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THE COMPUTER-CONTROLLED OCULOMETER: A PROTOTYPE INTERACTIVE EYE MOVEMENT TRACKING SYSTEM

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FINAL REPORT

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THE COMPUTER-CONTROLLED OCULOMETER: A PROTOTYPE INTERACTIVE EYE MOVEMENT TRACKING SYSTEM

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SUMMARY

One kind of eye movement tracking device which has great potential is the digital computer-controlled Oculometer, an instrument which non-invasively measures point of regard of the subject, as well as pupil diameter and blink occurrence. In conjunction with a computer-generated display which can change in real time as a function of the subject's eye motions, the computer-controlled Oculometer makes possible a variety of interactive measurement and control systems. Practical applications of such schemes have had to await the development of an instrument design which does not inconvenience the subject, and which conveniently interfaces with a digital computer (see Ref. 1).

This report describes an Oculometer subsystem and an eye-tracking/control program designed for use with the PDP-6 computer of the M.I.T. Project MAC Artificial Intelligence Group. The Oculometer electro-optic subsystem utilizes near-infrared light

reflected specularly off the front surface of the subject's cornea and diffusely off the retina, producing a bright pupil with an overriding corneal highlight. An electro-optic scanning aperture vidissector within the unit, driven by a digital eye-tracking algorithm programmed into the PDP-6 computer, detects and tracks the centers of the corneal highlight and the bright pupil to give eye movement measurements. A computer-controlled, moving mirror head motion tracker directly coupled to the vidissector tracker permits the subject reasonable freedom of movement. Various applications of this system, which are suggested by the work reported here, include: (a) using the eye as a control device, (b) recording eye fixation and exploration patterns, (c) game playing, (d) training machines, and (e) psychophysiological testing and recording.

INTRODUCTION

In some measurement and control situations involving human vision it appears advantageous to monitor, or in some manner utilize, certain eye movements. The Oculometer is an instrument which was developed by the Honeywell Radiation Center under Contract NAS 12-531 for the NASA Electronics Research Center for the purpose of investigating problem areas involved with the above.

The instrument simultaneously and dynamically measures pupil centroid position (eye position), pupil size, eye optical axis pointing direction and blink occurrence. When the instrument is operating the subject's eye is irradiated by a collimated source of near-infrared energy. The near-infrared radiation reflected from the subject's corneal and retinal surfaces is detected by a scanning aperture image dissector (vidissector) which is sensitive to the source output (see Fig. 1). Both the near-infrared source and vidissector are located within the Oculometer electro-optical unit and share the same optical axis. Eye movements are electronically derived from measurements of the vidissector output signals, which include information about the position of the corneal reflection relative to the centroid of the pupil-iris boundary. This latter information is used to determine eye pointing direction (see Fig. 2). By using near-infrared techniques for measuring eye movements, the Oculometer presents virtually no interference to normal vision. The outputs of the instrument are real-time electrical signals directly proportional to the measured eye movements.

Two different laboratory prototype models of the Oculometer were designed and fabricated for NASA. One model was a proximate instrument (Ref. 2) and the other a remote version (Ref. 3). The feasibility of the Oculometer concept was successfully demonstrated

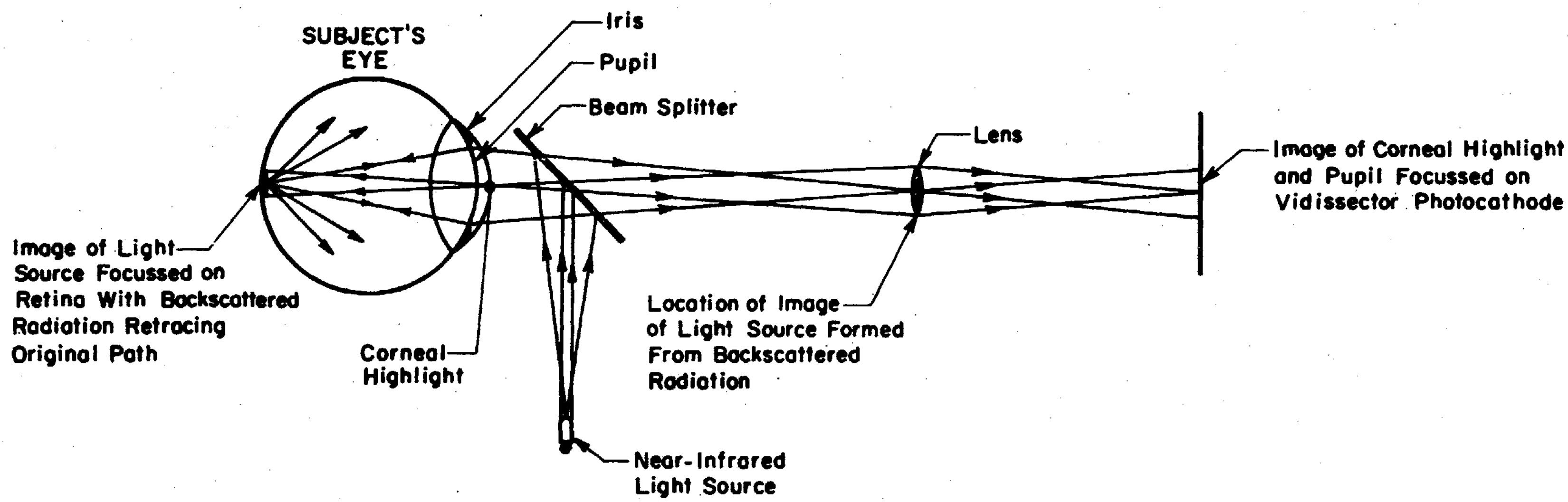


Figure 1 OCULOMETER EYE ILLUMINATION/DETECTION TECHNIQUE

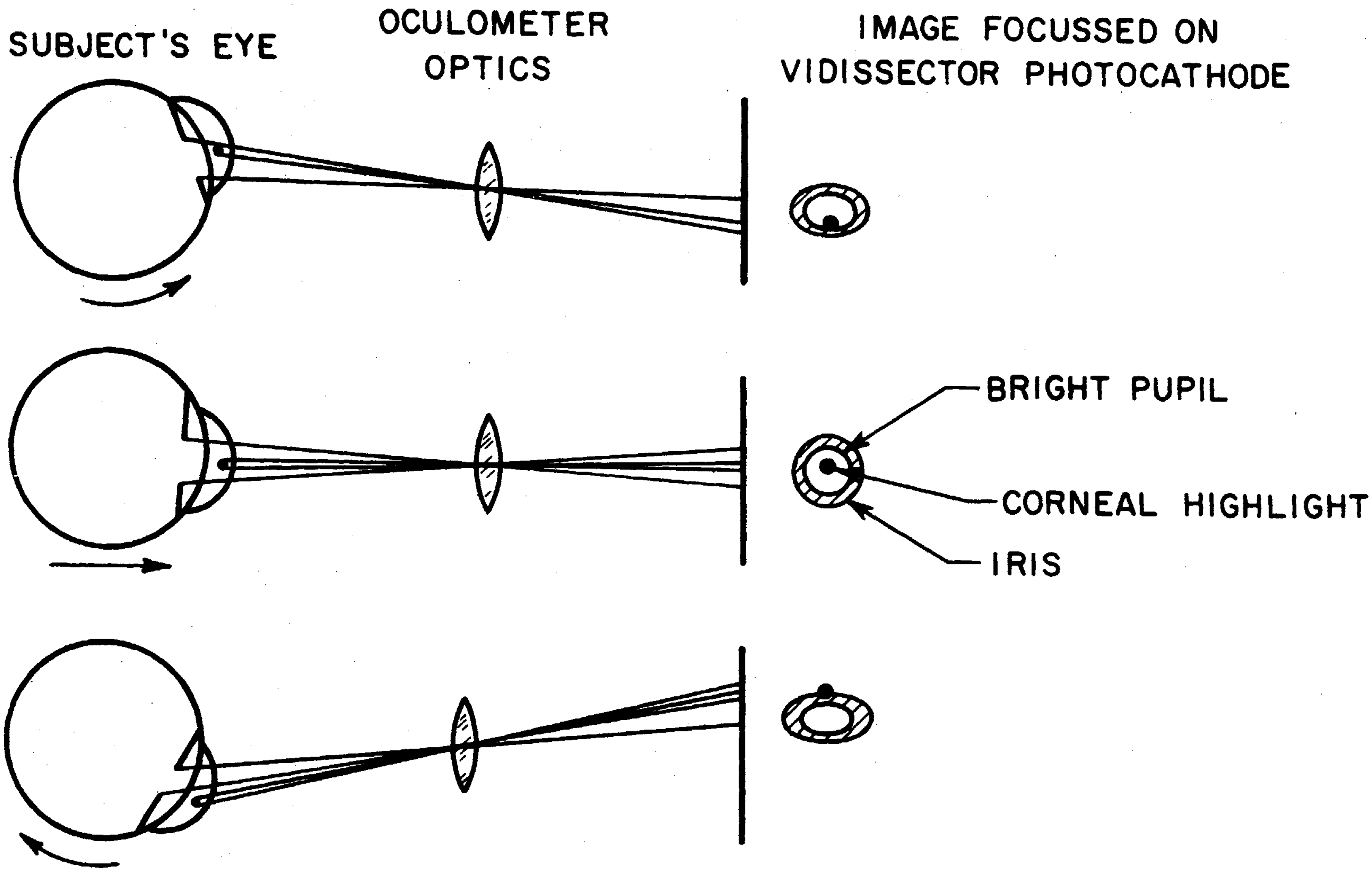


Figure 2 EYE POINTING DIRECTION VS. PUPIL/CORNEAL HIGHLIGHT POSITION

with these instruments; however, being developmental units their operational and measurement capabilities were somewhat limited.

With the Proximate Oculometer, which was the first version of the instrument to be built, the user observed the field of view through a 7-cm diameter dichroic beamsplitter attached to the instrument's optical head. This particular optical configuration restricted subject head motions, accommodating only a $\pm$1.3-cm lateral and longitudinal range of eye positions. Nevertheless, both horizontal and vertical angular eye pointing directions of up to $\pm 15^{\circ}$ and pupils of 2-mm to 9-mm diameter could be measured with accuracies of approximately 0.5° and 0.2 mm respectively. Blinks were detected and measured as they occurred.

The Remote Oculometer, which was built some months after the proximate unit, was a more versatile instrument. The user was allowed a $\pm$6.3-cm lateral and $\pm$2.5-cm longitudinal range of head motions and accompanying eye positions at a distance of approximately 1 meter from the optical unit, and was not required to view the scene through an intervening aperture, such as a beamsplitter. This method of operation was accomplished by using a servo-controlled moving mirror system to automatically track eye position as the head moved. With this latter system lateral head movement rates up to 25 cm/sec could be followed. The remote version of the Oculometer also retained the other eye movement measurement features and accuracies described for the proximate unit.

Proposed NASA plans for future Oculometer work included investigating the feasibility of using a small digital computer to replace the existing analog-digital hybrid electronic control unit (see Refs. 2 and 3). This latter unit suffered from electronic instability problems over long periods of operation and was not amenable to control program change since it was a hard-wired system. The digital computer technique of Oculometer control was expected to allow electronically stable and simplified instrument operation, ease of control program change, and convenient calibration of output signals. Also, with digital computer control, eye characteristics peculiar to a specific user and common subject-to-subject eye variations could be readily dealt with. In addition, the digital computer could be flexibly programmed to allow selected visual functions of the subject to control external devices, if desired.

Based on the proposed NASA plans, the M.I.T. Project MAC Artificial Intelligence Group was contracted by the NASA Electronic Research Center to investigate the feasibility of a digital-computer-controlled Oculometer. This work, the results of which are reported here, involved the development of an on-site (M.I.T. Project MAC) Oculometer measurements facility, as well as several specialized computer programs and I/O interfaces suitable for use with an Oculometer electro-optical unit and the M.I.T. Project MAC PDP-6 computer. An Oculometer electro-optical unit with its associated electronics (power supplies and A-D hybrid control unit) was provided as government-furnished equipment. The A-D hybrid control unit section of the Oculometer electronics was disabled for the performance of this work since it was to be replaced by the PDP-6 computer, the I/O interface, and the control programs. At a later date during the contract period the original Oculometer power supplies were replaced with an improved unit (see Appendix B). The computer programs generated during the performance of the work reported here were developed by and modeled in part on earlier work of Geffner (see Ref. 4).

THE COMPUTER-CONTROLLED OCULOMETER SYSTEM

Basic Description of a Prototype Interactive Eye Movement Tracking System

The prototype interactive eye movement tracking system developed under this contract consisted of the following components:

a) The Remote Oculometer electro-optical unit and power supply;

b) The PDP-6 computer (a PDP-10 computer also was available and could be used interchangeably with the PDP-6 without program modification);

c) The I/O interface circuitry;

d) The Oculometer eye-tracking/control programs;

e) An X,Y video display;

f) A TTY or video display-type I/O terminal;

g) A high-speed line printer.

The basic interconnections of this particular system are shown diagrammatically in Fig. 3. The experimental apparatus described here is unique in that it is unlikely to be duplicated elsewhere in this particular configuration. However, the flexibility of the digital computer approach to eye tracking is such that the programs developed here could be rewritten without excessive difficulty for other suitable computer facilities. For complete eye-tracking system operation it would of course be necessary to obtain an Oculometer electro-optical unit and power supply and develop the necessary I/O interface circuitry.

Oculometer Electro-Optical Unit and Power Supply

The Oculometer electro-optical unit and power supply used in this work has been described in Refs. 2 and 3. Basically, the Oculometer electro-optical unit consists of the following:

a) A near-infrared radiation source and optical assembly used to illuminate the pupil and cornea of the subject's eye;

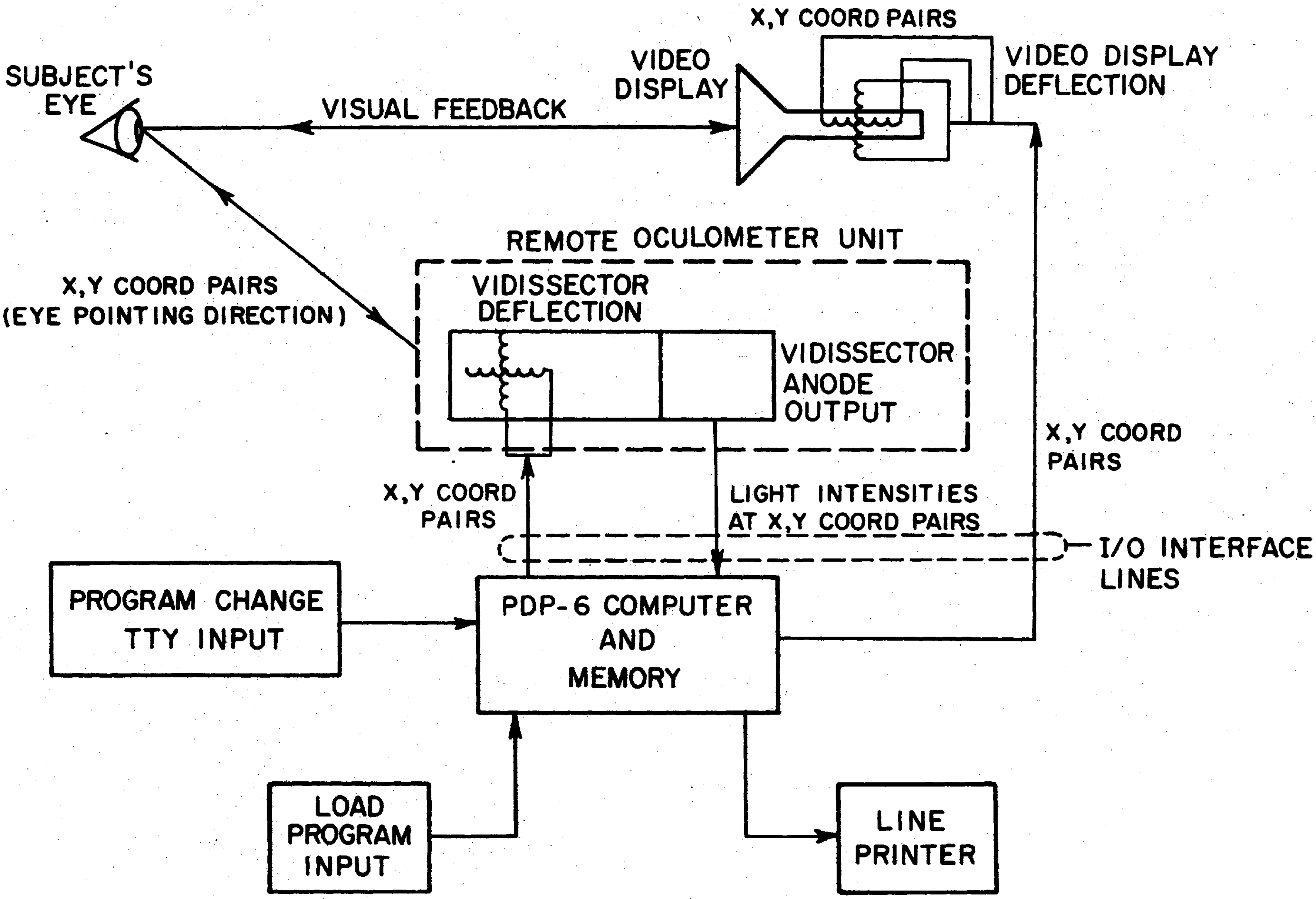


Figure 3 COMPUTER-CONTROLLED OCULOMETER SYSTEM (BASIC)

b) A dual-axis moving mirror optical assembly (capable of being disabled and operated in a stationary mode) for tracking gross head-eye motions in a lateral plane perpendicular to the optical axis;

c) A scanning aperture image dissector (vidissector) and optical assembly used to acquire and track the pupil and corneal images of the sugject.

A line drawing of this unit is shown in Fig. 4. A detailed description of a modified Oculometer power supply appears in Appendix B.

Oculometer/Computer System Environment

The computer environment of the prototype interactive eye movement tracking system was the Incompatible Time-Sharing System (ITS) of the M.I.T. Project MAC Artificial Intelligence Group. The ITS system consists of the following major components:

a) One PDP-10 computer;

b) One PDP-6 computer;

c) One 256K, 36-bit word, mass core memory;

d) Four 8M, 8-bit character, disc memory units;

e) Peripheral terminals and I/O interfaces.

However, the eye movement tracking system was not run in a time-sharing mode. The mode of operation used in this work was as follows:

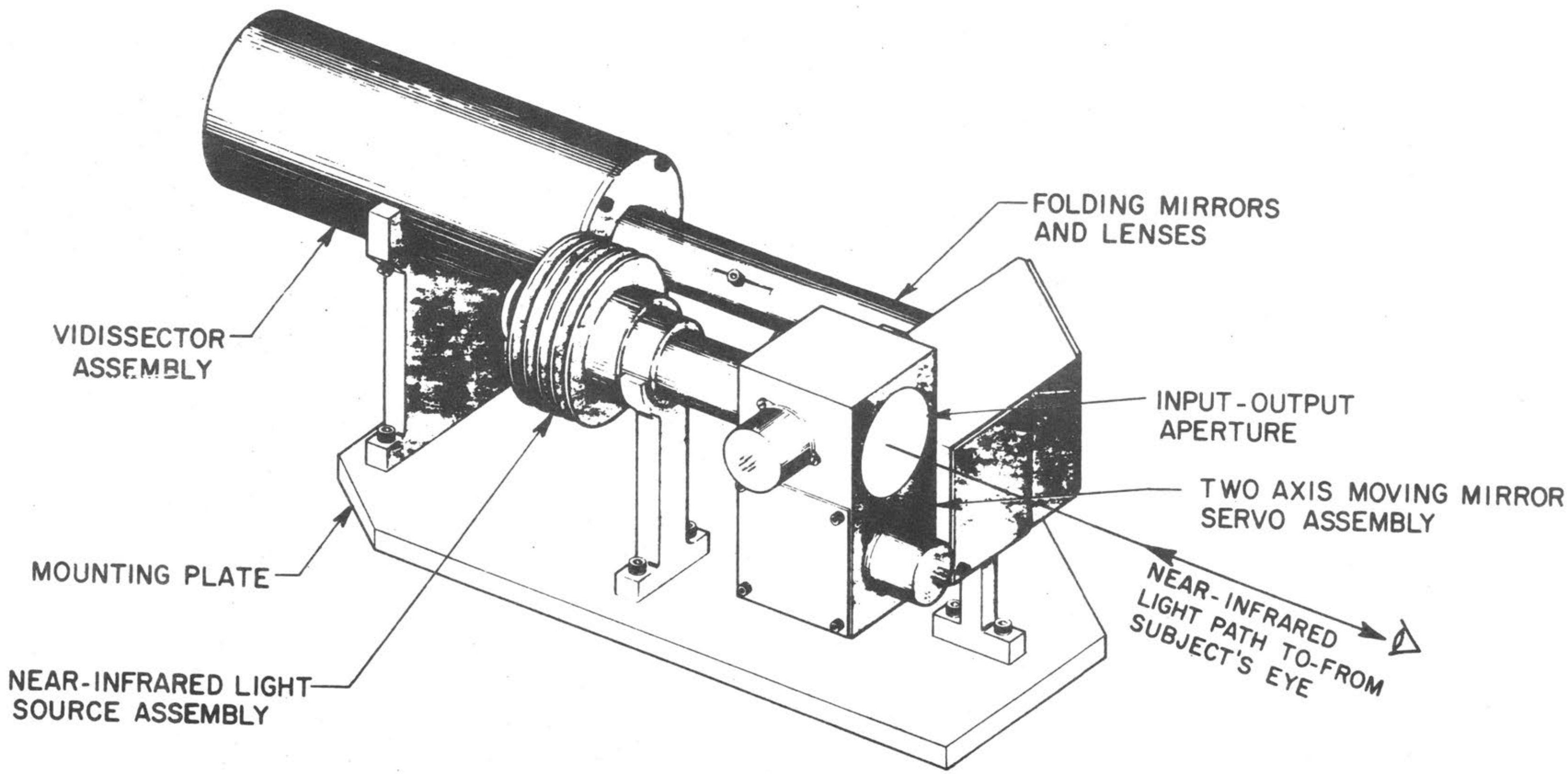


Figure 4 REMOTE OCULOMETER ELECTRO-OPTICAL UNIT

a) The Oculometer eye-tracking/control programs were loaded into the mass core memory from the disc memory unit. That operation was accomplished through the PDP-10 computer and a display-type I/O terminal located near the Oculometer electro-optical unit.

b) From the above, the tracking/control programs were subsequently loaded into the 16K, 36-bit word memory of the PDP-6 computer, again using the I/O terminal located near the Oculometer electro-optical unit.

c) Oculometer operation depended only upon the PDP-6 computer once its memory was loaded. Program changes/inputs to the Oculometer/PDP-6 system were buffered through the PDP-10/mass core memory system from the Oculometer I/O terminal. This was the only concession made to the ITS system during the Oculometer/computer system operation. Fig. 5 shows the complete system block diagram.

Physical Arrangement of the Oculometer/Computer System

The physical arrangement of the Oculometer/computer system is shown in Figs. 6, 7, 8 and 9. The Oculometer electro-optical unit, X,Y video display, display-type I/O terminal, and I/O interface circuitry were located in the M.I.T. Project MAC A.I. Group Eye Tracking Laboratory. These components of the system were coupled by approximately 50 ft of coaxial cable to the PDP-6 computer which was located nearby. Fig. 10 is a line drawing depicting the location of the subject relative to the position of the components of

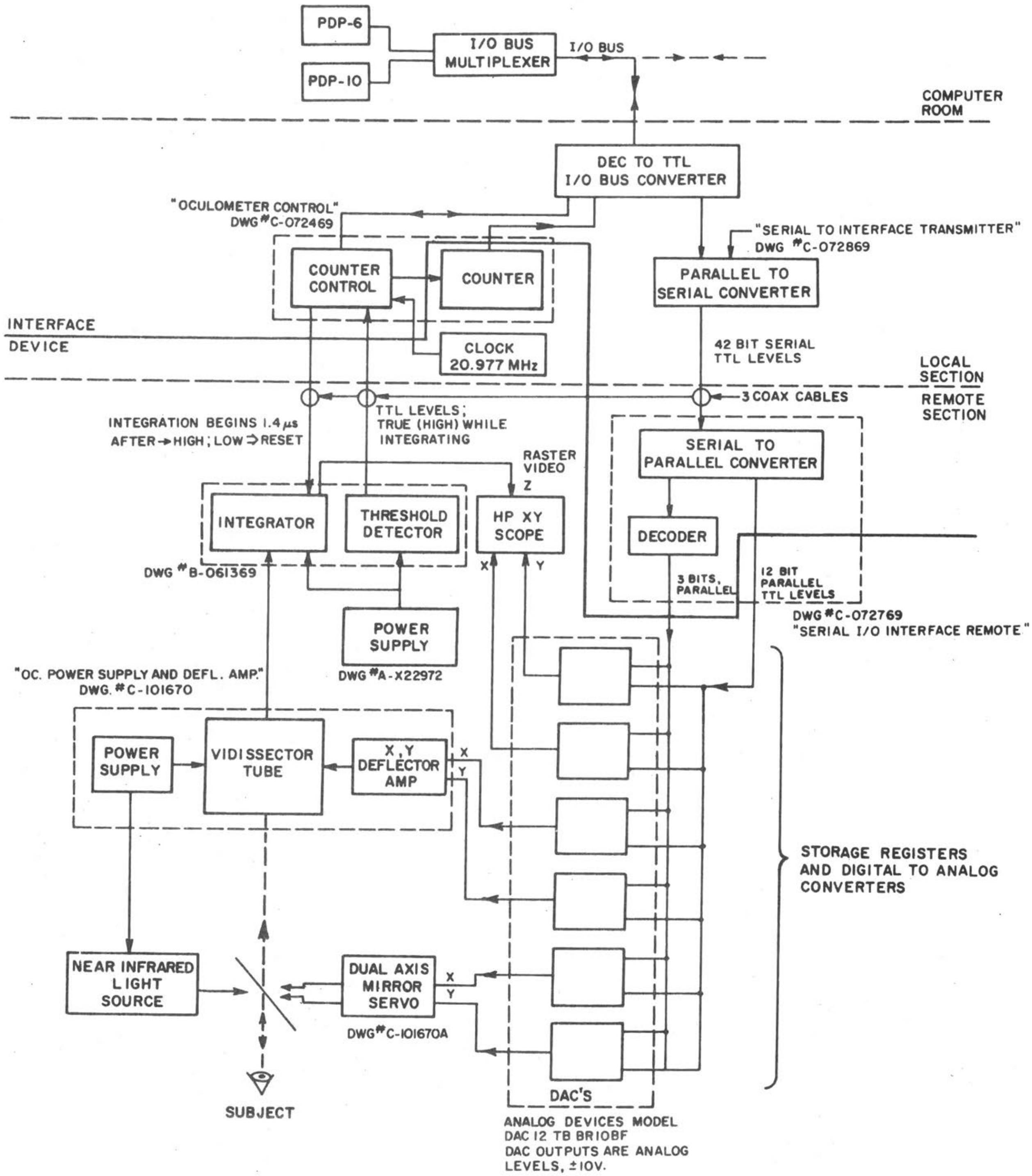


Figure 5 COMPUTER-CONTROLLED OCULOMETER SYSTEM (DETAILED)

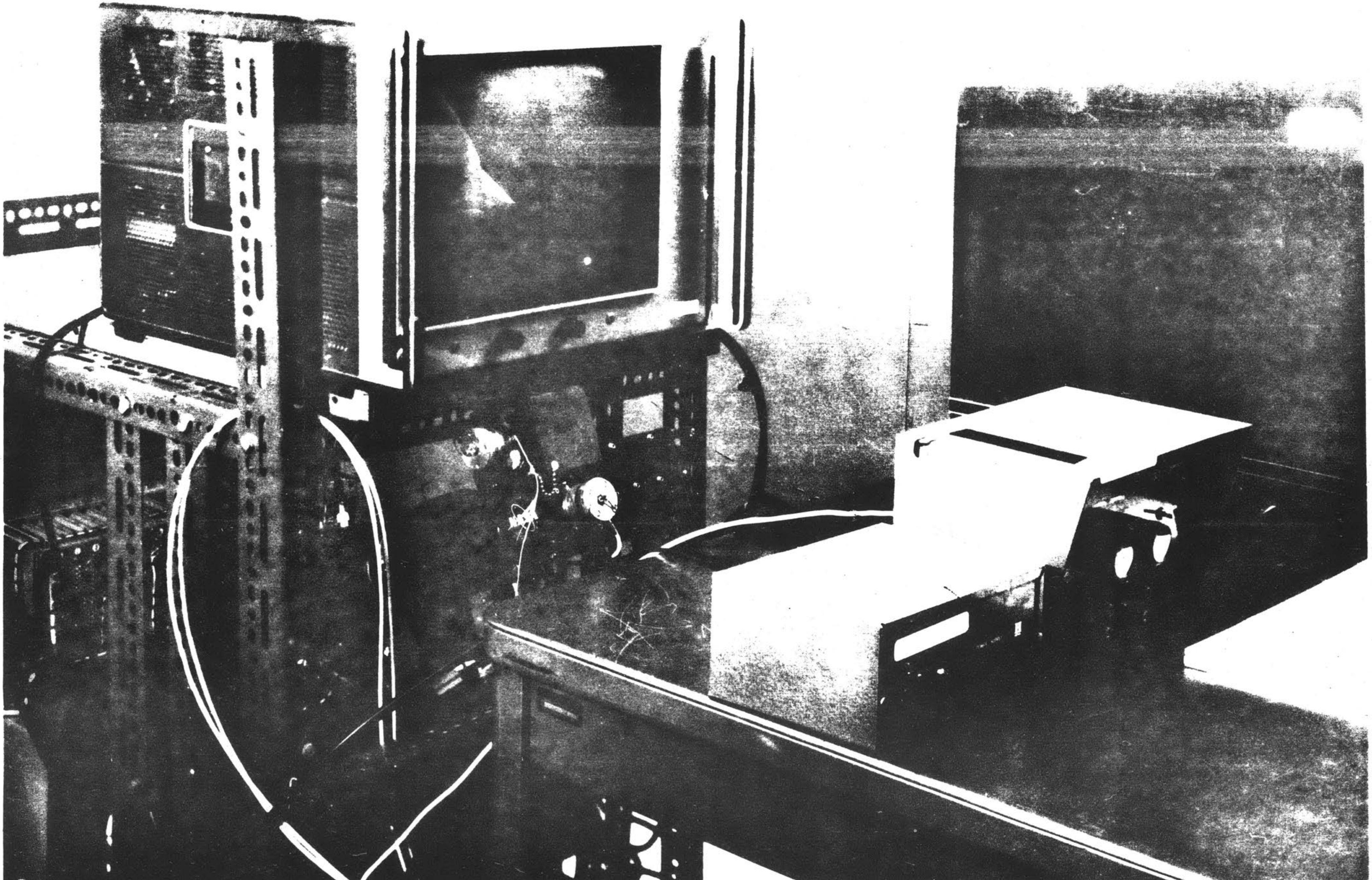


Figure 6 REMOTE OCULOMETER ELECTRO-OPTICAL UNIT, X,Y VIDEO DISPLAY AND HEAD TRACKING MIRROR SERVO CONTROLS

Figure 7 REMOTE OCULOMETER AND VIDEO DISPLAY I/O TERMINAL

Figure 8 REMOTE OCULOMETER WITH SUBJECT AND OPERATOR

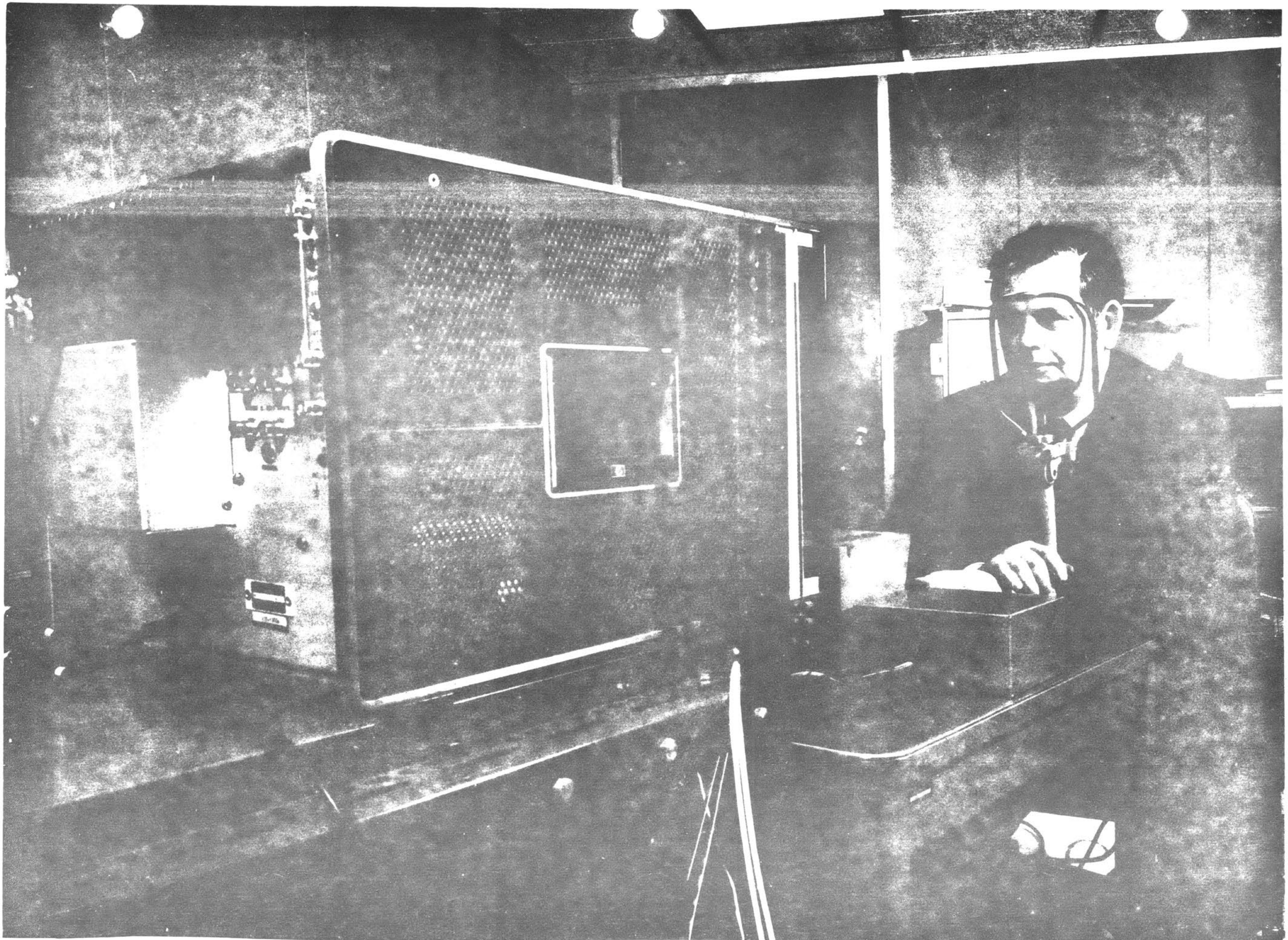


Figure 9 REMOTE OCULOMETER WITH SUBJECT IN OPERATING POSITION

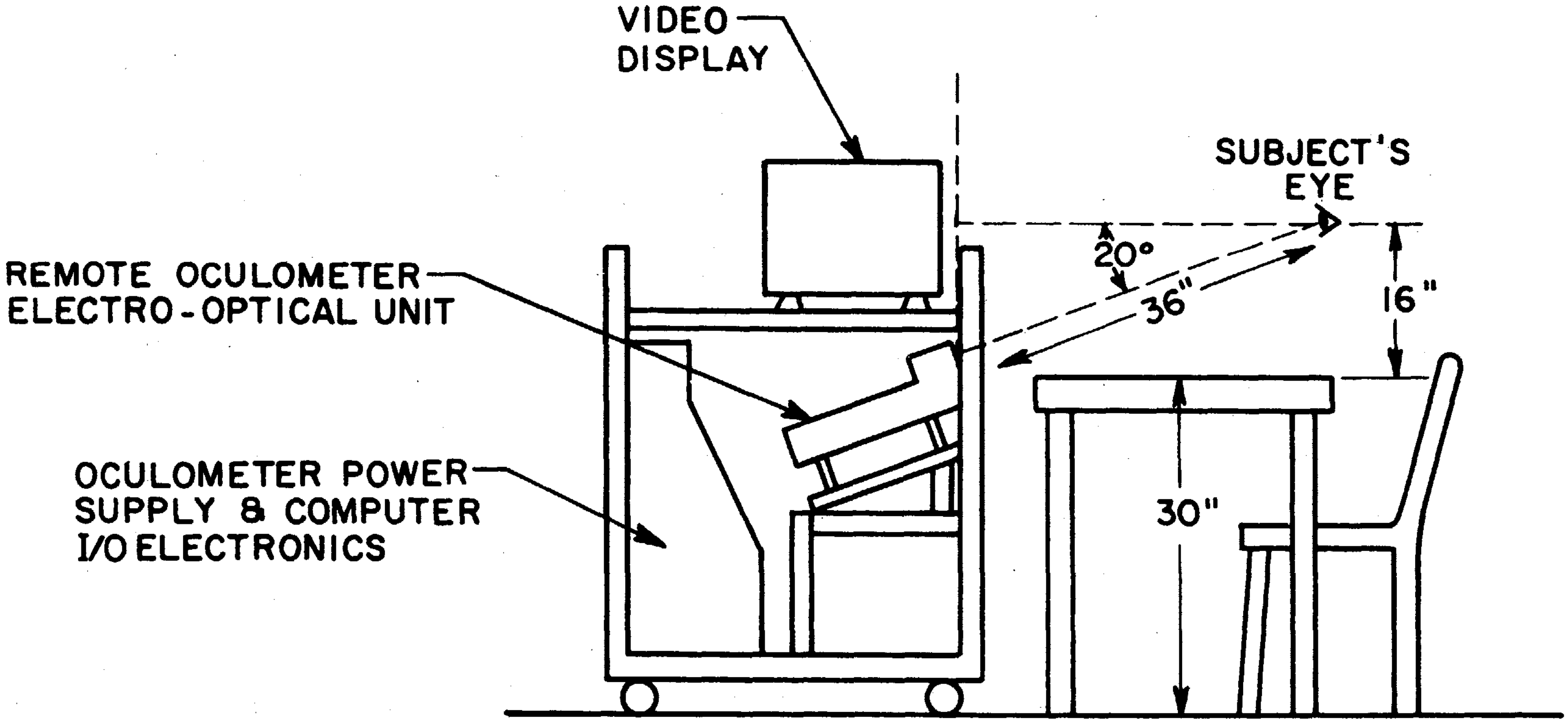


Figure 10 SUBJECT POSITION RELATIVE TO SYSTEM COMPONENTS

the eye-tracking system which were located in the Eye Tracking Laboratory.

To operate the eye tracking system the subject first was comfortably seated at the proper position in front of the Oculometer electro-optical unit. The operator would then command the PDP-6 with the routine eye-tracking/control programs through the I/O terminal and proceed with the experiment. Either eye of the subject could be used for eye tracking experiments, and the operator and subject often were the same person.

Oculometer Electro-Optical Unit/X,Y Video Display Hardware

The Oculometer/video display hardware performs three functions:

a) It enables the eye-track/control program to measure (at approximately 300 microseconds per point) the brightness of any point or series of points in the field of view of the Oculometer vidissector (normally a point in the pupil or on the cornea of the subject's eye).

b) It enables the Oculometer (vidissector) field of view to change by repositioning the dual-axis head/eye tracking mirrors, either under manual or mirror-track program control.

c) It enables the video display program to write a point or a series of points (to constitute a line drawing) on the X,Y video display.

The hardware is linked to the computer via the I/O bus by the I/O interface circuitry. This circuitry consists of level converts (see Fig. 5), (the I/O bus uses DEC levels of -3 V and 0 V; the Oculometer electro-optical unit logic uses TTL levels of +3 V and 0 V), Oculometer control (see Fig. 11), and the serial I/O interface (see Figs. 12, 13, 14 and 15). The serial I/O interface (see below) recognizes device numbers 544, 550 and 554. These devices specify dual-axis mirror, vidissector, and video display deflections respectively. The larger part of the interface circuitry is at the I/O bus itself. The interface circuitry serializes data for the above three devices and sends it via one coax cable to the serial I/O interface remote, which is located with the Oculometer electro-optical unit. The I/O interface circuitry also does the final decoding and loading of the proper DAC's. The Oculometer control recognizes device numbers 534 and 540; the latter device starts the (eye) point brightness measurement, while the former is used to input the result of the measurement to the eye-track program for processing. The computer word data format used in the operation of the above is shown in Fig. 16.

Operation of the Oculometer/video display hardware is as follows:

a) To measure the brightness of an eye point in the vidis-

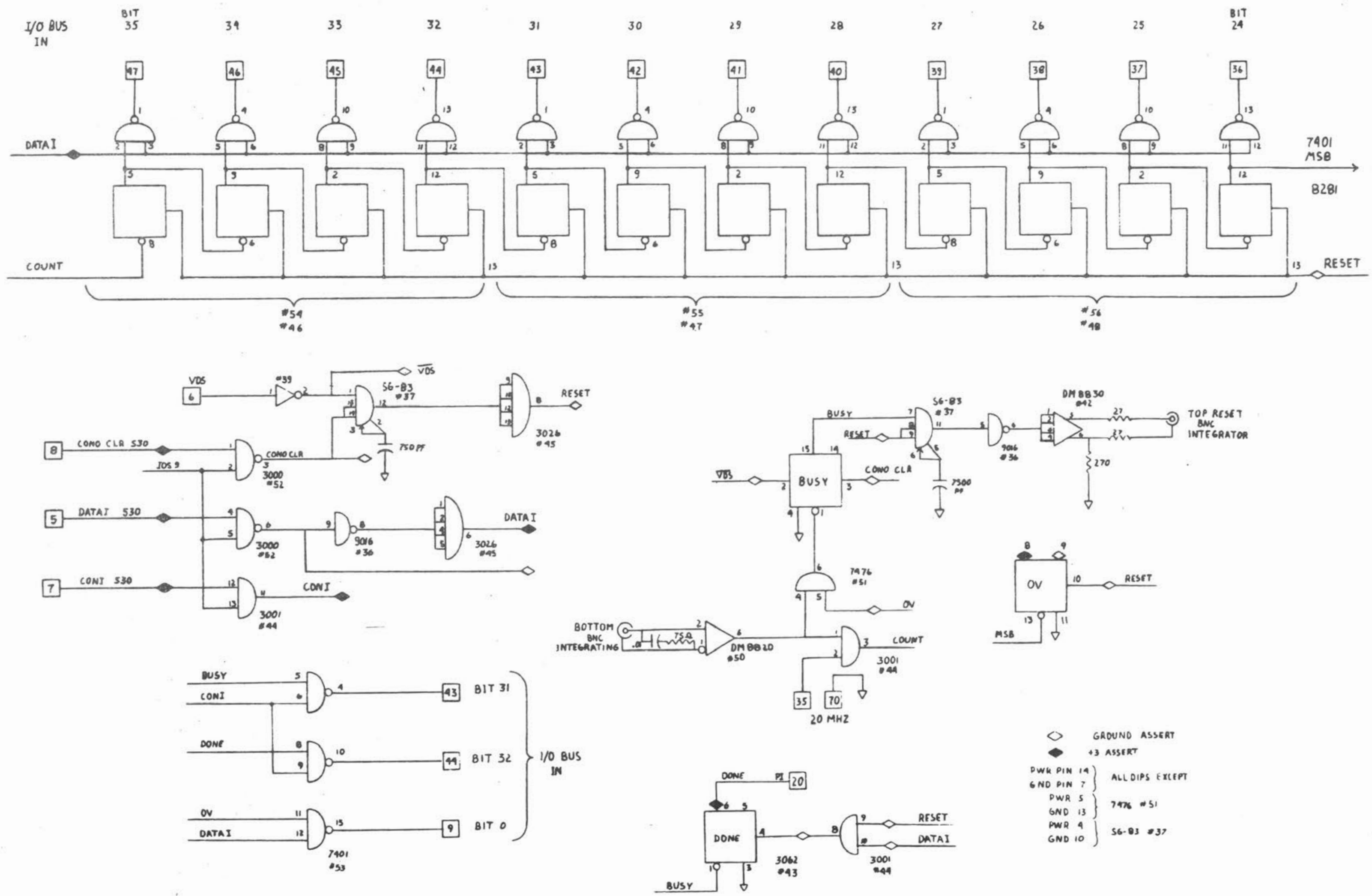
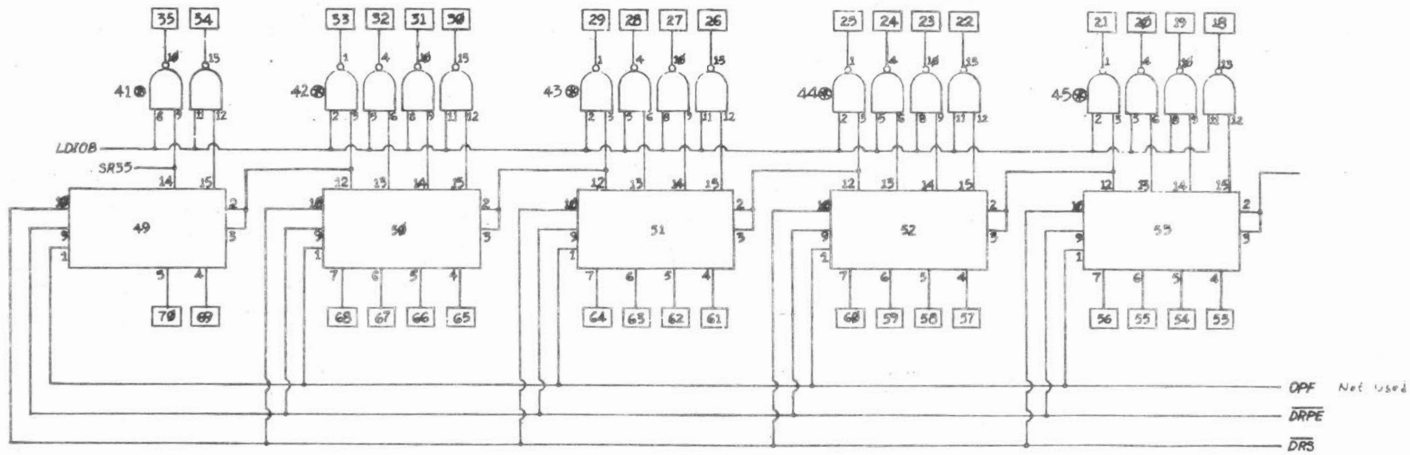
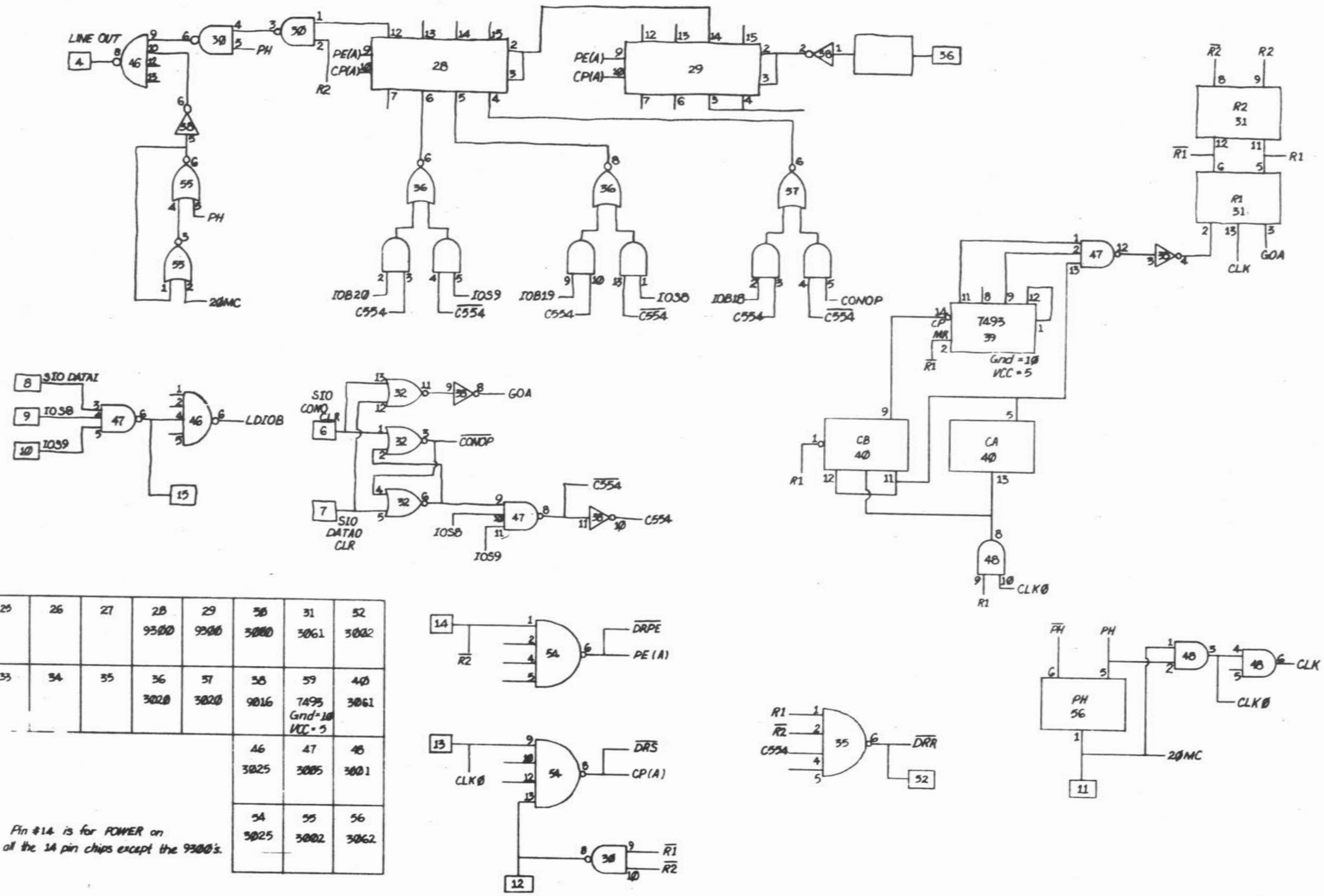


Figure 11 OCULOMETER CONTROL (DWG. #C-072469)



41 7401 14 pin	42 7401 14 pin	43 7401 14 pin	44 7401 14 pin	45 7401 14 pin
49 9300 16 pin →	50 9300	51 9300	52 9300	53 9300

Figure 12 SERIAL I/O INTERFACE (COMPUTER) (DWG. #C-072869-1)

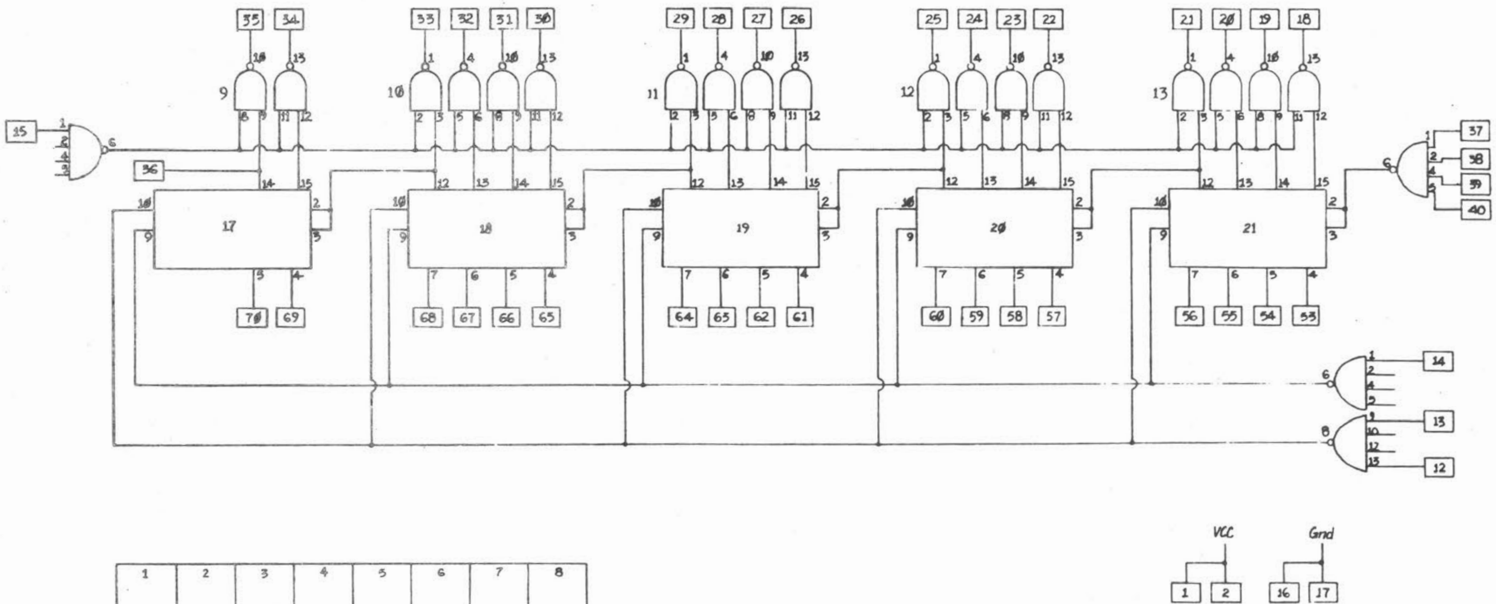


25	26	27	28 9300	29 9300	30 3000	31 3061	32 3002
33	34	35	36 3020	37 3020	38 9016	39 7493 Gnd=10 VCC=5	40 3061
					46 3025	47 3005	48 3001
					54 3025	55 3002	56 3062

Pin #14 is for POWER on all the 14 pin chips except the 9300's.

One board

Figure 13 SERIAL I/O INTERFACE (COMPUTER) (DWG. #C-072869-2)



1	2	3	4	5	6	7	8
9 74Ø1	1Ø 74Ø1	11 74Ø1	12 74Ø1	13 74Ø1	14 3Ø25	15	16
17 93ØØ	18 93ØØ	19 93ØØ	2Ø 93ØØ	21 93ØØ	22 3Ø25	23	24

Figure 14 SERIAL I/O INTERFACE (COMPUTER) (DWG. #C-072869-3)

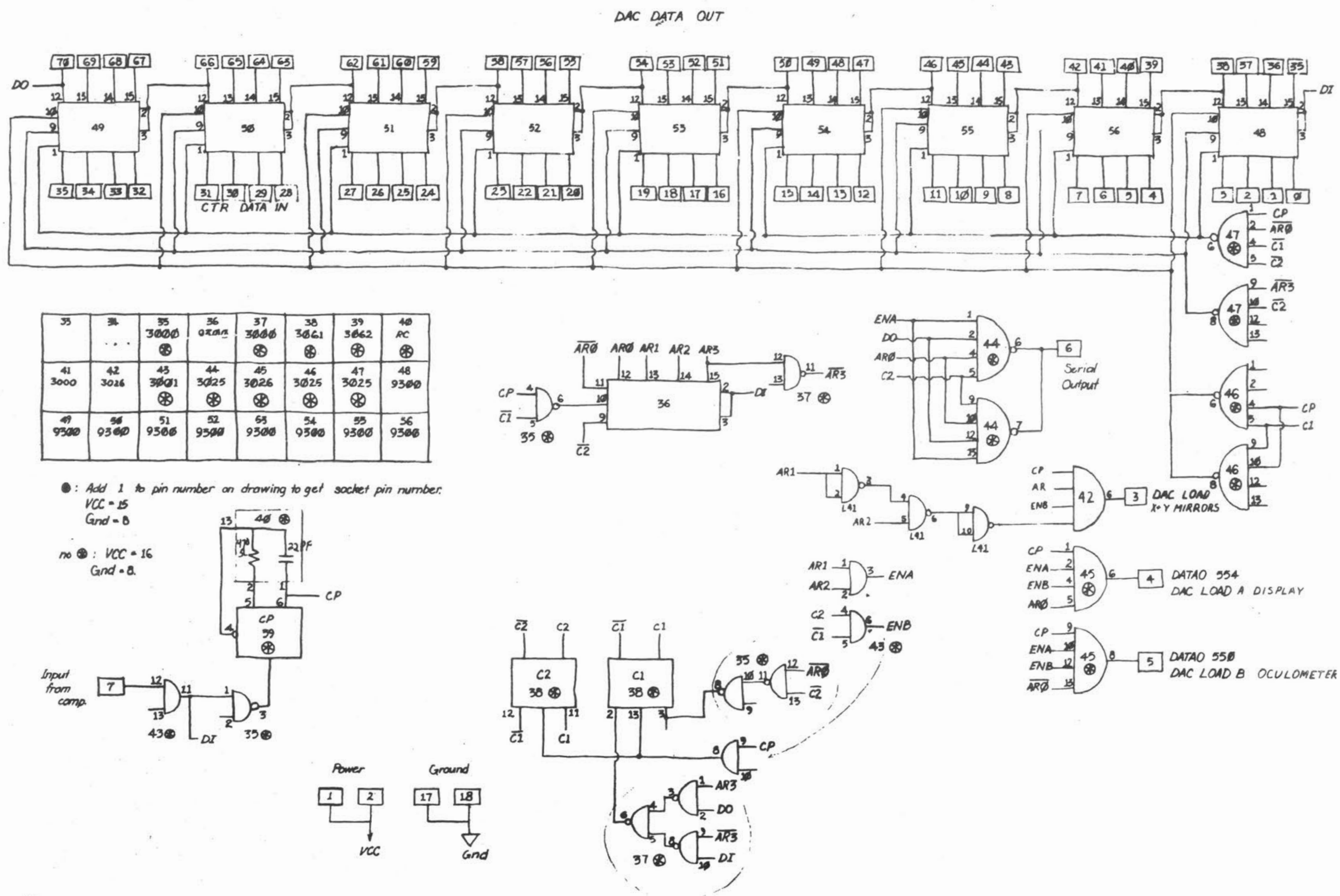
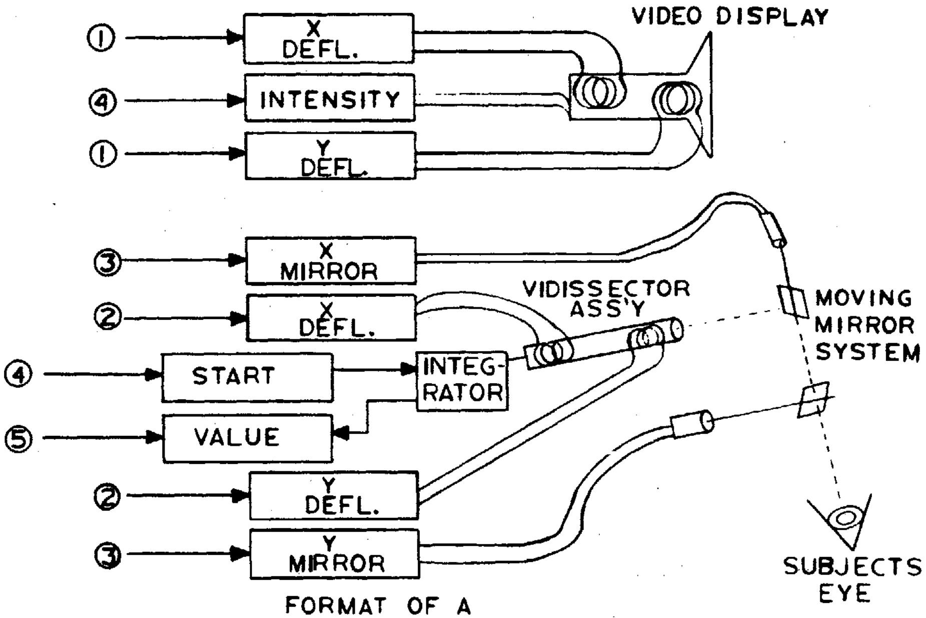
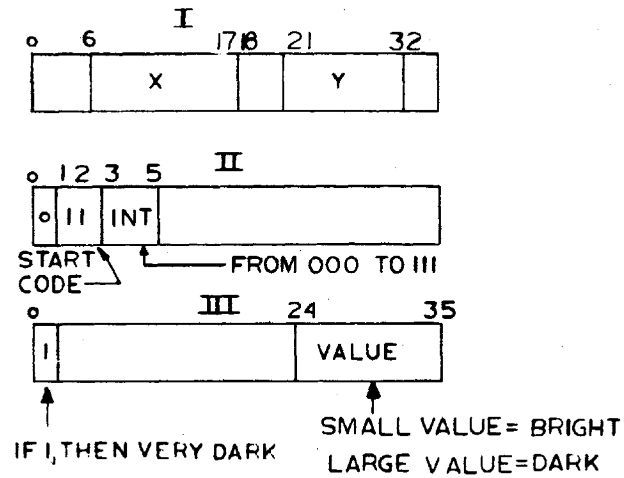


Figure 15 SERIAL I/O INTERFACE (REMOTE) (DWG. #C-072769)





		FORMAT OF A
① DATA O	554, A	I
② DATA O	550, A	I
③ DATA O	544, A	I
④ DATA O	540, A	II
⑤ DATA I	534, A	III

Figure 16 COMPUTER WORD DATA FORMAT

vidissector field of view, the coordinates of the desired point are loaded (by the eye-track program) into the DAC's which drive the vidissector deflection amplifiers. The video signal developed by the vidissector as a result of the deflection-detection function is time-averaged by an integrator in an integrator-threshold detector (see below) to reduce its noise content. The final result is made available to the I/O bus by the I/O interface, which may request an interrupt when data is ready for processing.

b) The head/eye tracking mirror servos' command inputs may be taken either from manual (or off-line) control potentiometers (for static control) or from two DAC's loaded by the mirror-track program (for on-line dynamic control). However, during the major portion of this work, electro-mechanical difficulties experienced in the computer-control mode of operation of the tracking mirror servo assembly (see Ref. 3) (resulting from inefficient torque motors) forced the abandonment of its operation, other than under manual control.

c) The display program loads DAC's which drive the video display deflection amplifiers and cause the display beam to be positioned at the desired on the video display, the beam is deflected off screen.

Operation of the Serial I/O Bus Interface

A serial interface has been constructed to drive the Oculometer. This device can also connect to additional transceivers for remote I/O transmission. The device consists of a master transceiver at the computer and one or more slave transceivers which connect to the master through two coaxial cables.

The line from master to slave sends self-clocking bits at 10.5 mhz. A zero is sent as a 25-ns pulse. A one is 75 ns long. The leading edges of both ones and zeros are in the same phase and occur every 95 ns. When the line is idle a stream of ones is sent continuously. If an output command is given (CONO 554 550 or DATAO 554 550 554) a 42-bit message is sent. It consists of a zero, the state of IOS9, the state of IOS8, a bit to indicate CONO (0) or DATAO (1), two ones, and 36 bits of data (bit 35 first).

An input command is initiated with a CONO 554. The 42 bits sent are a zero, IOB20, IOB19, IOB18, and 38 zeros. The lines from slaves to master are active-low and are all or-ed together. The addressed slave sends its data low-order bit first during the last 36 bits of the message. The data can then be read into the computer with DATAI 554.

Operation of the Integrator-Theshold Detector

The integrator-threshold detector (Fig. 17) (and power supply, Fig. 17a), together with the counter (a part of the Oculometer control), performs the actual eye-point brightness measurement. When an eye-point measurement is started (after the desired vidissector deflection has occurred) an integrator sums the vidissector anode current until the sum reaches a manually adjusted threshold, T. This sum at any instant during integration is proportional to the total number of photons incident on the selected port of the vidissector photocathode since integration was begun; the actual value of the sum is

$$\int (\text{output of integrator}) = V_{int} = \frac{q_e \eta A_m}{C_{int}},$$

where $q_e = 1.6 \times 10^{-19}$ coulombs, η = photocathode quantum efficiency (~1.5% at 7500 Å), A_m = vidissector electron multiplier gain (~1.4×10^6), and C_{int} = integrating capacitor (~27 pf). Thus, for this system, $V_{int} \cong 1.25 \times 10^{-3}$ volts/photon, or if we define $I = 1/V$, $I \cong 800$ photons/volt. Since the arrival of photons, their conversion by the photocathode, and the instantaneous value of the multiplier gain are all random processes obeying Gaussian statistics, the standard deviation (i.e. probable error) of the integral $\int$ (output of integrator) is $\frac{\sqrt{N/t}}{N/t}$, where N/t is the number of photons observed as of time <u>t</u>

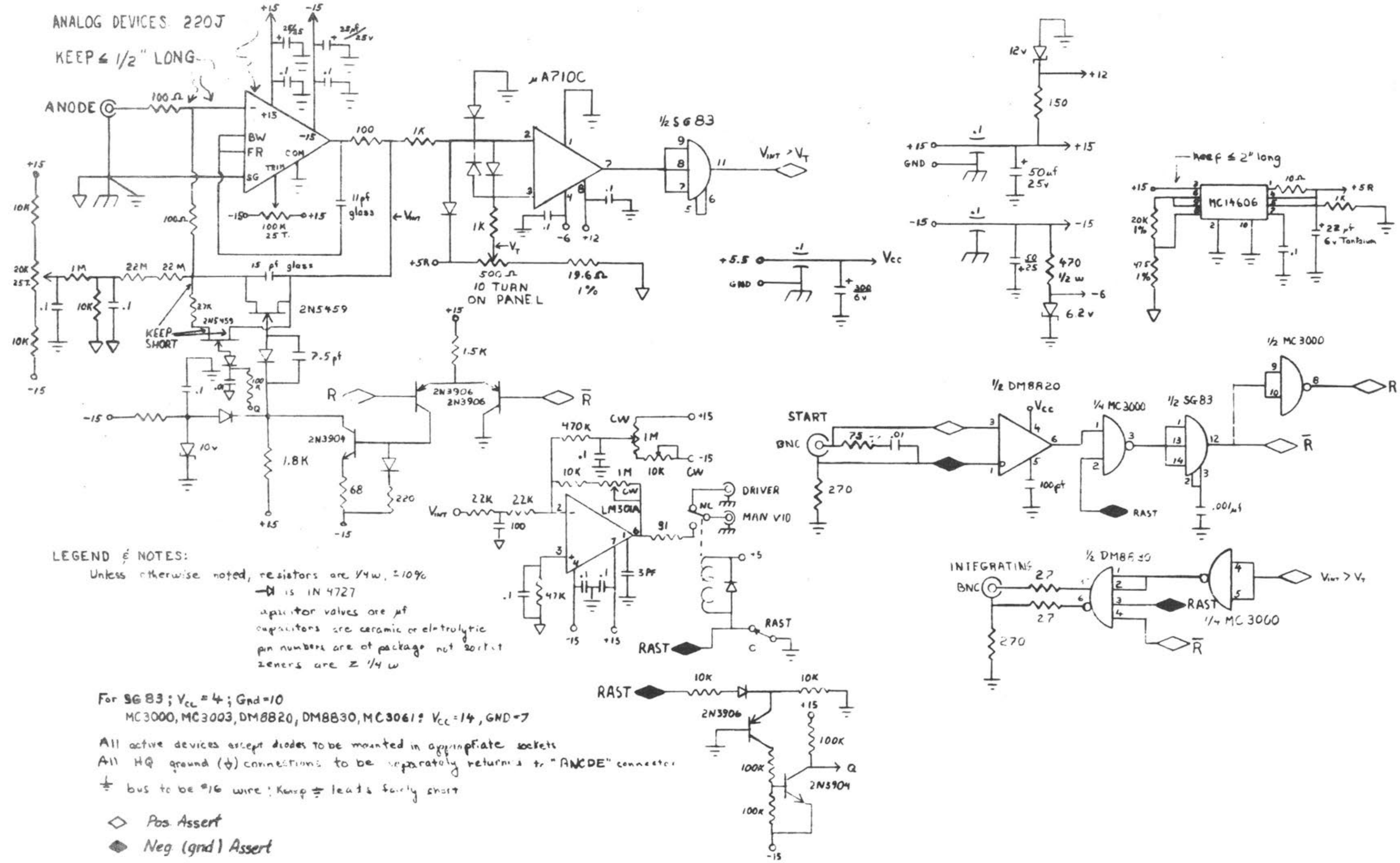


Figure 17 OCULOMETER INTEGRATOR -- THRESHOLD DETECTOR AND LOGIC (DWG. #B-061369)

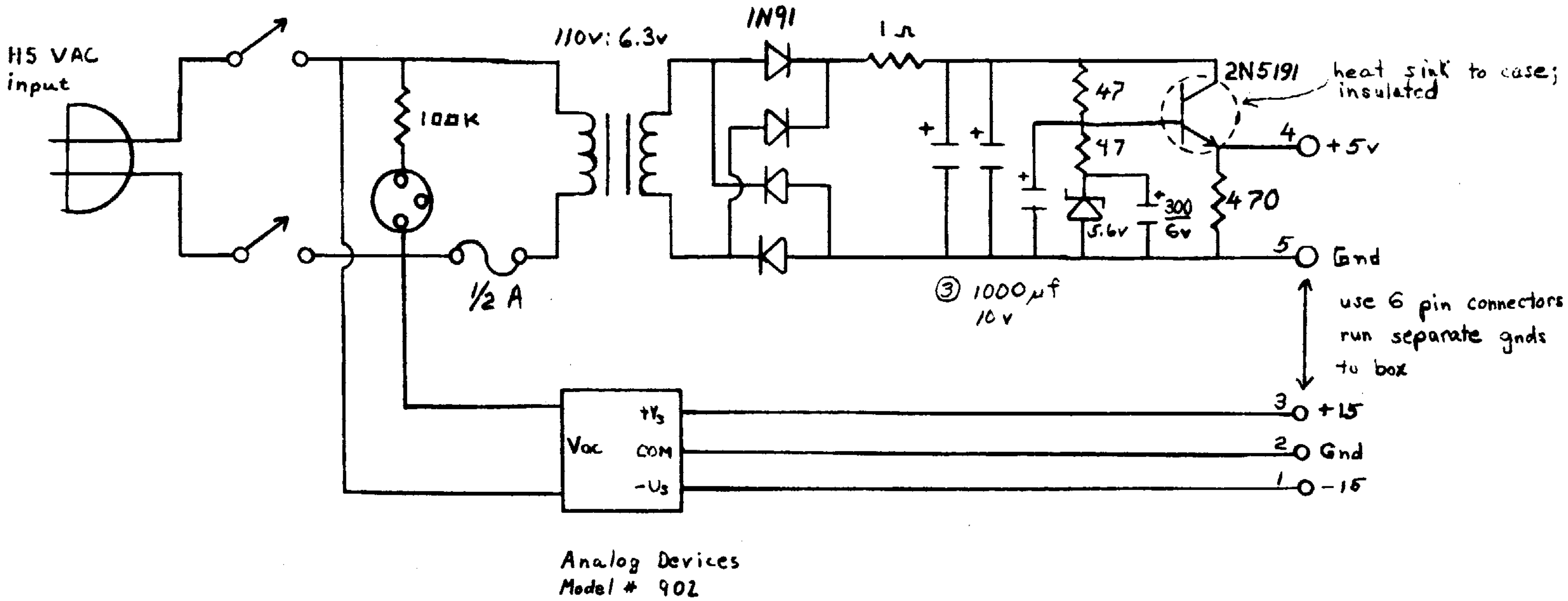


Figure 17a OCULOMETER INTEGRATOR -- THRESHOLD DETECTOR POWER SUPPLY (DWG. #A-X22972)

during the integration. Because the threshold T corresponds to a certain number ($N_T = IT$) of photons, the accuracy of the measurement is proportional to $\sqrt{T}$; in this device 10 mv $\leq T \leq$ 5 V $\Longrightarrow 8 \leq N \leq 3500$. Thus, available signal-to-noise ratios are 3.5:1 to 63:1; any value in this range may be chosen by the experimenter to optimize the inherent trade-off of measurement accuracy vs. speed of operation.

The integrator is reset and started by the Oculometer control logic via one coaxial cable. When the logic level on this cable is low ("false") the integrator is reset; this level is stretched by 1.4 μs to ensure complete reset. When the level is high ("true") the integrator is allowed to run. It returns to the control logic level via another coaxial cable which is high ("true") when the integrator has been started but not yet reached the threshold, i.e. $V_{int} < V_T$, and low ("false") at all other times. The counter, located on the Oculometer control card, times the "true" interval in increments of 47.6 ns. Since the counter has 12 bits, the longest integration time measurable is $47.6 \times 2^{12} = 194$ μs. If the integration takes longer, the counter overflows, measurement stops, and the overflow flag is set in the returned value. This tells the program that the point was dimmer than $N_T/194 \times 10^6$ photons/sec at the photocathode.

Basic Description of the Oculometer Eye-Tracking/Control Program

The body of the Oculometer eye-tracking/control program consists of thirty-two (32) pages of standard line printer listing written in MIDAS, the machine language assembly system. The entire program utilizes approximately 6K words of the 16K-word core memory of the PDP-6 computer. The following is a summary of this program, including page number (s), routine title(s), and a brief description of the indicated routines:

Program Page(s)	Routine Title(s)	Description
1-2	--	Constants and variables
3	CIB	TTY or display I/O terminal input routine
4-5	--	More constants and variables
6	SCRTST	Coarse raster display of pupil/corneal intensity seen by the vidissector
	INIT	Initialization routine
7-8	RASINI, ROSINI	Subroutines which generate successive X,Y coordinates of a raster
9	CIRINI	Subroutines which generate successive X,Y coordinates of a circle
10	EYTRAK	Main eye-track routine
11-12	BLINK	Routine which handles various contingencies when eye-tracking fails
13	PUPTK	Pupil tracking routine

14	CORTK	Corneal tracking routine
15	PUPGET	Pupil acquisition routine
16	SNAPS	Detailed raster display of pupil/ corneal intensity seen by vidis- sector
	CORGET	Corneal acquisition routine
17	VIDI, VID	Vidissector input routines
18	READVS	Converts vidissector anode output values to light intensities
19	SAVE, WRITE, RUN	Main loop of program
20-21	REPLAY	Routines to replay (on the video display) tracking patterns that had been saved during actual eye- tracking experiments
22	INTEG	Routine for doing moving average smoothing of eye-track values
23	FAST	Fast mode routine
24	CIRC	Plots a circle on the display in- dicating the present fixation point of the eye; also does the saving for later replay if in that mode
25	DPYSUB	Routine that display all odd points of eye fixation that have been saved
26-27	DISPIR ...	Display subroutines
28	FOCUS	Displays pupil/corneal intensities along the horizontal (x) coordi- nate, through the corneal highlight
	FOSAVE	Saves then displays last "FOSVNO" FOCUS lines

29	TRANS	Converts vidissector coordinates to cooresponding display coordinates
	CALIB	Five-point calibration routine
30	CALIST	Used by calibration routine
31-32	--	Various back-up routines for responding to teletype input

While all the above routines are essential to the operation of the Oculometer system developed here, the routines entitled EYTRAK, BLINK, PUPTK, CORTK, PUPGET, CORGET, INTEG and CALIB contain the heart of the eye-tracking section of the program. The remaining routines are utilitarian or parametric in nature and are primarily concerned with general system operation and testing.

The Oculometer eye-tracking/control program has a number of modes of operation as described above. These are commanded from either a TTY or display-type I/O terminal. Commands consist of double characters which appear on page one (1) of the program listing. Page two (2) lists the meanings of these character sets. The program is arranged to interrupt its computation whenever a character set is inserted by the operator. The character set is tested against the list of possible program commands. The set is ignored if not meaningful; otherwise it is processed immediately. The commands are so chosen that processing corresponds simply to a jump to an appropriate routine, from which computation proceeds. These commands are basically of two types: (1) those which are used to change the value of parameters which are involved in the operation of a program, and (2) those which switch the program to a different operation routine. After completion of the first type of command the program continues from its point of interruption. However, the program does not return to its interruption point after responding to the second type of command.

Description of the Eye-Tracking/Control Program Variables

The following is a description of the program variables used by the EYTRAK, BLINK, PUPTK, CORTK, PUPGET, CORGET, INTEG and CALIB routines:

a) Input Variables

TIMLIM	Number of cycles to be spent in eye-track
FASTSW	≠ 0 if in fast mode

b) State Variables

CORFND	≠ 0 cornea "seen" on last entry
PUPFND	≠ 0 pupil "seen" on last entry
PUCHA	tells PUPTK the state of PUPFND
PLAGE	holds number of BLINK or STINK cycles left to try
MODE	state EYTRAK is in, as follows:

Relevant Program	Value of Mode	Meaning
BLINK, BLINK1, BLINK2	3	Pupil, cornea in track; keep tracking (PUPTK and CORTK)
	2	Pupil in track, cornea lost; continue to track pupil while trying to acquire cornea (CORGET)

	1	Both pupil and cornea lost; assume a blink, i.e. continue to try tracking pupil in hopes it will be in same place when eyelid opens. Do this BLMAX times.
STINKY, STINK2	0	Both pupil and cornea lost and it does not seem to be a blink, i.e. we have lost track and need to go looking for the pupil. First search field of view of vidissector (PUPGET). Do this CMAX times.
RINKY	-1	Mode zero failed. Pupil not within field of view, so start moving mirrors. First try a spiral out from last known position of pupil; do once.
DINKY	-2	Mode -1 failed. Move mirrors over their whole range in a coarse raster. Do this until acquisition.

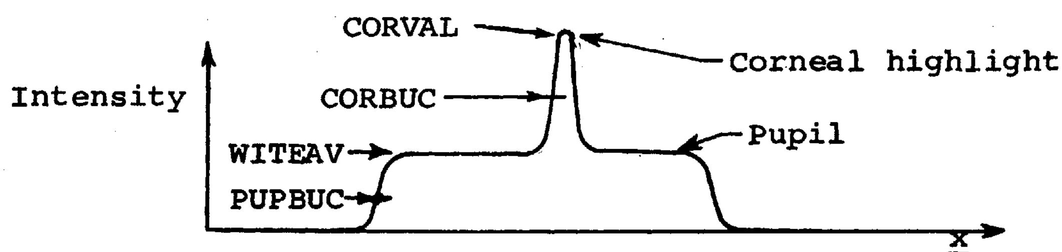
LOSTS ≠ 0 lost eye completely (modes 0, -1, -2)

BLINKS ≠ 0 loss of track, assume blink (mode 1)

BLMAX number of cycles to assume blink

CMAX number of cycles to search before resorting to moving the mirrors

WITEAV, PUPBUC, CORBUC



(Pupil/corneal intensity along horizontal (x) coordinate, through the corneal highlight)

PUPX, PUPY X,Y coordinates of center of pupil

PUPRAD Radius of pupil

CORAX,
CORAY — X,Y coordinates of center of corneal highlight

CORRAD — Radius of cornea

CORX,
CORY — X,Y coordinates of center of corneal highlight relative to center of pupil

c) Local variables

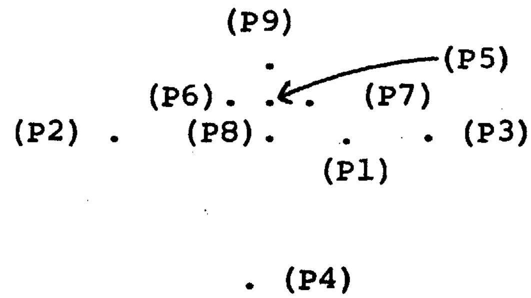
TCT — Number of cycles we have been in eye-track this time

WITEAV (P1)

Points stored for computation:

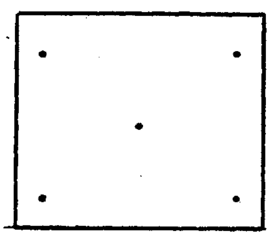
PAVAL (P2)
PBVAL (P3)
PCVAL (P4)
CORVAL (P5)
AVAL (P6)
BVAL (P7)
CVAL (P8)
DVAL (P9)

} Points actually read by vidissector. Points define pupil and corneal highlight boundaries.



These intensity values are used in calculation of PUPX, PUPX... (see State Variables).

PA
PB
PC
PD
PE — CORX, CORY at the five points on the X,Y video display used to calibrate the Oculometer



X,Y video display
horizontal field of view $\approx 12.5^{\circ}$
vertical field of view $\approx 9.5^{\circ}$

MXZ
MYZ
MXR
MYR — Computed by CALIB (the calibration) and used to transform a given CORX, CORY pair into a point of regard (see INTEG - TRDAB).

SCRMAX — Maximum screen coordinates (0 = min)

In CALIB:

$$MXZ = \frac{4*PE_x+PA_x+PB_x+PC_x+PD_x}{8}$$

$$MYZ = \frac{4*PE_y+PA_y+PB_y+PC_y+PD_y}{8}$$

$$MXR = \frac{SCRMAX*2}{PA_x+PB_x-PC_x-PD_x}$$

$$MYR = \frac{SCRMAX*2}{PA_y+PD_y-PB_y-PC_y}$$

In TRDAB:

$$POR_x = (CORX-MXZ)MXR$$

$$POR_y = (CORY-MYZ)MYR$$

POR = point of regard relative to center of screen

Initialization of the Oculometer Eye-Tracking/Control Program

Two types of initialization must occur prior to operating the computer-controlled Oculometer system. They are defined as program initialization and tracking initialization. Program initialization generally need happen only once -- when the system program begins to be executed. It is concerned with loading the computer memory with the eye-tracking/control program, opening the channels for the several I/O devices used, and preparing to process TTY or I/O terminal inputs. Tracking initialization refers to identifying and localizing the subject's eye in the vidissector field of view. This procedure is accomplished through the use of the SCRTST and CALIB routines. After the CALIB routine is accomplished the program proceeds to the EYTRAK routine and normal system operation, barring any tracking malfunctions. Should a tracking malfunction occur after CALIB, the routines SCRTST and CALIB can be repeated.

Oculometer Eye-Tracking Algorithm

The Oculometer eye-tracking algorithm is concerned with the following problem: given a two-dimensional image of the subject's eye, consisting of a bright pupil with an overriding corneal highlight, which a) is focussed on the vidissector photocathode, b) can move within the vidissector field of view (as with head motion), and c) can be occluded so as to momentarily vanish (as in a blink), repeatedly determine, with high cycle rate, the position of the center of the pupil in the vidissector field of view and the position of the center of the corneal highlight relative to the center of the pupil.

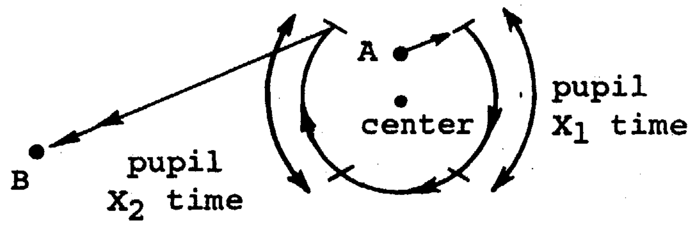
The requirement of high cycle rate (to insure tracking of swift eye movements) demands the utmost of simplicity in the tracking algorithm. Also, the natural, dynamic geometry of the human eye makes it necessary to deal with situations when the pupil is noncircular (as is the case when the upper eyelid is partially lowered and obscures the upper portion of the pupil).

The algorithm evolved here appears to meet the tracking requirements.

The (EYTRAK) program organization itself is unusual; when tracking the eye, it operates as a closed subroutine, calling a pupil tracking subroutine (PUPTRK) and a cornea tracking subroutine (CORTRK), then exiting to its calling procedure. This code takes about five pages. PUPTRK and CORTRK are each one page long, the rest being utility routines.

The bulk of the code is a rather elaborate collection of contingency routines to be used when either PUPTRK or CORTRK fail. This may happen when initially acquiring the pupil image (PUPGET), acquiring the corneal image (CORGET), or in the event of blinks, sudden movements or changes in light levels (BLINKY, BLINK, etc.).

Although the tracking program described here was originally intended to be exactly analogous to the tracking program of the previous analog-digital hybrid electronics version of the Oculometer, it makes some concessions to continuous techniques of the latter. In particular, the tracking algorithm of the previous version of the Oculometer involved gating the anode current of the vidissector (less a bucking voltage) into several different integrators with sign of either +1 or -1 (see Ref. 2). The PUPIL x-dimension loop is illustrative. During the circular scan of the pupil two intervals were designated as PUPIL x times, as as indicated below:

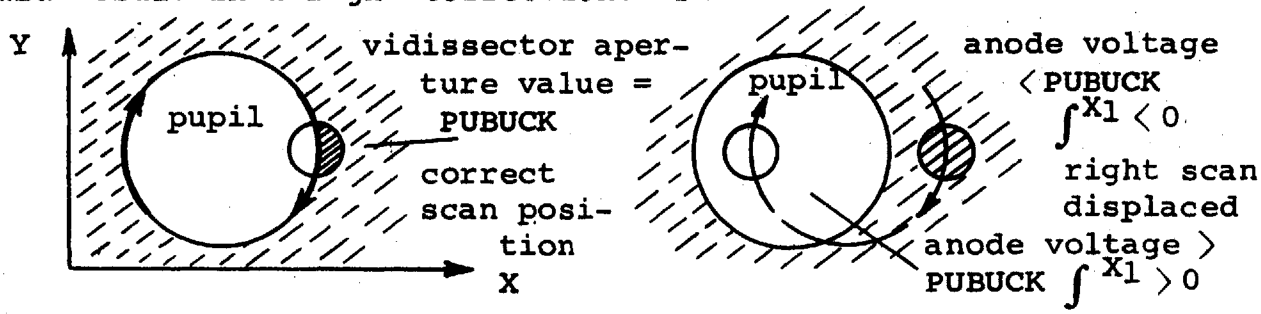


PUPIL x_1 extended from 67.5° to 135°; PUPIL x_2 time covered the symmetrically opposite interval. The pupil bucking voltage (PUBUCK in EYTRAK) was selected to be the mean of the pupil intensity (white sense) (A) and the background intensity (black sense) (B). The PUPIL x value (PUPX) was derived as PUPX$\leftarrow$PUPX +

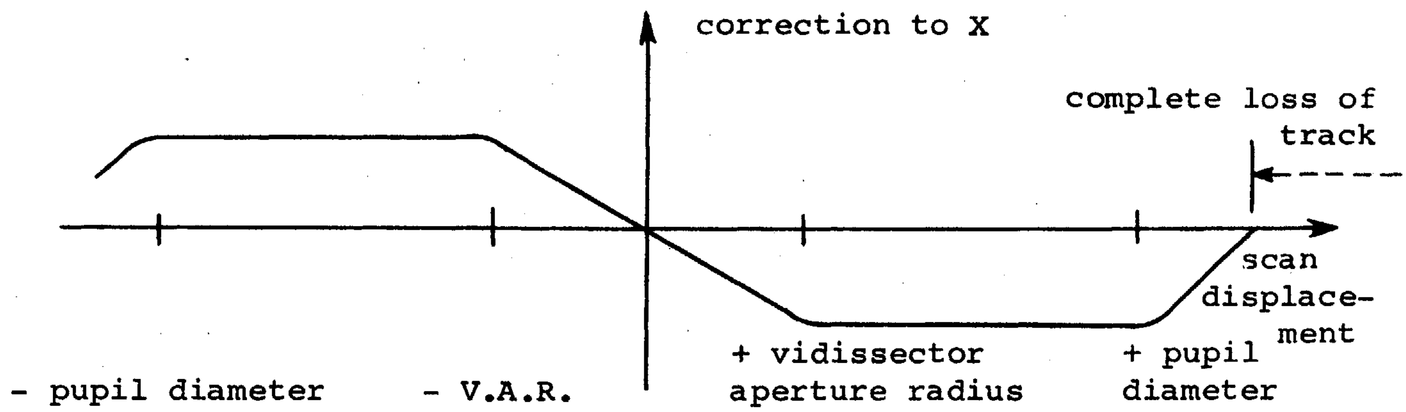
$$\int^{\text{pupil } x_1} (\text{anode voltage} - \text{pupil buck voltage})\, dt -$$

$$\int^{\text{pupil } x_2} (\text{anode voltage} - \text{pupil buck voltage})\, dt.$$

Thus, if the circular scan (centered around (PUPX, PUPY)) coincided exactly with pupil-iris boundary, the anode voltage value would be exactly the mean of dark value and light value (=PUBUCK), both integrals = 0, and PUPX would be correct. A displacement of the scan to the right would make $\int^{x_1} < 0$ and $\int^{x_2} > 0$, resulting in a leftward correction of PUPX. Similarly , a left scan displacement would result in a right correction. This is indicated below:



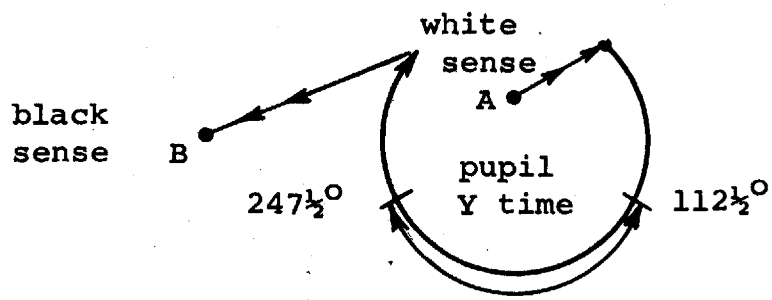
Note that, in general, this correction is not linear with displacement, as indicated below:



X scan correction (Y scan correct)

The correction is pseudolinear for a range nearly the diameter of the vidissector aperture, but gives only a displacement direction for greater errors. This abbreviated linear range is a serious drawback. If the Y scan value is also incorrect, even the saturated range is shorter. This property was also a serious drawback of the scanning algorithm of the previous analog-digital hybrid system.

In the previous system there was a pupil x tracking loop as described, and a pupil y tracking loop, which used only the bottom of the eye image (to permit the eyelid to close down over the pupil slightly), as indicated on the following page:



At the end of the 3/4 circular scan there was a black sense time (B). At the beginning of the 3/4 circular scan there was a white sense time (A). Thus,

$$\mathrm{PUPY} = \mathrm{PUPY} - \int^{\text{pupil y}} (\text{anode voltage} - \text{pupil buck voltage})\,dt$$

and

$$\mathrm{PUBUCK} \leftarrow \mathrm{PUBUCK} \int^{\text{white sense (A)}} (\text{anode voltage} - \text{pupil buck voltage})\,dt$$

$$+ \int^{\text{black sense (B)}} (\text{anode voltage} - \text{pupil buck voltage})\,dt\ .$$

Similarly, the pupil radius is calculated as

$$\mathrm{PUPRAD} \leftarrow \mathrm{PUPRAD} + \int^{\text{whole scan}} (\text{anode voltage} - \text{pupil buck voltage})\,dt\ .$$

Although the tracking equations are represented above as discrete substitutions occurring once per cycle (as they are in the present EYTRAK program) the previous version of the tracking program actually updated each variable value continuously during the whole scan. This had the annoying effect that the pupil radius value just after the PUPIL X_1 interval would be decreased if the tracking were right-displaced and increased if track were left-displaced. Thus, the scan was seldom quite exactly circular, an effect minimized by scaling the correction factors downward by a constant multiplier (a potentiometer) to decrease loop gain. This reduced output jitter, but it reduced response rates also.

The present program PUPTRK works substantially as described above, but the 3/4 circular scan has been replaced by a three-point discrete scan; the intervals replaced by sums; and the anode current integrated while measuring time to reach a threshold level, then the time reconverted to light values by a division. The variables PUPX, PUPY, PUPRAD and PUBUCK are corrected once each cycle. The value of PUBUCK gives a criterion for whether the tracking is successful: if PUBUCK decreases below a minimum value, it is assumed the WITEAV point (P1) has been outside the pupil image for too long, and that pupil track is lost (the switch PUPFND = 0 for lost, +1 for OK). Each time PUPTRK is entered the cycle count PUPCYC is incremented by 1. For the first 50 cycles (or whenever PUCHA $\neq$ 0) the test on PUBUCK is relaxed; it is assumed that the pupil has just been acquired and PUBUC K may not yet have reached its steady state value. A complete cycle of PUPTRK involves four vidissector points. These are indicated on the following page:

P1 → WITEAV
P2 → PAVAL
P3 → PBVAL
P4 → PCVAL

```
P2      P1      P3
 .       .       .

     . P4
```

(In the present program "black sense" is arbitrarily set to "0" value.)

In the previous version of the Oculometer the PUPIL tracking loop described above was executed alternately with a corneal tracking loop. The same procedure is used in the present EYTRAK program and the few differences are relatively minor. In the previous version corneal bucking voltage and corneal radius were manually-set constants. The corneal scan covered a full circle, i.e. CORNEA Y has two equal intervals, as did CORNEA X. In making the corneal scan discrete in the present program the pattern has been changed from a circle to an X-like pattern of five points, as indicated below:

P5 → CORVAL
P6 → AVAL
P7 → BVAL
P8 → CVAL
P9 → DVAL

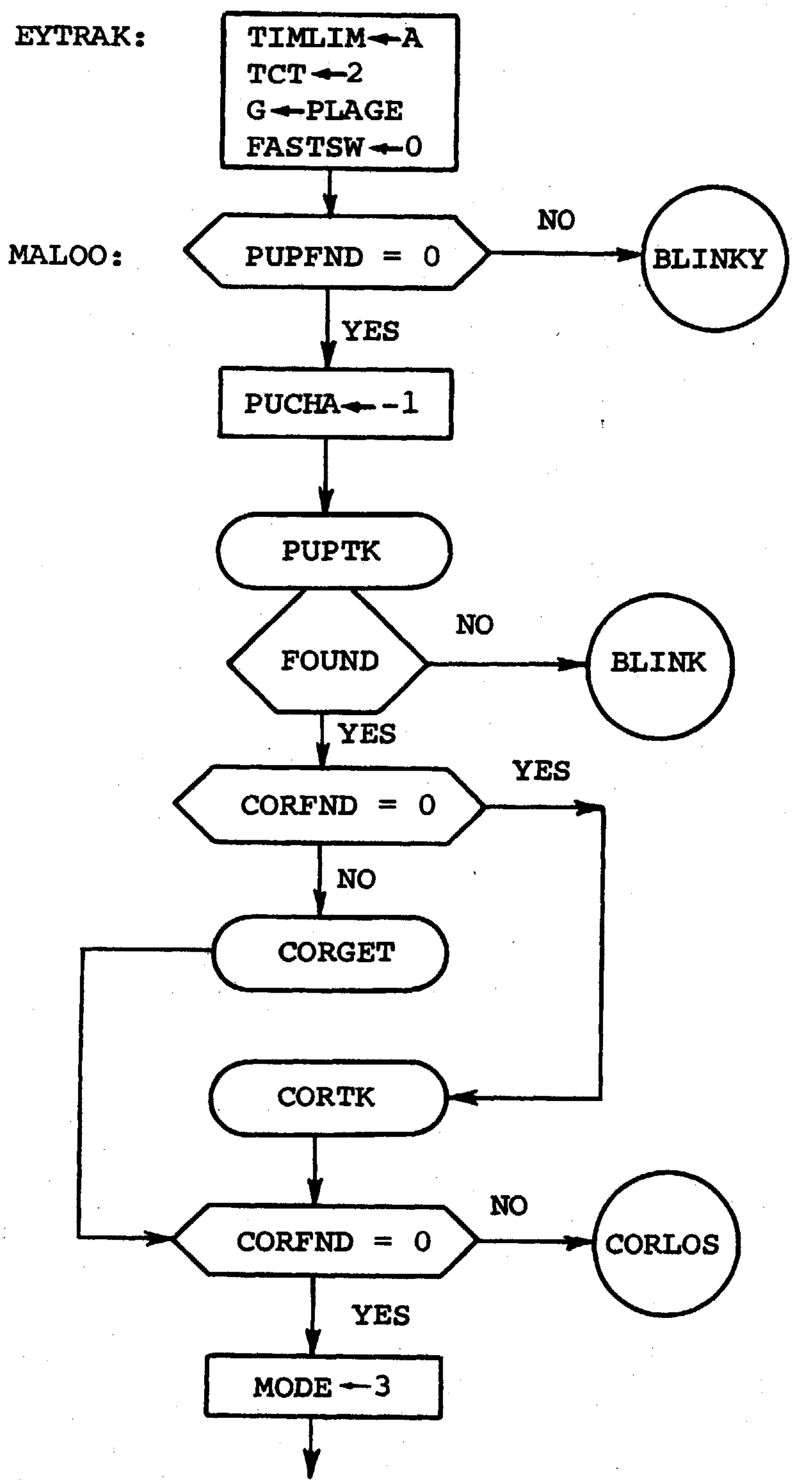
```
              . P9    P5

P6 .          .        . P7

              . P8
```

The corneal bucking voltage (CORBUC) is taken as the average value of CORVAL and WITEAV. The values calculated by CORTRK are CORAX, CORAY, CORX, CORY, CORRAD and CORBUC. CORBUC is tested against WITEAV except during the first 50 cycles (CORCYC $<$ 50). The scan radius is fixed. The time allotted by the program to measure any point (P1 through P9) is not more than 194 sec per point, although the average total time consumed per point is approximately 300 sec because of program overhead.

Oculometer Eye-Tracking Program Flow Charts

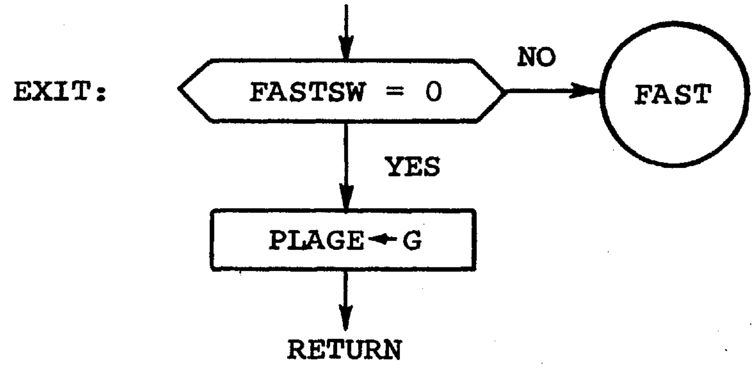
Flow charts for the Oculometer eye-tracking program routines EYETRAK (Eye Track), PUPTK (Pupil Track), CORTK (Cornea Track), PUPGET (Pupil Get), and CORGET (Cornea Get) are presented on the following pages:

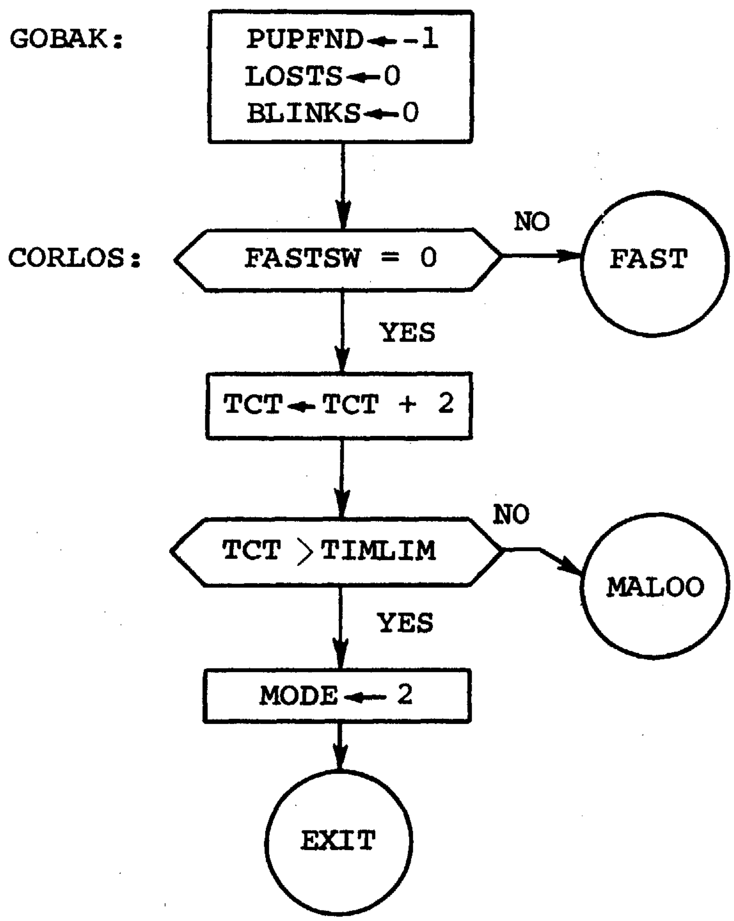
EYTRAK



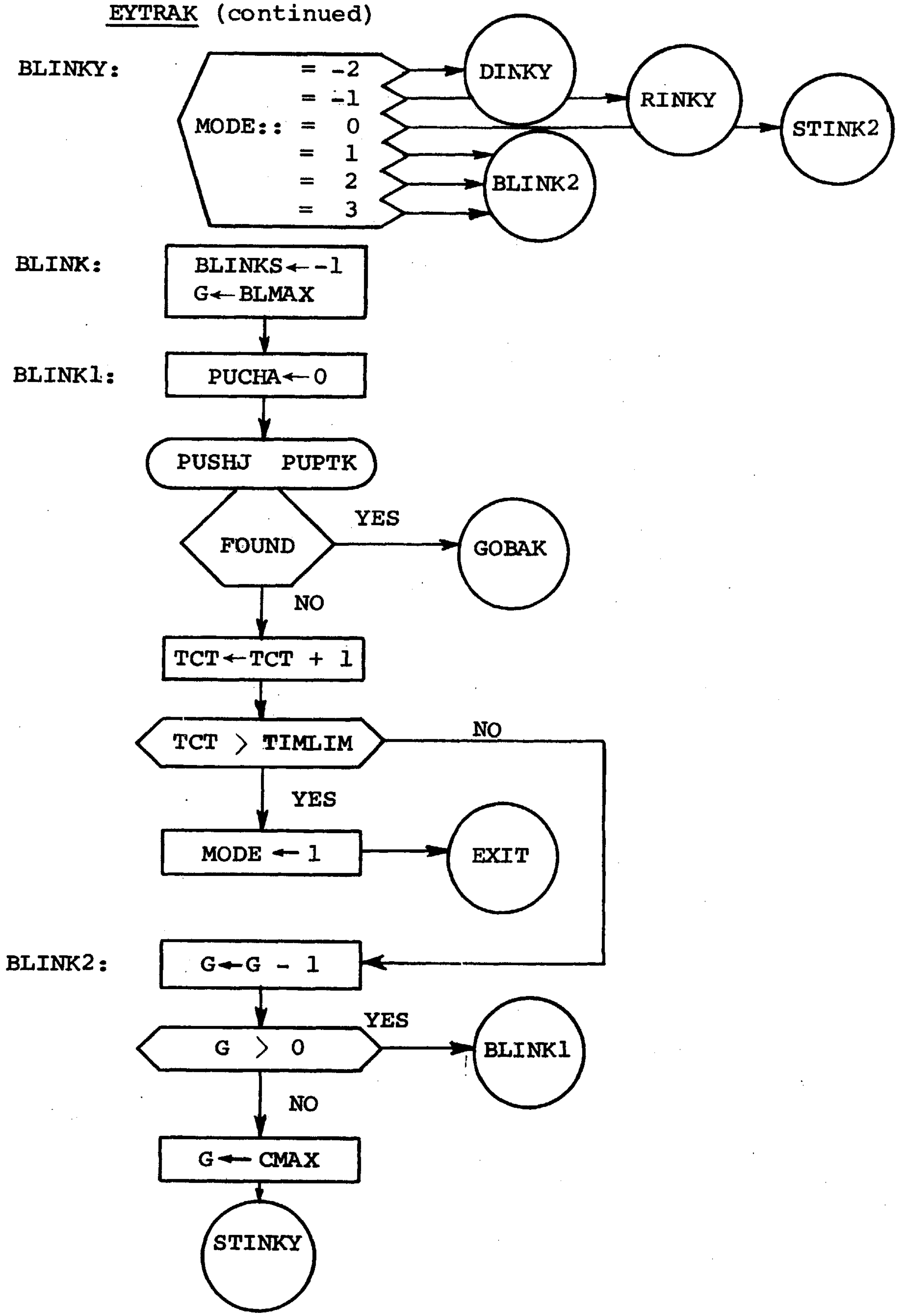
EYTRAK:
TIMLIM←A
TCT←2
G←PLAGE
FASTSW←0
MALOO:
PUPFND = 0
NO
BLINKY
YES
PUCHA←-1
PUPTK
FOUND
NO
BLINK
YES
CORFND = 0
YES
NO
CORGET
CORTK
CORFND = 0
NO
CORLOS
YES
MODE←3

EYTRAK (continued)

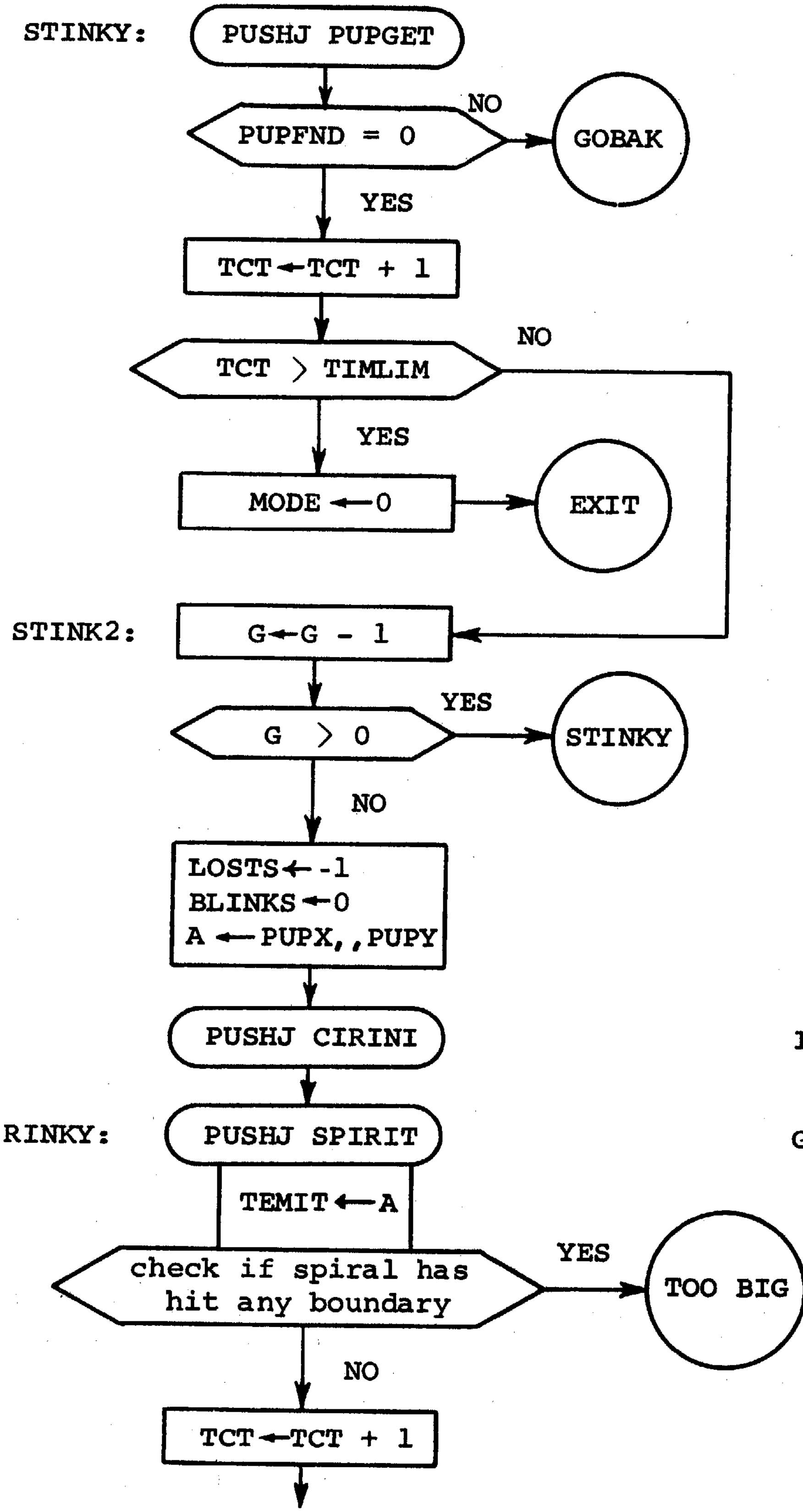




EYTRAK (continued)

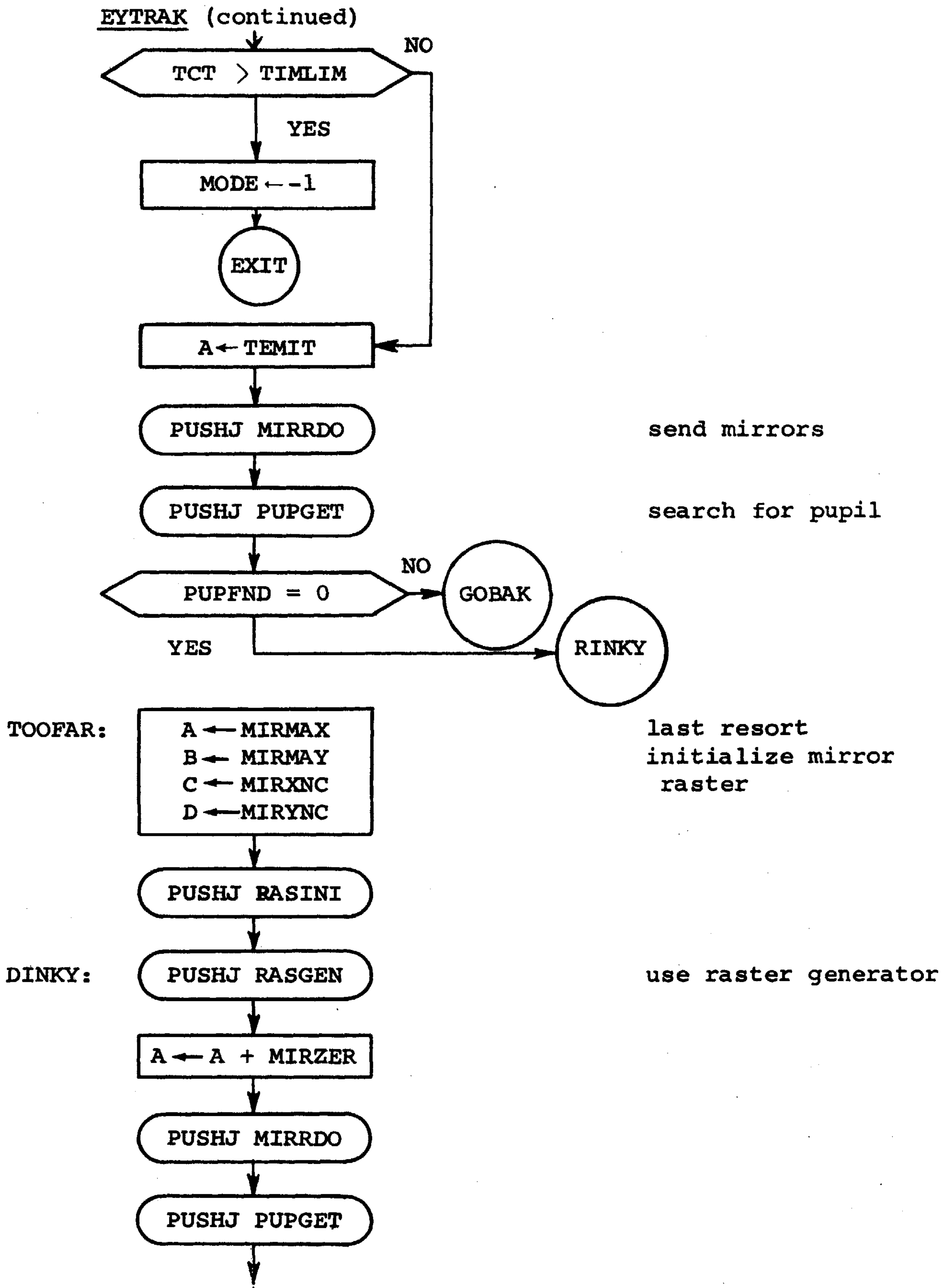


EYTRAK (continued)

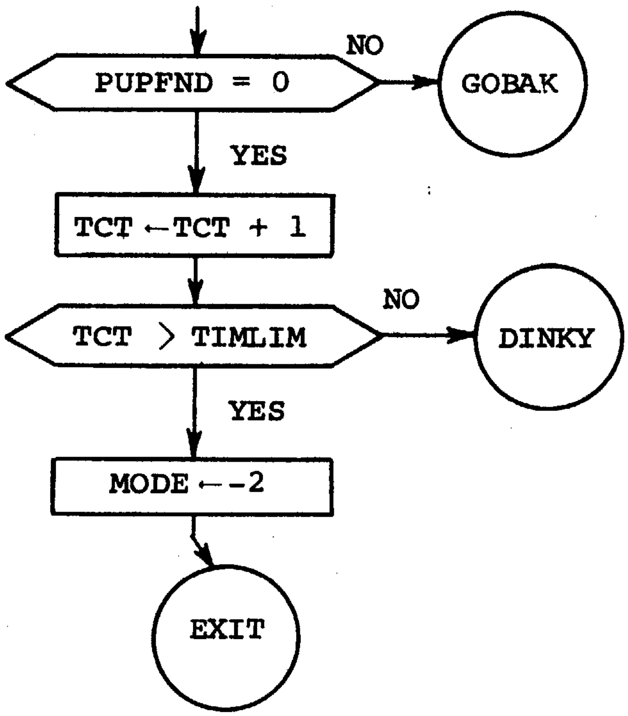


Initialize spiral mirror search

Get next X,,Y mirror coord

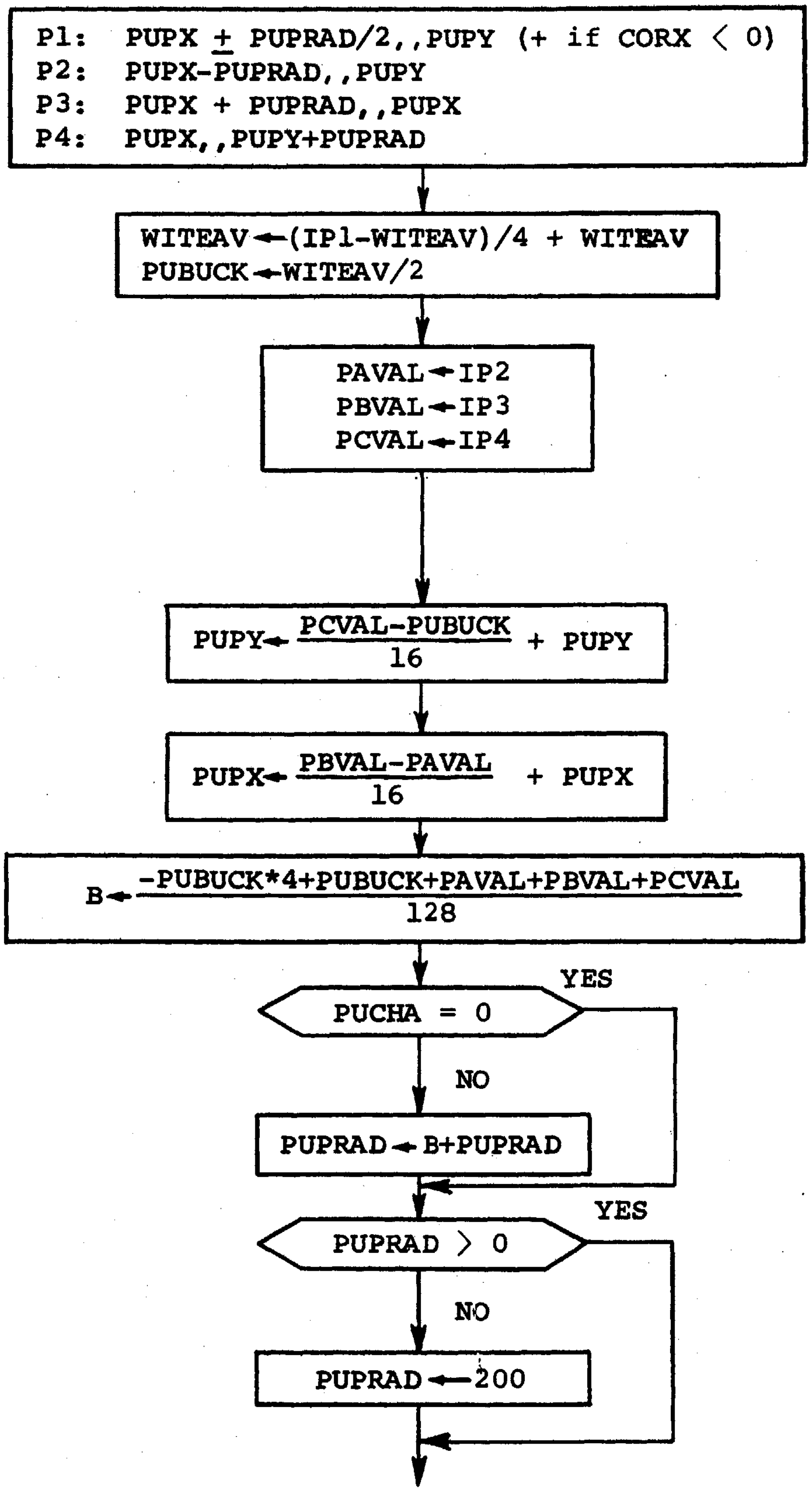

EYTRAK (continued)
TCT > TIMLIM
NO
YES
MODE ← -1
EXIT
A ← TEMIT
PUSHJ MIRRDO
send mirrors
PUSHJ PUPGET
search for pupil
PUPFND = 0
NO
GOBAK
YES
RINKY
TOOFAR:
A ← MIRMAX
B ← MIRMAY
C ← MIRXNC
D ← MIRYNC
last resort
initialize mirror
raster
PUSHJ RASINI
DINKY:
PUSHJ RASGEN
use raster generator
A ← A + MIRZER
PUSHJ MIRRDO
PUSHJ PUPGET

EYTRAK (continued)

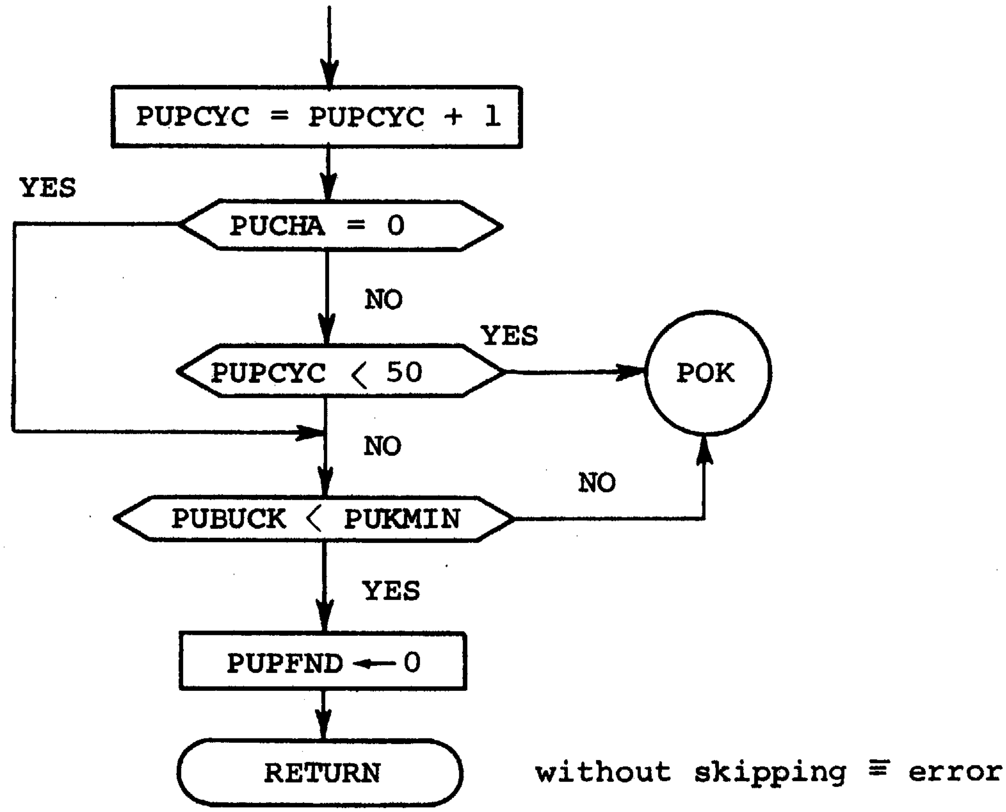


PUPIL TRACK

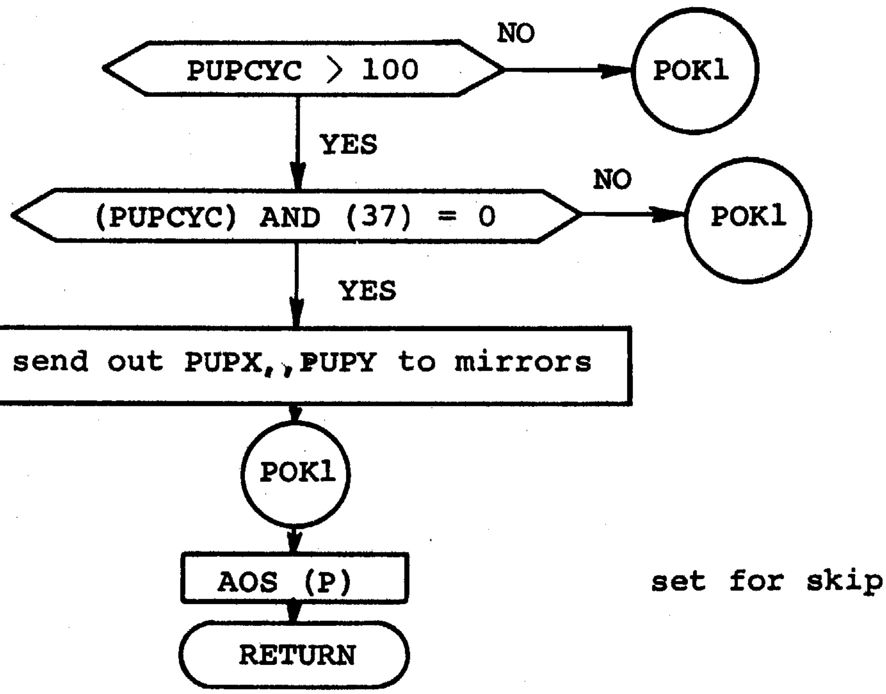
PUPTK: Set up to read following points from vidissector



PUPIL TRACK (continued)

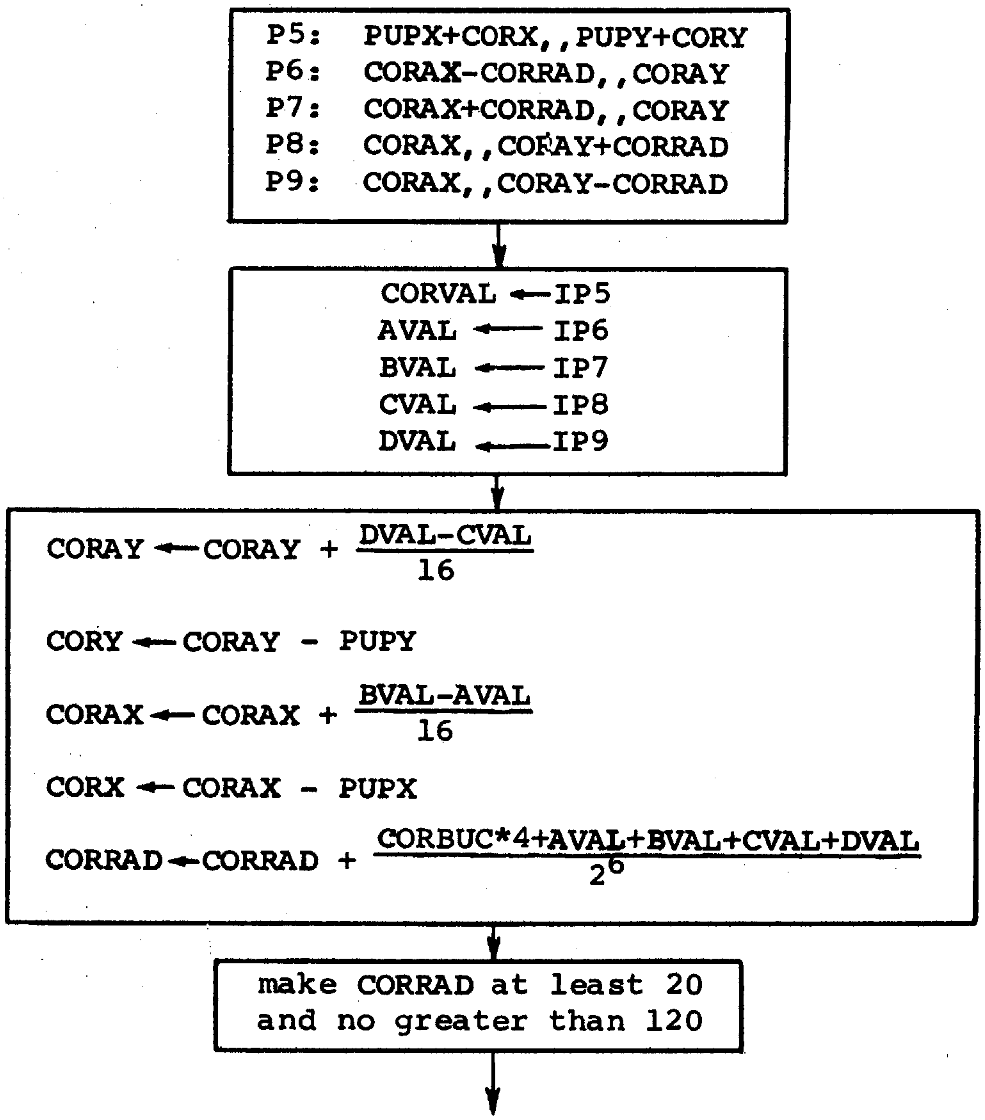


POK:

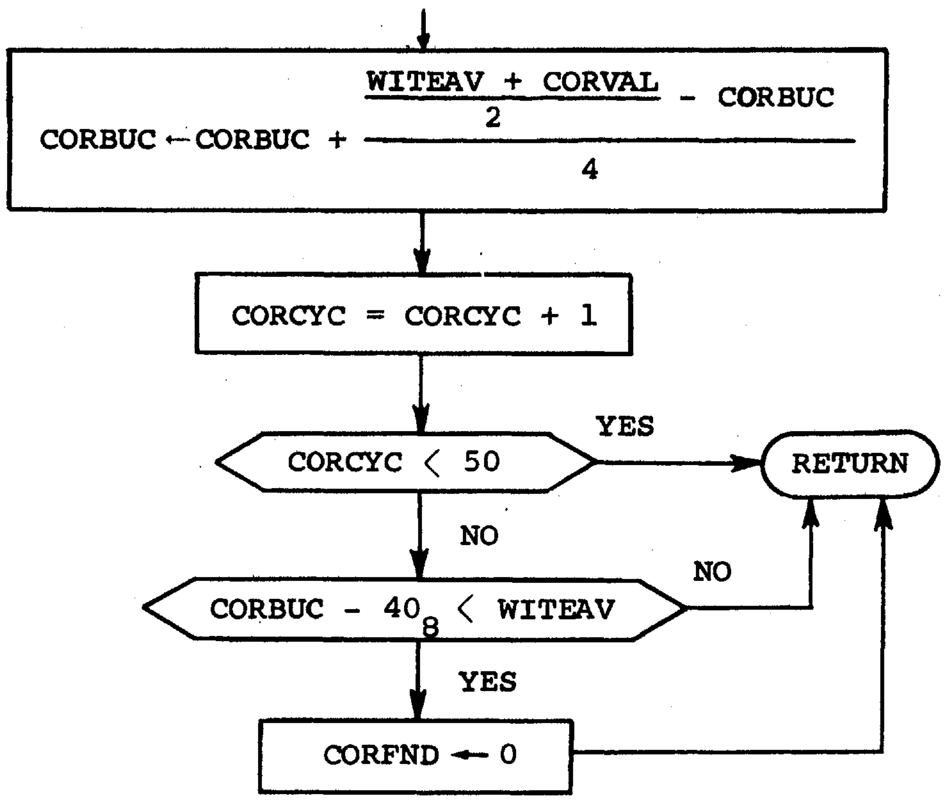


CORNEAL TRACK

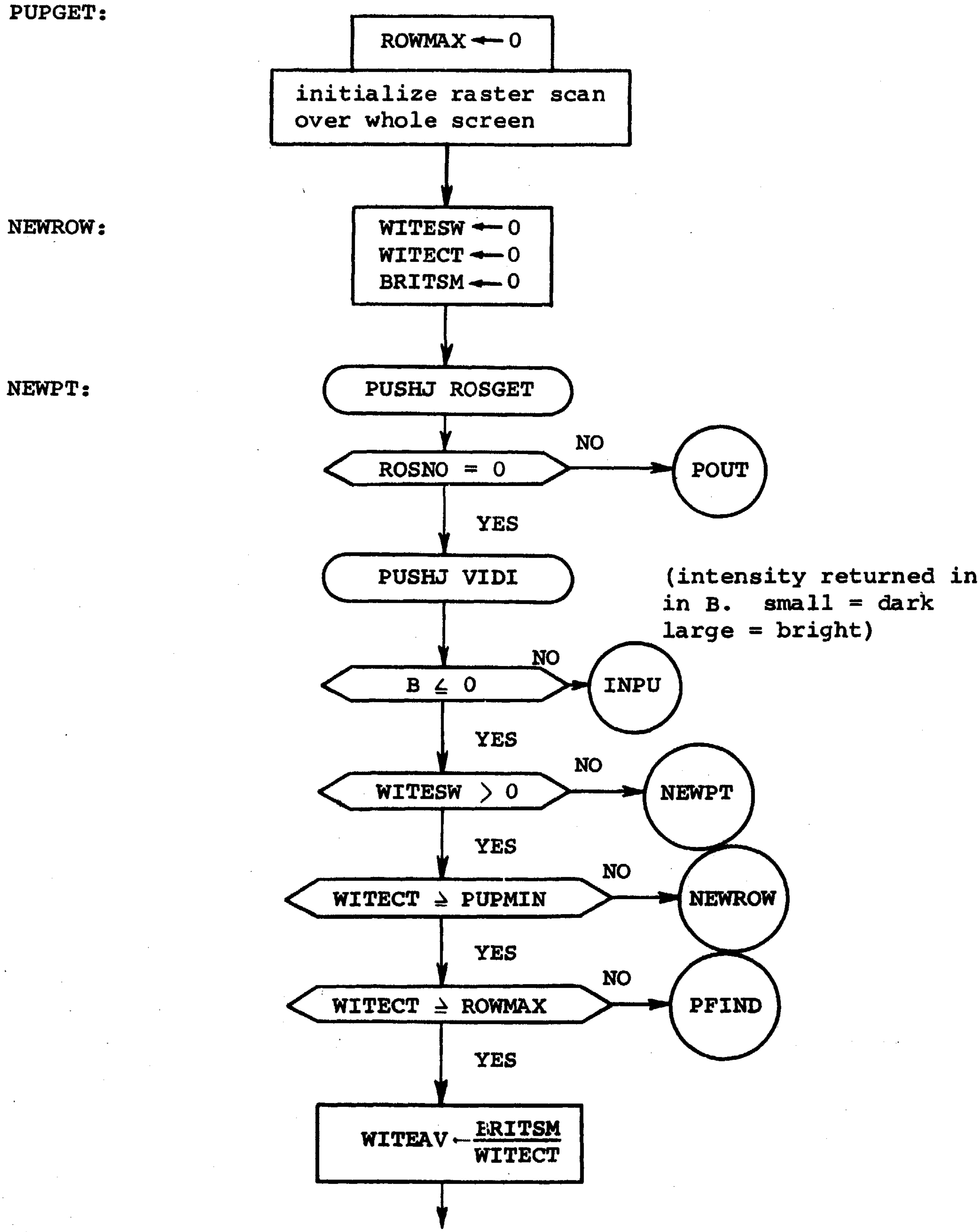
CORTK: Set up to read the following points from the vidissector



CORNEAL TRACK (continued)

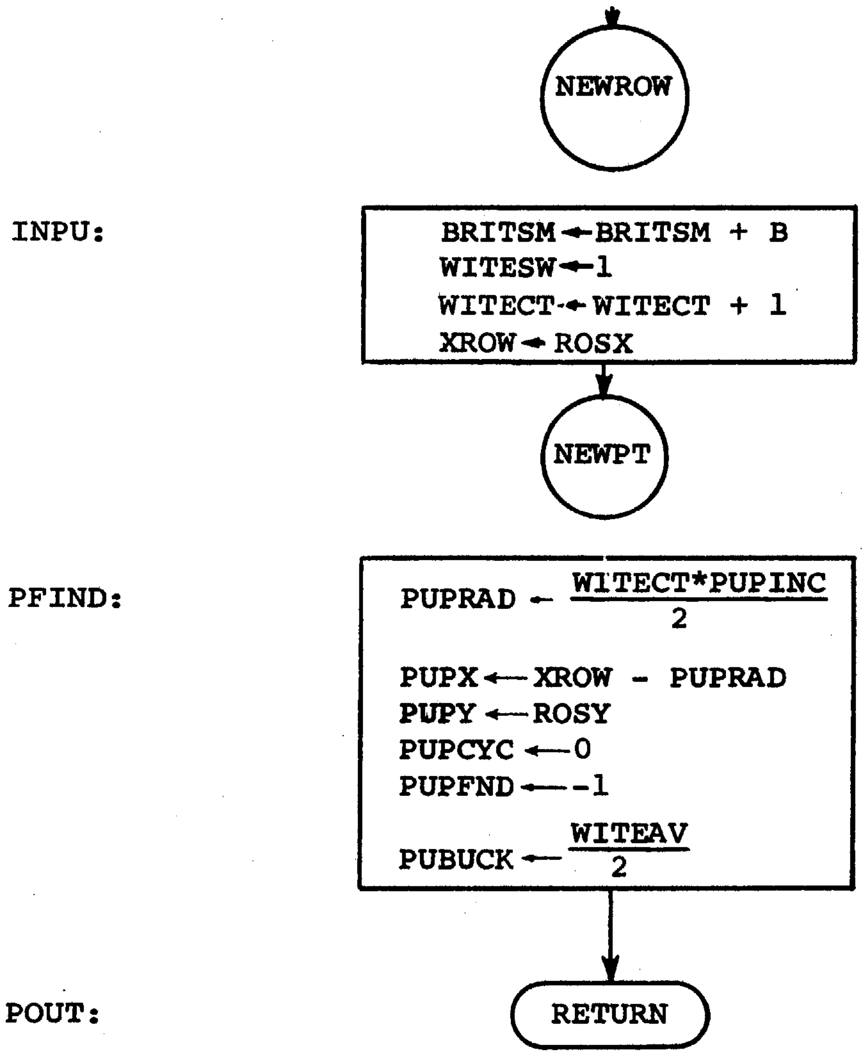


PUPIL GET



PUPGET:
ROWMAX ← 0
initialize raster scan over whole screen
NEWROW:
WITESW ← 0
WITECT ← 0
BRITSM ← 0
NEWPT:
PUSHJ ROSGET
ROSNO = 0
NO
POUT
YES
PUSHJ VIDI
(intensity returned in in B. small = dark large = bright)
NO
B ≤ 0
INPU
YES
NO
WITESW > 0
NEWPT
YES
NO
WITECT ≥ PUPMIN
NEWROW
YES
NO
WITECT ≥ ROWMAX
PFIND
YES
WITEAV ← BRITSM / WITECT

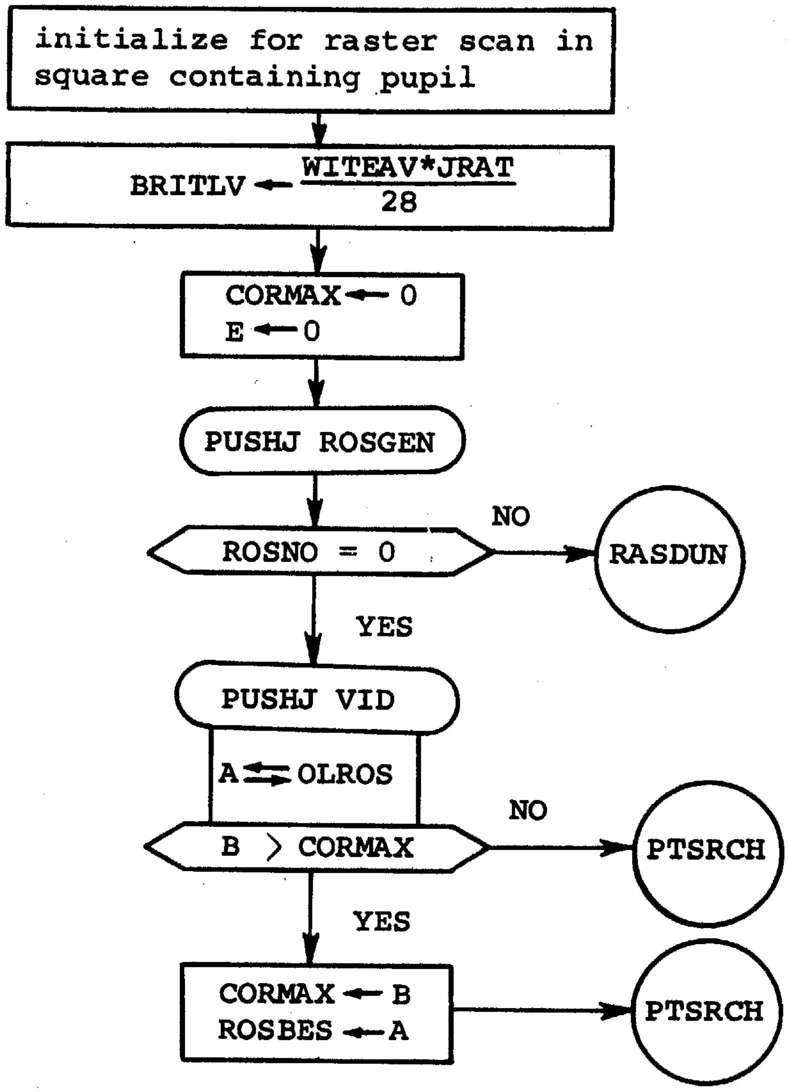
PUPIL GET (continued)



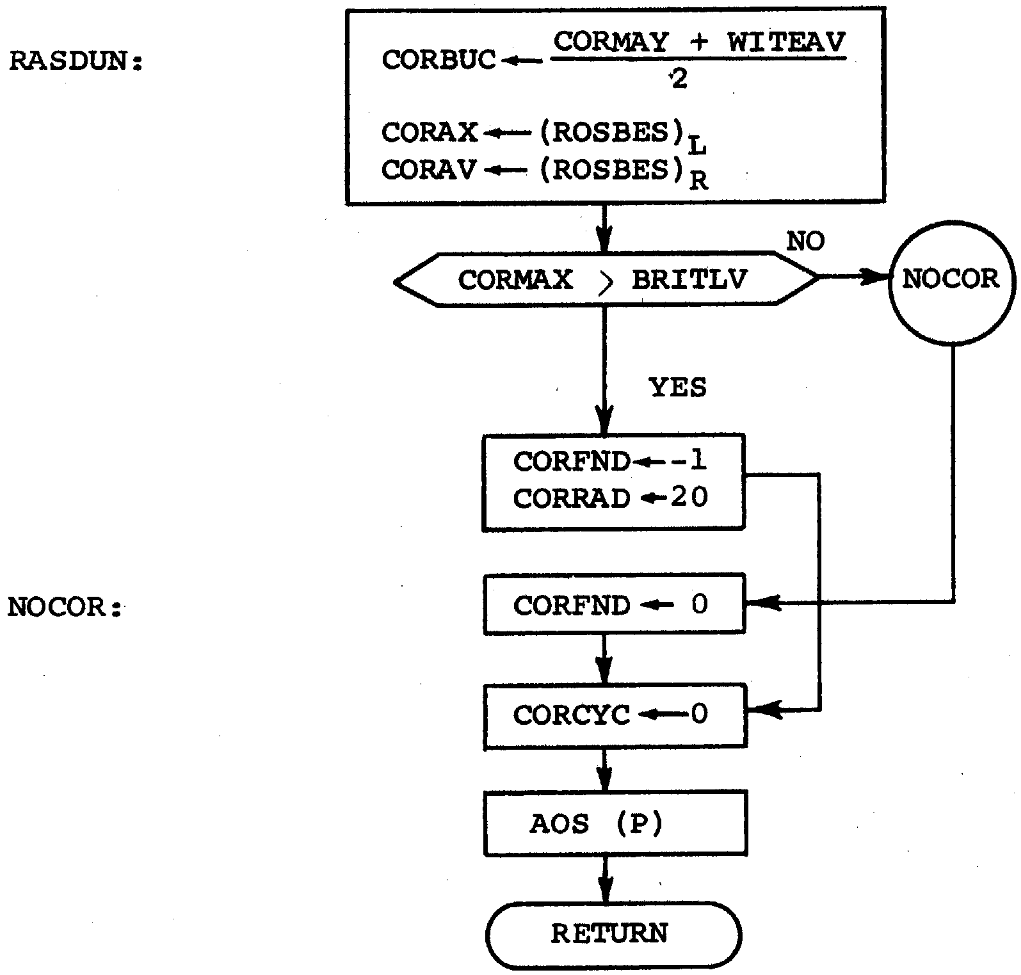
CORNEAL GET

CORGET:

PTSRCH:



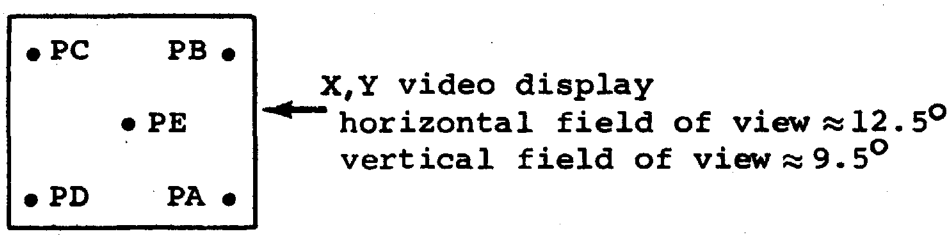
CORNEAL GET (continued)



Calibration and Point of Regard Calculation

The eye-tracking algorithm described above requires an outer loop to make use of the raw data it supplies for the purpose of calculating the subject's point of regard. Calibration permits the relationship to be established between the raw eye-track data and the point of regard. The point of regard is normally construed to be located within the boundaries of the video display screen. Calibration is accomplished as follows, after the subject is properly positioned at the Oculometer and after the routine SCRTST has been completed and EYTRAK is operating:

a) The CALIB routine presents five (5) points, PA, PB, PC, PD, and PE, in succession on the video display to the subject as indicated:



b) The EYTRAK routine is then required to obtain sixty-four (64) consecutive measurement periods at each of the five (5) calibration points.

c) The sixty-four (64) measurements at each calibration point are averaged by CALIB to get one CORX and one CORY value for each of the five (5) points.

d) The CORX and CORY values are used by CALIB to calculate "0" offset values MXZ and MYZ.

e) The values SCRMAX (maximum video display screen coordinates) and the averaged values of each of the PA, PB, PC and PD points are used by CALIB to calculate values MXR and MYR.

f) The values PORX and PORY (values for point of regard in x,y coordinates on the video display) are calculated by CALIB using values CORX, CORY, MXZ, MYZ, MXR and MYR.

Data Display

After the routine CALIB has been successfully accomplished and the routine EYTRAK is running, the routine CIRC will display the subject's point of regard (fixation point) at the correct fixation position on the video display.

A certain amount of smoothing of the displayed fixation point (to reduce fixation "jitter") is accomplished by using routine INTEG. This smoothing is obtained by doing a moving average of the last ten (10) values of EYTRAK output provided to CIRC.

Other display features of the present Oculometer program are the routines REPLAY and DPYSUB. The former routine will replay (on the video display) the fixation point pattern of a subject developed during an eye-tracking experiment. The latter routine DPYSUB will display all the old points of an eye fixation pattern that the program has been instructed to save.

DISCUSSION OF COMPUTER-CONTROLLED OCULOMETER SYSTEM PERFORMANCE AND APPLICATION

Evaluation of System Performance

The work reported here was primarily in the nature of a system feasibility study, i.e. the initial development of specialized computer-Oculometer eye-tracking/control programs and I/O interfaces for a prototype interactive eye movement tracking system. Because of this, the time allotted for quantitative evaluation of the system was minimal. However, the qualitative results were encouraging. Digital computer control of the system allowed Oculometer performance that was generally equal to, and in some instances superior to, the performance obtained with the previous analog-digital hybrid system control circuitry. An example of the improved performance capability of the present Oculometer system is its ability (unlike that of the previous system) to operate under well-lighted room conditions. This performance feature is a particular result of the present EYTRAK program and the integrator-threshold detector described elsewhere in the report.

During the development of the calibration program (CALIB) for the present system some quantitative information was obtained regarding values of fixation point (eye point of regard) random noise level and repeatability of measurement. These values, which are listed below, represent the video display output of the system after the raw eye-track data has been smoothed by the moving average INTEG routine:

a) Fixation point random noise level --

For artificial eye (see Appendix C) $\approx \pm\ 3/8^{\circ}$

For human eye (subject fixated on static point on video display with head position fixed in holder) $\approx \pm\ 1/2^{\circ}$

b) Repeatability of measurement (human eye only) --

Subject head position fixed in holder $\approx \pm\ 1/4^{\circ}$

Subject head position not fixed in holder $\approx \pm\ 5/8^{\circ}$

The above values (over horizontal and vertical fields of view of 12.5° and 9.5° respectively) are indicative only of the general performance of the particular Oculometer electro-optical unit used in the present system, which employs a vidissector with a circular scanning aperture of approximately 20 mils diameters and a nonsophisticated near-infrared optical subsystem. An Oculometer electro-optical unit utilizing a smaller aperture vidissector and an improved near-infrared optical subsystem (see Ref. 5) would be expected to provide even better performance.

System Demonstrations and Applications

The success of the computer-controlled Oculometer system developed here shows the feasibility of developing a compact Oculometer system utilizing a small, dedicated, digital computer for Oculometer control.

The applications of such a system appear to be many and varied. As an example, eye-tracking data developed by a compact, digital-computer-controlled Oculometer system could be used as an input to a large digital computer, as suggested by Geffner (see Ref. 6 and Appendix E) for large-scale interactive experimentation.

Some other examples of Oculometer system applications, based on demonstrations performed during the accomplishment of this work, are as follows:

a) Using the eye as a control device. In this demonstration (see Fig. 18) the subject's eye movements controlled the position of a "box" which could be made to overlay a "moving bird" target which moved with random acceleration in various directions. The movements of the "bird" would be minimized so long as the subject continued to eye-position the "box" over the "bird".

b) Recording eye fixation point and exploration patterns. In this demonstration the subject's eye movements were monitored and displayed while he "flew" a flight simulator. The flight

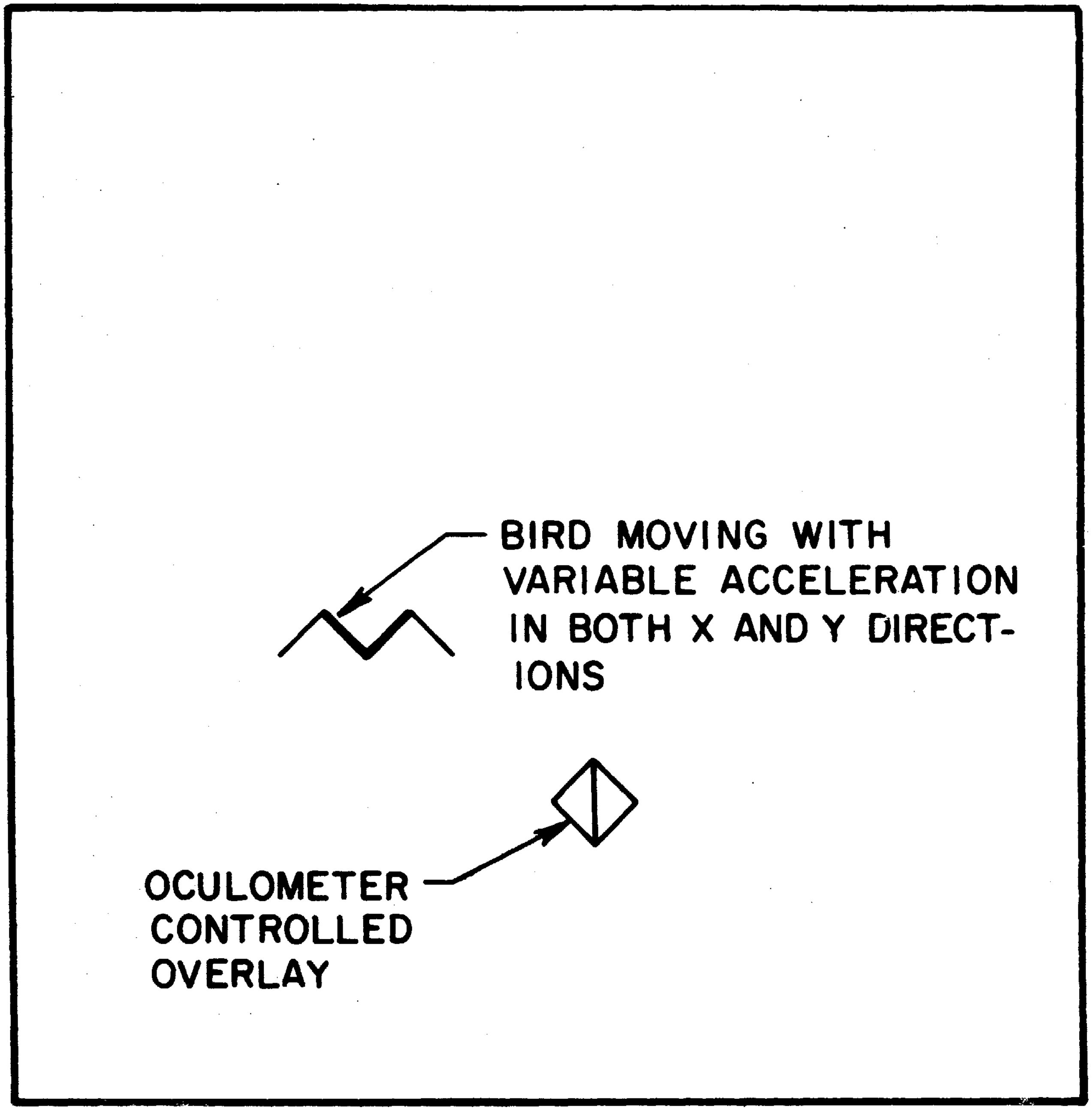


Figure 18 OCULOMETER AS A CONTROL DEVICE

simulator consisted of a PDP-6 computer (using a special program (see Appendix D)) with an instrument panel displayed on its X,Y video display (see Fig.19). A particular eye fixation point of the subject is clearly displayed on the video display below the center of the central instrument as shown in Fig. 20.

c) Using the eye in game playing. In this demonstration (see Fig. 21) a "ball" game was being played by two subjects. Two box-like "bumpers", one of which was controlled by one subject manipulating a joystick and the other controlled by the other subject's eye movements, were independently maneuvered in front of the "ball" so as to deflect it and cause it to cross a particular set of boundaries, thus making a score for one or the other player (see also Appendix E).

d) Using the eye in training machines and in psychophysiological testing. Demonstrations in these areas are explained and depicted in Appendix E.

CONCLUSIONS

The feasibility of using the digital computer technique of Oculometer control has been successfully demonstrated here in the development of a prototype interactive eye-movement tracking system. This technique is capable of providing the following

Figure 19 PDP-6 COMPUTER WITH FLIGHT SIMULATOR DISPLAY

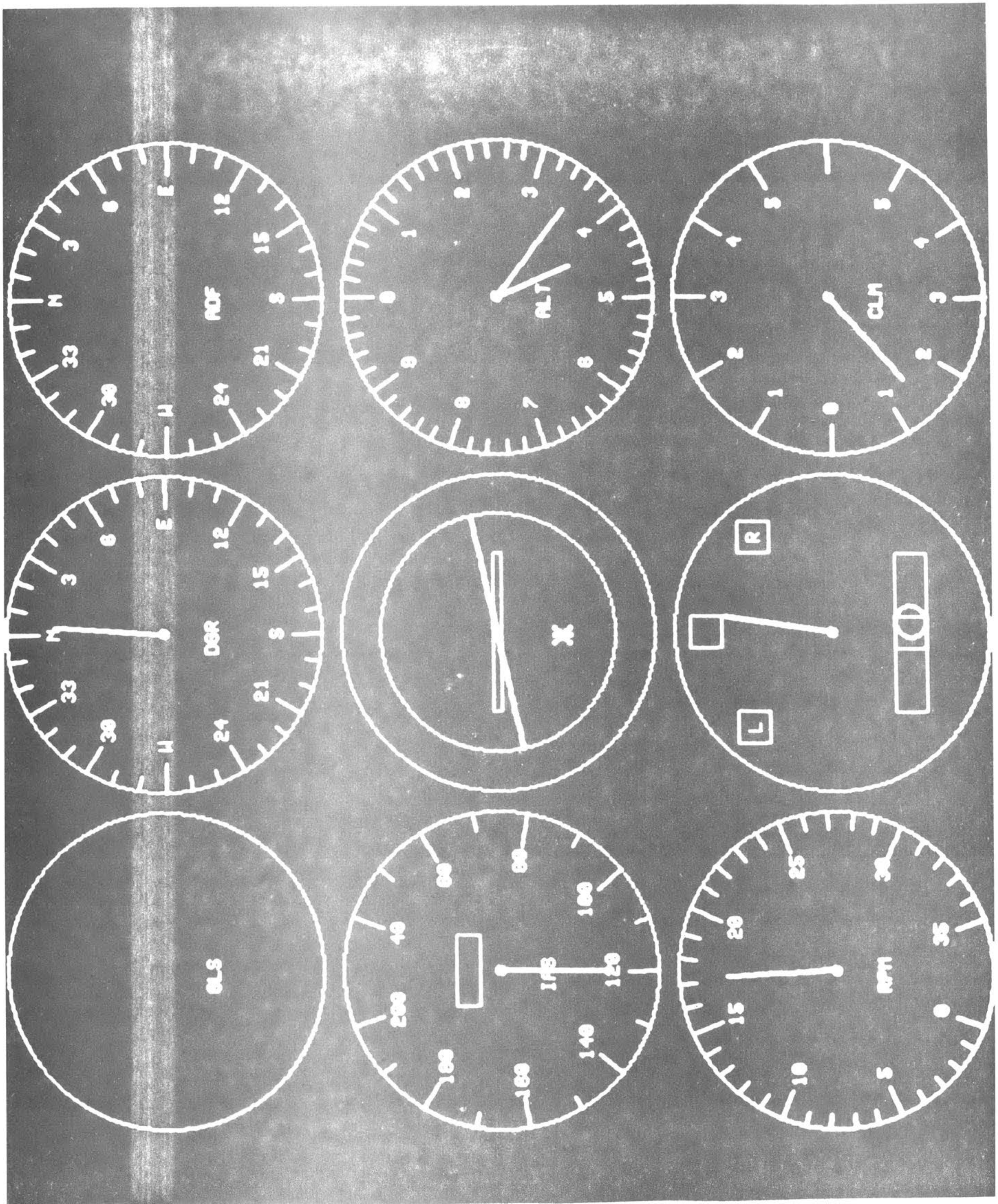


Figure 20 FLIGHT SIMULATOR INSTRUMENT PANEL DISPLAY

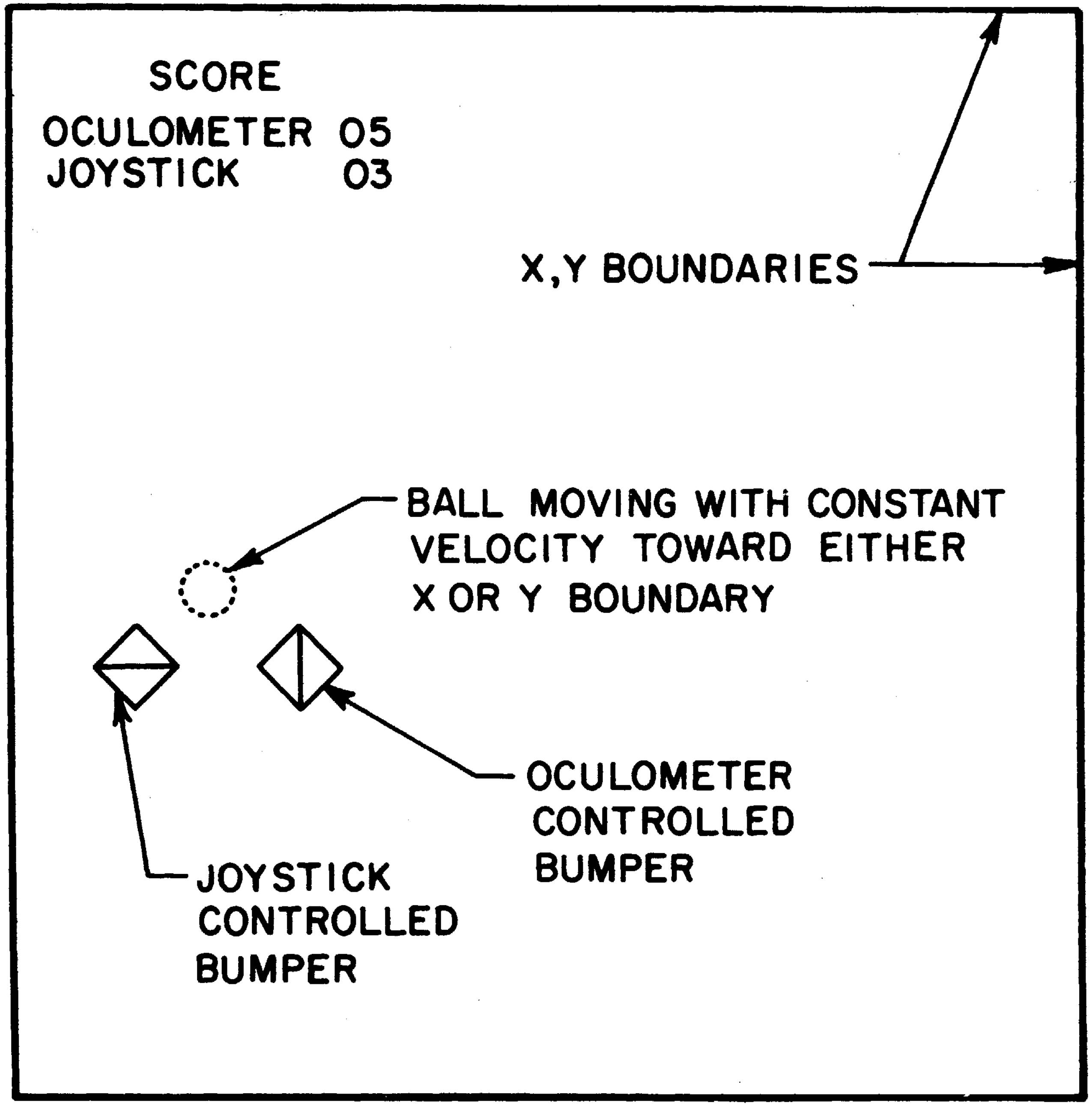


Figure 21 OCULOMETER USED IN GAME PLAYING

advantages:

a) real-time analyses of data,

b) interactive experiments,

c) precision timing source,

d) flexibility of experiments,

e) improved eye-tracking accuracy by using predictive programs,

f) new eye-tracking schemes by using program flexibility,

g) improved system accuracy resulting from removal of nonlinearities by special programming.

The results of the work described here seem sufficiently promising to warrant further development of both Oculometer electro-optical subsystems and Oculometer eye-tracking/control programs, to be utilized with dedicated, compact, digital computers, which could be combined to form complete Oculometer systems.

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APPENDIX A

OCULOMETER EYE-TRACKING/CONTROL PROGRAM

A digital computer eye-tracking control program has been written for the Oculometer. A listing of this program may be obtained from the M.I.T. Artificial Intelligence Laboratory.

77 Massachusetts Avenue
Cambridge, MA 02139
http://libraries.mit.edu/ask

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APPENDIX B

IMPROVED OCULOMETER POWER SUPPLY AND NEAR-INFRARED LIGHT SOURCE

Power Supply

An improved power supply unit has been designed to accomodate nearly any oculometer electro-optical unit (see Fig. B-1). The design utilizes components selected for excellence of performance, and no other criteria were used. Consequently, the unit is rather heavy, but it represents a highly reliable piece of laboratory equipment.

A transistor-relay fail safe circuit has been incorporated in the power supply unit to protect the vidissector deflection amplifiers in the event that the vidissector yoke coils have not been connected. The circuit has a series connection through the x and y yoke coil output connectors, and power will not be delivered until these connectors are in place. Two pins have been clipped in each of the output connectors to insure that the yoke coils are connected before the relay is connected. Also, if the feailure of either supply causes it to go to ground level, the relay will open and prevent an unbalanced supply to the amplifiers.

The deflection amplifiers incorporate a damping control to minimize overshoot regardless of yoke coil inductance. This control is adjusted with R_6 on the amplifiers. R_7 on the amplifiers adjusts

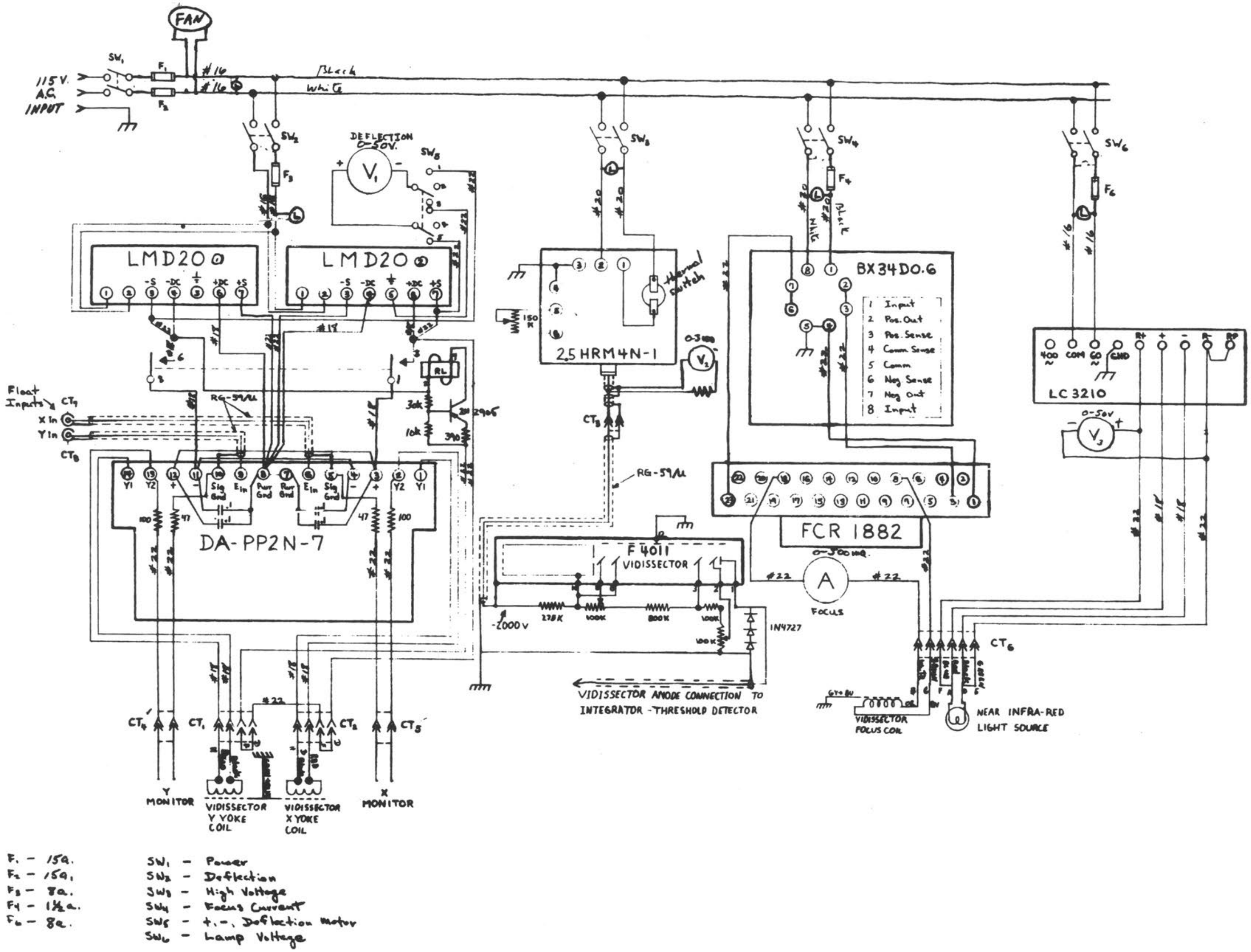


Figure B-1 IMPROVED OCULOMETER POWER SUPPLY SCHEMATIC the DC level at the output. R_6 should be adjusted before R_7 since it will have an effect on the zero signal output current.

Spurious oscillations occurred in the deflection amplifier outputs during the initial tests of the power supply unit. It was determined that this was due to the capacitive effects of the leads to the X and Y monitor outputs. A small resistor was placed in series with these leads at the amplifier to isolate the monitoring circuit from the amplifier. Capacitors were also placed between the outputs of the defelction supplies and power ground to eliminate any ripple that may be present there. These additions are included in the schematic wiring diagram of the power supply unit, Fig. B-1.

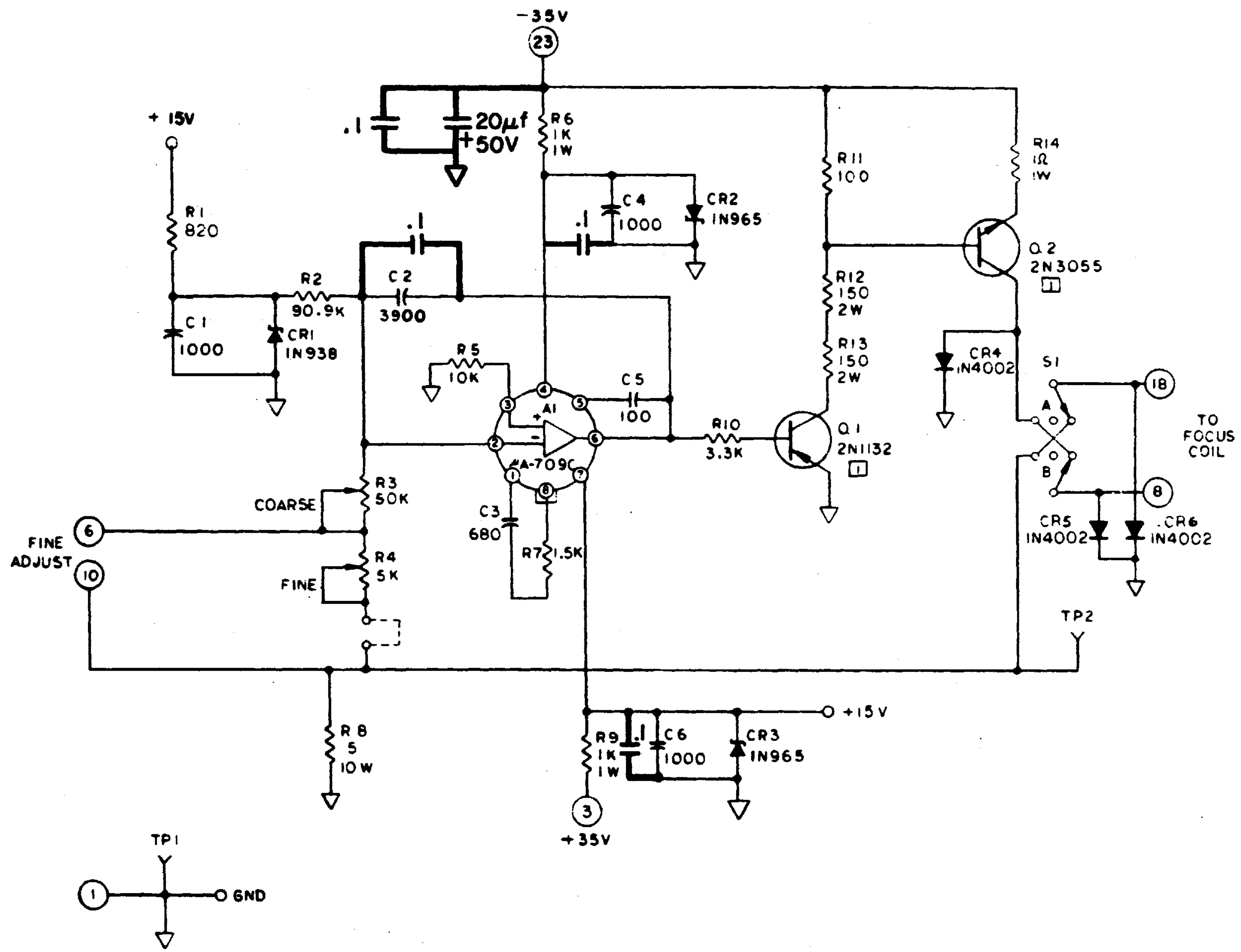
Vidissector focus current is adjusted with a trimmer potentiometer at the top of the focus current regulator card (FR 1882). A switch is also available on this card to switch the direction of the focus current. Once the switch position is selected, it should not be disturbed, since reversing it could damage the focus current ammeter (unless the ammeter connections are reversed also).

Upon initial testing of the power supply unit, it was observed that a herringbone pattern was present in the video output of the vidissector during a test-raster display mode of operation. The focus current regulator was found to be the source of the problem, and appropriate components were added to it to eliminate the aberrations in its output. The added elements are illustrated in the focus current regulator circuit diagram (see Fig. B-2) by heavy, dark line drawing.

The power supplies (LM-D-20-Y) of the deflection amplifiers are grounded at the power ground terminal of the amplifiers and at no other point. The BNC input connectors of the deflection amplifiers are floated off the panel face with insulators. This means that the ground level of the deflection circuit will be established at the signal source. All other power supplies are chassis grounded.

The shield of the vidissector high voltage coax is chassis grounded and no ground connection should be made to the body of the optical head.

The wiring diagram of the vidissector in the oculometer electro-optical unit is included in Fig. B-1 for completeness.



1 REQUIRES HEAT SINK

Figure B-2 FOCUS CURRENT REGULATOR SCHEMATIC (MODIFIED)

Power Supply Recommended Operating Values

Focus Coil	150 ma
Vidissector High Voltage	-2000 V
Vidissector DT - Gnd	-1600 V
Vidissector DT - D1	0 V
Vidissector DT - D2	-36 V
Vidissector D9 - Gnd	-265 V
Vidissector D10 - Gnd	-119 V

Power Supply Parts List

	Quantity
Power Supplies	
Electronic Research Associates, Inc. Model #LC3210 4-32 VDC, 12.5a. @ 35°C	1
ACDC Electronics, Inc. Model #BX34DO.6-12 ±34 VDC, 0.6a. @ 71°C	1
Lambda Electronics Corporation Model #LM-D-20-Y 20 VDC, 7.4a. @ 40°C	2
Del Electronics Corporation Model #2.5HRM4N1 1.3 KV - 2.5 KV @ 4 ma.	1

Deflection Amplifier

Celco Model #DA-PP2N-7 input ±2 V output ±2 a	1

Focus Current Regulator

Beta Instrument Corporation Model #FR 1882 20 ma. to 800 ma.	1

Relay

Potter and Brumfield Model #KRP 11 D coil - 500Ω 24 volts nominal	1

Transistor

PNP-2N2905 or equivalent	1

Resistors

30 kΩ, 1/4 W	1
10 kΩ, 1/4 W	1
390Ω, 1/2 W	1
resistor as desired for high voltage adjustment (temp. coeff., 30 PPM or better)	1

Connectors

Burndy (box mount receptacle) Part #BT02-P-10SX 10 socket contacts (#20)	1
Burndy (box mount receptacle) Part #BT02-P-12-10SW 10 socket contacts (#20)	1

Burndy (straight plug) Part #BT06-AC-12-10PX 10 pin contacts (#20)	1
Burndy (straight plug) Part #BT06-AC-12-10PW 10 pin contacts (#20)	1
Burndy (box mount receptacle) Part #BT02-P-14-12SY 12 socket contacts (4 #16, 8 #20)	1
Burndy (straight plug) Part #BT06-AC-14-12PY 12 pin contacts (4 #16, 8 #20)	1
MHV high voltage connector (receptacle and plug) UG932/U	1
Banana jack (heavy duty)	4
BNC jack (standard)	2

Meters

Simpson - Wide Vue Model #1327, 0-50 V	2
Simpson - Wide Vue Model #1327, 0-500 ma	1
Simpson Model #29, 0-3000 V (with external multiplier)	1

Switches

Arrow-Hart and Hegeman Model #82611 DPDT - 15 A @ 125V	5
Arrow-Hart and Hegeman Model #82609 DPDT, 3 position, on-off-on	1

Indicator Lights

Dialco Model #95-0408	5

Lamps

Model #NE-51H	5

Fuse Holders

Littlefuse Model #372001 8AG fuse extractor post	5

Near-Infrared Light Source

The Proximate Oculometer electro-optical unit light source housing has been modified to utilize an A.S.A. FCS tungsten-halogen lamp. This lamp replaces the original GE No. 1982 tungsten-halogen lamp. The FCS lamp has a close-wound, rectangular filament nominally 0.215 x 0.114 x 0.055 inches in size. It is capable of producing a more uniform illumination of the eye space than the former G.E. lamp. The FCS lamp is mounted in a Sylvania TP-3 ceramic socket, attached to the lamp housing by two screws, and is easily replaced, unlike the previous lamp which required wire-soldered connections. Although the lamp is rated at 150 watts (24 V, 6.25 A), it is being operated at a reduced input of approximately 80 watts (16.5 V, 4.9 A). Provision is made on the lamp power supply (LC 3210) for changing the lamp input wattage. The lamp power supply is variable in steps from

4 to 32 VDC by connecting the proper terminals on the bus at the back of the supply. Within each step the voltage is varied by adjusting R_{26} located on the top of the supply.

The lamp output is filtered by the original optical system filters F_1 and F_2 to produce a near-infrared beam to illuminate the subject's eye at the eye space. The illumination beamspread is approximately 1.2^o as determined by the optical system aperture A_2 and lens L_3. (See Ref. 2, pp. 7, 14 and 15.)

The nominal life of an FCS lamp is 50 hours when operating at rated wattage under recommended cooling conditions. An 80-hour lifetime can be expected for the lamp operating at the 80-watt level under the conditions found in the oculometer lamp housing.

When a lamp is replaced due to failure or aging (discoloration of the lamp envelope internally) the following procedure should be used: (1) Remove the socket and the lamp from the lamp housing; (2) remove the lamp from the socket; (3) replace the old lamp with a new one, being careful to keep the lamp envelope free of any contamination such as finger moisture or oils; (4) replace the socket with the screws (5) turn on lamp power and observe position of lamp filament in aperture A_2. This is done by placing the eye at eye space. The lamp filament should be centered in the circular aperture A_2. If it is not centered, remove the socket (with power off) and reposition lamp slightly in the socket. (6) Repeat steps (4) and (5) as often as necessary to secure proper lamp position in aperture A_2. The above procedure insures uniform illumination at the subject's eye on the optical axis of the image dissector in the oculometer.

APPENDIX C

ARTIFICIAL EYE AND MOUNTING DEVICE

An artificial eye and an artificial eye mount were constructed to aid in the testing of the Oculometer system.

The dimensions of the artificial eye, which was machined and polished out of methylmethacrylate plastic ($n = 1.49$), are shown in Fig. C-1. These dimensions match closely those of the human eye and were found to be adequate in the use of the artificial eye assembly to relieve a human subject during tedious system adjustments and calibration tests.

The artificial eye mount (see Figs. C-2 and C-3) was constructed from a modified laser mirror mount, with the addition of protractor plates which are used to determine the horizontal and vertical eye angles.

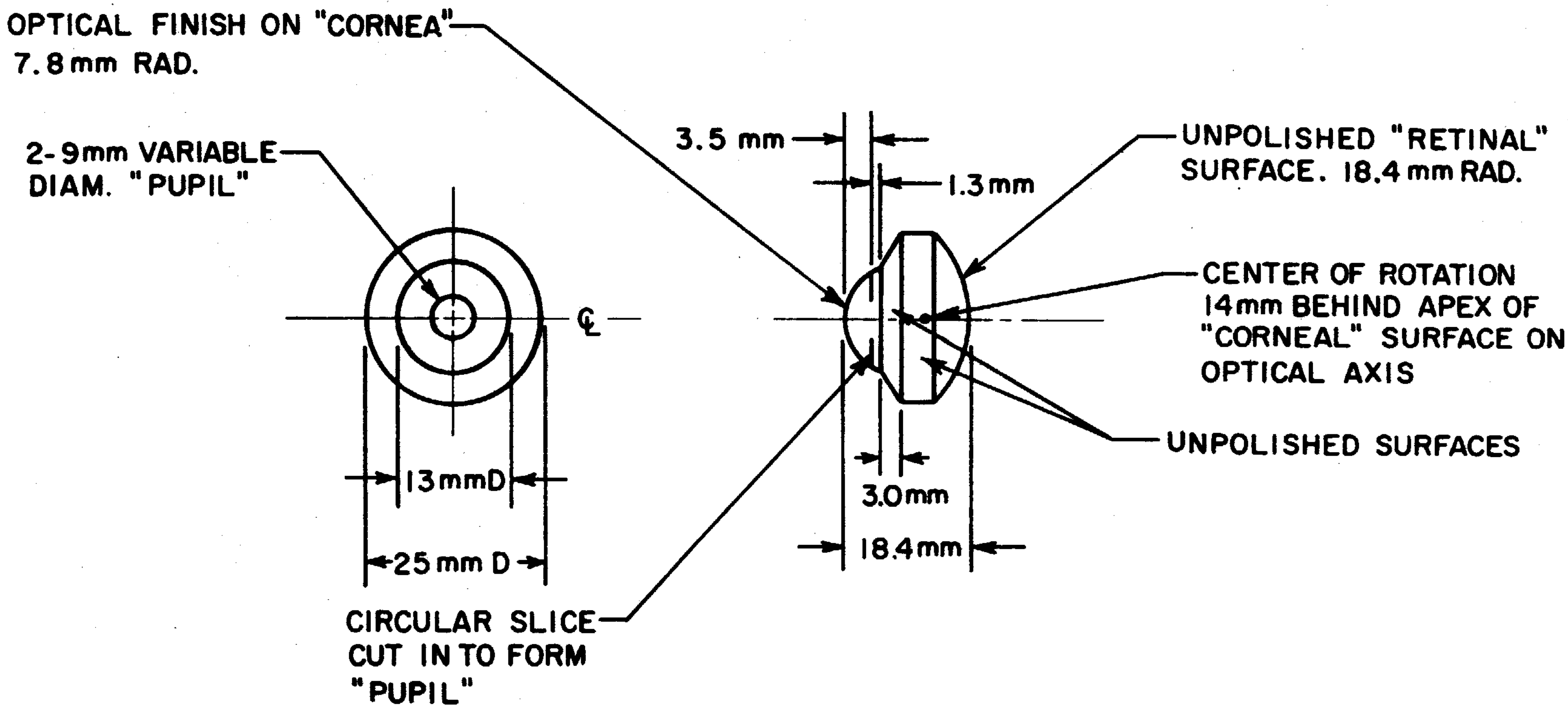


Figure C-1 ARTIFICIAL EYE (PLASTIC)

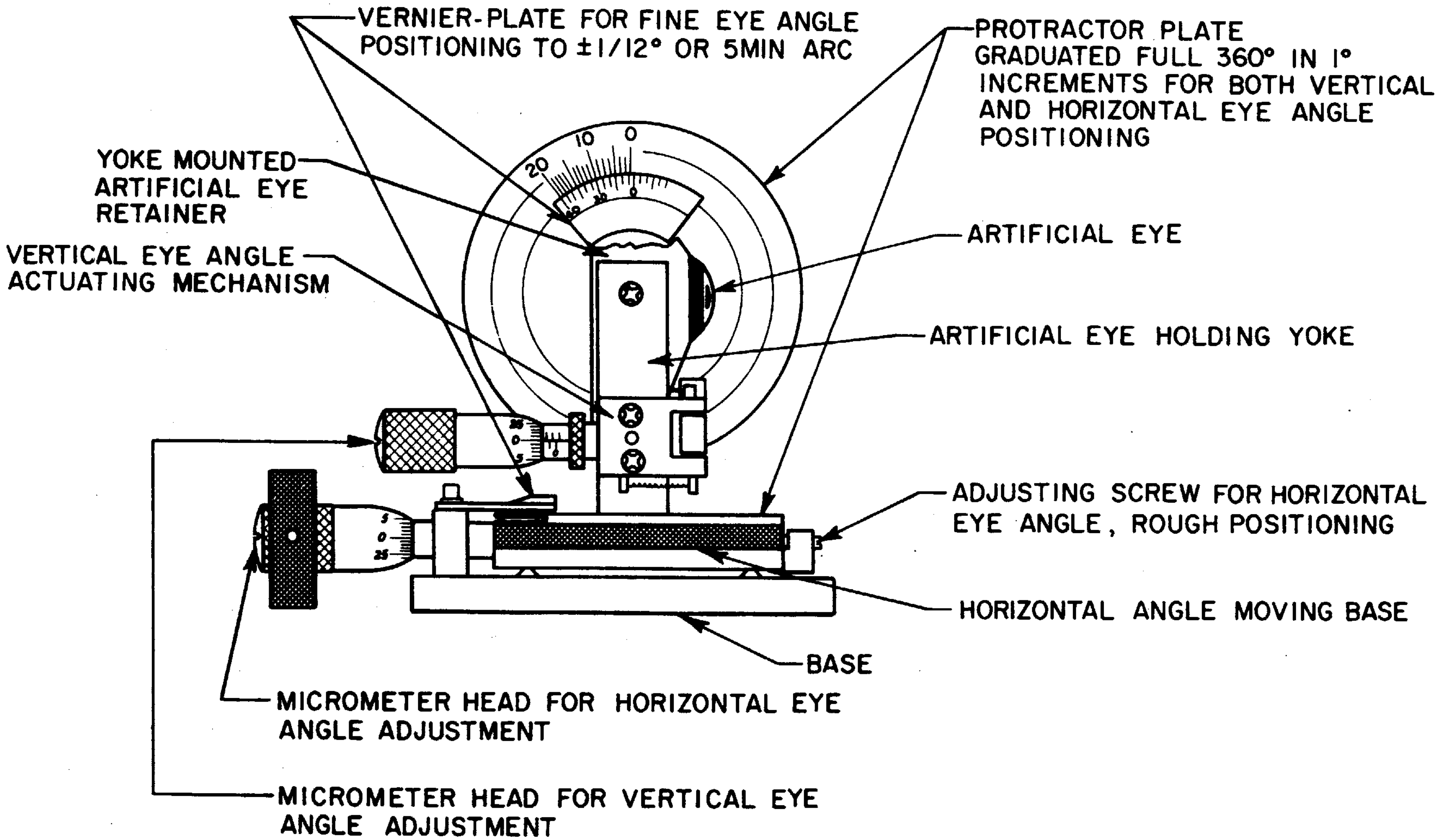


Figure C-2 ARTIFICIAL EYE AND MOUNT ASSEMBLY

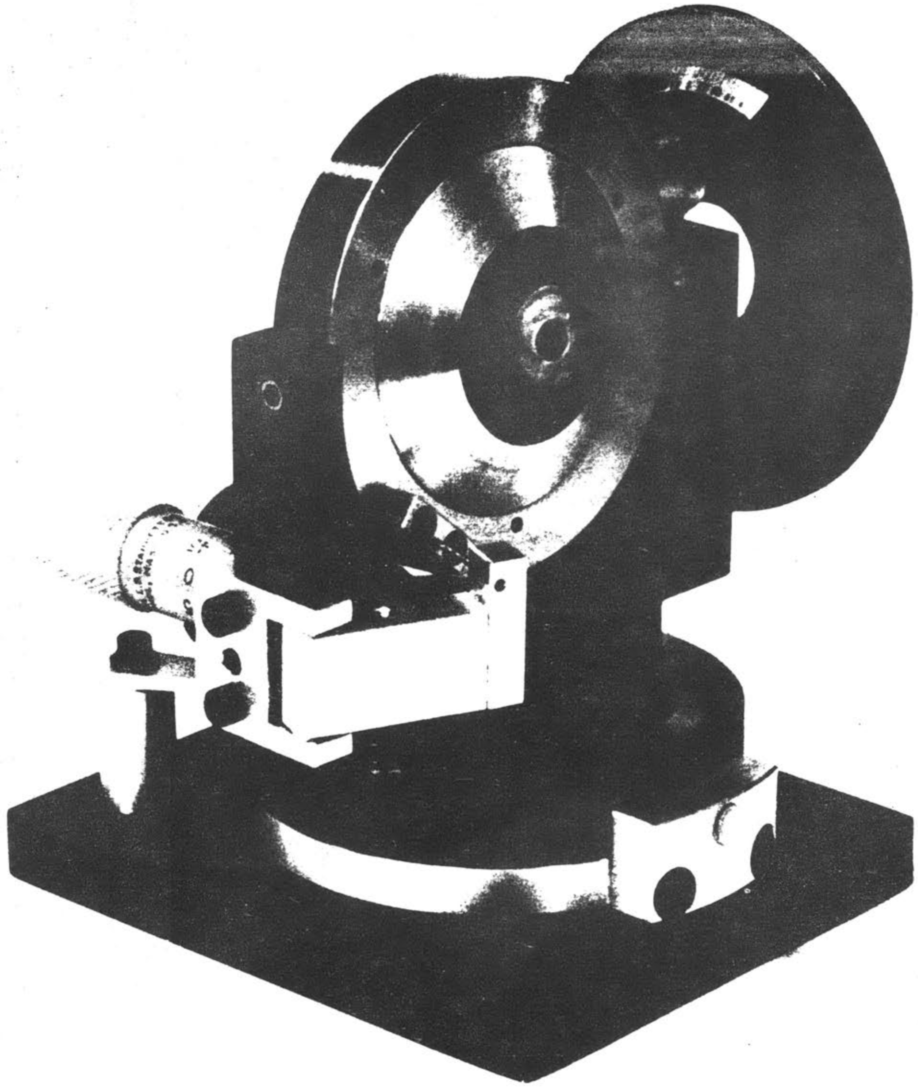


Figure C-3 ARTIFICIAL EYE AND MOUNTING DEVICE

APPENDIX D

DIGITAL COMPUTER FLIGHT SIMULATOR PROGRAM

A digital computer flight simulator program has been written for the M.I.T. Project MAC A.I. Group PDP-6 computer (see A.I. Memo 209, "Digital Computer Flight Simulator," by D. Silver).

The flight simulator instrument panel is displayed on the computer video display while the subject "flys" the simulator with a joystick and a "throttle". The subject is presented with seven (7) instruments on the video display as follows:

a) Gyro compass

b) Air speed

c) Artificial horizon

d) Altimeter

e) R.P.M. (power)

f) Combination rate of turn/slip

g) Rate of climb

The mode of operation of the simulator is as follows:

1) The subject manipulates the joystick with one hand, using three (3) degrees of freedom:

a) left-right for aileron control,

b) forward-backward for elevator control,

c) torque movement for rudder control.

2) The subject's other hand is used to control the "throttle"

in a push-pull motion.

3) The subject is instructed to perform certain maneuvers. The output of the displayed instrument panel (viewed by the subject) is a function of the maneuver performed.

A listing of the digital computer flight simulator program appears on the following pages:

APPENDIX E

"THE OCULOMETER" FILM NARRATIVE

This film was designed to demonstrate the flexibility (and some possible applications) of both digital-computer-assisted and digital-computer-controlled Oculometer systems.

The first scenes show the Proximate Oculometer, the first prototype Oculometer developed for NASA by the Honeywell Radiation Center. In this demonstration the computer is simply utilizing the analog output (eye fixation data) of the Oculometer analog-digital hybrid circuitry. No computer control of the Oculometer is occurring. The Proximate Oculometer is set up in front of the computer video display and the subject views the display through the circular dichroic beamsplitter. Computer-generated words appear on the video display in French. As the words are fixated by the subject their positional coordinates are transmitted by the Oculometer to the computer, which translates them into their English equivalents and redisplays them. In addition, the computer is programmed to vocalize the words as they are fixated and translated.

The next sequence of scenes shows the Remote Oculometer. In these scenes the Remote Oculometer is being program-controlled by the PDP-6 computer through an I/O interface system and an I/O display-type terminal, unlike the Proximate Oculometer shown in the previous sequence. The moving mirror head-tracking system is disabled here and the headrest is used to locate the subject in the field of view of the Oculometer vidissector. On the computer video display are seen images of the various control program eye-tracking patterns and program subroutine displays.

The following scenes show the subject forming various letters by eye movements. The subject is tracking the end of a pointer which doesn't appear in the scene. It should be noted that the eye movements produced are relatively smooth pursuit motions. In the next sequence the formation of letters is attempted without the use of a pointer to follow. The eye movements are not smooth, but rather are a series of saccadic jumps.

The next scene shows the results of the subject's eye tracking a square pattern to provide some suggestion of system output linearity. The linearity depicted here proved adequate for a wide variety of simple demonstrations.

For the demonstrations which appear in the following sequence of scenes a slide was projected on the video display (where the subject was fixating) and the subject (a male) was asked to look at the slide and formulate an answer to a question he would be asked. The first slide is of an attractive young lady and the question asked the first time was "Is this a ship's figurehead?" The subject scanned all the relevant features of the young lady and determined that the features were rather more lifelike than a ship's figurehead. The fixation pattern is shown. Using the same slide the same subject was asked two more questions, "Is it a windy day?" and "Which direction is up in the picture?" The fixation patterns produced by the subject are shown for these latter two questions. Then the sequence of the three fixation patterns are replayed to show the differences that exist.

In the next sequence of scenes a new slide of a young lady is projected and three different subjects are all asked the same question, as follows: "What part of the country was this photograph taken in?" The scanning pattern of the first subject (a rather shy female) indicated a rather strict attention to terrestrial detail. The second subject (a male) indicated by his scanning pattern first an interest in the young lady in the photograph and then proceeded to scan the background for clues. The third subject (another male) showed little interest in the background but much interest in the young lady, as indicated by his scan pattern. Thus, three different fixation patterns of the same object are displayed by three different subjects, which indicate differing approaches to the same visual task.

The final sequence of scenes shows a simulated "ball" game. The ball is being served from up-down and from left-right. The object of the game is to deflect the ball across the proper boundary using the bumper. The bumper with the horizontal bar is joystick-controlled. The bumper with the vertical bar is eye-controlled by means of the Oculometer. Left-right boundary crossing scores for the joystick and up-down boundary crossing scores for the Oculometer. The bumpers, to be effective, must be positioned in front of the ball, in the direction of its motion.

<u>N.B.</u> Because of prohibitive reproduction costs one (1) copy only of this film is submitted with this report.