AUTOMATED MASK ALIGNER FOR MULTILEVEL MASK EXPOSURES

by

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Abstract

An automated alignment system for multi-mask exposures on optical substrates has been built and tested. This system is used in the binary optics fabrication program at M.I.T. Lincoln Laboratory to produce multi-level binary optic lenses.

At present, alignment of masks and substrates is done by simultaneous viewing under a microscope. Manual micrometers are used to perform the alignment.

The automated system includes a CCD camera mounted in the original microscope alignment port. The image received by the CCD camera is sent to a VICOM Image Analysis computer which detects and by image correlation aligns edges. Software, implemented in FORTRAN, computes the polar and translational offsets needed between masks and wafers. This offset controls a piezo-electric amplifier which drives a set of piezo-electric transducers for re-alignment.

Thesis Supervisor: Dr. Wilfred Veldkamp
Title: Associate Group Leader of Opto/Radar Systems at M.I.T. Lincoln Laboratory

Dedication

I would like to thank Dr. Wilfred Veldkamp for supervising my thesis, and especially for giving me the opportunity to work in such a stimulating environment as M.I.T. Lincoln Laboratories. Also, many thanks to Mr. Philip Bundman for pushing me forward when the project became more and more difficult. To Marsden Griswold, thank you for the immense technical expertise you shared with me throughout this project. This system is ultimately for you. To Dr. David Biron and Dr. Murali Menon, your help has proved invaluable to the success of this project. To my roommate Tom Wilson, thanks for being a friend even when the times really got rough. Finally, the ultimate thanks go to my parents. Without your support, I could not have survived these past four years. Let this be the first of many great thanks to you.

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Introduction

The function of the Binary Optics Fabrication Laboratory at M.I.T. Lincoln Laboratories is to fabricate novel optical components such as microlenses on optical substrates such as silicon dioxide, silicon, and germanium. These microlenses are used for conventional optics such as aberration corrected lenses, laser radar and passive surveillance applications. As their name implies, microlenses are extremely small. They can be on the order of 50 to 500 microns in diameter and are typically the thickness of a human hair. To make microlenses with continuous, aberration corrected profiles by conventional optics is very difficult with current machining tools. What we in the Binary Optics Fabrication Laboratory are doing is to utilize VLSI fabrication techniques to implement approximations of Fresnel phase patterns with a quality of $\lambda/50$. An example of what this approximation looks like is shown in the figure below.

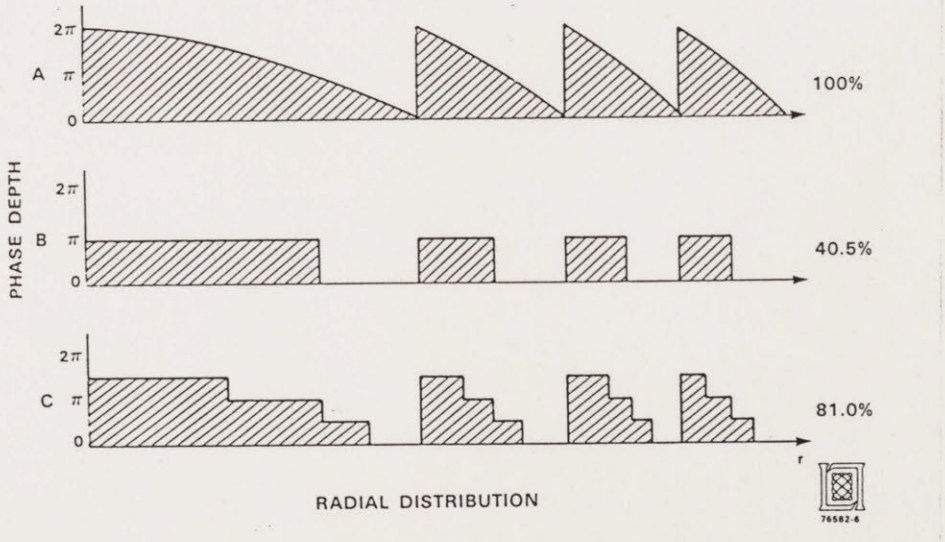


Figure 1: Fresnel approximations and their diffractive efficiencies

In the past researchers in the laboratory have used binary coded masks to implement up to

sixteen level phase patterns. The efficiency of a lens structure is often expressed in terms of its ability to focus light into a particular point. Sixteen level approximations of Fresnel zone plate phase patterns have 99% efficiency. The relationship between the number of levels in the lens structure and the efficiency of that lens are illustrated in figure 2. The only way to improve the efficiency of these lenses is to increase the accuracy of the approximation.

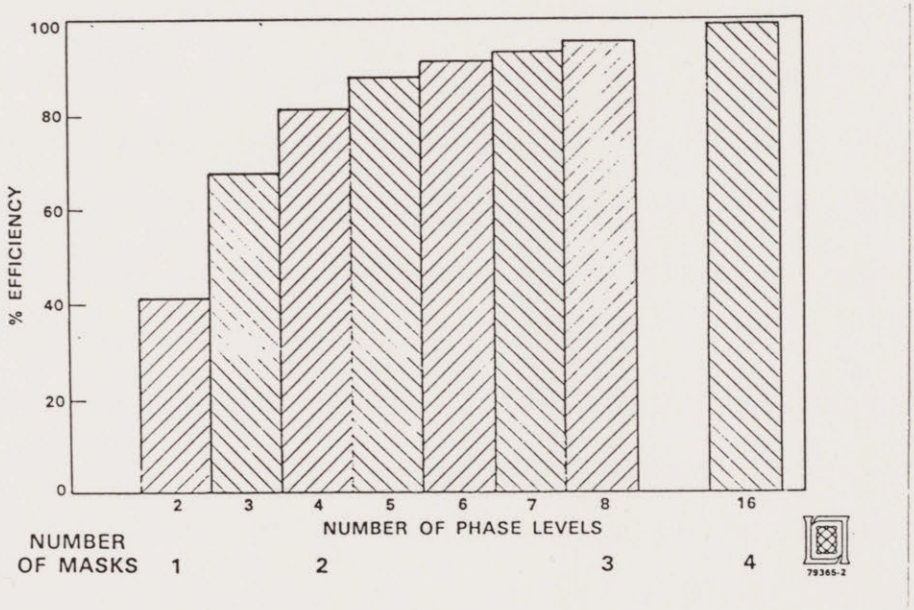


Figure 2: MULTILEVEL PHASE STRUCTURE
1st ORDER DIFFRACTION EFFICIENCY

The way these lenses are fabricated is by first coating a silicon dioxide substrate, or other material, with a layer of photoresist. A mask with the necessary microlens pattern etched into it is brought into contact with the photoresist. The photoresist is then exposed through the mask by ultraviolet light. The exposed photoresist is chemically dissolved. The exposed silicon dioxide is then etched using reactive ion etching and the photoresist as the etch-stop. When the remaining photoresist is removed, one is left with a binary approximation of a Fresnel zone phase pattern.

In order to create more levels in the substrate, thereby improving the efficiency of a microlens, the above process must by repeated with a different mask. Another coating of

photoresist is applied to the silicon dioxide substrate. A second mask is brought into contact with the substrate. Once this second mask is aligned with the features already present on the substrate, the process of photoresist exposure and etching is performed just as before, resulting in a more accurate Fresnel lens approximation. This process is shown in figure 3. This same process can be used to make arrays of such lenses as shown in figure 4.

Herein lies the difficulty in producing multilevel optic lenses. Since the smallest feature sizes are on the order of a half micron in width (close to the resolution limit of a 40x microscope objective), the alignment of the second mask to the substrate is very difficult. The mask must be aligned to the features of a half micron in width already present on the substrate. Currently, a technician performs the alignment by looking at the mask and substrate under a microscope. He positions the substrate under the mask by adjusting a set of three manual micrometers. The task requires an experienced technician about an hour to perform.

The goal of my work is to expedite this tedious process by designing and implementing an automated mask aligner system for multilevel lens exposures. This system will automatically perform fine alignment of a mask and substrate by image correlation. A CCD (Charge Coupled Device) camera captures the images of the mask and etched substrate. These images are digitized by a VICOM image analysis computer. I have developed an algorithm for correlating the two images. This algorithm utilizes a fast hill-climbing technique for finding the translational and angular difference between two images. I have configured a computer to use the output of this algorithm to control the movement of piezo-electric translators. These piezo-electrics position the substrate underneath the mask. The piezo-electric devices offer an extremely high degree of accuracy (about 100 - 200 angstroms) which cannot be achieved with manual micrometers. Hence, they are a very important part of this system and their properties will discussed in later sections of this thesis.

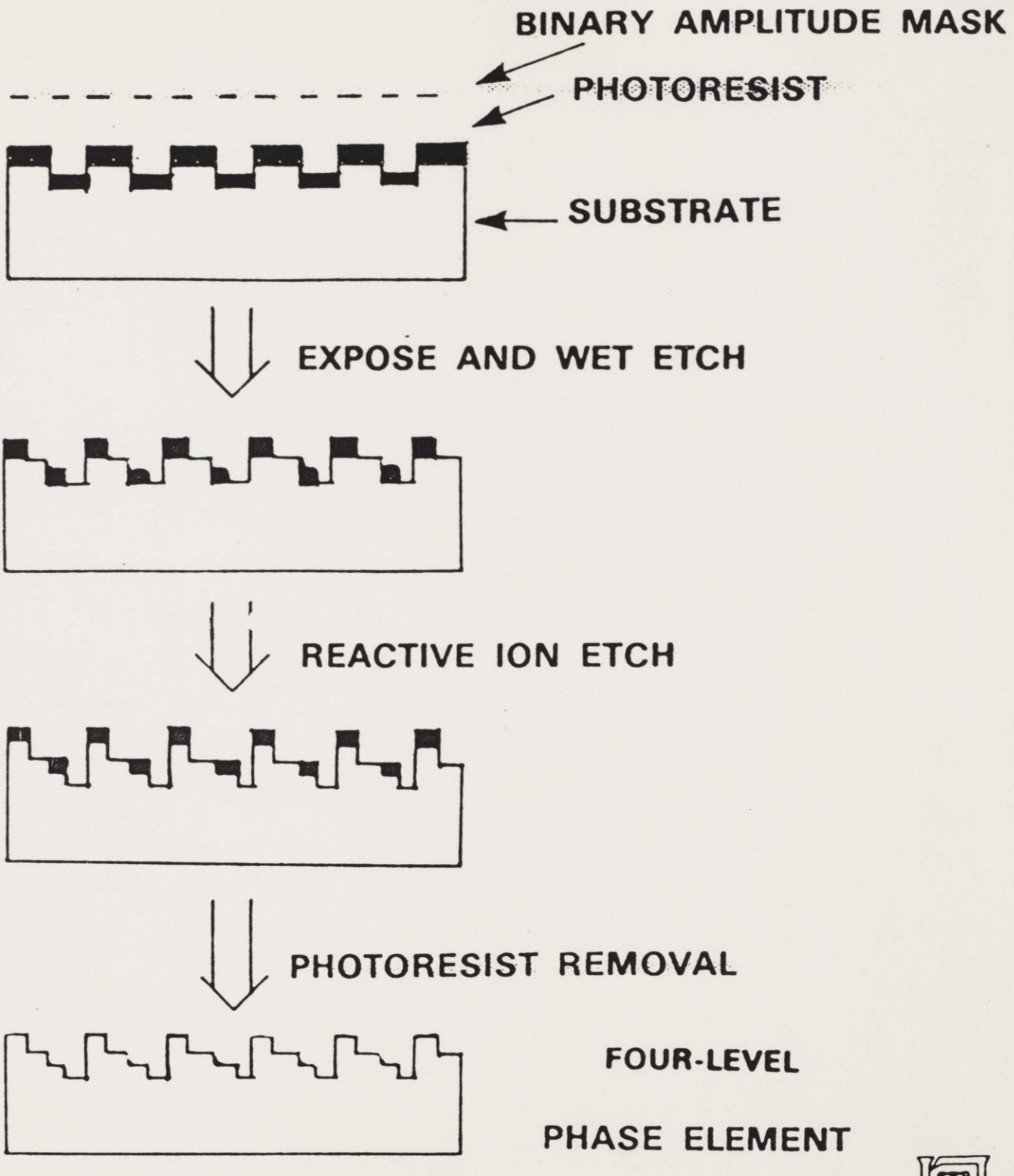


Figure 3: BINARY ELEMENT FABRICATION

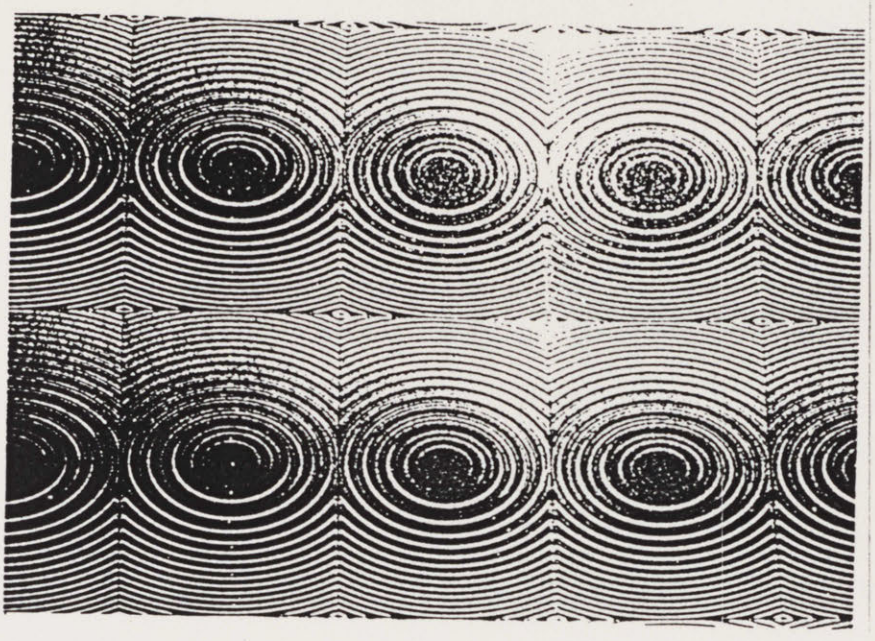


Figure 4: TWO-DIMENSIONAL MICROLENS ARRAY

Chapter 1

Understanding the Automated Mask Aligner System

As mentioned in the introduction, the mask aligner system automates the process of aligning masks to optical substrates. A diagram of the system is shown in figure 1-1. In this section I will outline how the system operates. I will describe in more detail the design and the testing of the individual system components in the sections to follow. The image correlation program is the brains of this entire project and its design, while only outlined here, will be described in greater detail in a later section. Prior to operating the system, the technician must check to see if the VICOM image analysis computer is operational. Appendix lists steps for troubleshooting the VICOM.

A Nikon microscope with a CCD camera attached to its body allows the technician to view the mask and the substrate on a TV monitor simultaneously. The TV monitor has an additional benefit of allowing several people to watch the alignment process at once. A BASIC program on a Turbo-XT personal computer allows the technician to control the alignment process. When the technician turns on the PC and enters "align" followed by return, the PC starts a system control routine written in BASIC on the PC. The PC is connected via an RS232 line to a VAX mainframe in another room. After the PC starts the system control routine, the PC runs a batch file which automatically logs the technician into an account on the VAX computer. Once the technician is logged onto the VAX, the image correlation program starts automatically. The program asks the user to focus the microscope on the substrate. The user does so and hits a key. Then the program calibrates the system. The correlation program runs a calibration test. This is necessary because the alignment stage, microscope, and CCD camera do not always have the same orientation with respect to each other. The correlation program needs to have some frame of reference by which to do the correlation and hence the alignment. The program sends a command to the VICOM to digitize and store the image of the substrate on the VAX hard disk. Next, the program sends a command to the PC via the RS232 line. The system control routine,

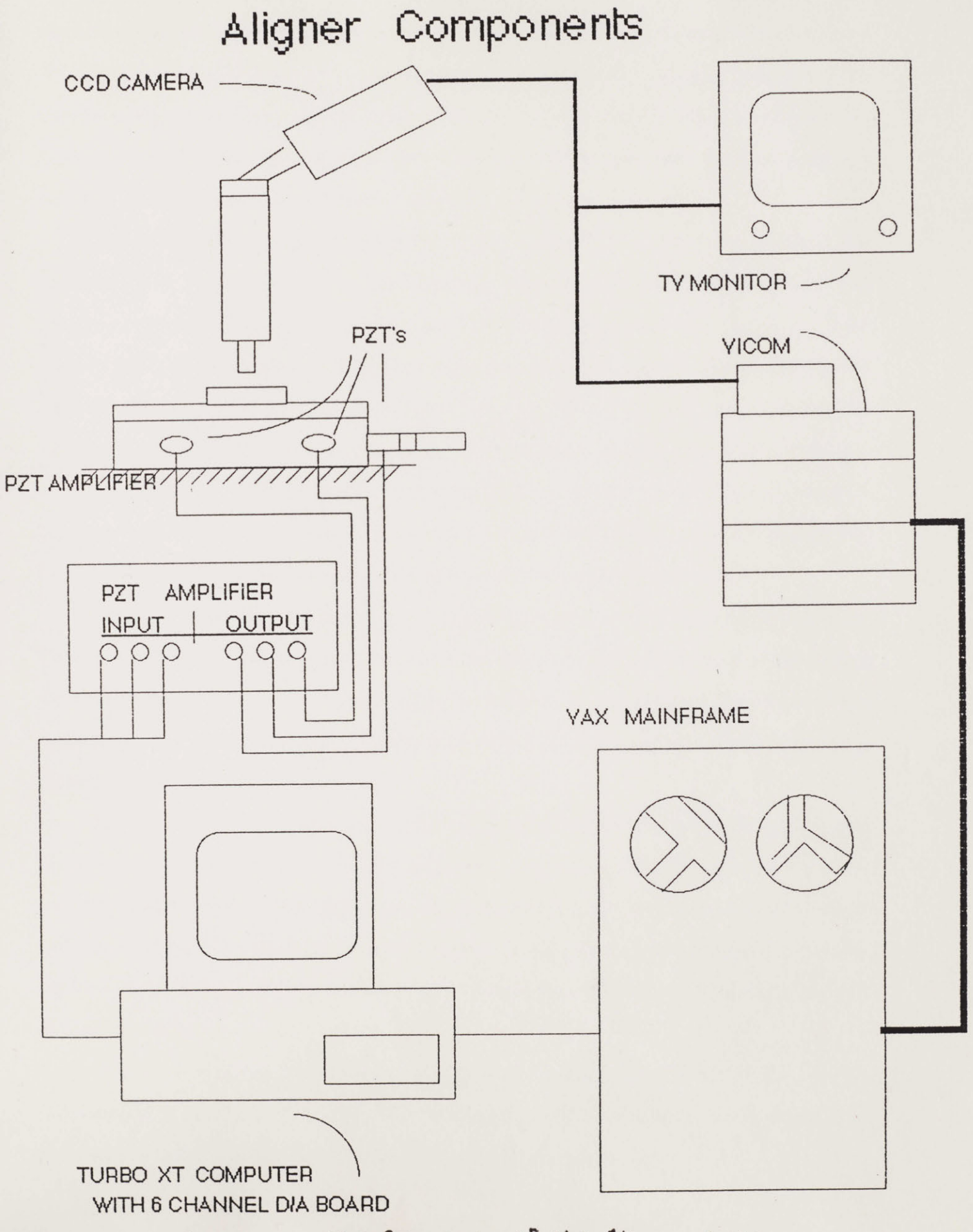


Figure 1-1 : The Components of the Aligner System

which is designed to trap messages sent over the RS232 lines, reads the message and moves one of the piezo-electric devices by a certain amount. The correlation program commands the VICOM to digitize and store this new image. With these two images the program computes the calibration factor for the alignment process. The correlation program then sends a message to the PC to move the piezo-electrics back to their original position.

Now the correlation program asks the technician to focus the microscope on the mask. The technician does so and hits a key. The technician does not have to do anything else. The correlation program once again commands the VICOM to digitize and store the image of the mask on the VAX hard disk. The correlation program calls two subroutines. The first subroutine reads the images of the mask and substrate from, the VAX hard disk and computes the coordinates of the centroids of the two images. The correlation program uses these coordinates to calculate the x-y offset (in pixels, as the image is represented on the VICOM monitor) between the mask and substrate. The second subroutine utilizes an iterative hill-climbing technique to rapidly calculate the angular offset between the mask and substrate.

So far all of the data calculated by the correlation program is in terms of pixel lengths. These x-y and angular displacement data have to be translated from pixel units into the voltage levels necessary to drive a set of piezo-electric transducers. This translation is performed by a subroutine called by the correlation program. How this translation is performed will described in the section on software.

The output of the correlation program is sent to the PC via an RS232 line. A data-trapping program written in BASIC on the PC stores this data as variables. A BASIC subroutine uses the variables to drive the PC's D/A (digital-to-analog) conversion card. The analog voltages that are the outputs of the D/A card drive an amplifier which, in turn, drives the piezo-electrics. Finally, the three piezo-electrics push the section of the alignment stage which holds the substrate into its desired orientation.

This is not a closed loop system. The system is designed to perform a highly accurate alignment on its first try. Real time feedback control cannot be accomplished in software because the number of calculations necessary to perform a correlation are too great.

Now that I have outlined what the system does, I will describe in detail how each of the individual hardware components operates and how they have been designed or configured to meet the needs of this thesis.

Chapter 2

System Hardware

2.1 Microscope & Camera

I feel that the best pieces of hardware to start off thesis with are those devices which provide the aligner system with its primary input. The key issues at this point of the thesis are (1) resolution, (2) magnification, (3) field of view, and (4) depth of field. In this section I will address these issues while a discuss how I configured this stage of the system.

The first step in the development of the automated mask aligner system entailed mounting a high resolution CCD camera to the body of the same Nikon microscope used for manual alignment. The Nikon microscope can be adjusted to utilize one of 4 different objectives: 5x, 40x, 60x, and 100x. The following table lists important data for these microscope objectives.

Magnification	Numerical Aperture	Working Distance (mm)	Focal Length (mm)
5x	0.1	7.528	37.64
40x	0.5	5.26	5.26
60x	0.7	4.898	3.49
100x	0.8	3.264	2.04

Table 2-I: Properties of the objectives

The masks and substrate under the microscope can be examined using back or front illumination. Light entering the microscope through the objective lens is focused out to infinity.

This collimation of light inside the microscope is important in trying to implement television microscopy. The CCD camera that I chose to use was a Sony XC57 high resolution

black and white camera. The CCD contains 510x492 picture elements. The camera has a horizontal resolution of 380 lines and a vertical resolution of 525 lines. The minimum illumination for the camera is 3 lux. The sensing area of the CCD is 8.8mm x 6.6mm. I removed the camera's lens in order to expose the CCD to the collimated light within the microscope.

In order to allow many individuals to watch the alignment process at the same time, the video signal from the CCD camera is sent via a 75 ohm coax cable to the video input of a Sony Trinitron color monitor. The specifications for the Sony Trinitron and Sony XC57 CCD camera are listed in the Appendix .

Two key issues are: (1) what is the resolution of the objectives and CCD camera together, and (2) how much of the specimen can be seen on the TV screen given the four objectives (i.e., the system's field of view). The resolution of a given objective (defined as the minimum resolvable spot size) of a given objective can be calculated from the following formula:

$$\Delta x = \frac{\lambda F}{A}$$

where Δx is the spot size in meters, λ is the wave length of the light used to illuminate the specimen, F is the focal length of the objective, and A is the diameter of the objective lens. The assumed wavelength of light is 5500 angstroms. Using this value and the data given in table 1, we can calculate the diameter of the smallest spot resolvable by our objective lenses.

Magnification	$\Delta x(\mu m)$
5x	2.80
40x	0.55
60x	0.39
100x	0.34

Table (2)

Table 2-II: Resolution of the Objectives

The resolution of this system is determined primarily by the objective lens. The CCD camera and television monitor can only reduce the total system resolution. The resolution of the CCD camera is a function of its number of picture elements on a sensing area of 8.8mm x 6.6mm. Therefore, each individual pixel element has an area of 17.3 μm x 13.4μm. With the

100x objective a spot of 0.34μm in diameter will be magnified to 34μm on the CCD. Since this is greater then the size of CCD picture element, system resolution is not reduced. For the 60x objective a 0.39μm spot will be magnified to 23.4μm, which still fully encompasses a CCD picture element. As we decrease the objective magnification to 40x, resolution begins to drop dramatically. A 0.55μm diameter spot will be magnified to 22 μm. This spot diameter is still greater than the diagonal of one picture element which is 21.9μm.

At 5x magnification the minimum spot size of 2.8μm will be projected onto the sensing area as a 14μm spot. Since this is below the size of the picture elements, resolution will be determined by the size of the picture elements rather than by the objective lens. This means that the minimum resolvable spot size for a system using a 5x objective and a CCD camera is

$$\frac{21.9\mu m}{5} = 4.38\mu m$$

.

This is a poor level of resolution given that the smallest feature size can be less than 1μm. Thus, the 5x objective lens is used by technicians in the laboratory for roughly orienting the substrate underneath a mask.

In order to calculate the field of view of the system, consisting of the microscope's objective lens and CCD camera we divide dimensions of a CCD picture element by the magnification of the objective lens.

Objective lens	Field of View
5x	1.32mm x 17.76mm
40x	0.165mm x 0.22mm
60x	83μm x 147μm
100x	66μm x 88μm

Table 2-III: Objective fields of view

Also, the Sony Trinitron TV monitor has a 2% zoom factor which reduces the effective field of view by 2%.

The final issue in this section is depth of field. This issue is important because one of the constraints on the aligner system is that it has to be able to focus on one image at a time, either the mask or the substrate. After testing the correlation program with various masks and substrates I found that depth of field would not be a problem.

2.2 Vicom Image Analysis Computer

The VICOM Digital Image Processor is a combination of general purpose computational and image processing elements. The VICOM contains an internal microcomputer for direct user control but also has the capability of being operated as a peripheral device to the VAX computer for digitizing, subsampling and storing images.

The output of the CCD camera described in the section on optics is transmitted into a TV monitor in the clean room and into the video input port of the VICOM I/O Box. The VICOM I/O box can be found in the computer room on top of the VICOM disk drive unit. Occasionally, other workers in the laboratory must remove the CCD camera cable from the VICOM. Therefore, whenever one is using the alignment system, one must check that the CCD camera is connected to the VICOM. The cable is marked with a green tag and can be found behind the VICOM disk drive unit.

If the camera is connected to the VICOM, and the VICOM is switched on and functioning properly, the question becomes: What does the VICOM do to an image coming from the camera? When the VICOM receives a real-time image from a camera, the image is sampled as 512 x 512 pixel arrays. When the camera receives an image, each pixel is represented as a 16-bit integer for logical and graphics operations. However, for my thesis, I am utilizing the images in mathematical operations. The VICOM manual states that if one wishes to use images for arithmetic operations one must convert the pixels from 16-bit integers to 16-bit two's complement numbers. In the next paragraph I will show how I did this. In two's complement format, pixels are scaled in amplitude between plus and minus one with an amplitude of zero representing black and amplitude of one representing white. I do not utilize the negative amplitude representations in this thesis.

When the operator digitizes the image, the last sampling of the real time image is loaded into one of four 512 x 512 x 16 bit memory circuit boards. Once an image has been digitized, the memory configuration of the VICOM can be changed in order to extract a 128x128 pixel subsection of the original image. This ability to extract and store a smaller section of an image is very important because it can reduce the number of calculations performed by the correlation program.

Now, I shall explain how I programmed the VICOM to perform the various tasks necessary for this thesis. As mentioned previously, one of the first tasks of the correlation program is to capture and digitize the image of the substrate. The correlation program does this by calling a VICOM command file called PRIME1.VC. The mechanics of how the correlation program calls a VICOM command file are explained in the software section. For now, allow me to focus on the VICOM itself. The PRIME1.VC file looks like this:

```
zer 1
vds clo=3
two (7)
cam
zer 1
vds clo=3
cam
zer 1
vds clo=3
cam
dig 2
mem 2>1 (128 128 128 128 1 1 1 1)
```

Figure 2-1: PRIME1.VC

The "zer 1" command clears memory circuit board #1 by loading it with an image whose pixels all represent zeroes (black). The vds clo=3 command sets the VICOM's internal clock source to phase-lock loop. Selecting phase-lock loop as the clock source is necessary in order to synchronize the VICOM with the CCD camera's signal frequency which is 59.94 hz vertically

and 15.734 khz horizontally (see Appendix . The "Two (7)" command performs the conversion from 16-bit integer pixel representation to 16-bit two's complement representation. The "cam" command activates continuous video acquisition from the CCD camera. Sometimes the VICOM's phase-lock loop does not perfectly lock onto the CCD camera's video frequency. The manifestation of this is a image that scrolls across the VICOM monitor. This is a problem because attempts to digitize a scrolling image can result in a split image. To solve this problem I repeat the above four commands, with the exclusion of the "two(7)" command, twice. Each successive iteration improves the phase-locking. The "dig 2" command digitizes the image and stores it into a secondary array. The MEM command removes a 128*128 pixel section from the center of the original image. Now the image is ready to be stored on the VAX hard disk.

2.3 AOB6 Digital-to-Analog I/O Board

By going from a discussion of the VICOM to describing the AOB6 D/A board, I have skipped software control. However, I think it will be helpful to anyone considering using, repairing, or possibly redesigning this system if I separate the hardware issues from the software issues. With this in mind, allow me to describe the function of the AOB6 D/A board.

The AOB6 board is an analog/digital I/O expansion board for the IBM PC and its compatibles. The board is built by Industrial Computer Source (ICS). The board provides 6 channels of 12 bit analog output and 24 lines of digital I/O. The 6 independent 12 bit D/A converters are individually switch and jumper selectable to the following ranges:

0 to 10 volts
0 to 5 volts
-2.5 to +2.5 volts
-5 to +5 volts
-10 to +10 volts
4-20mA current loop

Figure 2-2: D/A board output options

The D/A board has a rear 37 pin D type connector. Each D/A output uses one pin. See figure 2-3 for connector assignments. My application only requires 3 channels, which are indicated in the figure. The board's specifications are listed in Appendix .

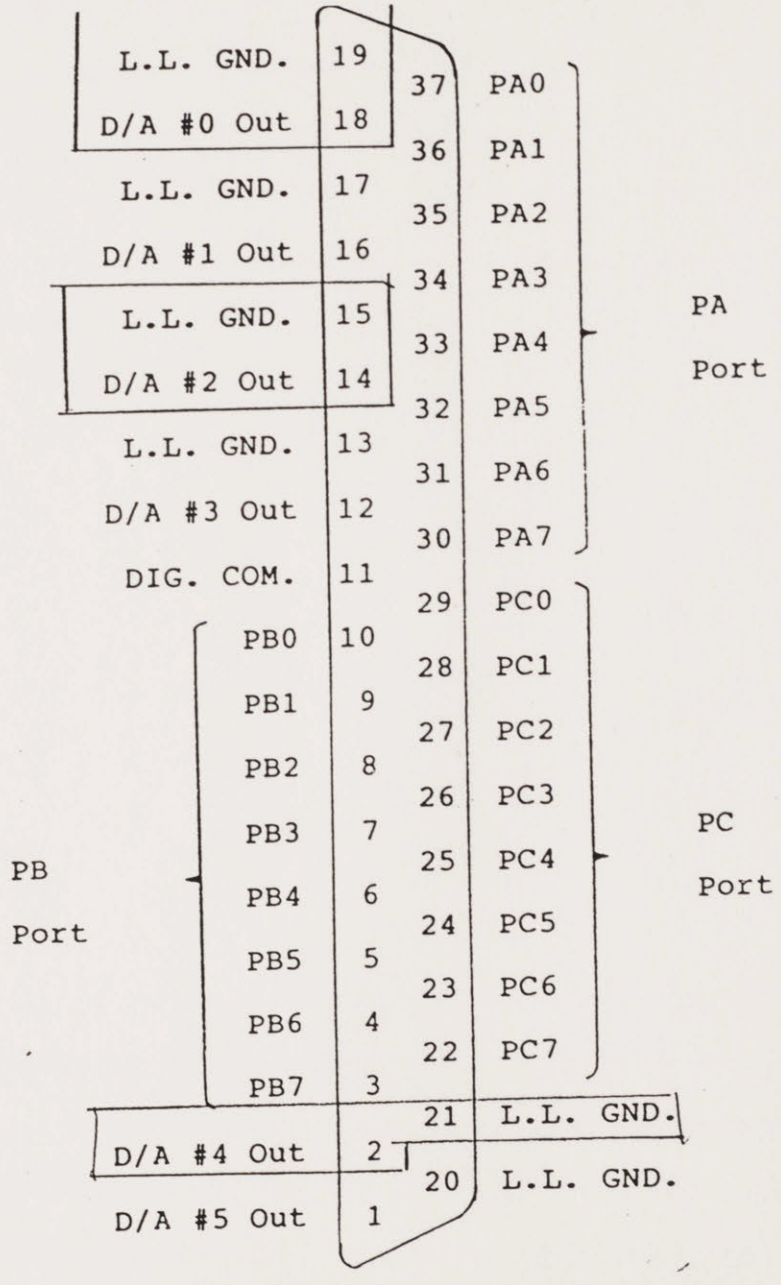


Figure 2-3: Pin Assignments for D/A board

The purpose of the D/A board is to interface between the PC and the piezo-electric amplifier. The PC, by communicating with the VAX, has calculated how much a given PZT has to be moved by. The PC then converts this positioning data into a number between 0 and 4095 (12 bit decimal representation for 10). This number is written to the D/A card which converts this number into a DC voltage between 0 and 10 volts.

The piezoelectric amplifier that I am using requires input voltages between 0 and 10 volts. I set the D/A channels to output in this voltage range by setting the board's dip switches to the following configuration:

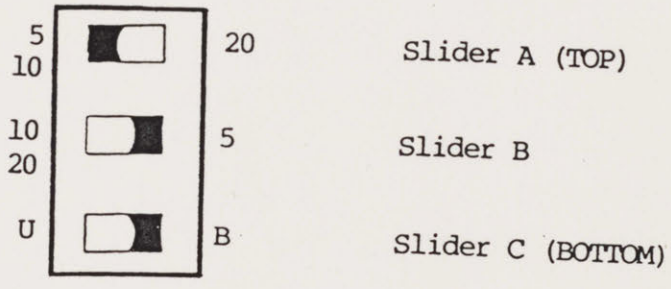


Figure 2-4: Dip switch configuration for 0-10V operation

The location of the dip switches on the board are shown below. Before inserting the board into the PC one must also set the jumper cables to voltage mode. The Base address switch is preset at &H300 (300 Hex, 768 Decimal). This address allows a software program on the PC to send data to the D/A card for conversion. Once the board has been plugged into the PC, one has to write a program to control the board. ICS provides the following BASIC program for performing this data transfer operation:

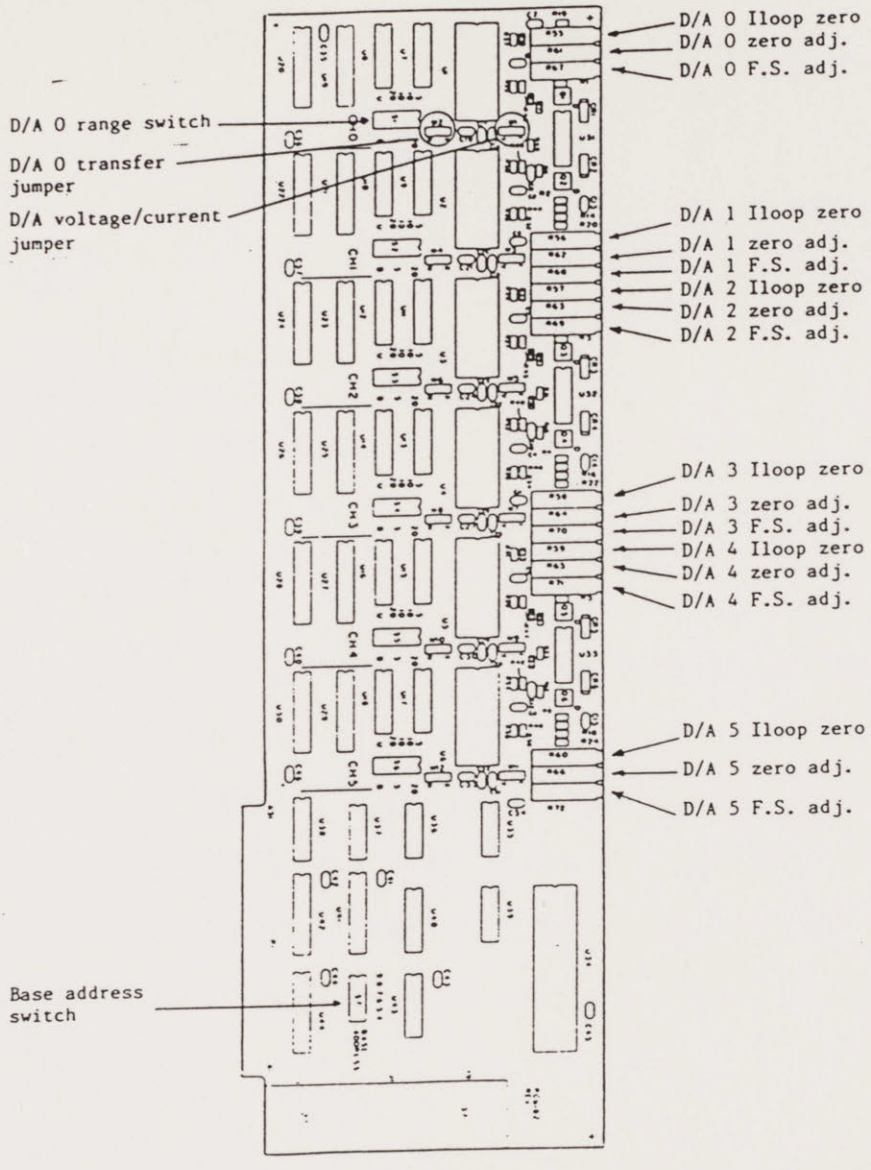


Figure 2-5: D/A Board Configuration

```
1000  XH% = INT(D/256)          'high byte
1010  XL% = D - XH%*256         'low byte
1020  OUT BASE + 2*N, XL%       'write low byte to D/A
1030  OUT BASE + 1 + 2*N, XH% 'write high byte to D/A
1040  RETURN

D = data (range 0 - 4095 decimal)
N = D/A channel number (range 0-5)
```

Figure 2-6: D/A board control routine

2.4 Piezo-electric Transducers and Piezo-Electric Amplifier

Now that the computer will generate 0 to 10 volt signals, these same signals must be amplified in order to drive the PZT's. The amplifier chosen is a model CTC-265-1 high voltage amplifier, built by Control Technics Corp. It can produce between 0 and -1000 volts at +/- 22 milliamperes. It has a slew rate of 6 volts/microsecond. The PZT's I am using are model CTC-6095-15's (specifications are in Appendix) which are also made by Control Technics. The key issues in selecting what types of PZT's to use were:

1. maximum excursion
2. minimum excursion
3. maximum load capacity

The maximum excursion of these PZT's is 15 microns, which is sufficient for our application. Minimum excursion is important because the technicians have to align microlens features which are less than half a micron in width. The PZT's have to be able to make movements smaller than this. The CTC-6095-15's provide excellent resolution. If one divides the maximum excursion of the PZT's by their voltage range, the resolution of the CTC-6095-15's is 15/volt nanometers! Finally, the springs contained within the alignment stage are very strong and can generate up to 25 lbs of force on a PZT. In this respect the CTC-6095-15's provide a very sufficient safety margin because they have a maximum load of 50 lbs.

2.5 Mounting PZT's to the Alignment Stage

Mounting PZT's to the alignment stage is a task which must be done with extreme care because any movements by them would ruin an alignment. First I will describe the alignment stage itself and how one operates it. Then, I will discuss the issues that went into designing the PZT couplings. Finally, I'll describe how I designed the PZT's.

Figures 2-7 and 2-8 shows the alignment stage. The alignment stage consists of 3 levels. The first level, which is in contact with the table, does not move. A set of three manual micrometers are mounted to the stage at this level. The second level is a moving stage. The manual micrometer heads push against this level. Springs within the stage force this level of the alignment stage to the right and towards the operator. This stage also contains a holder for the optical substrate. Two fiber optic cables which enter the alignment stage from the rear of the stage have their terminations just below the substrate. These fiber optic cables provide helium-neon laser and diffuse back illumination to the substrate. Also, a tube from a vacuum pump terminates at the substrate holder to provide suction which holds the substrate in place.

The top level, which is mechanically uncoupled from the bottom stage, contains a holder for the mask. A tube from the vacuum pump enters the stage and terminates in an air-tight gap between the mask and substrate. When the technician completes an alignment, he applies suction pressure to contact the mask to the substrate.

If PZT's are to be mounted to the alignment stage, they should be mounted on the tips of the manual micrometers already present. This allows the technician to perform gross alignment with the micrometers. Coupling the PZT's to the micrometers reduces the excursion range of the micrometers by about 3mm, however. The micrometers have an excursion range of 15 mm. Mounting PZT's to the tips of the micrometers moves the micrometers 9mm (the length of a PZT) away from the alignment stage. Therefore, either a new mount or an extension to the old mount must be designed. Clearance between the bottom of the PZT and the top of the first level of the alignment stage was a problem. Also, the PZT coupling must have a tight fit around the micrometer head. A tight fit will prevent the PZT from tilting when shear force is applied to its

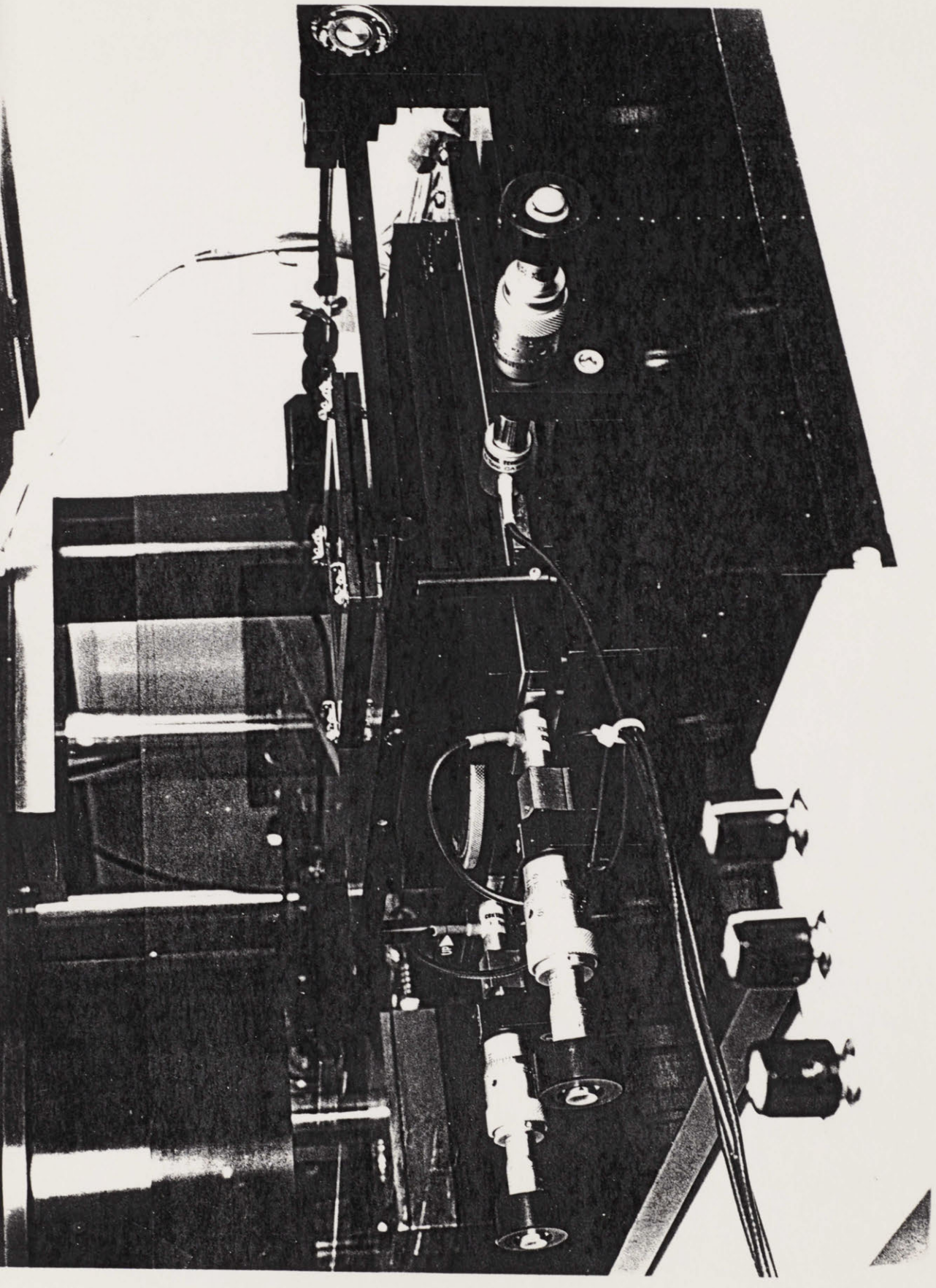


Figure 2-7: On-side view of the alignment stage

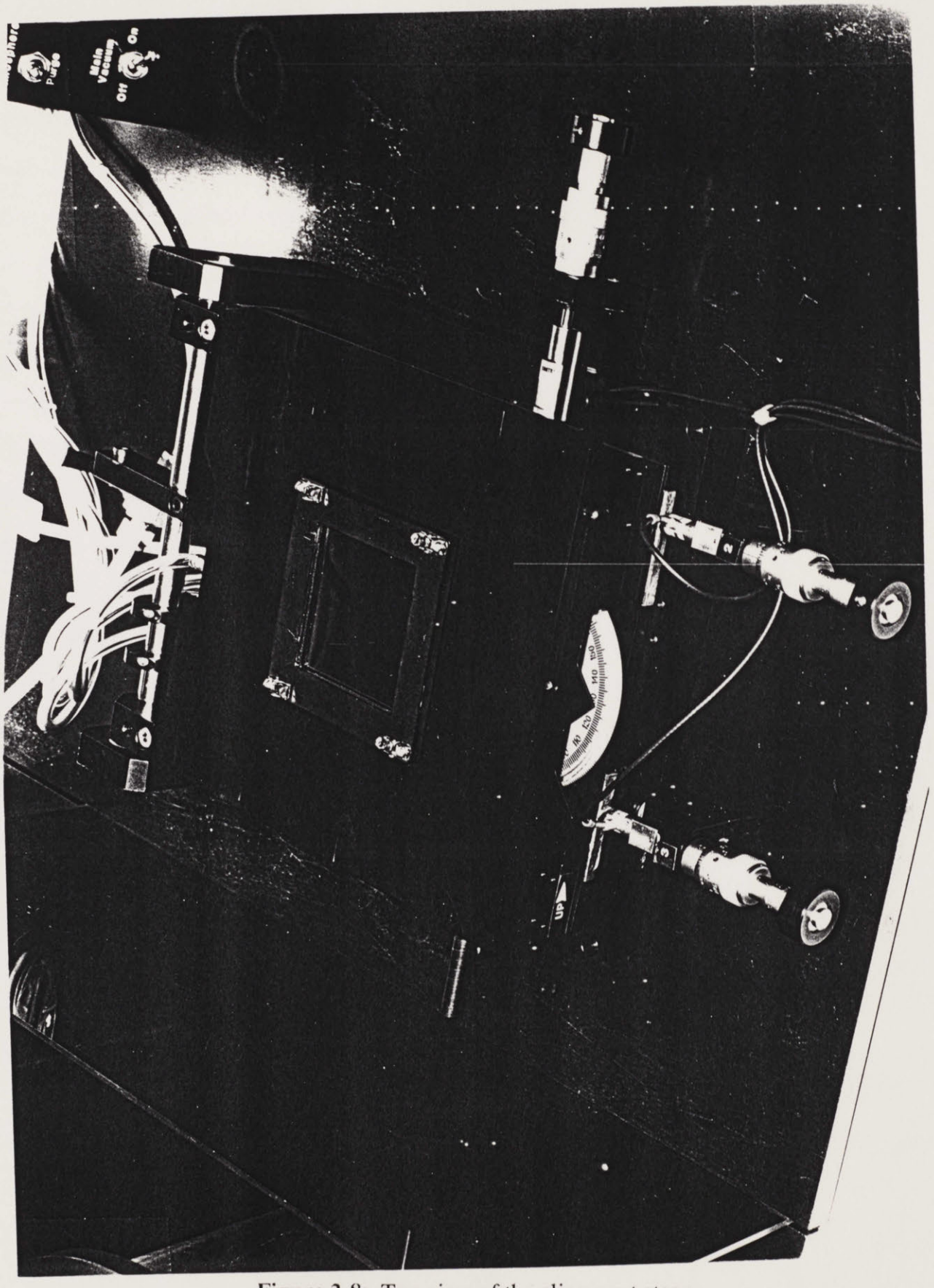


Figure 2-8: Top view of the alignment stage

tip in a direction perpendicular to its long axis. The PZT's have steel ball tips which are only 75/1000" in diameter. Since the alignment stage is made out of aluminum, the steel tips eventually etch grooves into the stage. The tips then catch the ends of these grooves when the alignment stage is pushed laterally with respect to the PZT. I ordered the PZT's with the steel ball tips because they reduce friction between the PZT and the alignment stage. It is this friction which can cause rotation of the PZT away from the long axis of the micrometer. Finally, the position of the cable entering at the side of the PZT can also be a problem. A tight coupling fit around the micrometer head will cause the PZT to rotate about its long axis due to friction between the coupling and the micrometer head. Eventually, the cable would be forced against the first level of the alignment stage. This causes the cable to bend, damaging the inner conductor of the cable at the point of entry into the PZT where it cannot by repaired.

The following is a description of a design which solved these problems. I ordered the PZT's with tapped holes in their base so that a coupling could be screw-mounted into the PZT. I designed the sleeve of the coupling with a tight tolerance in order to avoid any lateral movement by the PZT's. The micrometer head has a diameter of 0.197", so I designed the inside of the coupling sleeve to have a diameter of 0.2005". The couplings are square and wide enough so that they are flush with the top of the first level of the alignment stage. Being square prevents the couplings and the PZT's which are attached to them from rotating and inflicting damage on the cables. Finally, I cut out 2" x 1/4" filar polished stainless steel strips (20/1000" thick) and epoxied them to the stage at the points where the steel ball tips of the PZT's make contact with the aligner.

Chapter 3

Software Control

So far, the alignment system, as I have described it, is just a mass of bones and uncontrolled muscle. Now I will describe the brain that makes it all work. The software that controls this automated mask aligner system can be divided into two main branches of control united by a single MS-DOS command-level language file. Figure 3-1 presents a high level block diagram of this software system. I will describe this system by first describing the configuration of the skull, the ALIGN.BAT program. Then I will describe the PC program. Finally, I will describe the VAX software.

3.1 The PC Control Batch File

My goal throughout this project has been to make this software package as non-interactive as possible. I wanted to design the software system in such a way as to require as little information from the technician as possible. With this in mind I will begin describing the ALIGN.BAT file.

The ALIGN.BAT file automatically executes the following commands as soon as the PC is turned on:

```
cd mobius
mobius
task login3 aowens (my_password)
gwbasic PC8 /c:5000
```

This routine runs a task file, which automatically logs the user into an account on the VAX, and runs a BASIC program that captures data sent to the PC from the VAX via the PC's COM1 port. The "cd mobius" command sets the directory to the location of the MOBIUS program. MOBIUS is a PC-to-host integration software package marketed by Fel Computing. It is a powerful package which allows a user to custom design his/her own network to perform most any task

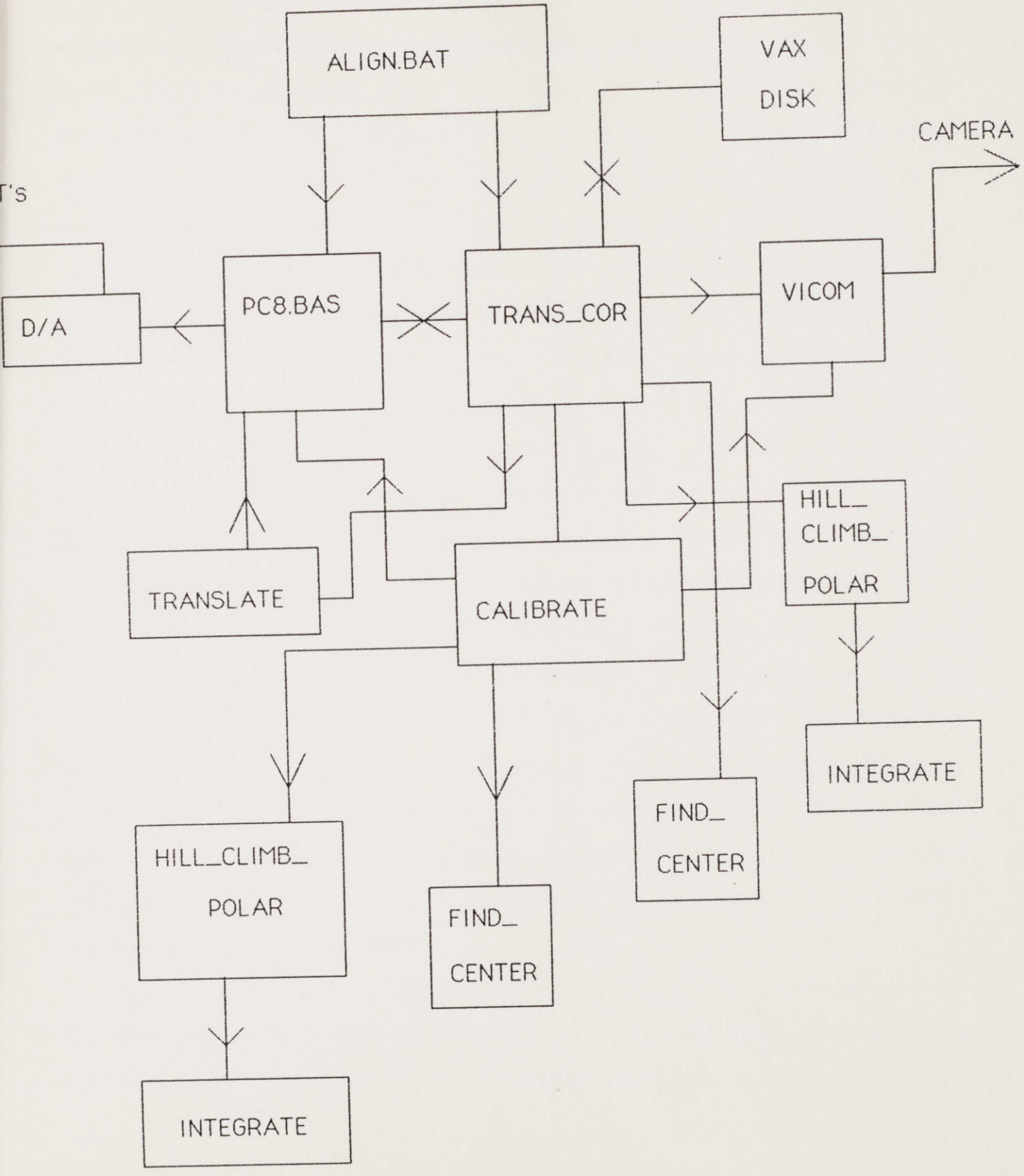


Figure 3-1: Block Diagram of Control Software

requiring communication between a PC and a host. In my case the host is the VAX mainframe. I used MOBIUS for its terminal emulation capabilities. The "mobius" command activates the MOBIUS system which was previously copied onto the PC's hard disk. The MOBIUS system acts like an adjunct to the MS-DOS command level interpreter in that it allows the PC to recognize certain commands specific to the MOBIUS software package, such as "task."

The "task" command is a MOBIUS command which executes .TSK files. These files are batch files which execute MOBIUS commands. The LOGIN3.TSK file is listed in Appendix . The LOGIN3.TSK file was originally "LOGIN.TSK," which is a facility included with the mobius software package. I had to modify this task file because it was not compatible with the DEC-22 system. The original LOGIN.TSK is listed in Appendix . The lines of the original code which were deleted have been underlined, and lines which have been inserted are boxed. The LOGIN.TSK program takes a username and a password and automatically logs the user into my account on the VAX. Because of the incompatibility problem, certain commands such as "Enter_Te" were not being recognized. LOGIN.TSK was unable to log one into an account and start a program running on the VAX. After discussing this problem with an engineering sales representative at Fel Computing, he came to the conclusion that I needed to order the updated version of the Mobius software package.[1] Instead of ordering another MOBIUS package, I decided to delete the lines which were causing the problem and add the line "SEND 'run trans_cor'." This automatically executed the image processing control routine which has been written in FORTRAN for the VAX. I also added the line "send logout" to close the VAX account once the alignment process was complete.

The "gwbasic pc8 /c:5000" command executes a BASIC program. This program controls the transfer of data from the VAX to the D/A board. It runs in parallel with the image processing control routine on the VAX. It will be described in detail in the following section.

---

[1]One thing I have learned by doing this project is that ordering equipment is process filled with too many intangibles. I once ordered a set of PZT's through an engineering sales representative at Control Technics. After promising me that he could send them to me in less than two weeks, I did not finally receive them until two months and several phone calls later.

3.2 PC Control

The main control routine on the PC side of the alignment system package is PC8.Bas. While the Trans_cor routine is busy controlling the VICOM and performing numerous calculations, the PC8 program waits for the expressions "D/A", "ERRVIC","ERRCEN","FOCUS", or "VXDONE" to be received at the COM1 port. When it sees "D/A", the PC8 program processes the next 12 bytes, which will be necessary for driving the D/A card. "ERRVIC" signals the PC8 program to tell the user that the VICOM is not functioning properly. On an "ERRCEN" message the PC8 program tells the user that the misalignment is beyond correction by the PZT's. When the PC8 program sees "FOCUS", it asks the user to focus on the mask and hit return. Finally, the "VXDONE" string signals PC8 to end the alignment process.

3.2.1 VAX to PC Networking

A listing of PC8.BAS is in Appendix . The main issue in the design of the PC8.BAS BASIC program was the following: How do I make the PC "listen" to whatever is happening on the VAX and do something about it (i.e., drive the D/A board) when the VAX program writes something to the PC's screen? The question contains part of the solution. The ALIGN.BAT file executes some commands and put the PC into terminal emulation mode. Whenever the VAX program prints an alphanumeric, this entails sending the PC those same symbols via its COM1 port. Hence, the solution to this PC-VAX networking problem was to find a way to monitor data entering the COM1 port's I/O channel. In order for the PC8.BAS program to act when it receives a proper VAX command, it must know what the VAX command looks like. The commands are character strings which the VAX program prints to the screen, which means that it it has to be sent at the COM1 port. These character strings have the formats mentioned in the previous paragraph.

The command executed by line 20 allocates a buffer to support RS-232 communications with the VAX. This buffer is assigned the logical unit number 1 and can be treated as if it were a

file for the purposes of executing read's and write's. This statement specifies the COM1 port as the "file" which PC8.BAS will read from. In order to allocate a buffer to the COM1 port the parameters of the incoming data stream, such as baud rate, parity, and stop bit must be specified. In the case of the VAX, these data stream parameters are 9600 bits/sec, O for odd parity, and 7 (i.e., every seventh bit of the incoming data stream is a stop bit respectively). The DS and RS parameters suppress request to send and control data set ready "handshaking" at the COM1 port. Without these parameters, the PC8 program cannot signal the arrival of data from the VAX FORTRAN program. The "ON COM(1) GOSUB 80" command creates an event trap such that whenever an ascii string arrives at the COM1 port the program executes line 150. The program will stay in a loop until it sees something at the COM1 port. Line 150 is a check in case a null character is sent to the COM1 port.

As bytes arrive at the COM1 port, line 150 counts the number of bytes. Lines 170 - 190 load the incoming character stream into a one dimensional array buffer, B$. Next, the program performs a ring buffer operation. As more data enters the COM1 port, it is attached to the end of the array which can hold up to 5000 characters (line 1). The program uses two pointers, I and J, to parse through the incoming data string and check it against a list of valid data strings ("D/A", "FOCUS","ERRVIC", "ERRCEN", "VXDONE"). "J," which points to a position within the incoming data stream, is constantly updated. "I" is updated whenever a match between a letter of the incoming data and a letter within the stored array occurs. As matches occur, a new array, C$, is formed consisting of the valid letters matched so far. If a mismatch occurs at any time in the process, then J is reset to 1, and C$ is cleared.

If the "J" pointer reaches the end of the data string buffer, B$, before a complete string match occurs, (an example of this is in line 280), the program goes back to line 150 to receive more data from the COM1 port. If a string match occurs, the program transfers control to line 3000, 3100, 3200, or 3300 depending on what the valid data strings were. For example, when a match occurs on "D/A", the next 12 bytes are stored into the string buffer J$ and control is transferred to line 4000. These 12 bytes contain the data necessary to control the PZT amplifier.

Lines 4100 - 4150 control the D/A card by using this data. When this operation is complete, a message is sent to the VAX computer to continue its process. After a successful string match the program closes the file connected with the COM1 port (line 480), erases the data contained in the ring buffer arrays B$ and C$ (line 470), and loops back to the beginning of the program. The program will continue execution until it receives "ERRCEN","ERRVIC"," or "VXDONE" at which it prints a message to the user and ends.

3.3 The Image Correlation Program

Now, we are finally entering into, what I feel is, the control part of the alignment system. Up until now much of what this thesis has dealt with has been hardware. Even the PC8.Bas program is fairly hardware-intensive in that it (1) has to interact with the RS-232 port and (2) has to control a D/A board. However, in TRANS_COR.FOR we see a highly algorithm-driven software routine designed to produce data rather than signals.

In order to understand TRANS_COR, one must first understand its most fundamental task: correlating two images in X, Y and Θ. By "correlation" I mean that process by which one finds out how much one has to move an image "left" or "right," "up" or "down," and by how much one has to rotate the image such that when it is overlaid above a similar image, the best match is achieved.

In this thesis I have divided the problem of correlating two images into two parts. The first part deals with finding the x-y offset between the two images, and the second entails finding the θ offset between the two images.

In order to calculate the x-y offset between the two images, I must first compute the coordinates of their centroids. I use the following algorithm to calculate the centroid of an image:

$$X = \frac{\sum_{x=0}^{128}\sum_{y=0}^{128} x(Intensity(x,y))}{\sum_{x=0}^{128}\sum_{y=0}^{128} (Intensity(x,y))}$$

$$Y = \frac{\sum_{x=0}^{128}\sum_{y=0}^{128} y(Intensity(x,y))}{\sum_{x=0}^{128}\sum_{y=0}^{128} (Intensity(x,y))}$$

The images as seen by TRANS_COR are two dimensional (128, 128) arrays. 128 x 128 pixels is the next lower image size below 512 x 512 that the VICOM will work with. Doing calculations on a 128 x 128 image is much faster than performing those same calculations on a 512 x 512 image. Using the algorithm above, calculating the centroid of a 128 x 128 image requires 32,768 summations compared to 524,288 summations for a 512 x 512 image. Each array element contains a number from 0 to 1 representing the intensity of the image at that point. In my algorithm X represents columns and Y the rows. Once the centroid coordinates have been found, TRANS_COR subtracts the x and y centroid coordinates of the second image. The result is the x-y offset between the two images.

Finding the angular offset between two images is more complicated and requires more computations. The purpose of the angular offset algorithm is to calculate the angle that you have to rotate one image so that it most closely matches a second image. The technique for doing this is the following:

1. Transform the x-y coordinates of the images into polar coordinates.
2. Rotate image #1 by a known delta-theta (i.e. 1 degree).
3. Multiply the two image arrays together.
4. Compare the multiplicand with the previous multiplicand.
5. Increment delta-theta by a known amount
6. Repeat steps 2-5 until the difference between successive multiplicands becomes minimal. The desired value at this point is delta-theta.

There are several issues that arise in implementing this algorithm which I will address when I describe the hill_climb_polar and the integrate subroutines. Now, I will describe the implementation of TRANS_COR and its subroutines. Listings of the FORTRAN code can be found in Appendix . In the chapter titled "Understanding the Automated Mask Aligner System" I described in superficial terms what TRANS_COR does.

The first issue I would like to address concerns how TRANS_COR and CALIBRATE routines tell the VICOM to capture and digitize images. The way these programs control the VICOM is by calling three programs: vicprocess, vicinit, and vic128. All three of these programs were written by Dr. David Biron, a computer scientist at Lincoln Laboratories. VICPROCESS accepts a file containing a list of VICOM commands and transmits them to the VICOM for execution. VICINIT is a program which initializes the VICOM hardware. VIC128 takes an image in a file called IMAGE.IM in my account on the VAX.

The second issue was how to read the images from the VAX disk when I needed them. I borrowed two more programs, which were written to perform this VAX retrieval task, from David Biron: disk_rd and unpack. Disk_rd reads a file with the given filename from the VAX disk and loads it into the two-dimensional array which can be used in any mathematical calculations. Unpack converts the data from 16-bit longwords into pairs of 8-bit words. IOSTAT is an integer returned by Vicinit indicating whether the Vicom initialization was successful or not. If the VICOM initialization is unsuccessful, then the Alignment System will not work. TRANS_COR and CALIBRATE check the iostat variable. If iostat is not equal to 1, the program sends a message to the user and ends. In Appendix , I list steps that one can take to trouble-shoot the VICOM.

FIND_CENTER is a fairly straight-forward program. It implements the weighted average algorithm discussed earlier to compute the centroid of an image.

The HILL_CLIMB_POLAR subroutine is designed to work for offset angles no greater than 10 degrees. I decided to "hard code" this value into my program so that the technicians would not have enter an angular correlation range every time they performed an alignment. Originally, I had written a subroutine called POLAR which computed angular offset by repeatedly rotating one image and multiplying it by the second image. It would rotate and multiply an image over a range of 10 degrees and use the "MAX" FORTRAN function to find the angle of rotation which produced a match. I found this technique to be extremely time consuming. This routine required 15 to 20 minutes to run. HILL_CLIMB_POLAR cut this run

time down to 90 seconds. HILL_CLIMB_POLAR uses a hill-climbing technique to find the maximum multiplicand. It starts at an offset angle of zero and calls INTEGRATE to compute the multiplicand. Then it rotates the first image, which is the image of the substrate, by a preset delta-theta of 0.2 degrees. If the second multiplicand is greater than the first by more than 2000 (I will discuss how I arrived at this number in the chapter about testing the system), the subroutine rotates the first image by the difference between the maximum angular offset, 10 degrees, and the minimum angular offset, 0 degrees, divided by two. If the second multiplicand was less than the first by more than 2000, the subroutine rotates the image halfway in the other direction. The subroutines iteratively cuts the range of possible angular offsets in half until either the difference between two multiplicands is less than 2000, or the range of possible angular offsets is less than 0.3 degrees.

The INTEGRATE subroutine performs the bulk of the calculations for HILL_CLIMB_POLAR. The main task of INTEGRATE is to rotate and multiply two image arrays. The image arrays and the rotational offset angles are supplied as input by HILL_CLIMB_POLAR. INTEGRATE returns the value of the multiplicand. In order to understand the nested do loops and the long condition checks which the INTEGRATE routine performs, imagine a situation where you have two black and white postcards with pictures of checkered boards on them (see figure 3-2). Imagine now that a pin pierces both post cards through their centers. Also, the pin has a string attached. If you could somehow multiply the intensities of the two images by "eyeball", one way that you could do it would be to stretch the string out, so that it forms a radius to an imaginary circle. Starting from the center with the string at 0 degrees with respect to the x axis, you move from the center to end of the radial. As you go along, you would translate your radial and angular position into a position in Cartesian coordinates because the intensity elements that you are multiplying are squares not arcs. Also, as you move along the string, summing multiplicands as you go, you reach situations where the string goes beyond the edge of the post cards. At these points you would say the multiplicands are undefined (in the INTEGRATE routine they are defined as having 0 intensity. When you

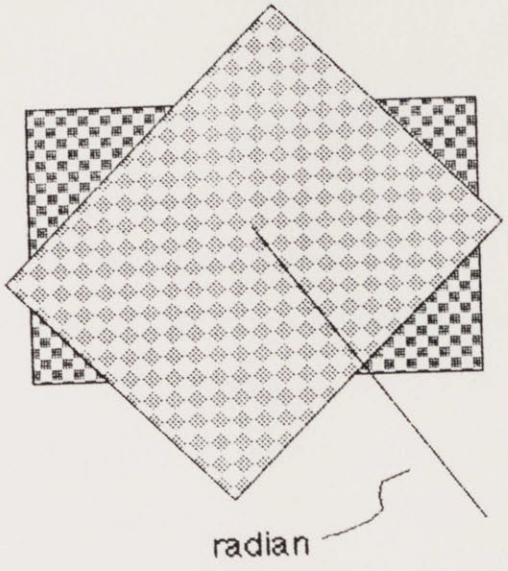


Figure 3-2:

reach the end of the string, you would rotate the string 1 degree and continue summing multiplicands. This process continues until the string has traveled 360 degrees and the entire postcard stack has been integrated. If INTEGRATE receives a entire postcard stack has been integrated. If INTEGRATE receives a rotational offset as input that is greater than 0, then the integration process starts with the radial at that given offset angle above the x axis of the first postcard. The squares of the postcard directly beneath the string become the new x axis. The integration is now performed as usual, but the resulting integral, of course, will be different.

3.4 CALIBRATE

At the beginning of TRANS_COR, the CALIBRATE subroutine is called. This subroutine is listed in Appendix . This routine calibrates the system. First, it waits for the user to focus on the substrate and hit return. Next, it controls the VICOM using the PRIME1.VC batch file discussed earlier. A program written by Dr. David Biron, in our group, writes images from the VICOM to the VAX's hard disk.

After this preliminary processing, the subroutine calls the FIND_CENTER subroutine in

"PRINT*, d_to_a" command to move the PZT's with -500, -750, -750 volts respectively. 2048, 3071, 3071 are the 12 bit representations of 5, 7.5, and 7.5 volts respectively. The PZT amplifier amplifies these D/A outputs to -500, -750, -750 volts. Printing the d_to_a variable initiates the process discussed in section 3.2.1 about PC8.

Next, the angular correction factor is calculated. This is necessary in order to define some absolute frame of reference for the system. Now the subroutine calls the ROTATIONAL_CAL routine which computes the rotational calibration factor of the system. This entails figuring out by how much PZT#1 and PZT#2 have to be moved in order to achieve one degree of rotation. ROTATIONAL_CAL is listed in Appendix .

3.5 Translate

This routine is listed in Appendix and is used to translate the data from TRANS_COR into the voltage levels needed to align the mask and substrate. It takes the offset data computed in TRANS_COR and angular and translational correction factors computed by CALIBRATE and generates the final voltage values by a trigonometric algorithm. These values are sent via the RS232 lines to PC8.

Chapter 4

Testing & Results

After configuring the system's hardware (CCD Camera, TV monitor, VICOM, PZT's, and D/A board), the testing of the system consisted of three parts: (1) Image Correlation, (2) VAX to PC networking, (3) system test.

The first part of testing the system was to test the software's ability to rotationally correlate two images. My first version of TRANS_COR called the subroutine POLAR instead of HILL_CLIMB_POLAR to compute the angular offset between two images. POLAR is listed in Appendix .

POLAR performs the same function as HILL_CLIMB_POLAR except that instead of performing the fast hill-climbing technique discussed earlier, POLAR iteratively multiplies two images for a range of angles specified by the user. For each angle, the program writes the angle and multiplicand data to a file, which is used for drawing graphs of the data. The program continuously updates variables containing the maximum multiplicand of the two images and the offset angle at which this value occurred. This program required 20 to 25 minutes to run because of the vast number of computations executed.

I wanted to eventually use a hill-climbing approach to compute offset angles in order to reduce this computation overhead. However, this required that the distribution of image multiplicand versus offset angle be a smooth Gaussian curve. If this curve was not smooth, the hill-climbing algorithm might mistake a local maximum in the multiplicand-offset angle curve for the absolute maximum value. This would produce a false offset angle.

Using the data written to file #99, I generated graphs of image multiplicand versus offset angle. Figures 4-1, 4-2, 4-3 show plots from three separate sets of images. In the first two plots we see lots of discontinuities. What caused this was that I was performing edge detection techniques on the images. This had the effect of passing the image through a spatial high-pass filter, adding spatial noise to the curve. However, figure 4-3 shows a smooth Gaussian-like

curve. In this case, no edge detection was performed on the image. Thus, much of the noise was reduced. The conclusion gathered from this experiment was that I could use the hill_climbing technique with non-edge-detected images.

Testing the HILL_CLIMB_POLAR program was trivial now because it performed the same operation as POLAR but in fewer steps. To test HILL_CLIMB_POLAR I used images stored on the VICOM disk. Using the VICOM, I could manually rotate an image and store it back onto the disk. Since I knew how much I had rotated the images by, it was a simple matter to test the accuracy of HILL_CLIMB_POLAR. When I tested the program, I found the subroutine to be accurate to within 0.2 degrees. This means that for a substrate that was 1000μm wide, the correlation program would have a maximum offset error of 3.5μm at the edges. To improve this I lowered the step size for rotating the image to 0.1 degrees and lowered the threshold value for minimum difference between multiplicands at different offset angles to 2000 units. This brought my angular resolution down to 0.1 degrees or 1.8 μm error over a distance of 1000μm.

To test the PC8 networking program I wrote a test program in FORTRAN on the VAX which waits to receive a return key input from the PC and then sends over 500 characters back to the PC via the COM1 port. Embedded within the 500 characters was the data string "PLEASE FOCUS ON THE MASK". This program allowed me to test several different issues:

```
1) Could the networking program run by just
   hitting a return key?
2) Could the COM1 port handle over 500 bytes
   arriving from the RS232 lines?
3) Can the program parse through all of the data
   and pick out the string "PLEASE FOCUS ON MASK".
```

Resolving the first issue required the use of the LIB$GET_INPUT VAX library routine. In order to give the networking program the ability to handle vasts amounts of data arriving at the COM1 port, I allocated 5000 bytes to the receive buffer. I implemented this memory allocation in ALIGN.BAT via the statement "gwbasic align /c:5000". The last issue was resolved by implementing the "ring buffer" approach described in section 3.2.1.

Finally, the system as a whole had to be tested. The final test entailed using the system as outlined in the manner outlined in the introduction and seeing if it worked. And if so, how

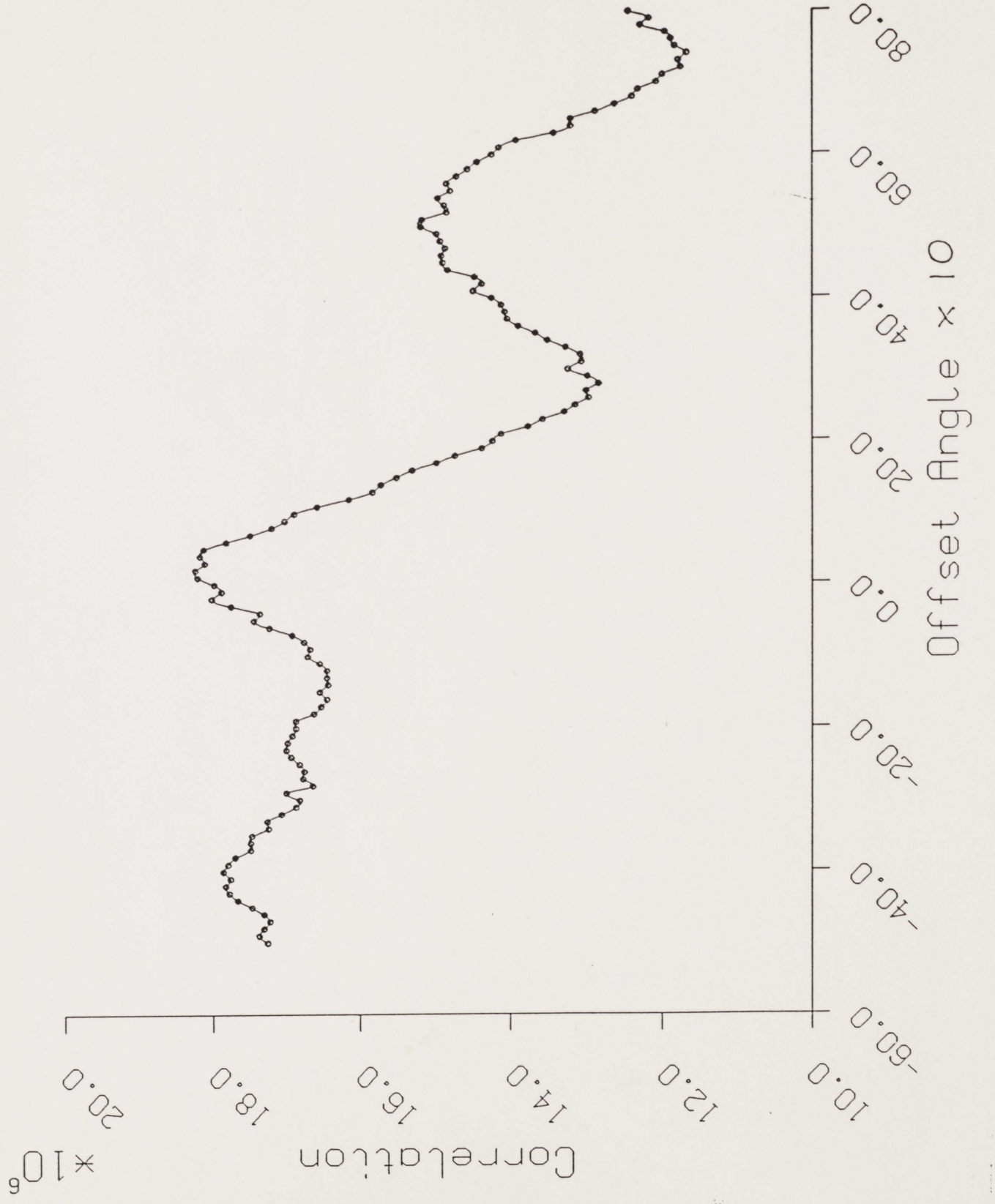


Figure 4-1: Image intensity vs. Angle of rotational displacement

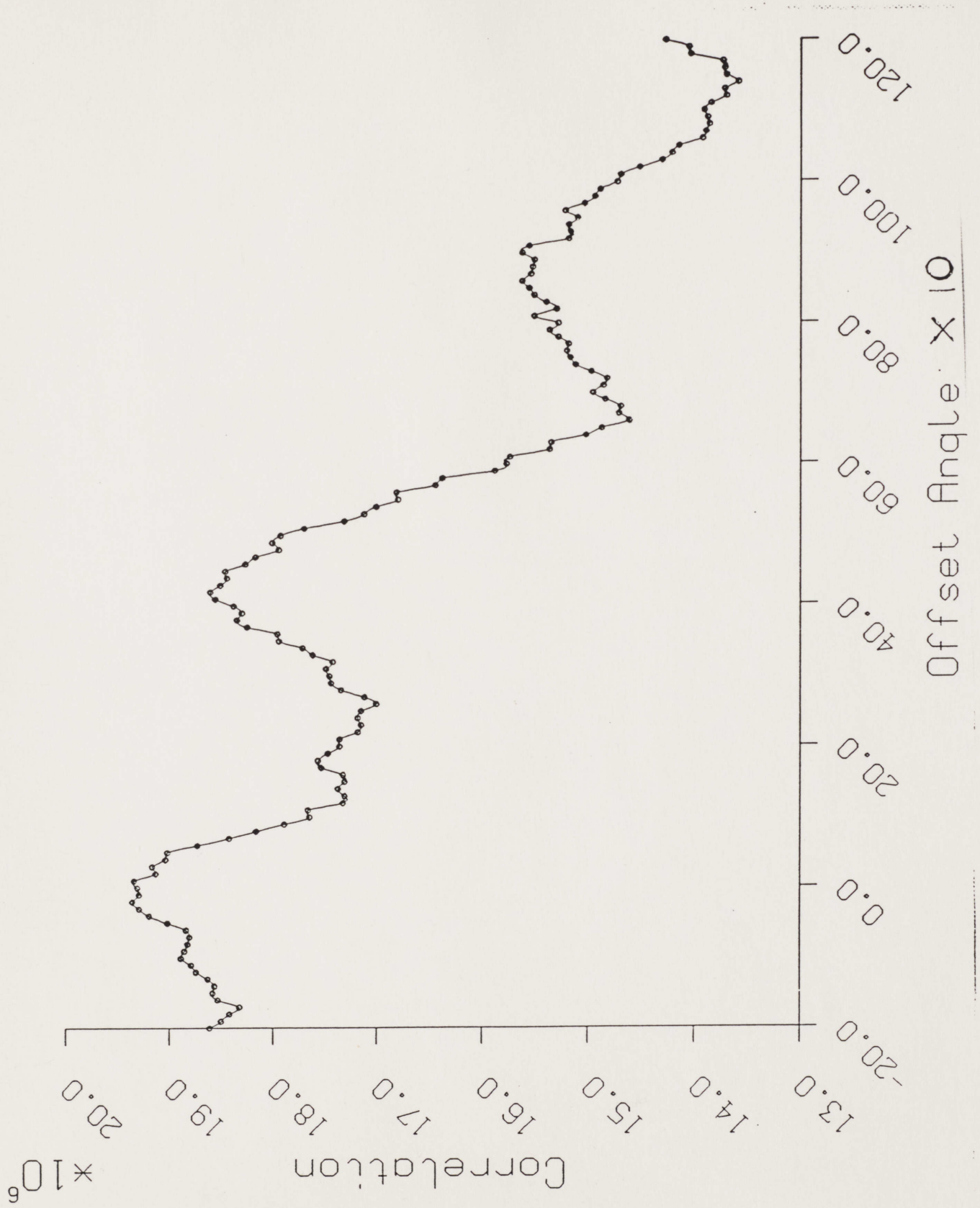


Figure 4-2: Image intensity vs. Angle of rotational displacement

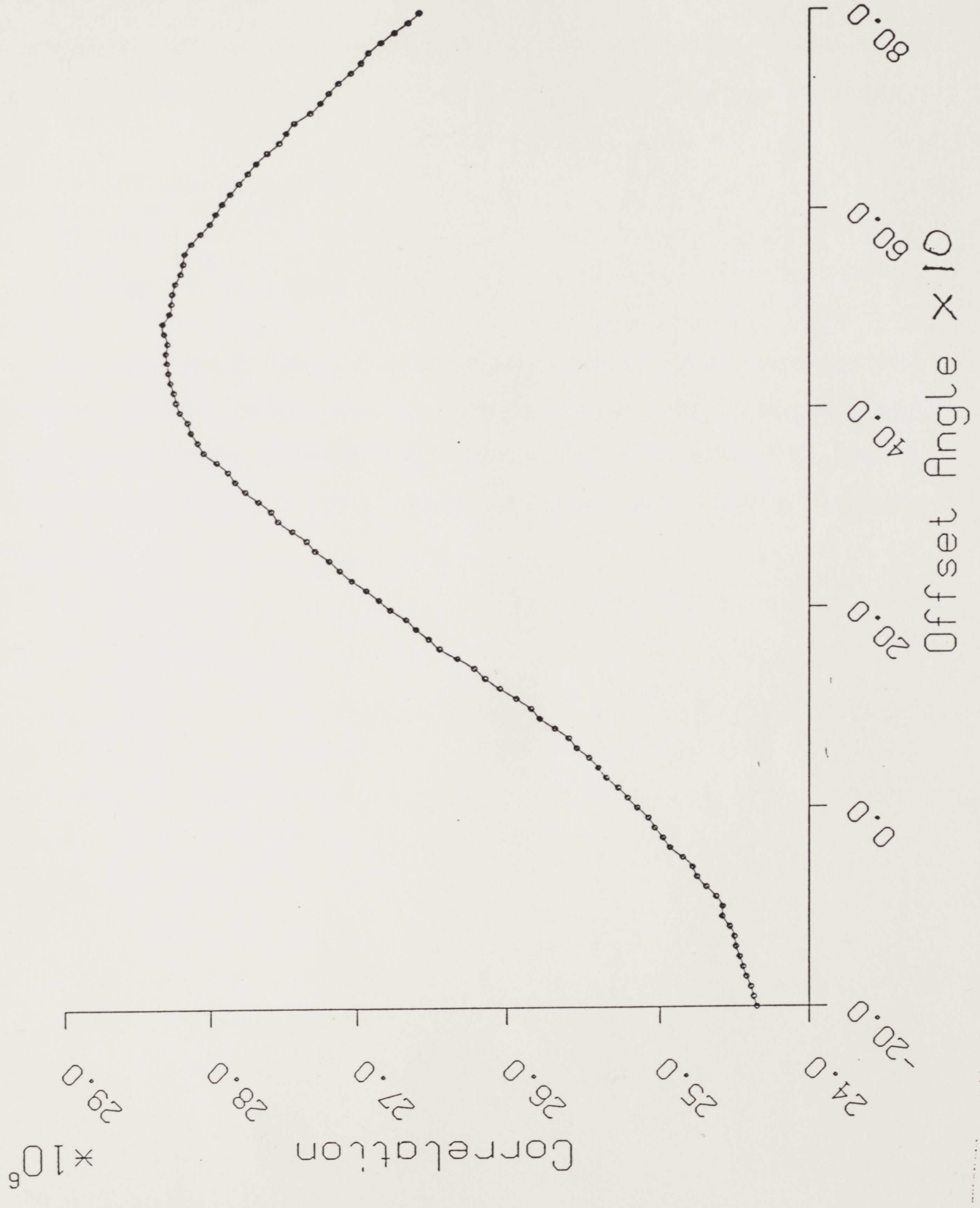


Figure 4-3: Image intensity vs. Angle of rotational displacement

accurate was it. By the time that I had reached this stage, all of the individual components had been tested and shown to work. Also, the following interfaces had been tested and shown to work:

1) **CCD camera > VICOM**
2) **VICOM <> VAX**
3) **VAX <> PC**
4) **PC > D/A > PZT amplifier**
5) **PZT's > alignment stage.**

Since I knew that all of these interfaces worked, the only remaining issues were: (1) how accurate the correlation and calibration routines were, and (2) would the PZT couplings provide a stable enough platform for consistent PZT motions. The stability of the PZT's about the alignment stage proved to be the primary issue, and more stable couplings are being designed for them.

Chapter 5

Conclusion and Suggestions for Improvements

In this thesis I have discussed the basic theory of image correlation and described a system that I have built to align a mask and substrate. It was an extremely diversified project in that I had to deal with issues that spanned many disciplines including optics, programming, computer networking, and machining of mounts. I feel that it is this diversity which kept this system from being better than maybe it could have been. By this, I mean that the system lacks the compactness desirable in a truly reliable system. Certain rather common events could keep the system from functioning properly. The VAX could be shutdown by the system manager, or the VICOM could either be in use or not properly reset.

Another area for improvement is speed. The system at the moment is beneficial to the technicians because it can perform alignments in about 5 - 10 minutes as opposed to an hour. However, if real time feedback control were implemented, the system could perform much faster (on the order of 1 minute) and accuracy would be greater due to feedback control. These issues of reliability, speed, and accuracy could by resolved by purchasing an array processor board and an image - capture board for the PC. Then, instead of doing computations on the VAX, VICOM, and PC everything can be done at the PC.

If one does not take the array processor approach to improving the system, another improvement would be to remove the VAX from the system. One can write programs directly on the VICOM for image correlation. Programming on the VICOM is extremely time-consuming, however, because the editing package is very archaic. Debugging is much more difficult than on the VAX. Finally, networking the VICOM to the PC is extremely intense and would probably require knowledge of ASSEMBLY language. Removing the VAX from the system, greatly increases the difficulty of the project, but it would improve the system as a whole.

Personally, I am glad that the approach to designing this system was not as elegant as a few boards inserted inside a PC. It was much more challenging this way, and I learned a great

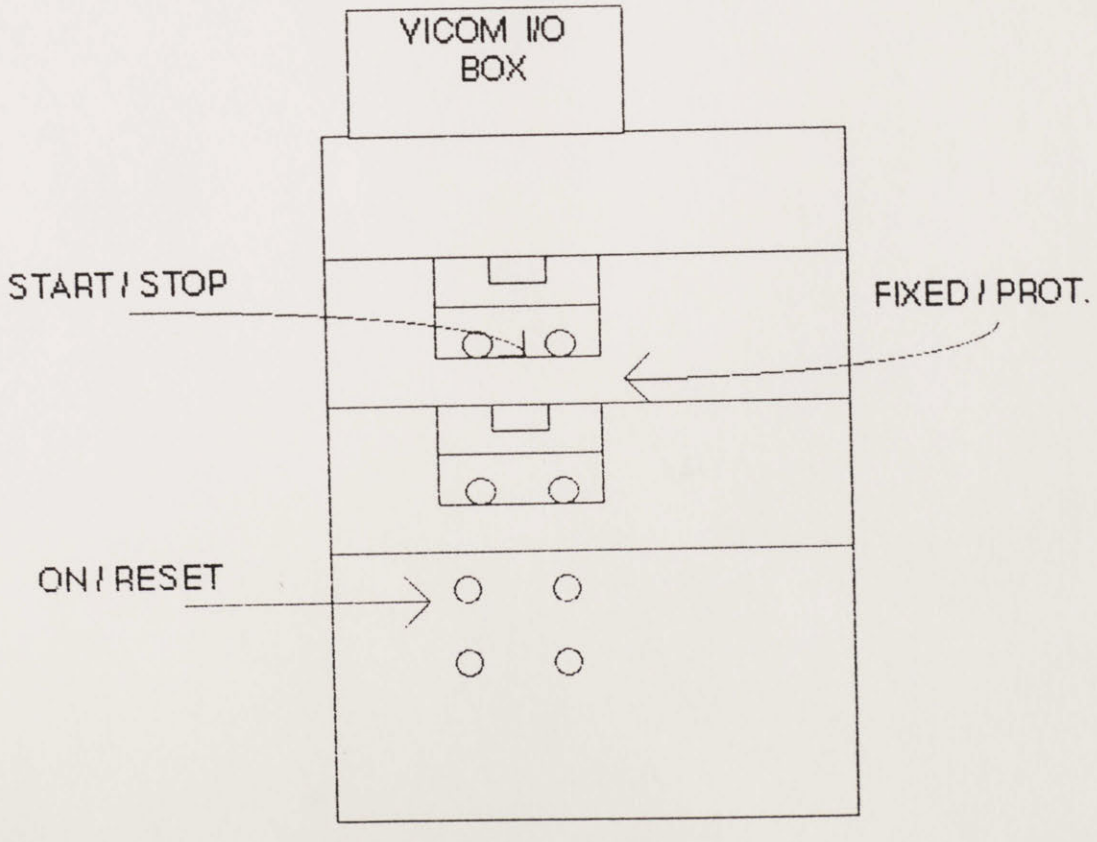
deal. Most of all I learned: (1) How to handle a very large project; (2) how to attack issues that arise after you have made a commitment to a design strategy; (3) finally and most importantly, how to deal with supervisors, coworkers, and sales representatives. This has been an awesomely challenging and rewarding experience.

Appendix A

Trouble Shooting The Vicom

```
The VICOM is either in use already or needs to be rebooted."
To reboot the VICOM, do the following:"
                "
                1) Make sure that the camera cable is"
                  connected to the VICOM i/O box in"
                  the computer room. The cable is "
                  marked with a green label."
                "
                2) Push reset button on lower half"
                  of VICOM"
                3) At the VICOM Terminal type: (hit return)"

                        A) BO 2,0,2"
                        B) Sys1:0"
                        C) date and time"
                        D) VDP
Now restart the alignment program"
```



Appendix B

Sony Trinitron and Sony XC57 CCD Camera

SONY

VIDEO CAMERA

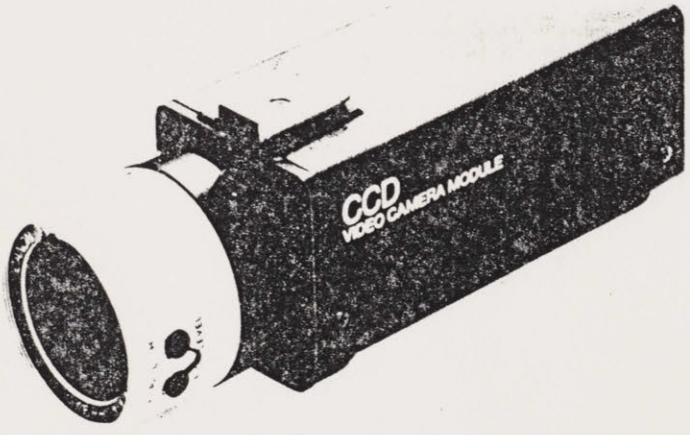
VIDEO CAMERA MODULE

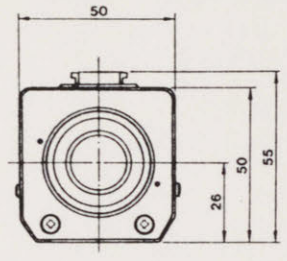
CCD

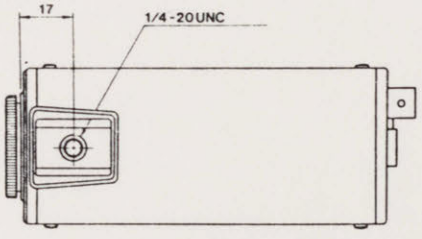
XC-57/57CE

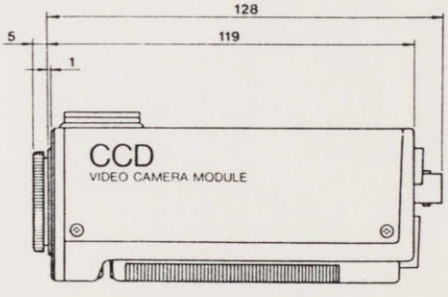
OEM/Component

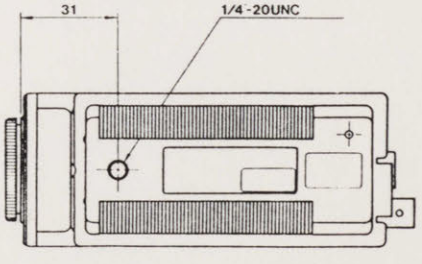
High Sensitivity and High Resolution with
2/3" CCD Solid State Image Sensor

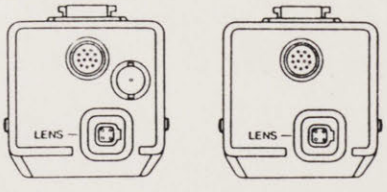










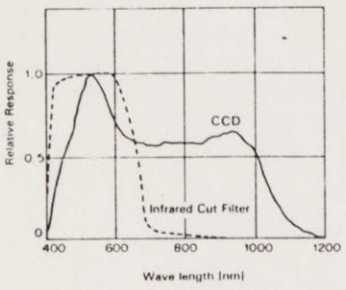


FEATURES

The XC-57/57CE is a monochrome video camera which uses a CCD (Charge Coupled Device), a solid state image sensor.

- High resolution picture
- Low lag, no image burning, and precise image geometry
- Quick start-up
- High sensitivity
- Shooting in a strong magnetic field
- Miniaturized and lightweight
- High resistance to vibration and mechanical shock
- External sync capability (composite sync)

SPECTRAL RESPONSE (TYPICAL)



SPECIFICATIONS

	XC-57	XC-57CE
Pick up device	Interline transfer CCD	Interline transfer CCD
Picture elements	510×492	500×582
Sensing area	8.8mm×6.6mm	8.8mm×6.6mm
Optical black	22 pixels each H line	32 pixels each H line
Horizontal drive frequency	15.734 KHz	15.625 KHz
Vertical drive frequency	59.94 Hz	50 Hz
Signal system	EIA	CCIR
Cell size	17μm×13μm	17μm×11μm
Lens mount	C mount	C mount
Flange back	17.526 mm	17.526 mm
Sync system	Internal/External sync	Internal/External sync
Scanning system	525 lines 60 fields 2:1 Interlace	625 lines 50 fields 2:1 Interlace
Video output	1.0 Vp-p sync negative, 75 ohms	1.0 Vp-p sync negative, 75 ohms
Horizontal resolution	380 TV lines	380 TV lines
Vertical resolution	525 lines 2:1 interlace	625 lines 2:1 interlace
Sensitivity	2000 lux F8	2000 lux F8
Minimum sensitivity	3 lux F1.4	3 lux F1.4
S/N	50 dB (r=1, AGC=OFF)	50 dB (r=1, AGC=OFF)
Power requirements	DC 12V	DC 12V
Power voltage tolerance	DC 11V to 16V	DC 11V to 16V
Power consumption	2.5W	2.5W
Operating temperature	0°C to 40°C	0°C to 40°C
Storage moisture	Under 90%	Under 90%
Operating moisture	Under 70%	Under 70%
Dimensions	50×50×119 mm	50×50×119 mm
External Sync Input	1.0 Vp-p VBS (VBS or Sync) Impedance high	1.0 Vp-p VBS (VBS or Sync) Impedance high
Horizontal frequency deviation	15.734 KHz ± 1%	15.625 KHz ± 1%
Weight	290 grams	290 grams

· Sony Corporation Component Marketing Gp. CCD Camera Module Sales 4-14-1, Asahi-cho, Atsugi-shi, Kanagawa-ken, 243 Japan
TEL: (0462) 30-5219 FAX: (0462) 30-6185 FLX. SONY CORP J22262

· Sony Component Products Division 10833 Valley View Street, Cypress, CA 90630-0016 TEL: (714) 229-4181 FAX: (714) 229-4271
(U.S.A.) P.O.Box 910, 15 Essex RD., Paramus, N.J. 07652 TEL: (201) 368-5017 FAX: (201) 487-2095

SPECIFICATIONS

Color System: PAL/SECAM/NTSC/ NTSC 4.43 switched automatically

Picture Tube: 12" (measured diagonally) Trinitron CRT, 90° deflection, Super Fine Pitch 0.25mm

Resolution: RGB input: 600 lines, 640 × 200 dots
Composite input: 550 lines

Color Temperature: 6500°K/9300°K, switchable

Frequency Response: 10 MHz (−3 dB, RGB)
5.5 MHz (−3 dB, composite video)

Horizontal Linearity: ±8%

Vertical Linearity: ±5%

Line Pull Range: Horizontal: ±500 Hz
Vertical: 8 Hz

Overscan of the Picture: 5%

Underscan of the Picture: 9%

Return Loss: 4 MHz, 35 dB (LINE A/B)

Zooming: Within 2%

Convergence: Central area: 0.6mm
Periphery: 0.8mm

Brightness: More than 35 foot-Lamberts

Inputs:
VIDEO IN: BNC connector
VTR: 8-pin connector (2 and 6 pins)
Composite 1 V p-p ±6 dB, sync negative, 75 Ohms and high impedance switchable
AUDIO IN: minijack
VTR: 8-pin connector (1 and 5 pins)
−5 dB high impedance
EXT SYNC IN: BNC connector, composite sync 2-8 V p-p, negative, 75 Ohms and high impedance switchable
RGB IN: BNC connector, 0.7 V p-p ±6 dB, non-composite
RGB AUDIO IN: minijack, −5 dB high impedance
CMPTR: 25-pin connector

Outputs: VIDEO OUT: BNC connector
AUDIO OUT: minijack
EXT SYNC OUT: BNC connector
RGB OUT: BNC connector
RGB AUDIO OUT: minijack, loop through

Audio Output: 1W

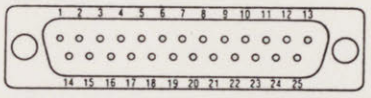
Power Requirements: 120 V AC, 60 Hz

Power Consumption: 105 W (max)

Dimensions: 13" × 13⅜" × 15¼" (HWD)
346mm × 330mm × 387mm (HWD)

Weight: 31 lbs. 15 oz. (14.5 kg)

OPTIONAL ACCESSORIES
SMK-0002 RGB Cable for SMC-70, SMC-70G
SMF-500 RGB Cable for IBM-PC
VMC-3425 Cable for Videotex Unit VDX-1000
MB-502 Rack Mount Bracket
SLR-102 Slide Rail



CMPTR: 25-PIN D CONNECTOR

Pin No.	Signal	Signal Level
1*	IBM Select	High state (5 V): IBM mode, Low state: 3 Bit TTL
2	Audio Select	High state (5 V or open): Audio inputs from pin 13. Low state (less than 0.4 V): Audio inputs from the LINE A AUDIO IN jack
3	H. Sync or Composite Sync	Negative polarity When the high state is selected at pin 9: 1 V p-p, 75 Ohm terminated When the low state is selected at pin 9: TTL level
4	Blue Input	Positive polarity When the high state is selected at pin 9: Analog signal (0.7 V p-p, 75-ohm terminated, non-sync) When the low state is selected at pin 9: Digital signal (TTL level)
5	Green Input	
6	Red Input	
7	+12 V Power Supply	0.3 A max
8	+5 V Power Supply	0.6 A max
9*	Analog/Digital Mode Select	High state (open): Analog signal (0.7 V p-p) Low state (ground): Digital signal (TTL level)
10	RGB/NORMAL Mode Select	High state (5 V or open): RGB inputs from a microcomputer Low state (ground): Composite video inputs from the LINE A VIDEO IN connector
11	V-Sync	Negative polarity, TTL level
12	Blanking	High state (5 V or open): Video inputs from a microcomputer only Low state (ground): Composite video input from LINE A VIDEO IN connector During the low state, the video signal from the microcomputer is blanked and the composite video signal from the LINE A VIDEO IN connector is superimposed over the signal from the microcomputer.
13	Audio Input	Input level −5 dB (100% modulation), input impedance more than 47 k Ohms
14	EXT/INT Mode Sync Switch	High state (open): Sync signal input from the CMPTR connector Low state: Sync signal input from the LINE A VIDEO IN connector
15-24	Ground	
25*	IBM Luminance Signal	Positive polarity When the high state is selected at pin 1: TTL level When the low state is selected at pin 1: Low state (ground)

EXAMPLES OF MICROCOMPUTER CONNECTIONS

Pin No.	1	9	25
Microcomputer			
SMC-70/SMC-70G	—	High state	—
IBM computer	High state	Low state	IBM luminance signal
TTL 3BIT computer	Low state	Low state	Low state

*Examples for microcomputer connections

DAWSON

SONY®

Video Communications
Sony Communications Products Company
Sony Drive, Park Ridge, New Jersey 07656

Appendix C

Specifications for the AOB6 Digital to Analog Board

POWER CONSUMPTION

+5v supply	- 450mA typ. / 550mA max.
+12v supply	- 60mA typ. / 100mA max.
-12v supply	- 140mA typ. / 180mA max.
Power dissipation	- 4.7w typ. (16 Btu/hr.)

D/A CONVERTERS

Channels	- 6
Resolution	- 12 bits (1 part in 4096 decimal)
D/A type	- DAC-80N (Six used)
Latches	- Double buffered with optional simultaneous update
Linearity	- +/- 1/2 bit.
Monotonicity	- +/- 1/2 bit.
Temperature drift of zero	- 1ppM typ./3ppM max. of Full Scale Range
Temperature drift of gain (full scale)	- 15 ppm typ. / 30ppm max.
Output ranges	- 0 to +5v 0 to +10v -2.5 to +2.5v -5 to +5v -10 to +10v 4-20mA (current sink to ground)

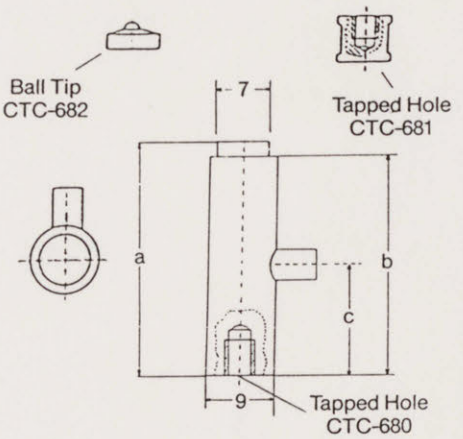
Appendix D

Specifications for the piezo-electric translators

CONTROL TECHNICS Corp.

PIEZO SERIES
CTC-6094, CTC-6095
9 mm DIA. MINIATURE

PIEZO SERIES:
CTC-6094 +500V max.
CTC-6095 -1000V max.



+500 VOLTS MAX.					
+500V MODEL NUMBER CTC-		6094-5	6094-10	6094-20	6094-25
EXTENSION INPUT AT +500V		5	10	20	25
DIMENSION IN MILLIMETER	a	13	19	30	37
	a + Thread	13.5	19.5	31	37.5
	a + Ball	16.5	22.5	34	40.5
	b	12	18	29	36
	c	6	9	14.5	24
THREAD	Top/Base	M3	M3	M3	M3
DEPTH OF TAPPED HOLE	Base	3	3	3	3
	Top	4	4	4	4
LOAD MAX.	lbs	100	90	90	90
STIFFNESS	lbs/μM	9	4.5	2	1.7
CAPACITANCE	nF	20	40	80	90
TEMP/COEFFICIENT	μM/C°	0.1	0.25	0.4	0.5
RESONANCE/FREQ	kHz	>60	>50	>40	>30

CTC-680 Piezo Base with Tapped Hole.

CTC-681 Piezo Top with Tapped Hole.

CTC-682 Piezo Top with Spherical Tip.

NOTES

Above chart compares the data and specifications of CTC's new miniature Piezo's Line in +500 volt. Please note that the correct power supply or amplifier will be employed. For details contact our engineering sales department.

-1000 VOLTS MAX.					
-1000V MODEL NUMBER CTC-		6095-5	6095-15	6095-25	6095-40
EXTENSION INPUT AT -1000V		5	15	25	40
DIMENSION IN MILLIMETER	a	13.5	21	30	40
	a + Thread	14	21.5	30.5	40.5
	a + Ball	17	24.5	33.5	43.5
	b	12.5	20	29	39
	c	8	10	15	20
THREAD	Top/Base	M3	M3	M3	M3
DEPTH OF TAPPED HOLE	Base	3	3	3	3
	Top	4	4	4	4
LOAD MAX.	lbs	65	50	50	50
STIFFNESS	lbs/μM	11	4.5	2	1.3
CAPACITANCE	nF	6	16	26	44
TEMP/COEFFICIENT	μM/C°	0.07	.2	0.3	0.4
RESONANCE/FREQ	kHz	>100	>75	>50	>20

CTC-680 Piezo Base with Tapped Hole.

CTC-681 Piezo Top with Tapped Hole.

CTC-682 Piezo Top with Spherical Tip.

NOTES

Above chart compares the data and specifications of CTC's new miniature Piezo's Line in -1000 volt. Please note that the correct power supply or amplifier will be employed. For details contact our engineering sales department.

Appendix E
The LOGIN3.TSK program

```
COMMENT *
        LOGIN3.TSK              FEL Computing

        USAGE: TASK LOGIN USERNAME PASSWORD

        For use as a standalone routine, from a .BAT file, etc.
        Logs into a VAX SYSTEM with your USERNAME and PASSWORD

        This expects a standard '$ ' VAX Prompt
        *

         PARAMETERS [ User_Name, User_Pass ]

         ALLOCATE Vax_Buffer, 512    ! This buffer is 512 bytes long

COMMENT *
        The PROMPT_TYPE is used to check for a
        sucessful LOGIN This could be a parameter or
        a better way to do this would be to look for
        the USER_NAME as a result of a SHOW PROCESS
        command
      *

          CLEAR_SCREEN
          PRINT "                                  Connecting to VAX"
          Prompt_Type = "$"


COMMENT *
        This is the MAIN routine

        This global variable is used to return a
        value to DOS when the program terminates.
        The BATCH ERRORLEVEL can be used to check
        this return status.  Initally set to 1 for
        an error.  Set to 0 on a succesful LOGIN and
        returned to DOS.
      *

        Log_Status = 1                ! Set for an error return

        Vax_Echo = _RECEIVE_ECHO      ! Save the echo

        _RECEIVE_ECHO = _FALSE        ! Set to _TRUE for DEBUGGING

        _SCREEN_LOCK = 1              ! Turn off the display for silent running

        CALL Get_Vax                  ! Try to Login


        _SCREEN_LOCK = 0              ! restore system operations

        _RECEIVE_ECHO = Vax_Echo


        PRINT "" ! PRINT ""

        QUIT Log_Status               ! make this a return for use
                                      ! by other Procedures
```

```
PROCEDURE Get_Vax

        Retries = 3

Retry_Loop:


        SEND _NAK               ! Send a ^U CR to clear out line garbage
        WAIT 1                  ! and get it's attention

        RECEIVE Vax_Buffer,
         [
          "Username: ": GOTO Enter_Name
         ], ,10

        Retries = Retries - 1

        IF ( Retries == 0 ) THEN GOTO Failed

        GOTO Retry_Loop

Enter_Name:


        SEND _NAK;              ! Send a ^U to clear out line garbage

        SEND User_Name          ! Send user_name followed by CR

        RECEIVE Vax_Buffer,
         [
           "Password: ": GOTO Enter_Pass
         ], , 10

        GOTO Failed

 Enter_Pass:

                                ! same as above, but now the Password
        SEND _NAK;
        SEND User_Pass

        RECEIVE Vax_Buffer,
         [
          Prompt_Type: GOTO Success
          "User authorization failure": GOTO Failed
         ], ,60

        GOTO Failed

Success:
            ! Start up Host M¦bius
            ! Report success to user, let her know what's going on
        PRINT "                                   Login  successful"
        PRINT ""
        PRINT "                                 Starting Host Mobius"

        SEND "@test"                ! executes test.com

        Log_Status = 0              ! Success return for DOS

        PRINT "                                 Host Mobius started."

        RETURN
```

```
        PRINT "Unable to LOGIN to VAX"

END_PROCEDURE
```

Appendix F
The LOGIN.TSK program

```
COMMENT *
        LOGIN.TSK           FEL Computing

        USAGE: TASK LOGIN USERNAME PASSWORD

        For use as a standalone routine, from a .BAT file, etc.
        Logs into a VAX SYSTEM with your USERNAME and PASSWORD

        This expects a standard '$ ' VAX Prompt
        *

         PARAMETERS [ User_Name, User_Pass ]

         ALLOCATE Vax_Buffer, 512    ! This buffer is 512 bytes long

COMMENT *
        The PROMPT_TYPE is used to check for a
        sucessful LOGIN This could be a parameter or
        a better way to do this would be to look for
        the USER_NAME as a result of a SHOW PROCESS
        command
      *

          CLEAR_SCREEN
          PRINT "                                Connecting to VAX"
          Prompt_Type = "$"


COMMENT *
        This is the MAIN routine

        This global variable is used to return a
        value to DOS when the program terminates.
        The BATCH ERRORLEVEL can be used to check
        this return status.  Initally set to 1 for
        an error.  Set to 0 on a succesful LOGIN and
        returned to DOS.
      *

        Log_Status = 1                ! Set for an error return

        Vax_Echo = _RECEIVE_ECHO      ! Save the echo

        _RECEIVE_ECHO = _FALSE        ! Set to _TRUE for DEBUGGING

        _SCREEN_LOCK = 1              ! Turn off the display for silent running

        CALL Get_Vax                  ! Try to Login


        _SCREEN_LOCK = 0              ! restore system operations

        _RECEIVE_ECHO = Vax_Echo


        PRINT "" ! PRINT ""

        QUIT Log_Status               ! make this a return for use
                                      ! by other Procedures
```

```
PROCEDURE Get_Vax

        Retries = 3

Retry_Loop:


        SEND _NAK               ! Send a ^U CR to clear out line garbage
        WAIT 1                  ! and get it's attention

        RECEIVE Vax_Buffer,
         [
          "Username: ": GOTO Enter_Name
         ], ,10

        Retries = Retries - 1

        IF ( Retries == 0 ) THEN GOTO Failed

        GOTO Retry_Loop

Enter_Name:


        SEND _NAK;              ! Send a ^U to clear out line garbage

        SEND User_Name          ! Send user_name followed by CR

        RECEIVE Vax_Buffer,
         [
           "Password: ": GOTO Enter_Pass
         ], , 10

        GOTO Failed

 Enter_Pass:

                                ! same as above, but now the Password
        SEND _NAK;
        SEND User_Pass

        RECEIVE Vax_Buffer,
         [
          Prompt_Type: GOTO Success
          "User authorization failure": GOTO Failed
         ], ,60

        GOTO Failed

Success:
            ! Start up Host M¦bius
            ! Report success to user, let her know what's going on
        PRINT "                                  Login  successful"
        PRINT ""
        PRINT "                                Starting Host Mobius"

        SEND "@test"

        Log_Status = 0          ! Success return for DOS

        PRINT "                                 Host Mobius started."

        RETURN
```

END_PROCEDURE

Test. Com

```
$ run/nodebug *rans_cor
$ logout
```

Appendix G

The PC8.BAS program

```
10 SUBFLAG = 0: X1=1: X2=1: DTOA=0
20 DIM B$(5000)
30 DIM C$(5000)
40 OLDALL = 0
50 DIM D1$(10)
60 DIM D2$(10)
70 DIM D3$(10)
80 DIM D4$(10)
90 DIM D5$(10)
100 FLAG = 0: FLAG2=0
110 OPEN "COM1: 9600, N, 8, 1, RS, DS" AS #1
120 ON COM(1) GOSUB 210
130 COM(1) ON
140 V=1: W =1: X=1: Y=1: Z=1
150 IF SUBFLAG GOTO 200
160 PRINT "Please focus on the substrate and hit return"
170 INPUT Z$
180 PRINT #1, Z$
190 REM COM(1) ON
200 GOTO 200
210 ALL = LOC(1): IF ALL < 1 THEN RETURN
220 FOR N = OLDALL TO (ALL + OLDALL - 1)
230 B$(N) = INPUT$(1, #1): PRINT (ALL+OLDALL), B$(N), N
240 NEXT N
250 OLDALL = OLDALL + ALL
260 IF FLAG THEN FLAG=0: J=OLDALL - ALL - 1: GOTO 330
270 IF FLAG2 THEN FLAG2=0: J= OLDALL - ALL - 1: J=1: GOTO 500
280 J=1: PRINT "processing"
290 FOR U = 1 TO 5
300 READ D1$(U), D2$(U),D3$(U), D4$(U), D5$(U)
310 PRINT D1$(U), D2$(U),D3$(U), D4$(U), D5$(U)
320 NEXT U
330 D$ = B$(J)
335 RESTORE
340 IF D$="" THEN FLAG=1: GOTO 210
350 IF  ASC(D$)<32 THEN J=J+1 : PRINT "sci asci asci":GOTO 330
360 PRINT "check character = ",D$, Z , D1$(Z)
370 IF D$ = D1$(Z) THEN Z=Z+1 ELSE Z=1: GOTO 390
380 IF (Z= 5) THEN PRINT DA, DTOA :ELSE GOTO 390
385 IF DA=DTOA GOTO 480 ELSE DA=DA+1
390 IF D$ = D2$(Y) THEN Y=Y+1 ELSE Y=1: GOTO 410
400 IF Y=X2+5 THEN X2=X2+1: GOTO 570
410 IF D$ = D3$(X) THEN X=X+1 ELSE X=1: GOTO 430
420 IF X=5 GOTO 620
430 IF D$ = D4$(W) THEN W=W+1 ELSE W=1: GOTO 450
440 IF W=5 GOTO 810
450 IF D$ = D5$(V) THEN V=V+1 ELSE V=1: GOTO 470
460 IF V=5 GOTO 850
470 J=J+1: GOTO 330
480 J$="": J=J+1
490  FOR K= 1 TO 12
500 IF B$(J) = "" THEN FLAG2=1: GOTO 210
510 J$= J$ +B$(J): J=J+1
520 NEXT K
530 GOTO 880
540                 RESTORE
550 SUBFLAG=1: OLDALL=0: DA=0
560 GOTO 140
570 PRINT "Please focus on the mask and hit return"
580 INPUT T$
```

```
600 COM(1) ON
610 GOTO 540
620 PRINT " The VICOM is either in use already or needs to be rebooted."
630 PRINT " To reboot the VICOM, do the following:"
640 PRINT "                                       "
650 PRINT "                1) Make sure that the camera cable is"
660 PRINT "                  connected to the VICOM I/O box in"
670 PRINT "                  the computer room. The cable is "
680 PRINT "                  marked with a green label."
690 PRINT "
700 PRINT "                2) Push reset button on lower half"
710 PRINT "                  of VICOM"
720 PRINT "                3) At the VICOM Terminal type: (hit return)"
730 INPUT Q$
740 PRINT  "                              A) BO 2,0,2"
750 PRINT "                               B) Sys1:0"
760 PRINT "                               C) date and time"
770 PRINT "                               D) VDP
780 PRINT " Now restart the alignment program"
790 CLOSE #1
800 GOTO 1120
810 PRINT "                The necessary amount of alignment is"
820 PRINT "                beyond the range of the PZT's"
830 CLOSE #1
840 GOTO 1120
850 PRINT "                                  AUTO - ALIGNMENT COMPLETE"
860 CLOSE #1
870 GOTO 1120
880 REM            DRIVE THE PZT=1
890 PZT = VAL(MID$(J$,1,4))
900 N=0: GOSUB 920
910 GOTO 980
920 XH% = INT(PZT/256)          'HIGH BYTE
930 XL% = PZT - XH%*256         'LOW BYTE
940 OUT BASE + 2*N, XL%          'WRITE LOW BYTE TO D/A
950 OUT BASE + 1 + 2*N, XH       'WRITE HIGH BYTE TO D/A
960 PRINT "D/A CHANNEL =" N " IS BEING DRIVEN BY " PZT
970 RETURN
980 REM            DRIVE PZT=2
990 PZT = VAL(MID$(J$,5,4))
1000 N=2: GOSUB 920
1010 REM            DRIVE PZT=3
1020 PZT = VAL(MID$(J$,9,4))
1030 N = 4: GOSUB 920
1040 REM SIGNAL VAX THAT D/A IS COMPLETE
1045 OLDALL = 0: RESTORE: ERASE B$: DIM B$(5000)
1050 PRINT#1, ""
1055 COM(1) ON
1060 GOTO 140
1070 DATA D,F,E,E,N
1080 DATA T,O,R,R,N
1090 DATA O,C,R,R,D
1100 DATA A,U,V,C,O
1110 DATA "",S,I,F,N
1120 END
```

Appendix H
The TRANS_COR routine

```
      integer*2       img1(128,128)
      integer*2       img2(128,128)
      integer*4 nr, nc, data_type, iopen, devblk(16)
      integer*4 vicinit

      real*8 offset_angle                          !  rotational offset
                                                   !angle between two images
      real*8 x_center1                                    !  center of image one
                                                   !projected onto x-axis
      real*8 y_center1                                    !  center of image one
                                                   !projected onto y-axis
      real*8 x_center2                                    !  center of image two
                                                   !projected onto x-axis
      real*8 y_center2                                    !  center of image two
                                                   !projected onto y-axis
      real*8 x_differential                        !  x_axis translational
                                                   !offset between two images
      real*8 y_differential                        !  y_axis translational
                                                   !offset between two images
      real*8 voltsx, voltsy, rotation, ltheta
      character*30 filename, filename2,v
      character*80 file, file2


C-------------------------------------------------------------------------
C       The calibration subroutine calibrates the system so that trans_cor  |
C               knows how to translate pixel offset data into voltage levels|
C               for movement of the pzts                                    |
C-------------------------------------------------------------------------

      call calibrate(voltsx, voltsy, rotation, ltheta)

      irec = 0
      data_type = 1
      iopen = 2
      filename = '[aowens.correlation]image.im'
      filename2 = '[aowens.correlation]image2.im'  !!!!!!!!!!!!!!!
      file = '[aowens.correlation]prime3.vc'
      file2 = '[aowens.correlation]prime4.vc'
      nr = 128
      nc = 128
      devblk(1)=1
      iostat = vicinit(1, devblk)
      print*, 'iostat = ', iostat
      call vicprocess(file)
      iostat = vicinit(-1,devblk)
      print*, 'iostat = ', iostat
      istatus = lib$spawn('run djb1:[biron.vicom.lib.test]vic128')

C**************************************************************************
C*      writes whatever is in image 1 on vicom into image.im in current    *
C*              directory                                                  *
C*      image shuffling!!!!!!!!!!!!!!!                                     *
C**************************************************************************

      call disk_rd (data_type, irec, filename, iopen,
     +          img1, nr, nc)
      call unpack (img1, nr, nc)
      call find_center( img1, x_center1, y_center1)
      print*, x_center1, y_center1
```

```
C-------------------------------------------------------------------------
C       signal user of successful processing of image 1
C       prepare second image for processing
C-------------------------------------------------------------------------

        call lib$get_input(v)           ! wait for user to press return
        devblk(1)=1
        iostat = vicinit(1, devblk)
        print*, 'iostat = ', iostat
        call vicprocess(file2)
        iostat = vicinit(-1,devblk)
        print*, 'iostat = ', iostat
        print*, 'vic128'
C       istatus = lib$spawn('copy image.im image2.im')
        istatus = lib$spawn('run djb1:[biron.vicom.lib.test]vic128')
        print *, 'disk_rd'
        call disk_rd (data_type, irec, filename, iopen,
     +          img2, nr, nc)
        call unpack (img2, nr, nc)
        call find_center( img2(ix, iy), x_center2, y_center2)
        print*, x_center2, y_center2

C   compute translational offset between two images

        x_differential = x_center1 - x_center2
        y_differential = y_center1 - y_center2
        print *, 'x offset = ',x_differential
        print *, 'y offset = ',y_differential

C-------------------------------------------------------------------------
C       compute rotational offset between 2 images
C-------------------------------------------------------------------------

C       call polar( x_center2, y_center2, x_center1,
C     +         y_center1, img2, img1, offset_angle)
        call hill_climb_polar( x_center2, y_center2, x_center1,
     +          y_center1, img2, img1, offset_angle)
        print*, offset_angle

        call translate (x_differential, y_differential, offset_angle,
     +          voltsx, voltsy, rotation, ltheta)

        end
```

Appendix I

The CALIBRATE subroutine

```
      subroutine calibrate( nvoltsx, nvoltsy, rotation, theta)
      integer*2        img1(128,128)
      integer*2        img2(128,128)
      integer*4 nr, nc, data_type, iopen, devblk(16)
      integer*4 vicinit

      real*8 offset_angle                          !  rotational offset
                                                   !angle between two images
      real*8 x_center1                                    !  center of image one
                                                   !projected onto x-axis
      real*8 y_center1                                    !  center of image one
                                                   !projected onto y-axis
      real*8 x_center2                                    !  center of image two
                                                   !projected onto x-axis
      real*8 y_center2                                    !  center of image two
                                                   !projected onto y-axis
      real*8 x_differential                        !  x_axis translational
                                                   !offset between two images
      real*8 y_differential                        !  y_axis translational
                                                   !offset between two images

      real*8 theta
      character*30 filename, filename2,v
      character*30 file, file2
      character*15 d_to_a                          ! string sent to PC for control
                                                   !of ort amplifier.
      integer*2  pzt1,pzt2,pzt3, cal_pzt
      real*8     rotation, nvoltsx, nvoltsy

      data pzt1,pzt2,pzt3,cal_pzt / 2048,3071,3071,1024/

      irec = 0
      data_type = 1
      iopen = 2
      filename = '[aowens.correlation]image.im'
      filename2 = '[aowens.correlation]image2.im'  !!!!!!!!!!!!!!!
      file = '[aowens.correlation]primel.vc'

      call lib$get_input(v)              ! wait for user to hit return key
      nr = 128
      nc = 128

      devblk(1) = 1
      iostat = vicinit(1, devblk)
      if (iostat .ne. 1) then
              print*, 'ERRVIC'
              stop
      endif
      call vicprocess(file)
      iostat = vicinit(-1,devblk)
      if (iostat .ne. 1) then
              print*, 'ERRVIC'
              stop
      endif
      istatus = lib$spawn('run djb1:[biron.vicom.lib.test]vic128')

C*************************************************************************
C*      writes whatever is in image 1 on vicom into image.im in current  *
C*            directory                                                  *
C*      image shuffling!!!!!!!!!!!!!!!                                   *
C*************************************************************************
```

```
      call disk_rd (data_type, irec, filename, iopen,
     +          img1, nr, nc)
      call unpack (img1, nr, nc)
      call find_center( img1, x_center1, y_center1)

C-------------------------------------------------------------------------------
C       signal user of successful processing of image 1                       |
C       prepare second image for processing                                   |
C-------------------------------------------------------------------------------

      ipzt_3 = pzt3                     ! 12 bit decimal representation of 7.5
                                        !volts. Will cause amplifier to move
                                        !pzt #3 to 75% of its full excursion or
                                        !11.25 microns
      ipzt_2 = pzt2                     ! will move pzt#2 to 11.25 microns
      ipzt_1 = pzt1                     ! will maintain pzt#3 at 7.5 microns
      encode (15, 100, d_to_a) ipzt_1, ipzt_2, ipzt_3
      print*, d_to_a
      call lib$get_input(v)             ! wait for PC to finish
      devblk(1)=1
      iostat = vicinit(1, devblk)
      if (iostat .ne. 1) then
              print*, 'ERRVIC'
              stop
      endif
      call vicprocess(file2)
      iostat = vicinit(-1,devblk)
      if (iostat .ne. 1) then
              print*, 'ERRVIC'
              stop
      endif
      istatus = lib$spawn('run djb1:[biron.vicom.lib.test]vic128')
      call disk_rd (data_type, irec, filename, iopen,
     +          img2, nr, nc)
      call unpack (img2, nr, nc)
      call find_center( img2(ix, iy), x_center2, y_center2)

C   compute translational offset between two images

      x_differential = x_center1 - x_center2
      y_differential = y_center1 - y_center2

      print*, 'D/A204820482048'         ! signals PC to drive pzts back into
                                        !starting position at 7.5 microns

      call lib$get_input(v)             ! wait for PC to finish
C-------------------------------------------------------------------------------
C       compute angular correction factor                                     |
C               and voltage (in 12 bit dec. representation) per               |
C               pixels of required movement                                   |
C-------------------------------------------------------------------------------

      theta = atand(y_differential/x_differential)
      nvoltsx = cal_pzt/x_differential
      nvoltsy = cal_pzt/y_differential

C       Now perform rotational calibration                                    |
C                                                                             |
```

```
C               degrees of rotation for pzts 2 and 3                    |
C-----------------------------------------------------------------------
        call rotational_cal(rotation)

C-------------------------------------------------------------------------
C       pzt #1 movement = ( x*cos(theta) + y*sin(theta)) + 2048          |
C       pzt #2 & 3 movement = ( y*cos(theta) + x*sin(theta)) + 2048      |
C-------------------------------------------------------------------------

 100    format ('D/A',3I4)
        return
        end
```

Appendix J
The ROTATIONAL_CAL subroutine

```
      subroutine rotational_cal( rotation)
      integer*2       img1(128,128)
      integer*2       img2(128,128)
      integer*4 nr, nc, data_type, iopen, devblk(16)
      integer*4 vicinit

      real*8 offset_angle                       !  rotational offset
                                                !angle between two images
      real*8 x_center1                                  !  center of image one
                                                !projected onto x-axis
      real*8 y_center1                                  !  center of image one
                                                !projected onto y-axis
      real*8 x_center2                                  !  center of image two
                                                !projected onto x-axis
      real*8 y_center2                                  !  center of image two
                                                !projected onto y-axis
      real*8 x_differential                     !  x_axis translational
                                                !offset between two images
      real*8 y_differential                     !  y_axis translational
                                                !offset between two images

      real*8 theta
      character*80 filename, filename2
      character*80 file, file2
      character*15 d_to_a                       ! string sent to PC for control
                                                !of pzt amplifier.
      integer*2  pzt1,pzt2,pzt3, cal_pzt
      real*8     rotation

      data pzt1,pzt2,pzt3,cal_pzt / 2048,3071,1024,1024/

      irec = 0
      data_type = 1
      iopen = 2
      filename = '[aowens.correlation]image.im'
      filename2 = '[aowens.correlation]image2.im'  !!!!!!!!!!!!!!!
      file = '[aowens.correlation]prime3.vc'
      file2 = '[aowens.correlation]prime4.vc'

      nr = 128
      nc = 128

      devblk(1) = 1
      iostat = vicinit(1, devblk)
      call vicprocess(file)
      iostat = vicinit(-1,devblk)
c     print*, 'iostat = ', iostat
      istatus = lib$spawn('run djb1:[biron.vicom.lib.test]vic128')

C*************************************************************************
C*      writes whatever is in image 1 on vicom into image.im in current  *
C*            directory                                                  *
C*      image shuffling!!!!!!!!!!!!!!!                                   *
C*************************************************************************

      call disk_rd (data_type, irec, filename, iopen,
     +           img1, nr, nc)
      call unpack (img1, nr, nc)
      call find_center( img1, x_center1, y_center1)
c     print*, x_center1, y_center1
```

```
C-------------------------------------------------------------------------
C       signal user of successful processing of image 1                  |
C       prepare second image for processing                              |
C-------------------------------------------------------------------------

        ipzt_3 = pzt3                       ! 12 bit decimal representation of 7.5
                                            !volts. Will cause amplifier to move
                                            !pzt #3 to 75% of its full excursion or
                                            !3.75 microns
        ipzt_2 = pzt2                       ! will move pzt#2 to 11.25 microns
        ipzt_1 = pzt1                       ! will maintain pzt#3 at 7.5 microns
        encode (15, 100, d_to_a) ipzt_1, ipzt_2, ipzt_3
        print*, d_to_a
        call lib$get_input(v)               ! wait for PC to finish
        devblk(1)=1
        iostat = vicinit(1, devblk)
c       print*, 'iostat = ', iostat
        call vicprocess(file2)
        iostat = vicinit(-1,devblk)
c       print*, 'iostat = ', iostat
c       print*, 'vic128'
C       istatus = lib$spawn('copy image.im image2.im')
        istatus = lib$spawn('run djb1:[biron.vicom.lib.test]vic128')
C       print *, 'disk_rd'
        call disk_rd (data_type, irec, filename, iopen,
     +          img2, nr, nc)
        call unpack (img2, nr, nc)
        call find_center( img2(ix, iy), x_center2, y_center2)
C       print*, x_center2, y_center2

C   compute translational offset between two images

        x_differential = x_center1 - x_center2
        y_differential = y_center1 - y_center2

        print*, 'D/A204820482048'           ! signals PC to drive pzts back into
                                            !starting position at 7.5 microns

        call lib$get_input(v)               ! wait for PC to finish

C-------------------------------------------------------------------------
C       compute angular correction factor                                |
C               and voltage (in 12 bit dec. representation) per          |
C               pixels of required movement                              |
C-------------------------------------------------------------------------

        call hill_climb_polar( x_center2, y_center2, x_center1,
     +          y_center1, img2, img1, offset_angle)

C-------------------------------------------------------------------------
C       now compute angular calibration factor: that is, the voltage for |
C               pzt 2 for one degree of counterclockwise rotation.       |
C               Pzt 3 uses the negative of this value                    |
C-------------------------------------------------------------------------

        rotation = offset_angle/ (ipzt_2 - 2048)

 100    format ('D/A',3I4)
        return
        end
```

Appendix K
The TRANSLATE subroutine

```
      subroutine translate ( x, y, theta, vx, vy, delta, otheta)
      character*15     A
      real*8           x,y,theta, vx, vy , delta, otheta
      integer*4        apzt1, apzt2, apzt3
      integer*4        xpzt1, ypzt2, ypzt3
      integer*4        tpzt1, tpzt2, tpzt3

C     first compute necessary pzt voltages for  angular correction

      apzt1 = 2048
      apzt2 = theta * rotation + 2048
      apzt3 = - ( theta * rotation) + 2048

C     next, compute pzt voltages for translational correction

      xpzt1 = (x * vx * cosd(otheta)) - (y * vy * sind(otheta)) + 2048
      ypzt2 = -((y * vy * cosd(otheta)) - (x * vx * sind(otheta))) + 2048
      ypzt3 = -((y * vy * cosd(otheta)) - (x * vx * sind(otheta))) + 2048

C     finally compute total necessary pzt voltages

      tpzt1 = apzt1 + xpzt1
      tpzt2 = apzt2 + ypzt2
      tpzt3 = apzt3 + ypzt3

C     Check to make sure that we are within the range of the PZT's

      if ((tpzt1 .gt. 4095) .or. (tpzt1 .lt. 0) .or.
     +    (tpzt2 .gt. 4095) .or. (tpzt2 .lt. 0) .or.
     +    (tpzt3 .gt. 4095) .or. (tpzt3 .lt. 0)) then
          print*, 'ERRCEN'
          stop
      endif

C     send PC a string containing necessary voltages for
C           driving pzt amplifier

      encode (15, 100, A) tpzt1, tozt2, tpzt3
      print*, A
  100 format ('D/A',3I4)
      return
      end
```

Appendix L
The POLAR subroutine

```
c
      subroutine polar (x0,y0,x1,y1,image_2,image_1,correlation_angle)
      real*8          correlation_angle, delta_theta
      integer*2       m,rho
      Integer         mmin,mmax,mstep
      real*8          r(-100:101), p
      real*8          x2,y2,x1,y1,x,y,x0,y0
      integer*2       image_1(128, 128), image_2(128, 128)

C*    delta_theta = 0.01                ! assuming rotational offset angles
                                        !are on order of hundredth's of radians
C     delta_theta = 0.0015              ! assuming rotational offset angles
                                        !are on the order of milli-radians
      max_ip_key = 0
      max_ip = 0
      delta_theta = .1

      write (6,*) 'Input min, max, step  '
      read (5,*) imin, imax, mstep
      mmin = imin/delta_theta
      mmax = imax/delta_theta

      write (99,*) (mmax-mmin)/mstep+1
      do m = mmin,mmax,mstep
         do rho = 0, 100
            do theta = 0.0, 360.0, 1
               x = (rho * (cosd(theta))) + x0
               y = (rho * (sind(theta))) + y0
               x2 = (rho * (cosd( theta + (m * (delta_theta))))) + x1
               y2 = (rho * (sind( theta + (m * (delta_theta))))) + y1
C-------------------------------------------------------------------------------
C     Round off coordinate values so they can be used as row and column
C           numbers for image look-up tables
C-------------------------------------------------------------------------------

               ix = nint(x)
               ix2 = nint(x2)
               iy = nint(y)
               iy2 = nint(y2)

               if (( x .lt. 1) .or. (y .lt. 1) .or.
     +              (x .gt. 128) .or. (y .gt. 128) .or.
     +              (x2 .lt. 1) .or. (y2 .lt. 1) .or.
     +              (x2 .gt. 128) .or. (y2 .gt. 128)) then
                  goto 100
               endif
               p = p + ((image_1( ix2, iy2)) * (image_2( ix, iy)))
100         enddo
         enddo
         r((m-mmin)/mstep+1) = p
         p = 0                          ! reset total image intensity
      write (99,*) REAL(m),REAL(r((m-mmin)/mstep+1))
         if (r((m-mmin)/mstep+1) .gt. max_ip) then
               max_ip_key = m
               max_ip = r((m-mmin)/mstep+1)
         endif
      enddo
      correlation_angle = max_ip_key * delta_theta
```

Appendix M

The HILL_CLIMB_POLAR subroutine

```
      subroutine hill_climb_polar (x0,y0,x1,y1,image_2,
     +          image_1,correlation_angle)
      real*8            correlation_angle, delta_theta
      integer*2         rho
      integer*4         m
      integer           mmin,mmax,mstep
      real*8            r(-100:101), integral
      real*8            x1,y1,x,x0,y0
      integer*2         image_1(128, 128), image_2(128, 128)
      real*4            i, remainder(0:201)

      parameter         ( zero = 0, imin = -5, imax = 5, mstep = 1 )
      delta_theta = 0.1
      mmin = imin/delta_theta
      mmax = imax/delta_theta

      i = zero

100   x = ((mmax - mmin)/2 + mmin)
      m = nint(x)
      if ((m - mmin) .eq. 1) then
          m = m - mstep
          goto 200
      endif
      call integrate(x0, y0, x1, y1, image_1, image_2, integral, m)
      r(m) = integral
      m = m + mstep
      call integrate(x0, y0, x1, y1, image_1, image_2, integral, m)
      r(m) = integral

      if ( abs(r(m) - r(m-mstep)) .le. 2000) then
              goto 200
      elseif (r(m) .gt. r(m-mstep)) then
              mmin = m
      else
              mmax = m
      endif
      goto 100
200   correlation_angle = m * delta_theta

      return
      end
```

Appendix N
The FIND_CENTER subroutine

```
      subroutine find_center ( intensity, x_center, y_center)
      integer*2 intensity(128,128)
      real x_arm                                    !  weighted sum of intensities
                                                    !along a given row of image
      real y_arm                                    !  weighted sum of intensities
                                                    !along a given column of image
      real total_intensity                          !  total intensity of image
      real x_center                                 !  center of image
                                                    !projected onto x-axis
      real y_center                                 !  center of image
                                                    !projected onto y-axis
C     intialize intensity summation variables
      total_intensity = 0.
      x_arm = 0.0
      y_arm = 0.0
      do ix = 1 , 129
         do iy = 1, 128
            total_intensity = total_intensity + float(intensity(ix , iy))
            x_arm = (x_arm + (intensity(ix,iy) * ix))
            y_arm = (y_arm + ( intensity(ix,iy) * iy))
         enddo
      enddo

c     compute center of intensity

      x_center = x_arm / total_intensity
      y_center = y_arm/total_intensity
      return
      end
```