the iris is the part that determines "what color your eyes are" e.g. blue eyes or brown eyes. It also expands and contracts to control the amount of light entering the eye and in response to various cognitive factors. The pupil is the dark area that is surrounded by the iris. Light enters the eye through this hole. The sclera is the white area that surrounds the iris. In addition, the front of the eye is covered by a transparent surface called the cornea.

As a person looks around, their pupil and attached cornea move vertically and horizontally. If a point light source is positioned in the field of view of the eye, it will be reflected back very brightly from the front surface of the cornea. This is because the cornea partially acts as a convex reflector. Hence, as the eye moves, the reflection off of the cornea will move. If the eye gaze sensor is fixed relative to the user's head, or if supplementary head location/orientation information is available, then the corneal reflection is sufficient to determine the point of gaze (given an initial calibration). An alternative technique is to use information about the pupil location along with the corneal reflection. In a helmet mounted system, this provides more tolerance to helmet movement relative to the user's head than using corneal reflection alone. As a person's gaze moves, the reflection off of the cornea relative to the position of the pupil changes. This is the eye gaze sensing method used in the EyeTyper model 100. This technique requires more computation.

The first issue to be dealt with when building a helmet mounted system based on SST's EyeTyper technology is obtaining an image of the eye within the helmet. Three specifications greatly impact this part of the design. The weight added to the helmet must be low, the production quantity price of the system must be low, and the helmet mounted packaging requirements must be practical. During phase I, SST personnel searched for an imaging technology that would satisfy these constraints. SST's early products (1984) that incorporated eye gaze sensing (EyeTyper 100) used a tube based video camera. While this technology supplies a good quality video signal, it lacks compact size, robustness to mechanical shock, and requires a relatively large amount of power.

With the recent large production volumes of low cost, consumer video products (camcorders), the functional performance and price of CCD (charge coupled device), solid state image sensors have been dramatically improved over the early generation CCD devices. After an extensive search, SST selected a lightweight, compact, high resolution CCD video module to acquire the eye image. This video module is made by Amperex electronics and is composed of the Philips/Amperex NXA1031 CCD image sensor (610 x 488 pixels) and three small circuit boards attached to each

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other with flex circuit connectors. The flex connectors enable the CCD video module to be mechanically shaped in many different ways. This is tremendously advantageous for the helmet mounted system because it will ultimately enable the video module to be packaged conformal to the side of the helmet. The module can be conformed to a 4" length, 2" height, and 1" depth exclusive of imaging optics and weighs approximately 8 ounces. The current production quantity price of the video module is \$485. It outputs a NTSC standard video signal (60 fields/sec) and consumes minimal power (165 mA at 12V).

To obtain the corneal reflection and to illuminate the eye area, low power (less than 1/100 the maximum power allowed under the American Conference of Governmental Industrial Hygienists guidelines for eye infrared exposure), near-infrared (850 nm) light emitting diodes were selected. Because infrared light is not visible by humans, it does not interfere with the user's visual performance. Silicon based CCD arrays are very sensitive to the near visible, IR wavelengths which are used. To minimize ambient lighting effects, a very tight IR bandpass optical filter was used in front of the image sensor. This approach has worked very well in the phase I system. The near-IR illumination energy is carefully channelled so that there would be no interference if used in conjunction with night vision equipment. The physical placement of the camera and light sources will be extensively discussed in a subsequent section of this report.

MICROPROCESSOR HARDWARE

The microprocessor hardware must be able to support both the low level image processing software algorithms and higher level eye gaze mapping software algorithms. In addition, it must provide for sending the eye gaze vector data to a host human factors computer or flight simulator. During phase I, SST constructed a "wire-wrapped" prototype circuit board that contained an 8 bit, 65C02 microprocessor running at 2 MHz, static RAM, EPROM, an interface to the eye image processing electronics, and a serial communications port. This basic design has been used in SST's EyeTyper products and supplied adequate processing power for the purposes of the phase I testbed. If this system is fully developed in a phase II effort, a 16 bit 68HC000 microprocessor will be used leading to a performance improvement with no significant cost penalty. This issue will also be discussed in a subsequent section of this report.

EYE IMAGE PROCESSING ELECTRONICS

The "wire-wrapped" prototype circuit board constructed for the phase I system also contained circuitry for interfacing the helmet mounted, CCD video camera to the microprocessor. This

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proprietary eye image processing hardware pre-processes the digitized video image from a CCD camera so that the software can quickly determine where a person is looking.

It consists of about 30 SSI, MSI, and LSI low cost, integrated circuits. This hardware generates a 2 level (dark and bright) pseudo run length encoded representation of the image. The two threshold levels are totally dynamic - one is used for the bright corneal reflection and one is used for the dark pupil. The x and y locations of threshold level crossings are stored in a 512 x 18 FIFO memory. We are essentially generating a list of the locations of dark and bright edges occurring in the input image. The microprocessor can then read the numbers representing the location of the edges from the FIFO memory. This enables a low cost system to process eye images in real time.

This basic FIFO memory-based design is used in the EyeTyper 300 although the EyeTyper 300 uses only a single threshold level. During phase I, the second programmable threshold level was added to the basic design so that pupil diameter could be computed and gaze location would be more robust to the helmet shifting on the user's head.

EYE IMAGE PROCESSING SOFTWARE

65C02 assembly language software running on the microprocessor analyzes the run length encoded image data to determine the location of the user's gaze. The software initially performs a region connectivity analysis of the edge list data, thus generating a region descriptor list. The region descriptor data structure contains information on the shape, size, and location of each region. After this, the regions representing the corneal reflection and the pupil are chosen from the region descriptor list. This selection process is straightforward because the pupil and corneal reflection regions have very distinguishing characteristics (unique shape, size range, relative location between pupil and cornea). The center of the corneal reflection and the center of the pupil are then computed (pupil diameter information is also computed). The vector composed of the x and y differences of these two centers is then correlated to a gaze location using information obtained from an initial calibration.

As stated previously, for some applications, only the corneal reflection may be required. If the helmet does not move relative to the user's eye then it is sufficient to determine gaze location. However, if the pupil and corneal reflection are used then substantial robustness to helmet shifting is obtained. This has been demonstrated on the phase I system.

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For the phase I testbed, once the x-y gaze vector is computed, it is sent to a host SUN Microsystems workstation via a 4800 baud, RS-232 link. If no eye is seen by the system then it sends a null (all zero) gaze vector. This allows monitoring of eye blinks. Software written in the C programming language running on the SUN computer allowed for experimentation and demonstration of helmet mounted eye gaze sensing.

To accomodate anatomical variability between users and the variability of eye location within the helmet relative to the eye imaging environment, eye tracking systems require the user to go through a calibration/training process. It is most desirable to make this as quick and robust as possible. Software on the SUN microsystems computer implemented a three point gaze calibration sequence. After this calibration was completed, the area on the SUN bitmap that the user was looking at was indicated with a dark square.

PACKAGING

Because of limited funding, phase I effort was designed to prove technical feasibility, not produce a production quality product, the packaging of the system was not a primary concern. However, it was very important that the overall conceptual design be amenable to a robust, practical package given full development in a phase II effort. For this reason, an extensive search was performed to find an imaging device which would meet the specifications. The chosen Amperex, CCD camera is compact, lightweight, and its flexible circuit board construction will greatly facilitate the helmet mounted packaging of a phase II system.

The phase I testbed uses a mechanical linkage attached to an oxygen mask latchpoint on the helmet to facilitate experimentation with the position of the lightweight, CCD camera relative to the user's eye. Results of these experiments have led to the packaging design for a production quality device as described in the phase II proposal and summarized at the end of this report. The bulky mechanical linkage of the phase I device will not be needed.

The helmet mounted, compact, CCD camera is connected via a cable to a 7" x 11" prototype, "wire-wrapped" circuit board containing the eye image processing electronics. This circuit board is housed in a metal case which provides for connection of the CCD camera, a power supply, video monitor to view the unprocessed eye image, video monitor to view the processed eye image, and a DB-25 connector for the serial digital communications link.

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Summary of Phase I Low Cost, Helmet Mounted Eye Gaze Sensing Testbed

During phase I, Sentient Systems Technology (SST) has demonstrated to Navy personnel that application of its low cost, eye gaze sensing technology will result in a practical, low-cost, helmet mounted eye gaze sensing system for use throughout the Department of Defense. SST has constructed, and demonstrated to Navy personnel, a low cost, helmet mounted, eye gaze sensing testbed. NATC personnel have operated the working phase I system and were extremely pleased with its operation. A photograph of the helmet mounted section of the phase I system showing the image of the eye on a video monitor is included at the end of this section.

This testbed consists of a low weight (8 ounces) CCD camera mounted to a Navy flight helmet via a mechanical linkage which facilitates experimentation with various camera angles for viewing the pilot's eye. The camera is connected to a "wire wrapped" circuit board which contains a microprocessor and custom, eye image processing electronics. Several near-IR light emitting diodes can be positioned for experimentation with different eye illumination techniques. Software running on the microprocessor analyzes images of the eye and outputs an x-y gaze vector to its RS-232 serial port. The eye image processing circuit board is connected to a SUN Microsystems workstation via a RS-232 serial link.

A user can sit in front of the workstation wearing the helmet and control a cursor on the bitmap screen by shifting gaze point, i.e., the area on the screen the user is looking at is highlighted with a black square. The user goes through a three point calibration sequence, then software on the SUN computer draws a grid of the appropriate resolution, updating the user's gaze point in real time (approximately 45 times a second). Gaze resolution to approximately 1/2 a degree has been demonstrated. Because the x-y gaze vectors input to the SUN computer are relative to the helmet frame of reference, the user's head must remain fixed relative to the SUN display in order for the indicated point of gaze to be correct. If a person blinks their eyes, then no gaze position is indicated on the screen. In this way, blinks are easily monitored. Pupil diameter can also be computed by the microprocessor software. There is evidence that this may be an indicator of workload stress.

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Prototype low-cost eye gaze sensor. Elements include an IR light emitting diode, a video camera circuit which can be mounted conformally in later stages, and test-bed mechanical fixtures and optics.

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Evaluation of the Phase I Testbed

The above described system constructed during phase I has satisfied the objectives defined for this limited funding, technical feasibility demonstration project. It has proven the technical feasibility of the approach, allowed prediction of operational parameters for the fully developed device, and has shown the engineering design space that will be optimized during the phase II development. We will now describe areas that will need to be more fully developed in a phase II effort based on the evaluation of the phase I testbed and conclude with a discussion of a helmet eye imaging study performed during phase I with the testbed.

MICROPROCESSOR

The phase I testbed uses an 8 bit, 2 MHz, 65C02 microprocessor. While sufficient for the phase I system, substantially higher performance levels will be attained by using a more powerful 16 bit, 12.5 MHz, 68HC000 microprocessor for the proposed phase II system. All computer-based devices can benefit from the availability of more compute cycles and the low cost, helmet mounted, eye gaze sensing system is no exception. Because this increase in computing power can be obtained with no cost penalty, it is desirable to incorporate it into the phase II system.

The theoretical maximum speed attainable using low cost, off the shelf, CCD camera technology, set by the NTSC synchronization standard, is 60 eye gaze vectors per second. The actual speed of an operating system is limited by the point of gaze computation time required by the software operating on the host microprocessor in conjunction with the custom eye image processing hardware. The phase I testbed, using the 8 bit microprocessor, operates at about 45 gaze vectors per second while doing corneal tracking only. Combination pupil-cornea tracking is slightly slower (40 per second). A faster microprocessor, running the same software algorithms, will increase the gaze sensing speed of the system and should approach the theoretical maximum rate.

In addition to increasing the speed of the system, a more powerful microprocessor will allow the use of increasingly sophisticated software algorithms. For example, the phase I system computes the center of the pupil by using a center of mass approach. This works well if the pupil region is imaged such that it has a regular shape, but does not work as well if the pupil region becomes connected with other dark eye features such as the top eyelid. This can partially be dealt with by using a lower camera angle, however the best solution is to use a more sophisticated center-of-pupil algorithm. Computer vision, region shape analysis algorithms can result in an accurate measure of the center of the pupil and its diameter

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given irregularly imaged pupils but require more computation time than simpler approaches.

CALIBRATION and GAZE MAPPING SOFTWARE

Once the calibration information has been gathered by the system, it must be used to map eye features to their proper gaze vector. The phase I system has shown that while a straightforward linear mapping will work at lower resolutions, because the cornea is spherical at the center and flattens out toward its edges, nonlinear, second order fitting functions must be used to obtain the best accuracy at the highest gaze resolution. This also necessitates the use of a more powerful microprocessor than that used in the phase I testbed.

The phase I system uses a three point calibration sequence for which pacing and presentation is automatic. The user needs only to look at the given gaze points and therefore this process takes approximately 10 seconds to complete. This has resulted in excellent performance at coarser resolutions but a small number of additional calibration points will be needed for maximum accuracy at the highest resolution. Extensive testing and experimentation will be done on this calibration mapping problem during phase II.

HELMET MOUNTED EYE IMAGING

Because the helmet mounted system must be usable with visual enhancement devices (e.g. night vision) and the visual performance of the pilot must not be degraded, an oblique camera angle view of the eye is desirable. The initial phase I system used a helmet mounted camera angle of approximately 35 degrees temporal to the eye and a single near-IR light emitting diode positioned at this same angle to obtain the corneal reflection. With this single light source, single oblique camera arrangement, the reflection of the light source off of the cornea of the eye was observable for all practical temporal gaze angles but only observable up to gaze angles 5 degrees nasal to the midline.

Further use of the testbed system indicated to SST personnel that an extensive helmet mounted, eye imaging design study should be done. It appeared to SST personnel that an extremely wide range of eye gaze angles could ultimately be accommodated in a fully developed system that used multiple light sources and two cameras each viewing an eye from an oblique angle. The fundamental issue to be investigated was determination of the range of resolvable gaze angles given a camera viewing angle and a position for the light source causing the corneal reflection.

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A helmet mounted eye imaging experimental system was constructed that enabled the camera angle of view to be varied, the position of a point light source to be varied, and the resulting resolvable gaze angle to be measured. This consisted of the lightweight, CCD camera used in the operational phase I system, an American Optical Company field of view measurement instrument, and a near-IR LED on a flexible arm for positioning at various 3-D locations.

EYE GAZE FIELD DETERMINATION CHARTS

For a given camera viewing angle and a given light source position, the field of view in which the corneal reflection was usable for gaze sensing purposes was plotted on an American Optical Company field of view chart. The coordinate system is eye-centered not helmet-centered; the data presented is from a user's left eye. Symmetrical results are obtained from the corresponding right eye data.

SYMBOL KEY

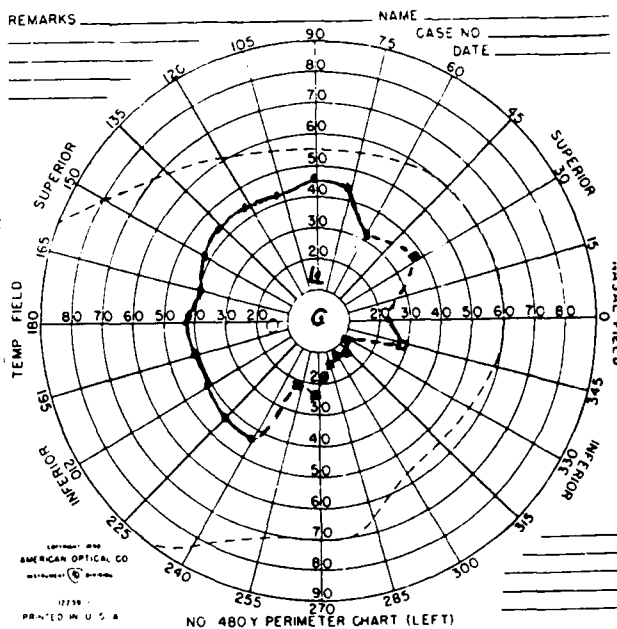
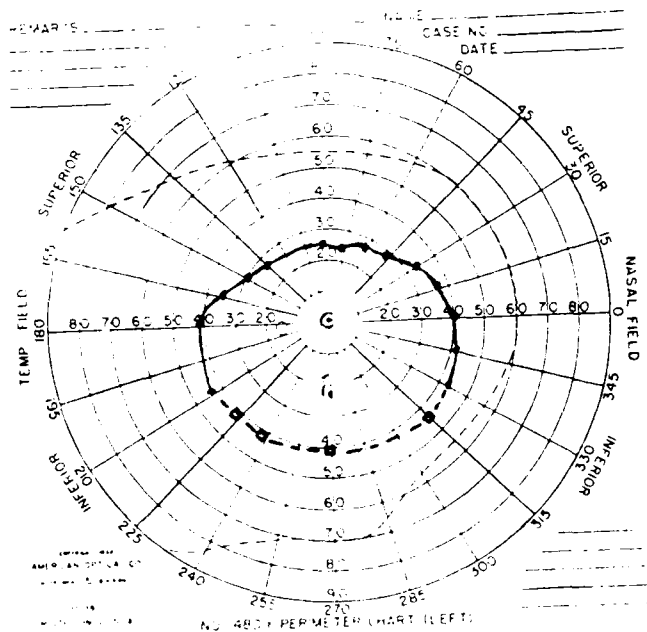
The camera's angular position in this coordinate system is indicated on each chart with a "C" and the light source angular position is indicated with an "L". The solid line on the following charts represents the measurable limit of gaze angle obtainable from a reflection off of a user's cornea. The dotted line represents limits imposed by physiological constraints or eyelid obstruction.

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Helmet Eye Imaging Data Set 1



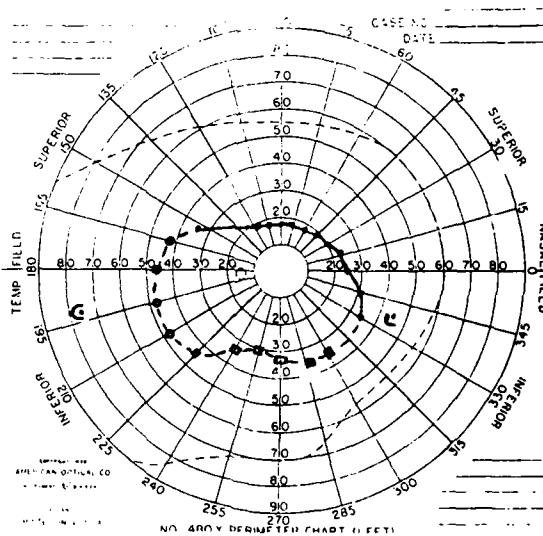
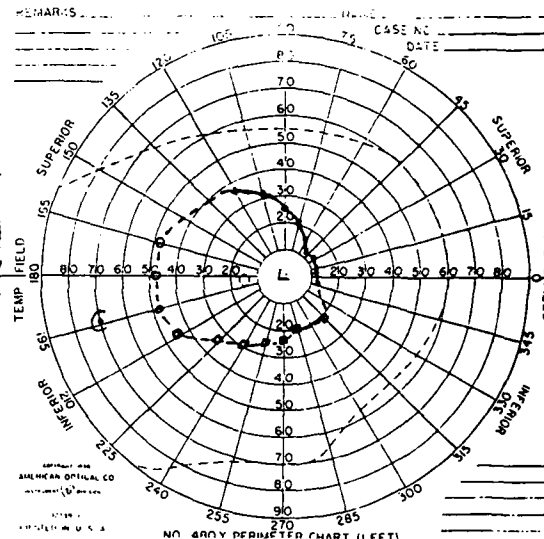
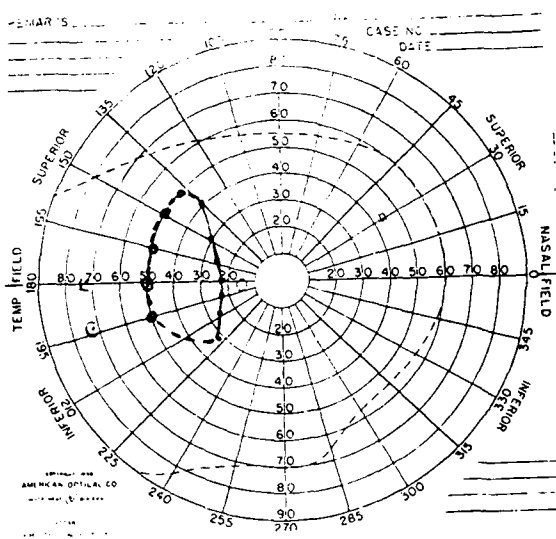
Camera is located in the center of the left eye monocular field of view.
Figure "a" reference light is centrally located, 25 degrees below the horizontal zero plane.
Figure "b" reference light is 15 degrees above the horizontal zero plane.

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Helmet Eye Imaging Data Set 2



Camera is located approximately 15 degrees below the horizontal plane and 70 degrees temporal from the midline.

Figure a: reference light on the horizontal plane, 70 degrees temporal.

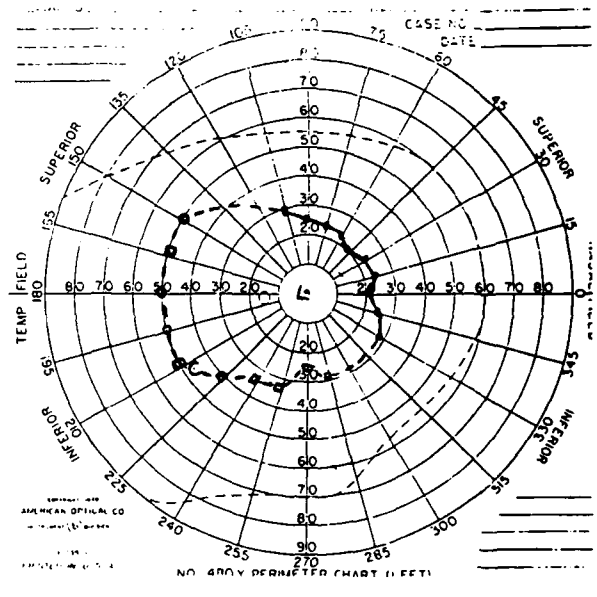
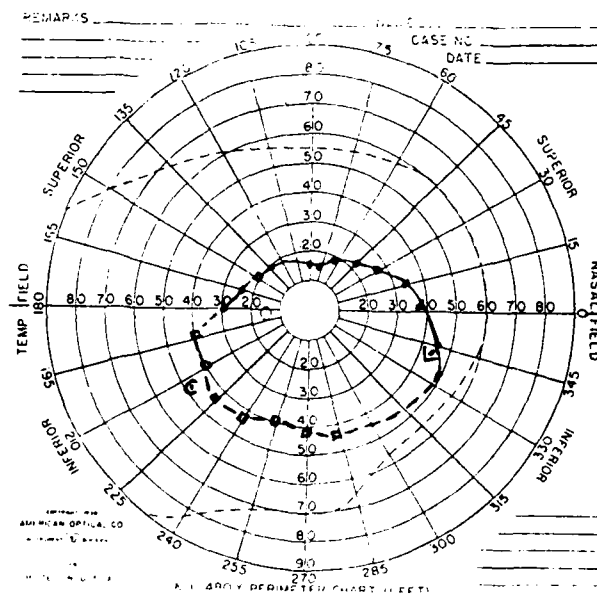
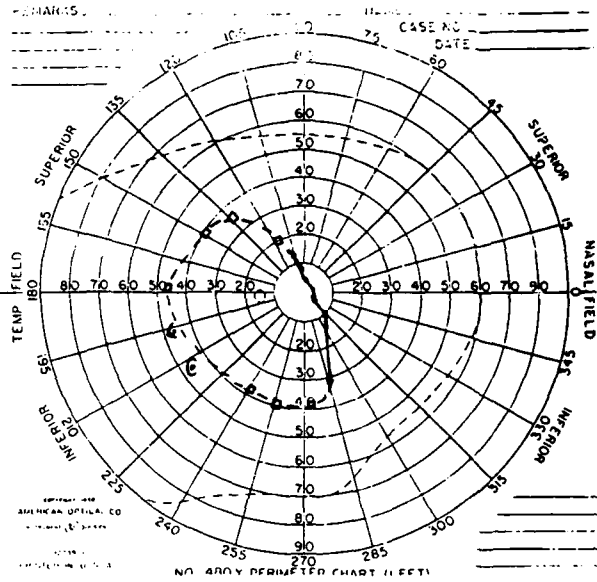
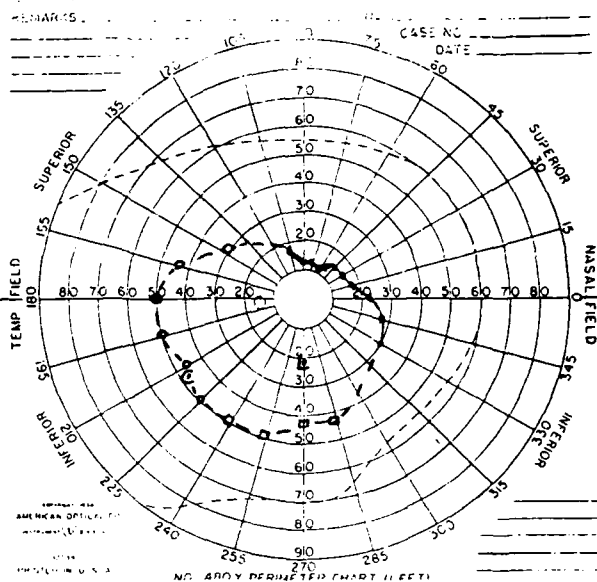
Figure b: reference light is centered on the left eye field of view.

Figure c: reference light is 45 degrees nasal and 20 degrees below the horizontal.

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Helmet Eye Imaging Data Set 4



Camera is located 45 degrees temporal and approximately 35 degrees below the horizontal.

Figure a: reference light 20 degrees below horizontal plane, and centered.

Figure b: reference light 15 degrees below horizontal, 45 degrees temporal.

Figure c: reference light is 15 degrees below horizontal and 45 degrees nasal.

Figure d: reference light is centered on the left eye.

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Helmet Mounted, Eye Imaging Design Study Summary

In figure 1a we see the expected broad symmetrical detectable gaze pattern from the centrally located camera. In contrast, figure 1b shows the highly asymmetric and irregular detectable gaze pattern that is a consequence of the top eyelid, anatomical interference with the reflection from the raised light source which is above the central camera location. In the actual experiment, the centrally located camera obscured a significant fraction of the subject's central field of view. In a practical helmet-mounted system, the camera would be physically located outside the user's field of view, and both relay and combiner optics would be used to provide this vantage point to the camera.

Figure 2 shows a series of experiments with the camera located in the extreme periphery of the field of view. With the light source above the camera, the detectable gaze angles are symmetric above and below the horizontal. As the light source is moved progressively more nasal, the same shift is seen in the detectable range of horizontal gaze. The apparent broad range of detectable gaze angles seen in figures 2b and c is misleading since the gaze angle measurements are imprecise in the nasal directions.

In figure 3, we show the camera location that we feel represents the best compromise between a desirable peripheral camera position and both detectable gaze range and gaze resolution. Figures 3a, c, and d show various positions of the light source in a horizontal plane at the vertical zero. As the light is moved from 45 degrees temporal, through zero, to 45 degrees nasal, the range of detectable gaze angles increases in the nasal direction. From figure c and d, it may be observed that if the light source is too far nasally located, detectable gaze range and resolution on the side of the camera is degraded. Similarly (figure 3b), positioning the light source below the camera seriously degrades range of gaze detectability.

It might be supposed that by further lowering the camera position, there will be less interference with the corneal reflection by the upper eyelid, and thus the range of detectable eye gaze angles should also increase. Figure 4 demonstrates that this is not the case for either the vertical or horizontal angles.

From the foregoing demonstrations, we may conclude that a reliable, helmet-mounted, eye gaze direction detection system can be built with two laterally mounted cameras and three visor mounted, near-infrared, light sources. Figure 3 demonstrated that a 45 degree temporal camera position provided for adequate range and resolution of detectable gaze angle when only two light source locations are used. This vantage point may be

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achieved when a camera is positioned, completely out of the pilot's field of view (near the oxygen mask latchpoint), with a simple dichroic beamsplitter. This optical design will not require complex relay elements and should be virtually transparent to the user. From this 45 degree, temporal camera vantage point, a single temporal light source and another light source mounted on the visor midline (resulting in it being significantly nasal to each eye), will permit a one camera system to crudely track the full range of gaze motions and a two camera system to track the full range at full resolution. The dichroic beamsplitter will be located at 45 degrees temporal on the horizontal arc and thus will be off the visual gaze line for most look angles.

Predicted Cost

As stated previously, the deliverable production cost of this helmet mounted, eye gaze sensing system is one of the primary motivating factors for this effort. The phase I testbed has shown that the production quantity cost of a dual camera system, if fully developed in a phase II effort, will include: 1) 2 lightweight, CCD cameras at \$485 per camera; 2) eye image processing printed circuit boards at a cost of approximately \$800; 3) helmet mounted optics and helmet mounted packaging at an approximate cost of \$1,000; 4) power supply and packaging for eye image processing electronics at approximately \$100; and 5) assembly and testing labor at ~\$300. This should allow room for any unforeseen costs and a fair commercial profit margin while still meeting the under \$10,000 deliverable production cost specification.

Phase II System Design

Based on the evaluation of the phase I demonstration testbed, a conceptual design for a production quality, low cost, helmet mounted, eye gaze sensing system has been generated and described, in detail, in a phase II proposal. Briefly, it includes: 1) using a 16 bit 68HC000 microprocessor for increased performance; 2) conformally side mounting two CCD cameras near the oxygen mask latchpoints such that they do not intrude into the pilot's field of view; 3) unobtrusive dichroic mirror optics to direct the view of the eye to the CCD cameras; 4) multiple, small, near-IR, point light sources to obtain wide gaze angle capability; and, 5) a highly flexible, low mass cable connecting the two helmet mounted camera/IR control modules with the remotely mounted image processing hardware. The remote hardware module and helmet module are separate, interchangeable entities, i.e., a user could purchase several helmet modules (small, medium, large) and only one eye image processing hardware module. The system digitally outputs x-y gaze location, pupil diameter, and a timestamp.

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