

DRAFTING WITH LIGHT

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in Partial Fulfilment of the Requirements
for the Degree of
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in the
Department of Electrical Engineering
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by

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UNIVERSITY OF SASKATCHEWAN

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"DRAFTING WITH LIGHT"

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ABSTRACT

This thesis describes the method of selection and implementation of a drafting device suitable for use with a high quality precision automatic drafting system intended for the production of navigational charts. This drafting system consists of a minicomputer for control (1), an industry compatible magnetic tape transport for data input (2), and a precision flatbed drafting table.

After consideration of various methods, a technique was selected in which a beam of light is used to expose photosensitive material. Lines are drafted by moving the beam across the film. Symbols are produced by shaping the beam into the desired configuration and flashing it onto the film. An optical mechanical light head, made by Barr and Stroud Limited, was chosen as being most suitable but it was necessary to design the control and interface for its interconnection with the plotter and the minicomputer.

Particular emphasis was placed on the use of stepper motor positioning controls as being most compatible with digital control circuitry and on the best method of controlling light intensity for varying drafting speeds on film. This entailed a detailed study of the properties of light sources, films and optical systems as well as control circuitry.

The final interface and control unit that was constructed for the Barr and Stroud light head is described. This is followed by an analysis of the performance of the light head in its working environment.

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1. INTRODUCTION

1.1 General

Manually drafting complex graphical information both accurately and to a high quality can be an extremely tedious and time consuming task. Automated drafting systems were introduced to alleviate this problem. A block diagram of a typical drafting system is shown in figure 1.1(a); it basically consists of an input device, controller and plotter. The controller reads data from the input device, interprets it and controls the movement of an X-Y plotting device to produce the desired drawing.

Only in recent years have these drafting systems been used where the requirement was for drawings of high standard. Examples of this are nautical charts, land maps, and printed and integrated circuit masks. In the past, plotters did not have sufficient accuracy; today, however, there are several available that have an absolute accuracy of $.001^{1,2,3,4,5}$.

Besides coping with the accuracy problem, careful consideration must be given to the selection of the drafting instrument that is to be attached to the plotter. It is essential that this device produce high quality line work. In many cases it also has to be versatile so that a large variety of lines and symbols can be drawn without human intervention.

This thesis deals with the selection and imple-

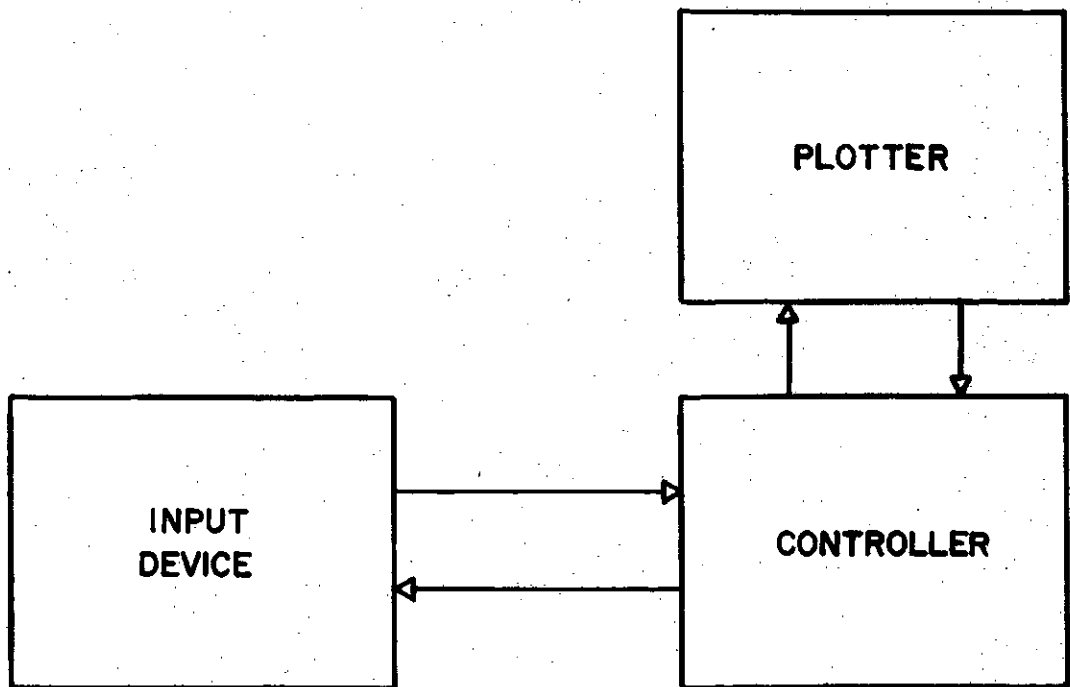


Figure 1.1 (a) Block Diagram of an Automatic Drafting System.

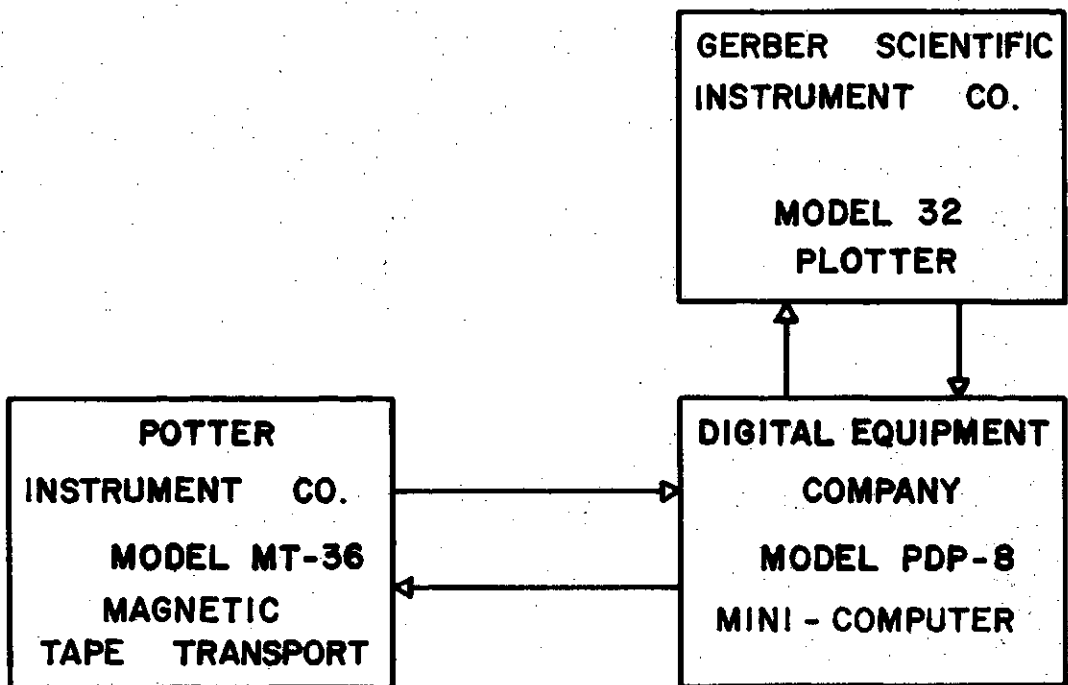


Figure 1.1 (b) Automatic Drafting System for Drawing Nautical Charts.

mentation of the most suitable drawing device for a automatic drafting system that is intended to be used to draw nautical charts. This drafting system was basically developed for the Canadian Hydrographic Service at the University of Saskatchewan by a development group headed by Dr. A.R. Boyle. This system is presently being used by the Hydrographic Service as an aid to the production of marine charts. Figure 1.1(b) shows the basic components of this drafting system. The controller is a Digital Equipment Company general purpose PDP-8 mini-computer. It reads graphical information in digital form from a Potter MT-36 IBM compatible magnetic tape transport and drives a Model 32 drafting table manufactured by Gerber Scientific Company.

Most of the digital input information intended for this system originates from a field survey which has been done on board ship. Traditionally, the results of such a survey were presented in graphical form on a document referred to as a "field sheet". This still holds true for most of the field data collected today. To be useful in an automatic cartographic system, the "field sheet" must first be "digitized", that is, translated into machine readable form. Before being plotted it is usually processed by a digital computer which can quickly and efficiently perform such tasks as scale conversion, critical depth selection and generalization.

Much work is being done today to automate the process

of collecting field survey data. One of the main benefits of this work will be that field survey data will now be available in digital form, thereby eliminating the tedious task of "digitizing".

The other type of input graphical data that is intended for the automatic drafting system is what is referred to as "mathematically" based data, that is, data that can be generated directly from a mathematical algorithm. Examples of this are chart projections, borders and lattices.

The automatic drafting system described in this thesis has been operational for more than two years and has been used mainly for plotting mathematically based data. However, a great deal of development work is being done both on the processing and plotting of data originating from a field survey.

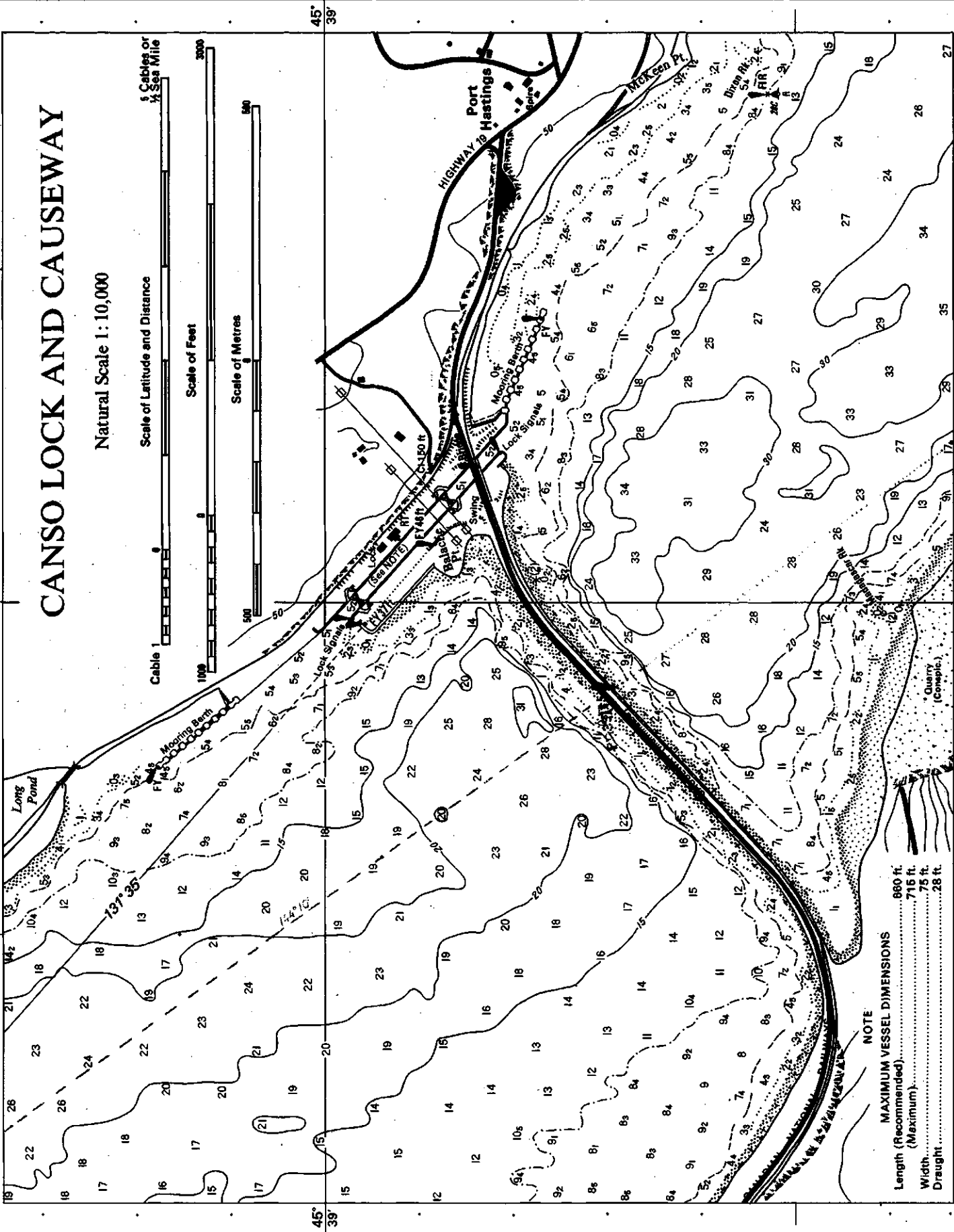
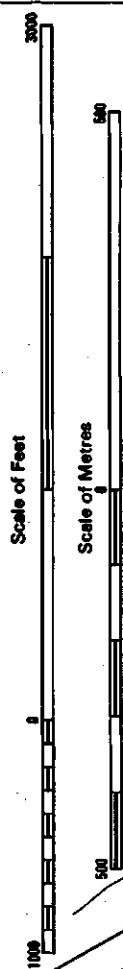
The cartographic requirements for the automatic drafting system can be best illustrated by referring to a sample of nautical chart shown in figure 1.2.⁶ The information presented on this chart has been manually drafted to a degree of high quality and precision.

Careful study of this chart reveals that several line widths have been used to produce this drawing. For example, an .008" width line is used to draft shore-line and a .005" line is used for the chart coordinate grid. The width of those lines have been drafted to an accuracy of $\pm .00025$ ". Examples of straight, smooth and sharply curved

CANSO LOCK AND CAUSEWAY

Natural Scale 1:10,000

Cable 1
Scale of Latitude and Distance
Scale of Feet
Scale of Metres



NOTE

MAXIMUM VESSEL DIMENSIONS	
Length (Recommended)	660 ft.
Length (Maximum)	715 ft.
Width	75 ft.
Draught	28 ft.

lines can all be found in figure 1.2. Not all lines are drafted continuously; for example, a combination of dots and dashes has been used to draft some of the depth contours (i.e. constant lines of ocean depth).

The reader will note the large degree of symbolization that has been used in this drawing. The most common symbol is the depth sounding, which numerically indicates oceanographic depth as a function of position. Pictorial symbols are used to represent aids to navigation. An example of this is the light buoy shown in the bottom right of figure 1.2. Symbols are also used to indicate to the mariner features of the foreshoreline. As an example, the symbolization shown at the bottom of figure 1.2 represents a sandy area. Chart lettering and names can also be classified as symbols although they are usually considered separately because of the large number of forms and sizes they can take. On the average, thousands of these symbols appear on a chart.

Most of the nautical charts produced by the Canadian Hydrographic Service are printed in colour using conventional lithographic techniques. Preparation of a chart for printing involves making a separate negative for each colour required. A printing plate is then constructed for each colour overlay and the final chart is printed one colour at a time. For proper colour registration, the relative accuracy of each colour overlay must be retained. This

is another important reason why drawing accuracy must be emphasized in this automatic drafting system.

1.2 Methods of Drafting

1.2.1 Ink pen on paper

There are several possible methods of drafting that could be considered for use in the automatic drafting system. The simplest is the conventional ink on paper technique. The lines produced by this method are jagged and irregular; consequently they are unacceptable for photographic reproduction. Other arguments against this method of drafting are that it requires constant operator attention due to ink drying and blobbing and lacks the versatility that is necessary to obtain many different line widths and symbols.

1.2.2 Scribing on plastic coated mylar

Scribing on plastic coated mylar is the technique now normally used to draft high quality graphical information manually. The scribing material consists of a thin plastic emulsion coated onto a transparent mylar base which is removed with a cutting tool called a scribe.

Automating the process of scribing, however, presents several difficulties. Firstly, the pressure of the cutting tool on the scribe coat is critical.⁷ If it is set too low the scribe point will not cut through the plastic emulsion; if set too high it will cut through the plastic base. Secondly, an automatic turret head scribe becomes bulky and complicated if a large number of line

widths are required. Thirdly, great care must be taken to remove the plastic swarf that is left from the scribe. Finally, the main argument against this method is that each chart symbol would have to be scribed individually (see method 3). This alone would be a time consuming task since on the average each chart contains thousands of symbols⁸.

1.2.3 Drafting on photographic film with a light beam

The concept of drafting on photographic film with a light beam is not new, although in the past it was not used specifically where high quality line information was a requirement. Graphical information is produced by drafting directly onto photographic film with a focussed image of light. Lines are drafted by moving this image of light across the film and symbols are produced by shaping the beam into the desired configuration and flashing it onto the film.

High quality lines can be produced using this method. Drafting times can be significantly reduced if symbols are produced by the flashing technique. This light beam drafting technique is well suited for automation since no manual adjustments are required for several hundred hours of operation.

The main disadvantage of this method is that the drafting material is photographic film. Therefore, a special darkroom environment has to be constructed for the plotter.

and film exposure conditions carefully controlled to ensure that high quality results are obtained.

The light beam method of drafting was selected over the other two because it best suited cartographic requirements. It was the most versatile and the only one to offer full possibility for automation.

This thesis first deals with the problem of selecting the most suitable light beam drafting instrument. Several names have been used in the literature to describe this type of device. For the remaining portion of this text, the term "light head" will be employed.

An optomechanical light head manufactured by Barr and Stroud Ltd. is described. The interface and control required to connect this device to the PDP-8 mini-computer and Gerber plotter is then discussed. This is followed by an analysis of the performance of the instrument. The system described is operational and is being used by the Canadian Hydrographic Service to produce high quality drawings for both development and production work.

2. SELECTION OF LIGHT HEAD

2.1 General

In this chapter the different ways of producing a light beam are discussed. The most suitable technique is then selected based on drafting and hardware requirements as well as such factors as cost and availability of commercial units.

2.2 Photographic Film

Some knowledge of the drafting material is required before light head requirements can be considered. The properties of photographic film are usually described by what is commonly known as its "characteristic curve".⁹ A typical characteristic curve is shown in figure 2.1. Film density is plotted as a function of the common logarithm of exposure. Exposure is defined as:

$$E = It$$

where E is the exposure,

I is the intensity of light seen by the film,

t is the time the film sees the light.

Density describes the developed film's ability to block the passage of light. The formula for density is

$$D = \log_{10} \frac{I_i}{I_t}$$

where D is the density,

I_i is the intensity of incident light on the film,

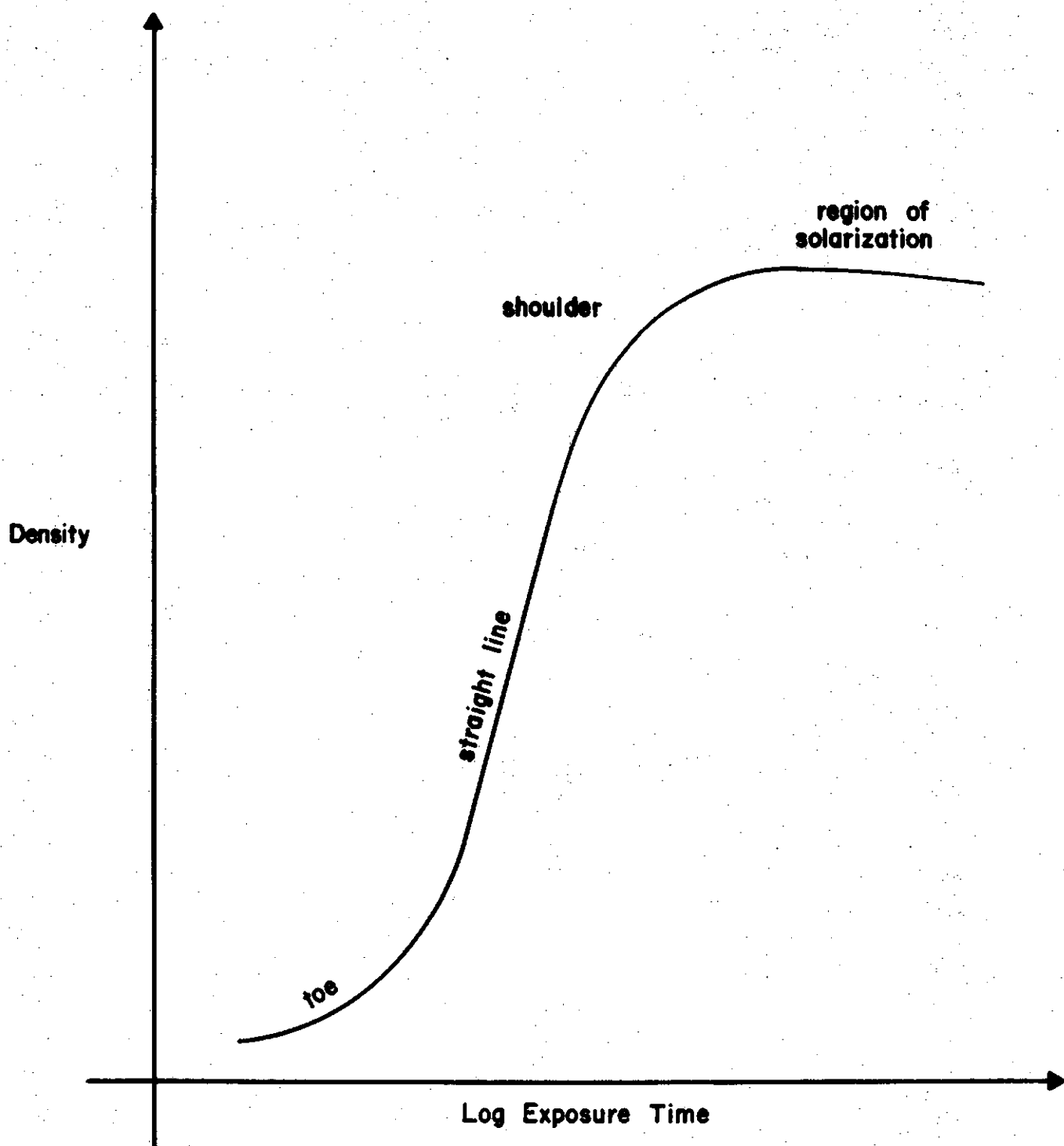


Figure 2.1 Characteristic Curve.

I_t is the intensity of light transmitted through the film.

The characteristic curve in figure 2.1 is divided into four regions although they might not all be present in some films. These four regions are the toe, straight line, shoulder and region of solarization. The aim in most photographic work is to capture the different illumination levels or contrast of a scene. The film is therefore exposed in the straight line region where density changes are linear to changes in the common log of exposure. The slope of this region determines the relationship between the contrast in the scene to that of the developed film. A high contrast film is one that has a very steep slope; a small change in light level of a scene will therefore produce a large change in film density.

The speed of a film is a measure of the sensitivity of the emulsion to light. It is related to the size of silver halide grains in the emulsion. Slower speed films have smaller grains and therefore better resolution. There are a variety of different procedures for measuring film speed. The ASA scale for black and white film is used in this text and is defined as

$$ASA = \frac{.8}{E}$$

where ASA is the speed rating

and E is the exposure in meter-candle-seconds required for a net gain in density of 0.10.

Usually a high contrast film is chosen for line work because only film densities of greater than 3.0 are required. The film is exposed well into the shoulder region of its characteristic curve so that changes in exposure will not produce significant changes in film density. A low speed emulsion is chosen to obtain the necessary line resolution.

Selection of the most suitable photographic film for an automatic drafting system is based on several considerations. Two important ones are exposure latitude and dimensional stability. Exposure latitude refers to the degree to which film exposure conditions can be varied and yet not significantly affect results. It is desirable to select a film that has a large latitude so that the requirements for the intensity control can be relaxed.

The film must be dimensionally stable if the accuracy of a drawing is to be retained. The two main factors that affect the dimensional stability of the film are temperature and humidity.³³ Usually an environmental control system is required to stabilize exposure and processing conditions. The cost of the control is related to the degree of stability of the film being used.

Besides being dimensionally stable, the film selected should also be easy to handle. It is for these reasons that plastic based films are in use today.

The dimensional stability of a film can be further improved by matching the temperature and humidity expansion coefficients of the emulsion to that of the base. This is done by substituting stable synthetic resins in place of the animal gelatin that is normally used in the emulsion.

Another factor to consider when selecting the most suitable film is the ease of film processing. Generally, it becomes less critical for slower speed films.

2.3 Requirements for Light Head

2.3.1 General

The overall cartographic requirements for the automatic drafting system have been discussed briefly in Chapter 1. They are summarized below:

- a) The accuracy of cartographic information should be better than $\pm .004"$.
- b) All cartographic information must be drafted to a high quality, that is, all lines must be sharply defined and have a constant density of greater than 3.0.
- c) A number of line widths are required, ranging from $.004"$ to $.060"$. The width of the line selected should be accurate to $\pm .0005"$ and should not vary by more than $.0005"$.

A light beam can be used to draft cartographic information either by drafting each line individually or by an image flashing technique. The basic difference between the two modes of operation is that the plotter is moving

for "line drafting" and is stationary for "image flashing".

2.3.2 Line drafting

When considering light head requirements for line drafting, the first step is to decide on the optimum shape of the projected light beam. The circle and rectangle were selected from several possible configurations.

Although the circle appeared to be the obvious choice, a more detailed study revealed several disadvantages. Firstly, it is difficult to draw squared corners and line ends, which is necessary requirement for nautical charts (see figure 1.2). Secondly, exposure conditions vary across the width of a line drawn with a circular image; this is not desirable in cases where precise line density and width is a requirement.

Figure 2.2 compares how exposure varies across .008" and .004" wide straight lines that have been drawn at constant speed with circular and rectangular shaped configurations. The fixed dimension, that is, that dimension which is facing in the direction of motion of the rectangle, is set to .004". The exposure has been normalized to the value obtained for the rectangle. As one would expect the exposure profiles for the circle are rounded in shape. This type of curve is not desirable because changes in light intensity or film processing conditions affect the width of line. On the other hand, exposure conditions for the rectangle are ideal because they are constant across the width of the line and change abruptly at its edges.

To illustrate this point, consider the following

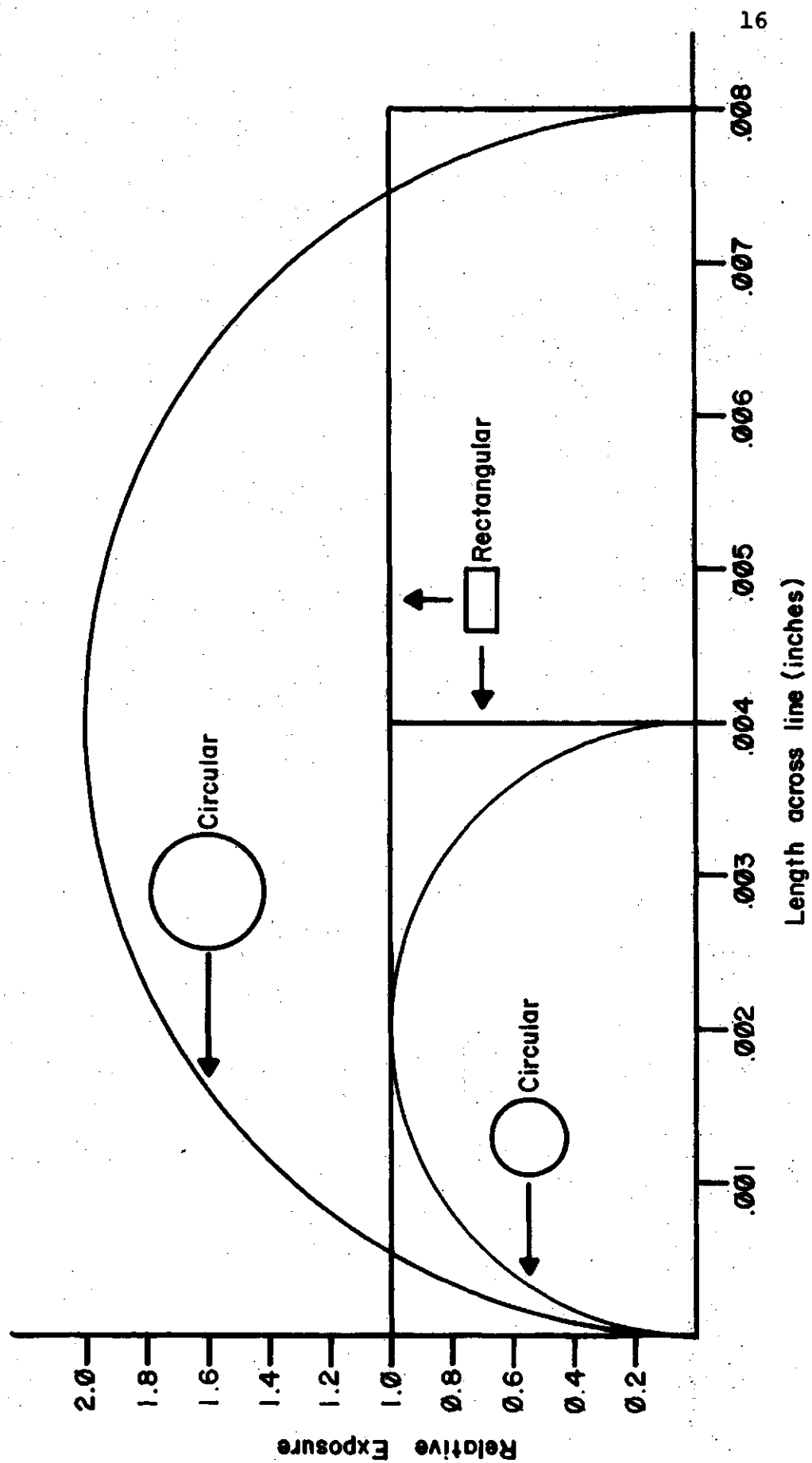


Figure 2.2 Relative Exposure Across a Straight Line.

example. Suppose conditions have been set so that the developed film becomes black if exposed at a relative value of .6. If the assumption is made that a very high contrast film is being used, then the width of the line can be estimated by drawing a straight line parallel to the X-axis and through the Y coordinate equal to .6. This line will intersect each exposure profile at two points. The width of the line can be approximated by projecting these intersection points onto the X-axis. For this example, the width of the lines drawn with a rectangle are .004" and .008" and those for the circle are .0032" and .0076". Now suppose film exposure conditions or processing is changed so the next effect is an increase in the exposure value of +20% (i.e. to .72). The width of the lines drawn with the rectangle will remain the same while those done with a circle will decrease by .0004" and .0001". Note that the change of line width is a function of the slope of the profile at the operating point used and therefore has the greatest effect on the smallest circle.

In these examples the effects of overexposure at the centre of the line and the contrast of the film have not been taken into account. The results of overexposure are the developed image loses its sharpness and increases in size. As illustrated in figure 2.2, the absolute value of exposure time for the circle increases proportionally to its diameter. It is therefore necessary to compensate for this change by varying the intensity of the circle as a function of diameter. On the other hand, the exposure

for each line width drawn by a rectangle can be held constant if the dimension facing the direction of travel is kept fixed.

Since, in practice, the slope of the characteristic curve is not infinite, the developed density of the film does not change abruptly as a function of exposure. As a result, a band of fuzziness is created at the edges of the line drawn by a circle. In this region the density of the film is changing from clear to black. On the other hand, the region of fuzziness is negligible for the rectangle because of the abrupt change of exposure time at its edges. This region of fuzziness is not significant if film contrast is kept high and is exposed with high intensity images.

The major advantage of the circle is that it is symmetrical about its central axis and therefore need not be rotated when drawing curved lines. The rectangle on the other hand must be rotated so that its fixed dimension is always facing in the direction of motion. Figure 2.3 shows a comparison of the relative exposure profiles across an .008" wide line whose radius of curvature is .009" and has been drawn at a constant speed with a circular and rectangular image. (The derivation of the general relative exposure expressions as a function of radius of curvature is given in Appendix A). The exposure time has been normalized to the value obtained for a straight line drawn by a rectangle with a fixed dimension of .004". In the case of the rec-

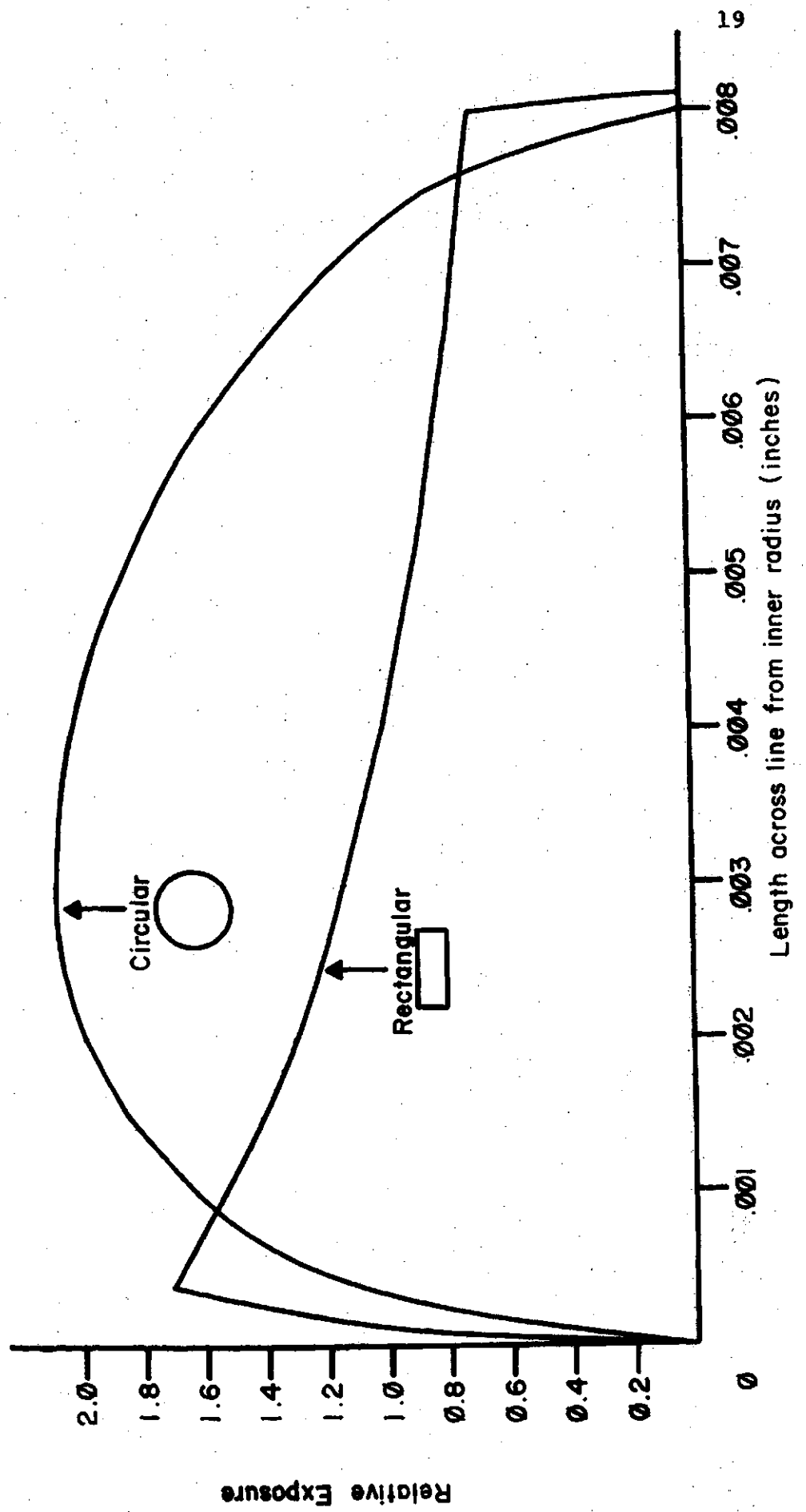


Figure 2.3 Relative Exposure Across a Curved Line. (Radius of Curvature .009")

tangle it is assumed that it is being rotated smoothly as it traces out the curved line. Note that the exposure conditions for the rectangle are no longer ideal. The side of the line closest to the centre of curvature receives up to a maximum of $1 \frac{7}{10}$ times what it normally receives while the side farthest away receives .3 less. The circular shaped profile for the circle also becomes distorted. The errors in line width and positional accuracy resulting from these distortions are small.

The rectangular image was chosen because it best suited system requirements, that is, square corners and line ends, tight tolerances on line density and width, and the relative ease with which different line widths could be drawn.

It is now possible to specify the light head requirements for line drafting:

a) Fixed Dimension of Rectangle.

Ideally the fixed dimension of the rectangle should be kept small so that it does not need to be considered when lines meet. However, as this dimension is decreased, the intensity of the projected image must be increased. Selecting the most suitable dimension therefore involves a compromise between these two factors. A reasonable dimension to use is .004" because it is equivalent to the smallest line width used on nautical charts.

b) Resolution of Image Rotation

Some of the factors to consider when specifying

the resolution of image rotation are its effect on exposure, line width and visual quality. For example, the error in line width, resulting from limitations in image resolution, can be approximated by the following expression:

$$W_{act} = W \cos\theta + L \sin\theta .$$

where W_{act} is the resultant line width,

W is the width of the rectangle,

L is the length of the rectangle in the direction of motion,

and θ is the error in angular setting in degrees.

A suitable selection for image resolution is 3 degrees. An error in setting of 3 degrees results in a maximum error of .0002" for the commonly used line widths (.005" - .060").

c) Speed of Image Rotation

Dynamic image rotation is required when tracing out a curve with a rectangle. The maximum speed of rotation is a function of the plotting speed and worst case radius of curvature.

$$\omega_{max} > \frac{V_t}{R_c} 2\pi$$

where ω_{max} is the maximum speed of rotation in rev/sec.,

V_t is the maximum plotter speed in inches per second,

and R_c is the worst case radius of curvature in inches.

Substituting approximately worst case values of .1 in/sec for V_t and .009" for R_c , then $\omega_{max} > 1.8$ rev/sec.

d) Accuracy of Rotation

Another important parameter that must be specified when using a rectangle for line tracing is the accuracy of rotation. The centre of the rectangle must remain stationary as it is being rotated. The net result of errors in rotation is that lines do not meet properly. This will not be noticeable if the error in the centre of rotation is kept to less than .001".

e) Light Intensity

The maximum required light intensity is usually specified for a maximum plotting speed with a certain projected light image for a specified film speed. The requirements in the automatic drafting system are for a maximum plotting speed of 1 in/sec with a rectangle whose fixed dimension is .004".

Normally the plotter operates over a range of speeds and so the light head must have some type of intensity control. The operating speed range of the Gerber plotter is approximately 28:1.

2.3.3 Image Flashing

As pointed out in earlier discussions, the "image flashing" technique eliminates the time consuming task of individually tracing out each symbol. For nautical charts this affords a significant reduction in plot-

ting time because on the average, thousands of symbols appear on a chart.

The parameters required for symbol projection are discussed in the next few sections.

a) Number of Symbols

The light head should at least have the capacity to access automatically up to 150 symbols for flashing. This is approximately the maximum number of symbols for plotting on one film negative.

b) Symbol Sizes

Symbol sizes ranging up to a value of .240" are required. Also a symbol magnification facility would be useful since several symbols are plotted at various sizes.

c) Symbol Orientation

The light head must be capable of projecting a symbol at different orientations. A resolution of 3 degrees for image orientation would be adequate.

d) Accuracy of Symbol Placement

The positional accuracy of projected symbols must be maintained at a high level. Errors in symbol positioning become particularly noticeable when two or more symbols are projected adjacently. An error of less than .003" is acceptable.

e) Intensity of Projected Image

The intensity of projected image should be as high as possible in order to reduce the time required to expose

each symbol.

2.4 Classification of Light Heads

2.4.1 Opto-electronic

In an opto-electronic light head, the symbolic image is produced electronically and is projected and focused onto film with a lens or system of lenses. This image may be formed in different ways.

a) Precision Cathode Ray Tube

The symbol is formed on the screen of a cathode ray tube (CRT) by carefully controlling the position and intensity of its electron beam. The advantage of this scheme is that there is no limit to the shapes that can be produced. The "shape" of each symbol would be stored in the control for the CRT. If the storage element were a read/write memory, the shape of these images could be changed at will.

The CRT selected for this application would require good resolution in order to obtain the necessary symbol quality. The electronic control for the CRT should include distortion correction in order to obtain the positional accuracy required. Precautions must be taken to minimize circuit drift and to compensate for aging of the CRT. The controller for the CRT would have to supply beam position and intensity information to the CRT electronics. It would also store each symbol shape and possibly contain the required logic for symbol orientation.

b) Matrix of Light Emitting Diodes

Another electronic approach to producing a symbolic image is to replace the CRT with a matrix of light emitting diodes (LED). The spacing of the diodes would have to be set so that a continuous image would be produced when projected on film. Each diode would be controlled individually so that an image of any shape could be formed. If such a diode matrix can be accurately fabricated, the problem of obtaining a stable position would be eliminated. The main difficulties with the LED matrix are obtaining uniform illumination and compensating for device aging. The electronics required to control the matrix would be similar to that for the CRT.

2.4.2 Opto-mechanical

The basic components of an opto-mechanical light head are a light source, a set of mechanical masks, an optical imaging system and a light shutter. Rays from the light source are shaped into a narrow beam with a system of condenser lenses. A mechanical mask is placed in the path of this beam to shape it into the desired figure; the image of this mask is then projected onto film by a system of lenses. A light shutter is used to control exposure of the image to photographic film.

In order to meet accuracy requirements, the mechanical and optical components of this light head have to be precise. On the other hand the electronics required to

control such a device is relatively simple compared to methods 1 and 2.

The main limitation of the opto-mechanical light head is its lack of flexibility. The shape of a symbol mask cannot be altered easily and only a limited number of these masks can be accessed automatically.

The opto-mechanical method of producing a light beam was selected for two basic reasons. Firstly, it was the simplest approach to meeting system requirements and secondly, because there were several commercial opto-mechanical light heads available^{10,11,12,13,14}.

These units were studied carefully in order to determine which one would offer the most advantages.

Several possible light sources could be used in this device. The least expensive one is the tungsten filament^{10,11,13}. The advantages of using this lamp are that it is rugged, inexpensive and does not require special high voltage power supplies. It can have a long lifetime if run below rated voltage. However, it is inefficient in that its spectral output is not well matched to the photographic emulsions commonly used for line drawing. The spectral output of tungsten is predominantly in the infrared region while the photographic emulsion is sensitive to shorter wavelengths. Gaseous discharge lamps^{10,14}, such as the mercury vapour lamp, are more efficient because they emit in the blue and ultra violet portion of the spectrum. However, they are

dangerous to use because of the need for high voltage supplies and the presence of dangerous gases in the event of breakage.

Other light sources such as the laser beam might offer advantages. (The laser is not being used in any of the present commercial units to the knowledge of the writer.) Only a very simple optical system would be required since the laser source emits a narrow beam of monochromatic light.

Most commercial units^{10,12,13,14} allow the user to select one of several mechanical masks automatically. For use in the present system the number of masks must be large and, even then, be easily interchangeable. Each mask selected must be accurately positioned in the optical system.

The light head must also be able to control the angular orientation of the projected image. Several different approaches have been used to meet this requirement. One method of achieving this is to rotate the complete light head¹⁴; such a control is bulky and limited in speed. A second more compact method is to rotate each individual mask¹³. A critical component of such a system is the device that accesses the desired mask and accurately locates it to the rotating mechanism. A third approach uses an optical technique to rotate the image of the mask¹¹; this simplifies the mask accessing device since each individual mask does not have to be attached to the rotating mechanism.

The intensity of the projected image can be

controlled in several different ways. The simplest approach is to adjust the drive voltage to the light source¹⁰. This is often rejected because of the non-linearity, and the limited response speed of the light source. A second approach utilizes an adjustable^{11,12,14} iris similar in principle to those found in most cameras. Another approach again is to place a variable neutral density attenuator disk in the optical path of the light source¹⁰. This disk is rotated to set the intensity of the projected image. The important parameters that must be considered when designing an intensity control are speed of response, precision and stability.

High speed shutters should be selected for the light head so that the end of lines will be properly exposed and to reduce the times required for "image flashing".

All optical and mechanical components must be precisely manufactured and aligned in order to meet the requirements for high quality and positional accuracy.

The model PS5 light head manufactured by Barr and Stroud was chosen over other commercial units for several reasons.

The PS5 head uses an inexpensive and easily replaceable 6 volt 10 watt tungsten halogen lamp. The main feature of this type of lamp is that its output intensity does not vary significantly throughout its lifetime. The halogen gases within its glass envelope react chemically with the tungsten vapour from the filament to form a new

gas. Instead of depositing on the glass envelope, this new gas decomposes redepositing the tungsten back onto the filament¹⁵. This lamp combined with an efficient optical system, produces enough light intensity for drafting speeds up to 2 in/sec with a .008" fixed dimension rectangle on film speeds with an ASA rating of 6.

The light head is fitted with a symbol disk which can contain as many as 96 automatically selectable symbols, a number larger than for other units. Another additional feature that can be made available in special models is a device called a mechanical slit. This device enables the user to draw large numbers of line widths utilizing only one symbol. (See next section for more detailed description of this device.) With this added facility it is possible to draft many widths of lines and flash up to 95 different symbols.

Many commercial units were ruled out because they did not contain provision for rotating the projected image about its axis. The PS5 head possesses this feature which is essential for both "line drafting" with a rectangle and for "image flashing".

The positional accuracies specifications for the PS5 head are listed in detail by the manufacturer. Errors are specified statistically within $\pm 3 \sigma$ tolerance band where σ is standard deviation of set of random error readings. Three σ covers a tolerance band of 99.73%. The

worst case positioning error is less than .003".

It should be pointed out that the PS5 light head was selected from commercial units that were available in 1967. Since then most manufacturers have made significant improvements to their instruments. Some have added a rotation facility^{10,13} and increased the number of available symbols¹³. The references made in this thesis are to the most "up-to-date" light heads marketed by these manufacturers.

Barr and Stroud also has made minor improvements to the PS5 light head. Since 1969, they have supplied three models, all on the same basic design. Each model is a slightly improved version over the previous one. This thesis deals primarily with the third model which was received in 1971.

2.5 Principle of Operation of the PS5 Light Head

Figure 2.4 shows the basic optical and mechanical components found in the light head. Light from a 6 volt 10 watt tungsten halogen light source L is condensed by lens J and is split into two paths I and O by right-angled prisms F and K. Two solenoid driven light shutters N and M normally block light from entering the main section of the projector along axis I and O. If shutter N is energized, light enters the projector along axis I and is shaped into a symbol by one of a maximum of 48 selectable mechanical masks located on a disk. The rays are bent ninety degrees by

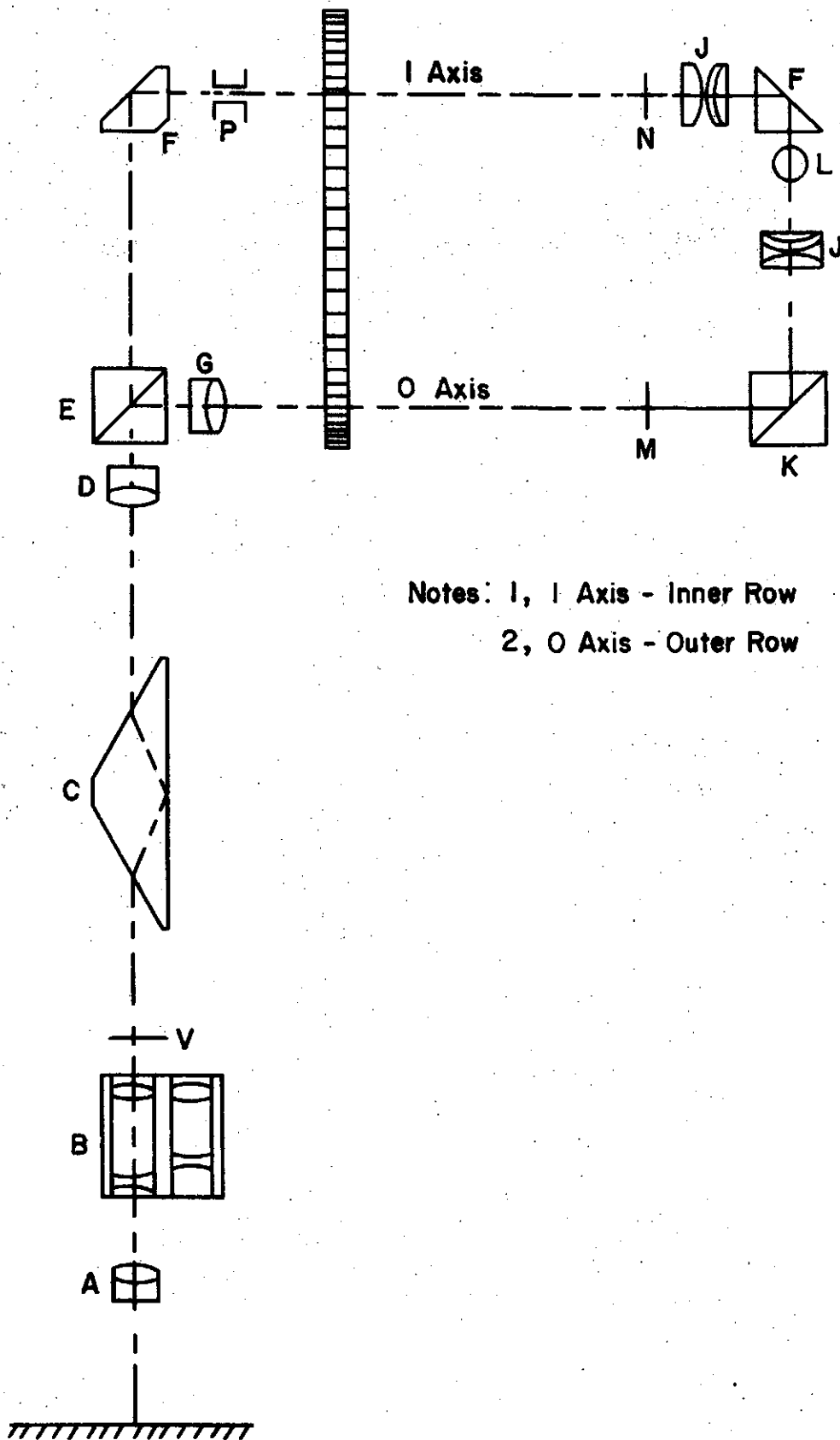


Figure 2.4 Basic Optical System Barr & Stroud, PS-5 Lighthouse

right-angled prism F and are fed through prism E and lens D. The mask is placed at the focal plane of lens D so that light rays emerging from any object point will be parallel. Rays are then passed through a dove prism C whose purpose is to rotate the image of the mask about the central axis of the optical system. (See appendix B for a more detailed explanation of the operation of the dove prism.) The image of the mask is focussed at the focal plane of the objective lens A. The magnification for this optical path is the ratio of the focal length of lenses A and D which is 1:4.

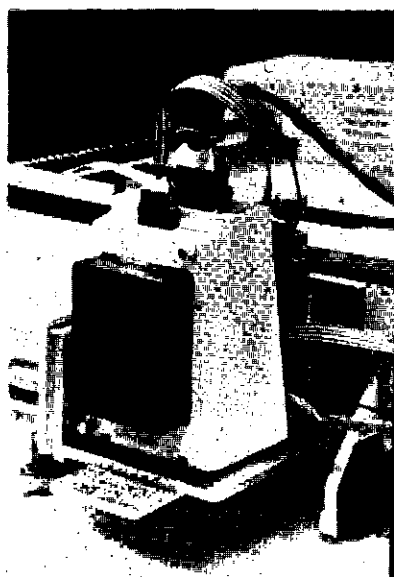
Light rays entering along axis O are shaped in a similar manner by one of a maximum of 48 masks located along the outer row of the symbol disk. (This row combined with the inner one gives the symbol disk a total capacity of 96 symbols.) They are then fed through lens G and are optically combined with those of path I by prism E. Rays emerging from prism E then follow the same route as was described for path I. The mask is placed at the effective focal plane of the combination of lenses D and G which is one half the distance of that for lens D making the magnification for this axis 1:2.

For an additional magnification of 2X and 4X, two Galilean telescopic lenses, B, can be switched into the optical system between A and V. The maximum image size that can be projected from both inner and outer row symbol positions is a .240" square. This means that the maximum aperture size for the symbol disk's inner and outer row is .240" and .120" respectively.

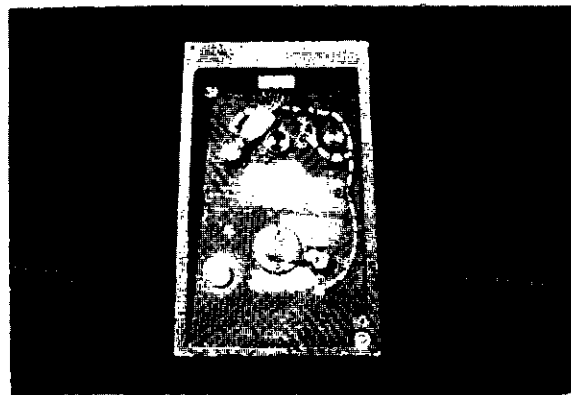
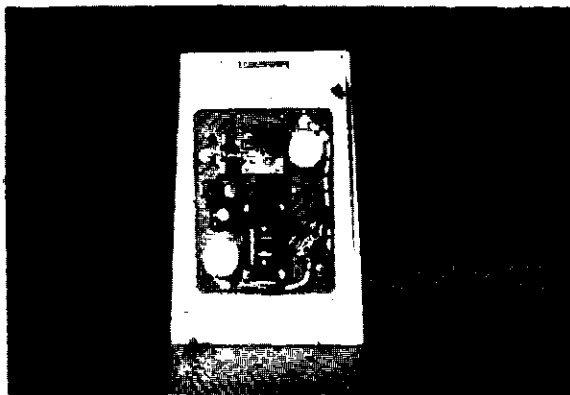
To give the projector added capability, a variable dimension slit P is also available. The purpose of this slit is to produce the variable dimension of a rectangular image which can be used for line drawing. Basically, it consists of two plates of metal with sharply defined edges whose spacing can be controlled. The fixed dimension is set by a mask located on the symbol disk.

To control the intensity of the projected image, the manufacturer provides a vane shaped piece of metal that can be moved across the optical path of the projector. The principle is the same as that for the iris diaphragm used for setting the f stop in a camera. This vane can also be used as a high speed shutter; its opening and closing times are two milliseconds compared to 20 milliseconds for the solenoid driven light shutters described earlier.

Physically the PS5 head is compact. Its dimensions are 6" x 7" x 12" and it weighs 12 lbs. This can be a desirable feature for some plotters where large weight and size cannot be tolerated. Several views of both inside and outside of the light head are shown in figure 2.5. It is basically comprised of two sections, the front cover and main section. The front cover contains the light source and optics required to condense and split the light into two beams as well as the light shutters for the inner and outer optical axes. The main section houses most of the optical and control components.



(a) Front view of PS-5 light head.

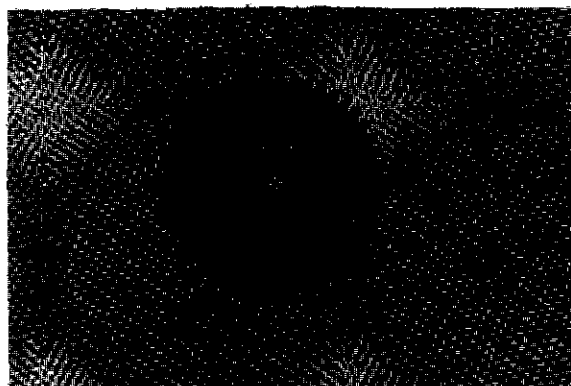


(b) Front cover : Projector light source. (c) Front cover : Inner & outer row light shutters.

Figure 2.5 Photographs of PS-5 Light Head.



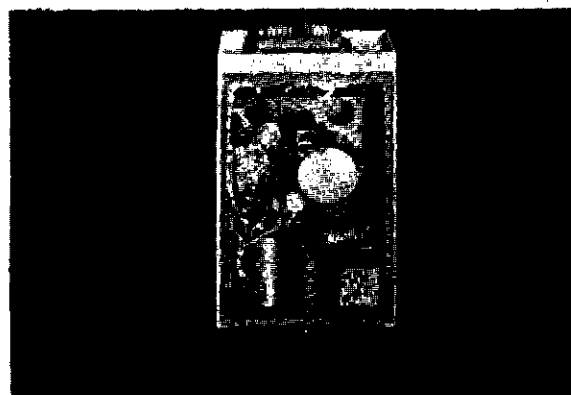
(d) Inside view of PS-5 light head with front cover removed.



(e) Symbol disk.



(f) Inside view of PS-5 light head with symbol disk mounted.



(g) View of PS-5 light head with rear cover removed.

3. REQUIREMENTS FOR INTERFACE AND CONTROL

3.1 General

This chapter deals with the problem of selecting the most suitable method for controlling the functions of the PS5 light head. This is followed by detailed hardware and software requirements for the interface and control to connect the PS5 light head to a PDP-8 mini-computer.

The writer assumes that the reader is familiar with the input/output facilities of the PDP-8 mini-computer^{16,17}.

3.2 Summary of Required Controls

The basic components of the PS5 light lead were discussed at the end of Chapter 2. The automatic controls that are required are summarized below:

a) Dove Prism

Control of the rotation of the dove prism is required to set image orientation.

b) Mechanical Slit

A control is required to adjust the spacing of the mechanical slit to set the one dimension of a rectangle that is used to draft lines.

c) Rotation of Symbol Disk

A control is required to rotate the symbol disk in order that different image shapes can be projected onto film.

d) Magnification Selection

A control is required to select one of three possible image magnifications.

e) Light Shutters

A control is required for both inner and outer row shutters which are used to allow the film to be exposed to an image.

f) Intensity of Projected Image

The intensity of projected image must be controlled for both line drafting and image flashing.

3.3 Methods of Control

Most light head functions require some form of positional control. The general approach is to use a servo system. The basic components in such a system are an amplifier, position sensing device and prime mover. The position sensing device measures the actual position of the prime mover and sends this signal back to the amplifier. The amplifier magnifies the difference between the desired and actual position signals and applies a drive signal to the prime mover. This drive signal decreases to zero as the prime mover approaches the desired position.

Often the prime mover consists of a DC or AC motor and the position sensing device is a potentiometer that has been coupled to its shaft. In theory, the positioning error of this control is zero. In practice, this error is finite because of the limited amount of torque

available for small voltages applied to the motor.

The main disadvantage of this control is that the circuitry required to implement it is analog in nature and therefore sensitive to temperature variations and component aging. Continual adjustments are therefore required to ensure system accuracy and stability. This control is further complicated by the need for digital to analog converter circuitry which is required to interconnect the digital signals of the PDP-8 to the analog ones of the servo-mechanism.

The D/A converters can be eliminated if the prime mover is replaced with a device called a stepper motor. Rotational movement of this motor is secured by supplying digital pulses to its driver control logic. Each pulse causes the shaft of the motor to rotate a small angle in either direction. The value of this angle is dependent on the internal construction of the motor and the method of driving its windings. Errors in angular movement are small and non-cumulative making this device an ideal choice for an accurate positioning control. These motors are extremely reliable if run in their proper operating regions. For this reason, they are often run under open loop conditions which greatly simplifies the electronic control. A photodiode and light source combination, or microswitch, can be used to enable the control to set the motor to a known shaft origin

position. It can then be set to any desired position providing the controller or computer keeps track of its present position. Periodic checks can be made on this present position by returning the motor to its reference position.

The main disadvantage of this motor is that it behaves erratically when pulsed at certain frequencies. This is due to the fact that this motor behaves like a lightly damped second order system¹⁸. This inherent resonance problem can be overcome by introducing electrical or mechanical damping or by avoiding operation in this region of frequencies.

The digital stepper motor with origin reference feedback was selected as the most suitable method of control because of its simplicity and compatibility. The manufacturer was therefore required to supply the PS5 light head with digital stepper motors instead of the analog servo types.

The advantage of using a mini-computer for a controller is that the hardware required for the control can be simplified by having the computer program handle several of its functions. The extent to which this can be done is a function of the number of tasks the computer has to perform as well as its memory capacity. The PDP-8 mini-computer used for the automatic drafting system is a 12 bit machine with 4 K of memory. It is programmed to be simultaneously reading magnetic tape, decoding data,

making calculations and initiating plotter and light control functions. These overall factors plus the complexity of the required hardware must be considered when determining the optimum hardware/software combination for each control.

3.4 Hardware Specifications for Interface and Control

3.4.1 Rotation of dove prism

A three phase permanent magnet stepper motor¹⁹ was supplied by the manufacturer for the dove prism control. The motor is coupled to the dove prism in such a manner that 10 motor revolutions produce 1 image rotation. After some experimentation with this motor, it was concluded that several convenient step sizes could be obtained by altering the method of driving the motor. A 30 degree motor step size was chosen in order to obtain a resolution in image rotation of 3 degrees.

Reference feedback is provided by a lamp and photodiode combination that senses for a slotted position on a disk coupled to the stepper motor shaft.

The PDP-8 should initiate each individual 3 degree image step so that it can have a direct control on the speed of rotation when drawing curved lines with a rectangular mask.

The hardware specifications for the dove control can now be listed in detail:

- a) Each individual motor step is to be initiated by

a computer input output instruction, the direction of rotation being specified by one bit in the computer's arithmetic register.

- b) Motor logic and driver circuitry is to be designed for a Vactric size 11 stepper motor so that it can be rotated in either direction with a step size of 30 degrees. The motor must operate reliably under all conditions. It must be able to rotate sufficiently fast so that the worst case curved line can be drawn with a rectangular image. For this to be true

$$f_{\max} > \frac{V_t 60}{R_c \pi}$$

where f_{\max} is pulses/second to stepper motor,

R_c is worst case radius of curvature
in inches,

and V_t is maximum plotter speed in inches
per second.

Substituting approximately worst case values .009" for R_c and .10 in/sec for V_t , then $f_{\max} > 213$ pulses/sec.

- c) The status of the dove prism reference signal is to be made available to the computer.

3.4.2 Variable mechanical slit

The manufacturer supplied a three phase permanent magnet stepper motor²⁰ for this control. This motor is coupled, via a reduction gear, to a cam shaped surface. Rotation of this surface varies the spacing between two metal vanes; this spacing is approximately linear to angular rotation. Again selection of a motor step size is based on the desired resolution of line width. A motor step size of 120 degrees was selected which gave a line width resolution setting of approximately .001".

Reference feedback is provided by a microswitch which is contacted when the slit is completely closed.

A reasonable compromise in the design of the mechanical slit control is to have the computer keep track of the present position of the slit and initiate the movement of a specified number of slit steps.

The specifications for the mechanical slit can now be listed in detail:

- a) A hardware operation is to be initiated by a computer input/output instruction and will cause the stepper motor controlling the mechanical slit to rotate a predetermined number of steps in either direction. This number is to be specified in 2's complement form by the computer arithmetic register and can be up to a maximum value of ± 128 steps. A device flag is to inform the computer

when a hardware operation has been completed.

- b) Motor logic and driver circuitry is to be designed for a Vactric size 8 stepper motor so that it can be rotated in either direction with a step size of 120 degrees. This motor need only be operated at one frequency.
- c) The status of the slit home microswitch is to be made available to the computer.

3.4.3 Homing of dove prism and mechanical slit

At the beginning of the drafting operation the exact position of the dove prism and slit control motor is unknown, thus, hardware or software must be used to home the motors to their reference position. Again the relative merits of hardware and software controls must be considered. A hardware approach to the initialization problem was selected because it was simple and faster.

The specifications for this initialization control are listed below:

A computer input/output instruction is to initiate a hardware operation, the purpose of which is to set dove and mechanical slit control motors to their reference positions. A device flag is to inform the computer when a hardware operation has been completed.

3.4.4 Symbol disk rotation

The manufacturer supplied a four phase stepper motor²¹ for this control. If it is driven with two phase

excitation (i.e. two coils energized at one time), it rotates with a step size of 7.5 degrees. This motor is coupled to the symbol disk via an 8:1 reduction gear. Since the symbol disk has 48 locatable symbol positions, 8 motor steps are required to rotate it between adjacent symbol positions. A set of 48 teeth are located on the outside perimeter of the symbol disk so each symbol position can be accurately located into position with a latching device.

Reference feedback is provided by a light source photodiode arrangement that monitors for the presence of reflective marker strips located on several of the 48 teeth of the symbol disk. These markers are used for symbol disk identification and for setting it to a known origin position.

A control is to be designed to allow the programmer to select any one of the 48 disk positions. The approach taken was similar to that for the mechanical slit. The computer is to initiate a hardware operation in which the number of symbol positions and direction of rotation can be specified. The computer must therefore keep track of the present symbol position of the disk.

A hardware homing control for the symbol disk would be complicated since reflective markers are also used for disk identification. It was therefore rejected in favour of a software approach.

The specifications for the symbol disk control can now be stated in detail:

- a) A symbol disk hardware operation is to be initiated by a computer input/output instruction and is to consist of the following sequence of events.
- (i) The symbol disk is to be disengaged by energizing the disk latching solenoid.
 - (ii) The symbol disk is to rotate a specified number of symbol positions. The number and direction of rotation is to be indicated in 2's complement form by the computer's arithmetic register; it can be any value up to ± 64 symbol steps.
 - (iii) When the symbol disk reaches its final position, the latching solenoid is to be de-energized to engage the symbol disk accurately into position.
 - (iv) After the termination of (iii), a device flag is to be set to inform the computer that the hardware operation has been completed.
- b) Logic and driven circuitry is to be designed for a Mullard AU5055 stepper motor so that it can be rotated in either direction in 7.5 degree steps. The motor need only be operated at one frequency.
- c) The status of the reflective marker detection circuit is to be made available to the computer.

3.4.5 Selection of magnification lens

The manufacturer supplies a 400 cycle synchro torque transmitter motor²² for this control. This motor is directly coupled to the three position turret through gearing. The three Galilean lenses mounted in the turret are equally spaced 120 degrees apart. The selected lens is latched into position by a mechanical detent.

The motor is intended to be operated in a similar fashion to a stepper. A motor step size of 120 degrees can be used to select one of the possible three magnification lenses directly.

The requirements for the magnification control can now be specified in detail:

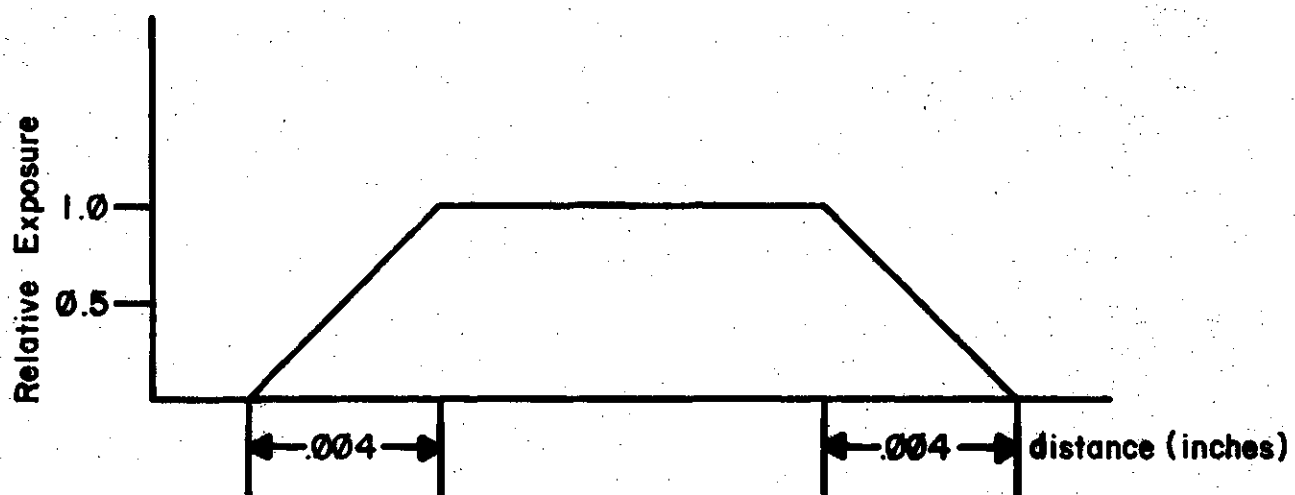
- a) Logic and driver circuitry is to be designed for a Muirhead 400 cycle per second synchro torque transmitter motor so that its shaft can be set to one of three positions which are angularly displaced 120 degrees in space.
- b) A computer input/output instruction is to initiate a turret hardware operation. Two bits in the computer arithmetic register are to specify which magnification lens is desired. A device flag is to inform the computer when the hardware operation has been completed.

3.4.6 Light shutters

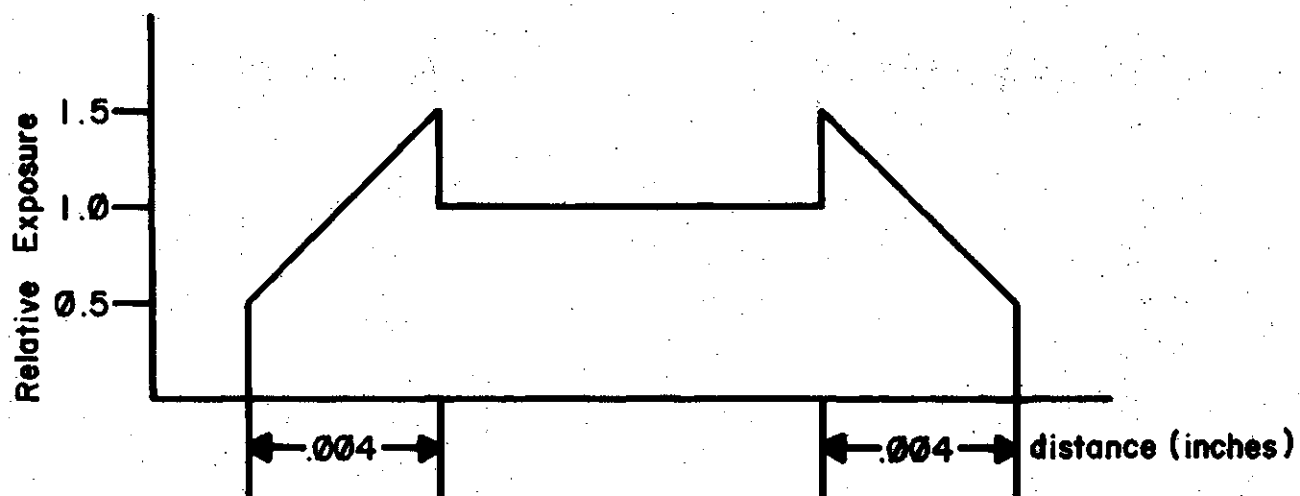
The light shutters supplied by the manufacturer

consist of a metal flange attached to a rotary solenoid. These shutters must be controlled for both line drafting and image flashing operations. In the case of line drafting, care must be taken to ensure that the end of lines are properly exposed. Figure 3.1(a) shows the exposure profile along the length of a straight line that has been drafted by a rectangle with a fixed dimension of .004". It has been assumed that the shutter opening and closing times are small and the plotter moves instantaneously after the shutter opens and that the shutter closes instantaneously after the plotter stops. Note that the ends of the line do not receive enough exposure. Figure 3.1(b) shows that this problem can be overcome by controlling the delay between when the shutter opens and closes and when the plotter stops and starts. (Although exposure conditions are still not ideal, they still produce acceptable results because of the exposure latitude of the film.) This delay can be controlled by software or hardware. The hardware approach was selected as being the simplest to implement.

For image flashing, exposure can be controlled by varying the period between shutter opening and closing time. For the PS5 head this period can be any one of six values depending on the magnification setting and the shutter being used. A software control for this period was selected because of its simplicity and flexibility.



(a) no delay



(b) with delay

Figure 3.1 Exposure Profile Along Length of Line.

The hardware requirements given below apply to both shutters:

A hardware operation is to be initiated by a computer input/output instruction. A computer arithmetic register bit is to specify whether the shutter is to be open or closed. A device flag is to inform the computer when the hardware operation has been completed. For line drawing, this operation is to be considered complete only when the ends of lines have been properly exposed.

3.4.7 Intensity control

The intensity control is the most difficult to specify in engineering terms. Its main purpose is to control exposure conditions so that high quality lines can be drawn and symbols projected to within a specified tolerance of line density and width. The degree to which these conditions must be controlled is dependent upon these tolerances and upon the type of photographic film being used.

The intensity control was initially designed on the basis that Dupont Cronar Ortho Sensitive (i.e. sensitive only to green, blue and ultraviolet portion of the spectrum) film would be used in the drafting system. This film has a high contrast, low speed emulsion deposited on a flexible plastic base.

Experiments performed on Cronar Ortho S film with a projected rectangular image showed that well-defined heavy

density lines could be drawn over a large exposure range. However the range of acceptable exposure times is restricted by the fact that the width of lines increases as they become more exposed. This is believed to be due to internal reflections of light rays within the photographic emulsion. Line width increases by approximately .001" for a threefold change in exposure time.

Another feature of Cronar Ortho S is that its emulsion has been stabilized by substituting synthetic resins in place of gelatin. The manufacturer quotes the following expansion coefficients for humidity and temperature²³.

Temperature coefficient of expansion = 9.5×10^{-6} inches per inch per degree F.

Humidity coefficient of expansion = 1.5×10^{-6} inches per inch per % RH.

These figures can be best illustrated by considering the example of a 50 inch length line that has been subjected to a rise in temperature of 5 degrees F and a rise in relative humidity of 5%. The overall length of the film would expand .006", .0023" due to temperature and .0037" due to relative humidity.

As explained earlier, the problem of controlling exposure time for line drafting is difficult because the range of speed of the plotter varies considerably. This is illustrated in figure 3.2. Shown is a typical velocity versus time profile of a straight line drawn by the plotter.

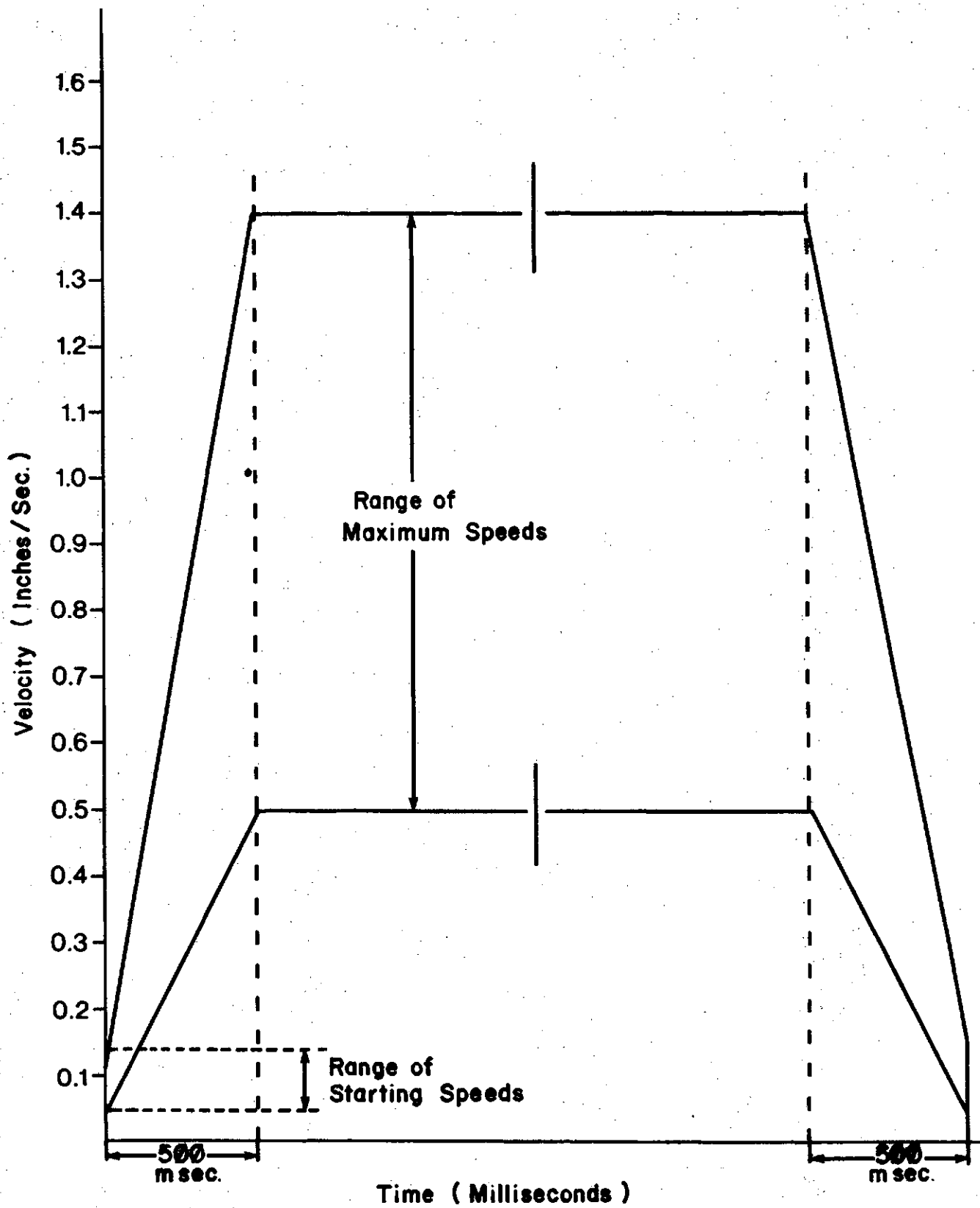


Figure 3.2 Velocity Versus Time Profile of Gerber Plotter.

The plotter begins at a start speed which has a range of .05" to .14" per second and in 500 milliseconds it linearly accelerates up to a maximum speed of between .5" to 1.4" per second. As it approaches the end of the line, it must linearly decelerate to its initial starting speed before coming to a full stop.

All lines drawn by the plotter are constructed from straight line segments. The length of each segment is a function of the radius of curvature of the line being drawn. As the radius of curvature decreases, the segment length decreases and the plotter does not have time to reach its maximum velocity before it has to decelerate.

The ratio of maximum to minimum speed in this graph is 28:1 which represents a significant variation. Therefore some method of control is required to vary the intensity of the projected image. Such a control need not be precise because of the large latitude of Cronar Ortho S film. However, it must have a large operating range and have a high enough speed of response to follow the plotter as its speed varies.

The equivalent velocity of the plotter can be calculated by either software or hardware. The software approach was rejected because the computer would frequently be required to supply this information while performing its many other tasks.

When line drafting, the velocity signal produced

by this control serves as the demand signal for the intensity control. There are several ways of controlling the intensity of the projected image. One method employs the use of a variable neutral density attenuator disk¹⁰. This device evenly attenuates the radiation from a light source that emits a continuous spectrum of wave lengths. The amount of attenuation is a function of the angular position of the disk. The position of the disk can be controlled under open or closed conditions. In this case closed loop conditions are desired in order to minimize variations in system components such as the output intensity of the lamp, to increase system response and to reduce the non-linear effects of the controlling device. A feedback signal is produced by a light sensitive device that monitors the light passed through the disk. The disk is rotated until this feedback signal is equal to the demand.

The intensity of the projected image can also be controlled by replacing the neutral density filter with an adjustable iris diaphragm. Again a closed loop control is desirable. The advantage of both these mechanical methods is that a fairly precise exposure control can be obtained which would be independent of the spectral response of the film.

A simpler method of control is to vary the current through the projector light source. A feedback loop can be

placed around the lamp to improve its linearity, increase its response and minimize the effect of its aging characteristics. A photodiode^{24,25,26} is often used for a light sensitive device because of the requirement for high stability. Sensitivity is not a problem in this application because the signal strength of the light intensity can be made large.

The disadvantage of using this type of control is that the spectral output of the light source changes with different current levels. For precise control of exposure time, the spectral response of the photodiode must be matched to that of the film. This problem did not appear to be a major one, however, as advantage can be taken of the large latitude of Cronar Ortho S film.

The method of varying the current through the light source under closed loop conditions was initially selected mainly because of its simplicity. Only a few minor alterations had to be made to the light head to implement this control.

As mentioned in Chapter 2. the PS5 light head does contain an attenuator blade that is meant for controlling intensity. Implementing a closed loop control for this device was impractical since fairly major modifications would have to be made to the PS5 light head. Nevertheless, an open loop form of control was developed for this device and is discussed in subsequent chapters.

The hardware specifications for the intensity control can now be stated in detail:

- a) Exposure for both line drawing and symbol projection is to be held constant to $\pm 25\%$. The choice of this tolerance is based on the exposure latitude of Cronar Ortho S film and a line width variation tolerance $.0005''$.
- b) The large signal response of this control should exceed 5 cycles/second.

Although these specifications deal with drafting on Cronar Ortho S film, an important part of this work deals with the evaluation of other possible films. The intensity control should therefore be designed so that it can be adjusted easily for use on other films.

3.5 Programming the Light Head

3.5.1 Machine language instructions

Figure 3.3 lists the machine language instructions that are to be used to allow the PDP-8 computer to control automatically the functions in the model PS5 light head. There are basically three types of instructions associated with each hardware function.

- a) Test device flag

This instruction is used to test whether the current hardware operation has been completed by sampling the status of the device flag.

- b) Clear device flag

This instruction is used to clear the device flag

<u>Mnemonic/ Octal Code</u>	<u>Operation</u>
SLS 6161	Skip on light shutter flag
CLS 6162	Clear light shutter flag
ALS 6164	Initiate light shutter operation AC0 = 0 Turn shutter on AC0 = 1 Turn shutter off AC10 = 0 Set to line mode AC10 = 1 Set to symbol mode AC11 = 0 Select inner row shutter AC11 = 1 Select outer row shutter
SFG 6301	Skip on initialize flag
CGF 6302	Clear initialize flag
GOL 6304	Initialize LSP (initialize mechanical slit to home) (initialize rotation to home)
RSR 6311	Read status word
SSD 6321	Skip on symbol disk flag
CSD 6322	Clear symbol disk flag
SDS 6324	Step symbol disk AC0 = 0 Disk rotates clockwise AC0 = 1 Disk rotates counterclockwise Number of symbol steps is specified in 2's complement form and can be up to a maximum of 77 ₈ steps
STF 6331	Skip on turret flag
CTF 6332	Clear turret flag
STP 6334	Select turret position AC10 & AC11 = 00 Select X1 lens AC10 & AC11 = 01 Select X2 lens AC10 & AC11 = 10 Select X4 lens
SRF 6341	Skip on rotation flag
CRF 6342	Clear rotation flag
SRT 6344	Step rotation AC0 = 0 Image on table rotates clockwise AC0 = 1 Image on table rotates counterclockwise
SLW 6351	Skip on line width flag
CLW 6352	Clear line width flag
STW 6354	Step line width AC0 = 0 Mechanical slit spacing increases AC0 = 1 Mechanical slit spacing decreases Number of line width steps is specified in 2's complement form and can be up to a max. of 177 ₈ steps
SEF 6411	Skip on error flag

Figure 3.3 Machine Language Instructions for PS5 Interface

to ensure that this flip-flop is in the zero state prior to the next hardware operation.

c) Initiate hardware operation

This instruction is used to signal the control to begin performing a hardware operation. As indicated in the hardware specifications, the computer's arithmetic register is used to supply the details of this hardware operation to the control.

3.5.2 Control status word

The present status of various bits in the light head control can be transferred into the computer's arithmetic register by machine language instruction 6311. Figure 3.4 shows the formatting scheme to be used for this status word and a summary of the purpose of each bit.

The next chapter describes in detail the interface and control that was designed for the PS5 light head.

0	1	2	3	4	5	6	7	8	9	10	11
---	---	---	---	---	---	---	---	---	---	----	----

Bit	Function
0	Error flag. This flip-flop will be set if any of the following events occur. (a) Light source failure. (b) Illegal line width request. Request is for a smaller line width and mechanical slit is already at its home position. (c) Improper line width hardware execution. Slit home microswitch is contacted before the completion of a line width hardware operation.
5	Rotation home This bit will be set if the dove prism is at its reference position.
7	Light source failure. This bit will be set if the projector light source has failed.
8	Symbol disk reflective marker. This bit will be set if a disk reflective marker is being sensed.
10	Slit home. This bit will be set if the mechanical slit is at its home position.

Figure 3.4 Explanation of Hardware Status Bits

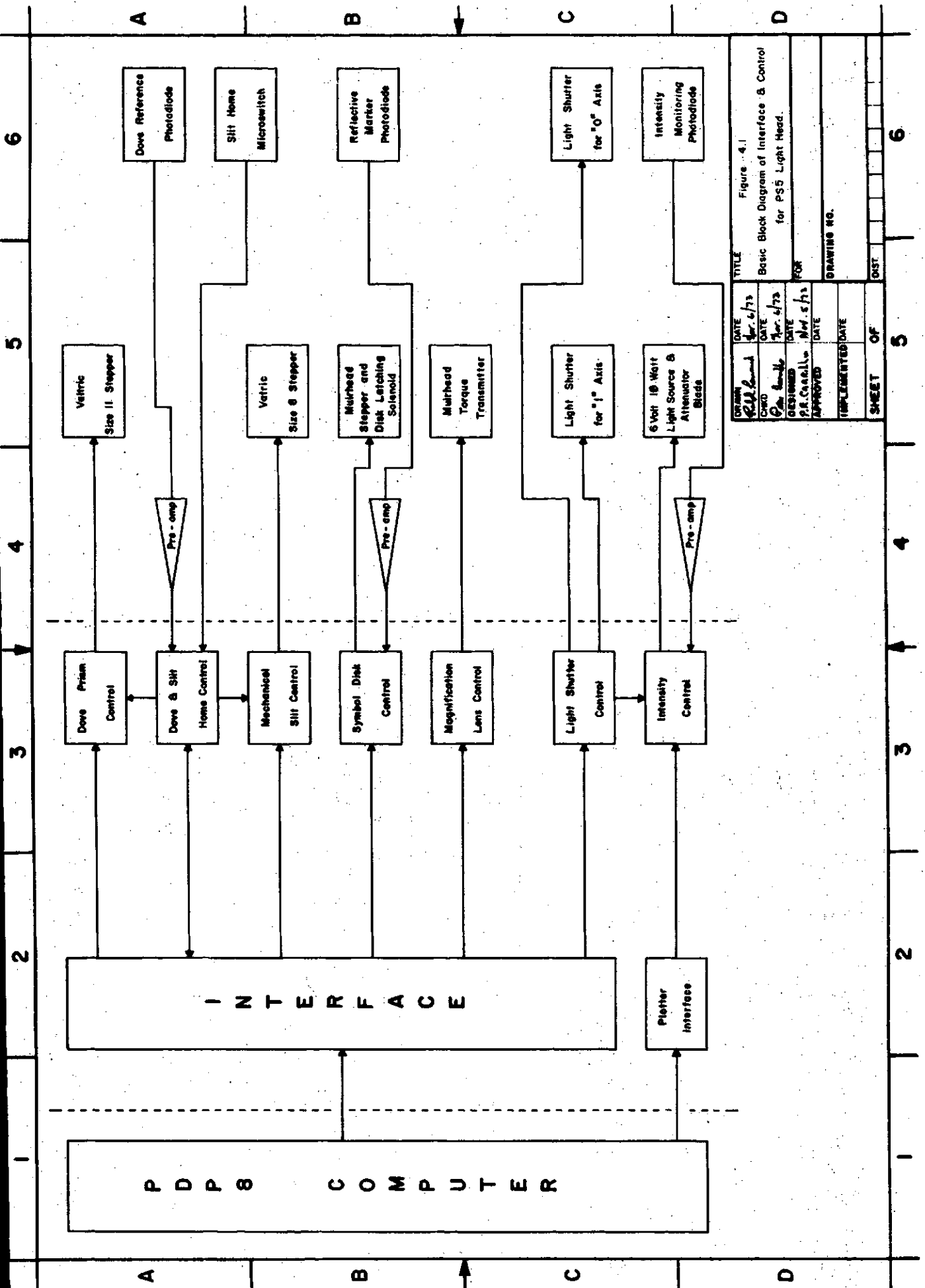
4. INTERFACE AND CONTROL HARDWARE

4.1 General

Figure 4.1 shows the basic block diagram of the interface and control for the PS5 projector. It consists of the seven controls (see Chapters 2. and 3.) required for the light head. Six of them are interfaced directly to the PDP-8 computer. The seventh, the intensity control, uses signals from the Gerber plotter interface and other parts of the light head control.

An attempt was made to construct as much of the hardware as possible out of standard Digital Equipment Company (DEC) "R" series modules so that it would be compatible with the rest of the automatic drafting system. This logic family is discussed briefly in appendix C. For more details the reader should refer to references 16 and 17. In certain instances it was not possible to use standard DEC logic and so special purpose circuits were constructed on blank module W994 boards. The details of this circuitry are discussed in the subsequent description.

The accompanying circuit diagrams for this hardware are found at the end of chapter 4. The old DEC "R" series logic conventions are used to describe this circuitry. (See appendix C.) Listed below is an explanation of the method of referencing used to enable the reader to locate logic signals and circuits on these drawings:



- a) When reference is made to a logic circuit or signal, it will often be accompanied by a bracketed reference indicating the drawing number and where this signal or circuit is located. The general format for this reference is: (Drawing number; X/Y). For example, reference (03; 2/C) indicates that the pertinent logic signal or circuit is found on drawing number 3, coordinate (2/C).
- b) Logic elements such as NAND gates are normally referred to by their pin connections. In cases where this approach is not clear (i.e. discussing several gates collectively), they will also be given a name. Flip-flops are always given a name.
- c) When a signal name is first introduced, it is given a full name followed by its bracketed mnemonic. Thereafter, only its mnemonic name will be used.

Since most of the controls are simple, they are only briefly discussed. Emphasis is placed on the philosophy of design rather than exact hardware details.

4.2 Rotation of Dove Prism

a) Basic operation

Machine language instruction initiates a rotation hardware operation by setting a flip-flop called TOGGLE 2 ENABLE (TG2 ENB: 03;5/C). It also loads direction information from accumulator bit "0" into a flip-flop called

DIRECTION ROTATION (DRTN ROT: 1/B). When TG2 ENB is set, it enables pulses from a real time clock (4/B) to be supplied to the rotation stepper motor driver logic control. When the motor is pulsed once, a flip-flop ROTATION FLAG (1/A) is set to inform the computer that the hardware operation is completed.

b) Resonance protect hardware

Experiments conducted revealed that the rotation motor did not operate properly when pulsed at certain frequencies. This problem was attributed to the mechanical resonance of the motor. Logic was therefore developed to prevent the motor from being pulsed for a certain band of frequencies. An integrating or retriggerable monostable circuit is used to sense for this region. This one-shot circuit has close to a zero recovery time and has the ability to respond to inputs while in its unstable state.

Integrating one-shot TUD (2/C) is triggered each time the stepper motor control logic is pulsed. Output D will remain negative for a predetermined time with respect to the last pulse it receives. If this time is exceeded, output D returns to ground; this positive going transition is used to trigger RESONANCE delay EFM (3/B). The inverted ground output of this delay inhibits NAND gate RSUV (4/B) preventing any clock pulses from reaching the stepper motor control logic. Normal operation of the control will resume when this delay is complete.

c) Stepper motor control logic

The table shown at the top of figure 4.2 illustrates the switching sequence that is used to energize the stator windings of the three phase permanent magnet stepper motor which controls the rotation of the dove prism. Twelve switching states are required to obtain a 30 degree motor step size. Columns 2,3 and 4 show what voltage polarity is applied to stator coils 1, 2, 3 for each motor state. A four bit register stores the present motor state of the control. The output of this register is decoded to produce the six logic signals which control the stepper motor driver switches. Each logic signal can be thought to control one switch as illustrated at the bottom of figure 4.2.

Four bit register ROTATION (RT:04) operates as a twelve state up down counter. The switching sequence for this register is shown in column 1 of figure 4.2. Clock pulses to this register originate from the real time clock. Flip-flop DRTN ROT controls the direction of this switching sequence; for example, if flip-flop DRTN ROT is set, signal DOWN (2/C) will go to ground and register RT will count down.

Register RT is decoded to produce levels $S1^+$, $S1^-$, $S2^+$, $S2^-$, $S3^+$, $S3^-$ by the gating shown in drawing 05. The minimal logic expression for these signals was obtained by using the Karnaugh map^{27,28}. (The Karnaugh map is a graphical technique that can be used to obtain the minimal

Rotation Register	Coil 1	Voltage Coil 2	Coil 3
0 0 0 0	—	+	Open
0 0 0 1	—	+	—
0 0 1 0	Open	+	—
0 0 1 1	+	+	—
0 1 0 0	+	Open	—
0 1 0 1	+	—	—
0 1 1 0	+	—	Open
0 1 1 1	+	—	+
1 0 0 0	Open	—	+
1 0 0 1	—	—	+
1 0 1 0	—	Open	+
1 0 1 1	—	+	+

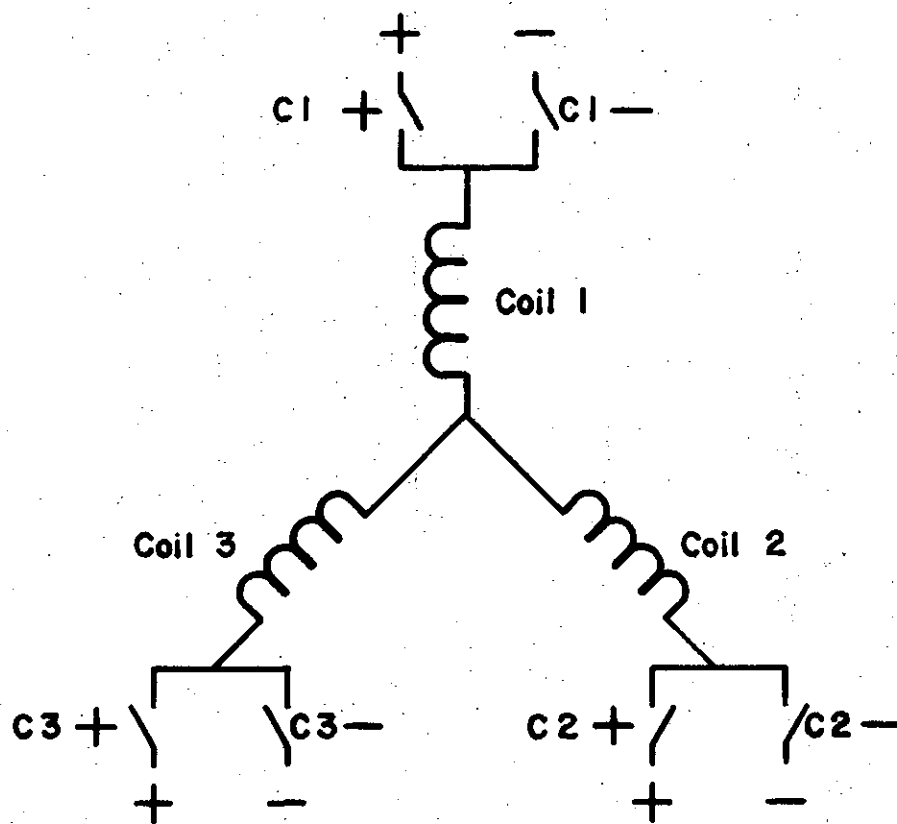


Figure 4.2 Switching Sequence for 30° Motor Step.

logic expression.)

d) Stepper motor drive circuitry

Logic signals $S1^+$, $S1^-$, $S2^+$, $S2^-$, $S3^+$, $S3^-$, control the stepper motor driver circuitry. A driver circuit had to be designed because the requirement was for bi-directional drive capability. A schematic of this circuit is shown in figure 4.3. Three such circuits are required, one for each stator coil. Input channels + and - control the switching of transistor switches T_3 and T_4 . If a negative voltage signal is applied to + input, transistor T_3 will turn on causing the output of this circuit to go to ground. If a negative signal is applied to - input, transistor T_2 turns on. Its output turns on transistor T_4 bringing the output of the circuit to -24 volts.

Transistors T_4 and T_3 are protected from being simultaneously turned on by transistor T_1 . (This applies only to steady state conditions.) If + and - input channels are negative, T_1 , turns on and disables T_2 and T_3 from turning on by applying a ground level to diodes D4 and D6.

e) Dove home monitoring circuit

Comparator VR (10; 4/C) converts ground and +10 volts from the Dove home photodiode preamplifier into DEC compatible ground and -3 volt logic levels. The comparator circuit consists of a standard Motorola 1439 general purpose operational amplifier and output transistor. Positive

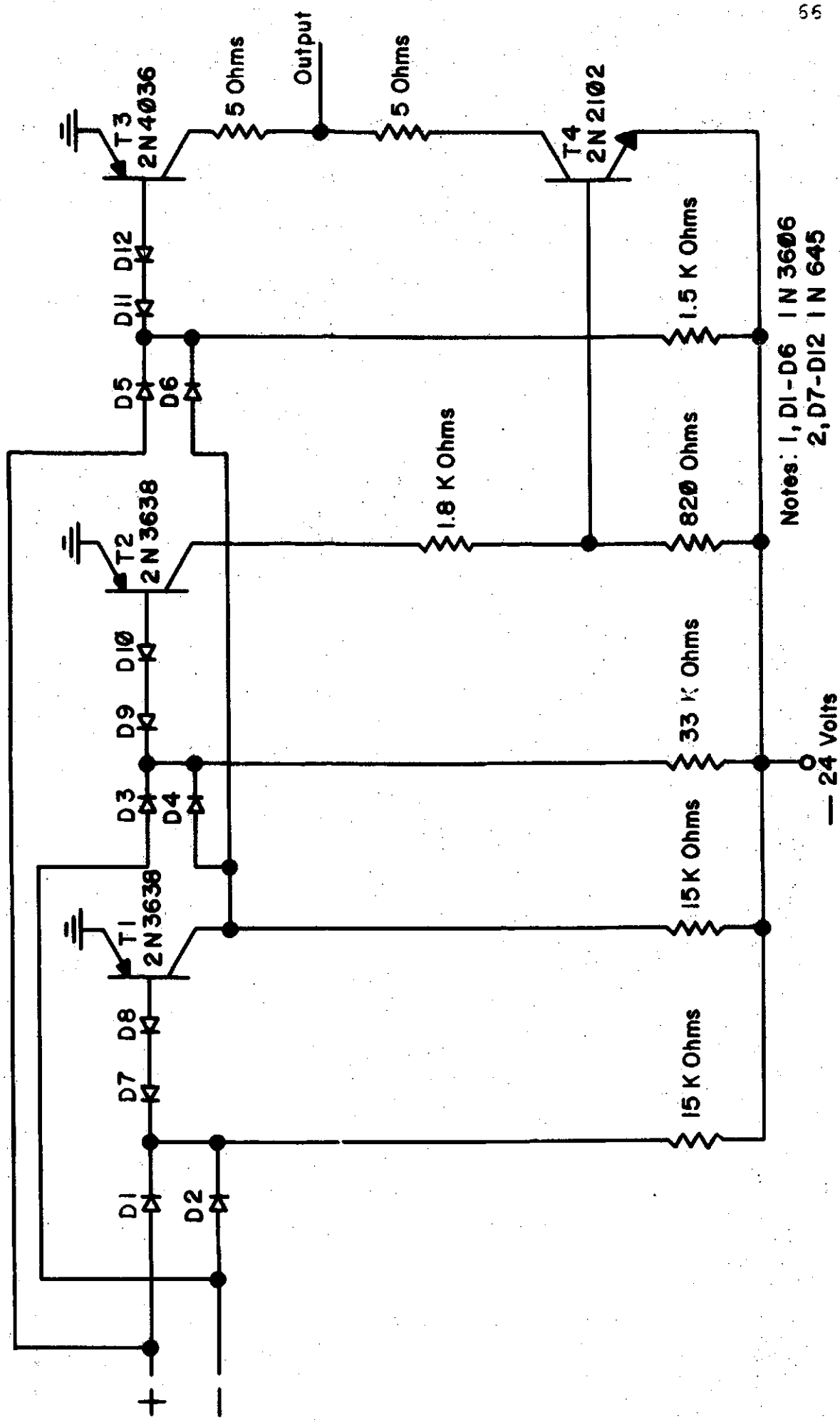


Figure 4.3 Bidirectional Drive Circuit.

feedback is employed to decrease the rise and fall times of the level ROTATION HOME enabling it to trigger DEC DCD gates and to introduce some hysteresis to the comparator circuit.

When the dove prism is at its reference position, the photodiode sees light and a +10 volt signal is sent to comparator VR causing its output to go to -15 volts. Since this home signal is obtained over several motor steps, it is necessary to gate it with one state of register ROTATION in order to obtain only one home position per revolution of the dove prism.

4.3 Variable Mechanical Slit

a) Basic operation

The flow diagram in figure 4.4 shows the normal sequence of events that take place during a mechanical slit hardware operation. Machine instruction 6354 loads the required number of motor steps from the AC into a 9 bit register called LINE (07). Register LINE stores this number in 2's complement negative form. Therefore if the number loaded is positive, it must be converted into its equivalent 2's complement negative form. This operation is performed in two steps. Firstly, register LINE is complemented and then incremented.

A delayed 10T 6354 signal then sets a flip-flop called TOGGLE 3 ENABLE (6; 2/B). This flip-flop enables pulses from a real time clock to be supplied to the stepper

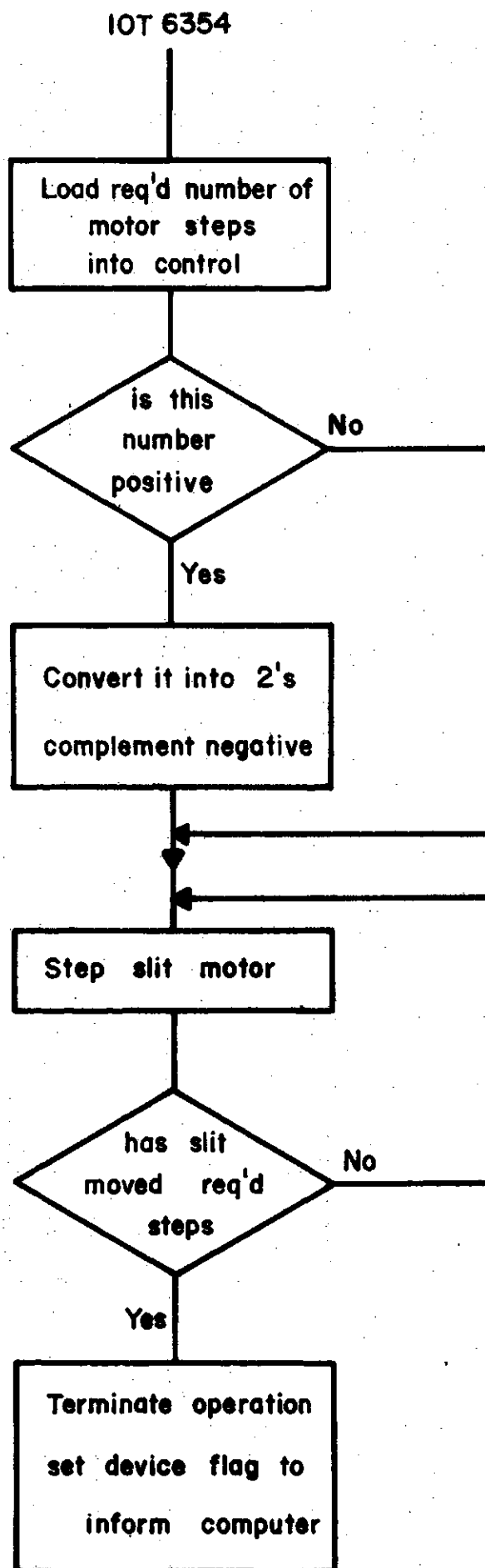


Figure 4.4 Mechanical Slit Control Flow Diagram.

motor driver control logic and to register LINE. Register LINE functions as an asynchronous up-counter incrementing each time the slit motor is pulsed. It overflows when the motor has moved the requested number of steps. When this event takes place, flip-flop LINE WIDTH FLAG (6; 5/A) is set to inform the computer that the hardware operation is completed.

In this control the request for zero steps is considered legal. Normal initiation of the hardware is disallowed by false ENABLE SET LINE WIDTH signal from gate (8; 2/C). A true ZERO level enables instruction 6354 to trigger pulse amplifier KLM (06; 4/A). The output of this logic circuit collector sets LINE WIDTH FLAG.

b) Illegal hardware execution

An illegal hardware execution operation occurs if a LINE CLOSE HOME signal is received at any time during a normal operation. This signal originates from a microswitch which is turned on when the slit is at its home position (10; 2/D). If this event takes place, a + 1 → ERROR (09; 5/A) pulse is generated. The + 1 → ERROR sets an ERROR flip-flop to inform the computer that an illegal operation has taken place. + 1 → ERROR will also be generated when a request is made for a negative number of slit steps when the mechanical slit is at its home position (i.e. fully closed).

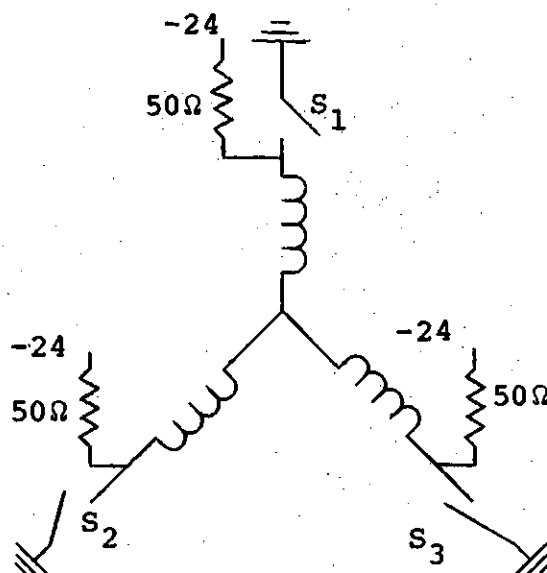
c) Stepper motor control logic

The table shown at the top of figure 4.5 shows how a 120 degree step size was obtained for the three phase, permanent magnet slit stepper motor²⁰. A two bit register is used to store the present switching state of this motor. The output of this register controls three motor driver switches as illustrated at the top of figure 4.5.

The two bit register consisting of flip-flops LN DRIVE 0 and LN DRIVE 1 is designed so that it will switch in a synchronous manner. (i.e. The states of all flip-flops in the register change simultaneously; they do not rely on the transition of other flip-flops within the register.) The specifications for this register are shown in the table in the middle of figure 4.5. This table, often referred to as the transition table, specifies how the states of flip-flops LN DR0 and LN DR1 are to change with each input clock pulse. This will be a function of the present state of the register (referred to as the internal state) and the input variables to this control. For example consider line 1 of the table. It states that if the input variable (i.e. signal DRTN LINWD) and the internal states (i.e. LN DR0 and LN DR1) are all zeros, then the next state of the control register is to be set to 01. Note that in some cases the letter "d" is found in the next state column. This indicates that it does not matter to what state the

Required Stator Coil Voltages for Vactric Size 8 Motor

State of Control	Voltage		
Register	Coil 1	Coil 2	Coil 3
00	+	-	-
01	-	+	-
10	-	-	+



Transition Table

PRESENT STATE			NEXT STATE	
Input Variable		INTERNAL STATE		
DRTN	LINWD	LN DRØ	LN DR1	
0	0	0	0	1
0	0	0	1	0
0	0	1	0	0
0	0	1	1	d
1	0	0	0	0
1	0	0	1	0
1	1	1	0	1
1	1	1	1	d

Level Gating for Control Register

F/F LN DRØ SET INPUT = DRTN LINWD (0) .LN DR1 (1) + DRTN
LINWD (1) .LN DR1 (0)

RESET INPUT = LN DR1 (0)

F/F LN DR1 SET INPUT = DRTN LINWD (0) .LN DRØ (0) + DRTN
LINWD (0) .LN DRØ (1)
RESET INPUT = 1

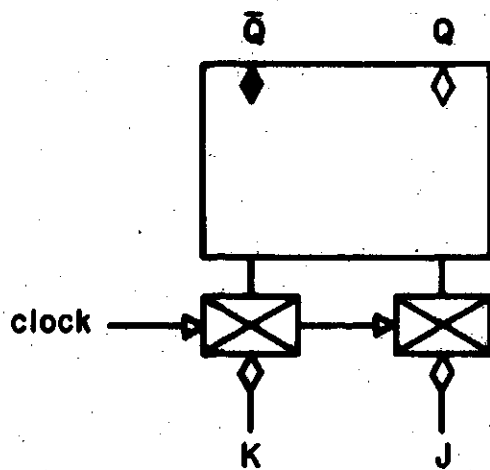
Figure 4.5 Design of Control Logic for Stepper Motor.

flip-flop goes. These are often referred to as "don't care" states; they arise because only three out of a possible four register states are being utilized. These "don't care" conditions should be listed because they can often reduce the required logic for a control.

The level gating required to implement this logic is summarized at the bottom of figure 4.5. The design of this gating is based on the transition table for the required logic and the type of flip-flop that is used. DEC flip-flops that have set and reset input DCD gates can be connected to function in several ways. (i.e. JK, D, RS, etc.) In this design, they were connected so that they operated as JK types. The transition table for a JK flip-flop is shown in figure 4.6. The bottom of figure 4.6 shows how JK inputs should be excited to set the flip-flop to its desired state.

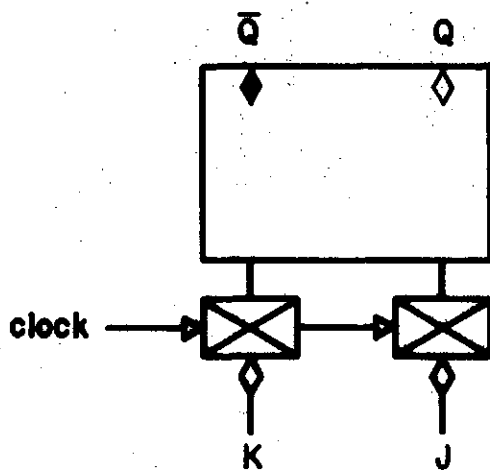
The general approach taken to obtain the minimal gating is summarized below.

- (i) Determine how each flip-flop is to change from its present state to its next state for all present state combinations. This is done by referring to the transition table for the control.
- (ii) Construct a truth table for J and K inputs from (i) and the JK excitation table.
- (iii) Obtain the minimal logic expression for J and K inputs of all register flip-flops.



t_n		$t_n + 1$
J	K	Q
0	0	Q_n
0	1	0
1	0	1
1	1	$\overline{Q_n}$

Transition table



Q_n	$Q_n + 1$	J	K
0	0	0	d
0	1	1	d
1	0	d	1
1	1	d	0

Note: 1, d = don't care

Excitation table

Figure 4.6 Transition & Excitation Tables for J-K Flip-Flop.

To illustrate this approach consider line 1 of the transition table in figure 4.5. It states that after the next clock pulse, flip-flop LN DR0 is to remain in the zero state and flip-flop LN DR1 is to be set to 1. Referring to the JK excitation table in figure 4.6, for flip-flop LN DR0, J and K inputs must be "0" and "d" respectively, and for flip-flop LN DR1, they must be "1" and "d". All present register states are considered in this same manner. A truth table is then constructed for both J and K inputs. The Karnaugh map can then be used to obtain the minimal logic expression for each level input.

d) Stepper motor drive circuitry

Flow of current through the stepper motor stator coils is controlled by three DEC driver switches (8; 5/A). The input diodes to these switches decode the present state of register LINE DRIVE. For all three states of register LINE DRIVE one switch is turned on. This means one coil input is at ground and the other two are tied to -24 volts through a 50 Ω resistor.

4.4 Homing Dove Prism and Mechanical Slit

Machine language instruction sets flip-flops INITIALIZE ROTATION (INTRT, 10; 5/B) and INITIALIZE LINE WIDTH (INTLD; 5/B). Flip-flop INTRT enables a real time clock to supply pulses to the rotation motor control logic (3; 5/B). This motor will continue to rotate until a ROTATION HOME signal is sensed. When this event takes place, flip-flop INTRT will reset, inhibiting pulses to

the stepper motor control. In a similar manner flip-flop INTLD enables real time clock to supply pulses to the slit motor control logic (6; 2/A). Initially the direction of the slit is set so it rotates open. A delayed 6304 instruction resets flip-flop DRTN LINWD (6; 5/B) causing the slit to begin to close. The slit motor will continue to rotate until a LINWD CLOSE HOME signal is generated (10; 2/D). When this event occurs flip-flop INTLD is reset inhibiting pulses to the slit stepper motor control logic.

When both flip-flop INTRT and INTLW return to the zero state they turn on NAND gate DEHJ (10; 3/B) whose output sets flip-flop INITIALIZE FLAG (1/B). This flip-flop informs the computer that the hardware operation is complete.

4.5 Symbol Disk Rotation

a) Basic operation

The control logic required for symbol disk rotation is very similar to that required for the mechanical slit. Figure 4.7 shows the normal sequence of events that takes place for this control. Machine language instruction 6324 loads the required number of symbol steps from the accumulator into a 6 bit register called SYMBOL. As in the mechanical slit control, this number is stored in 2's complement negative form.

Machine language instruction 6324 is also used to set flip-flop LATCH (11; 2/A). This flip-flop controls

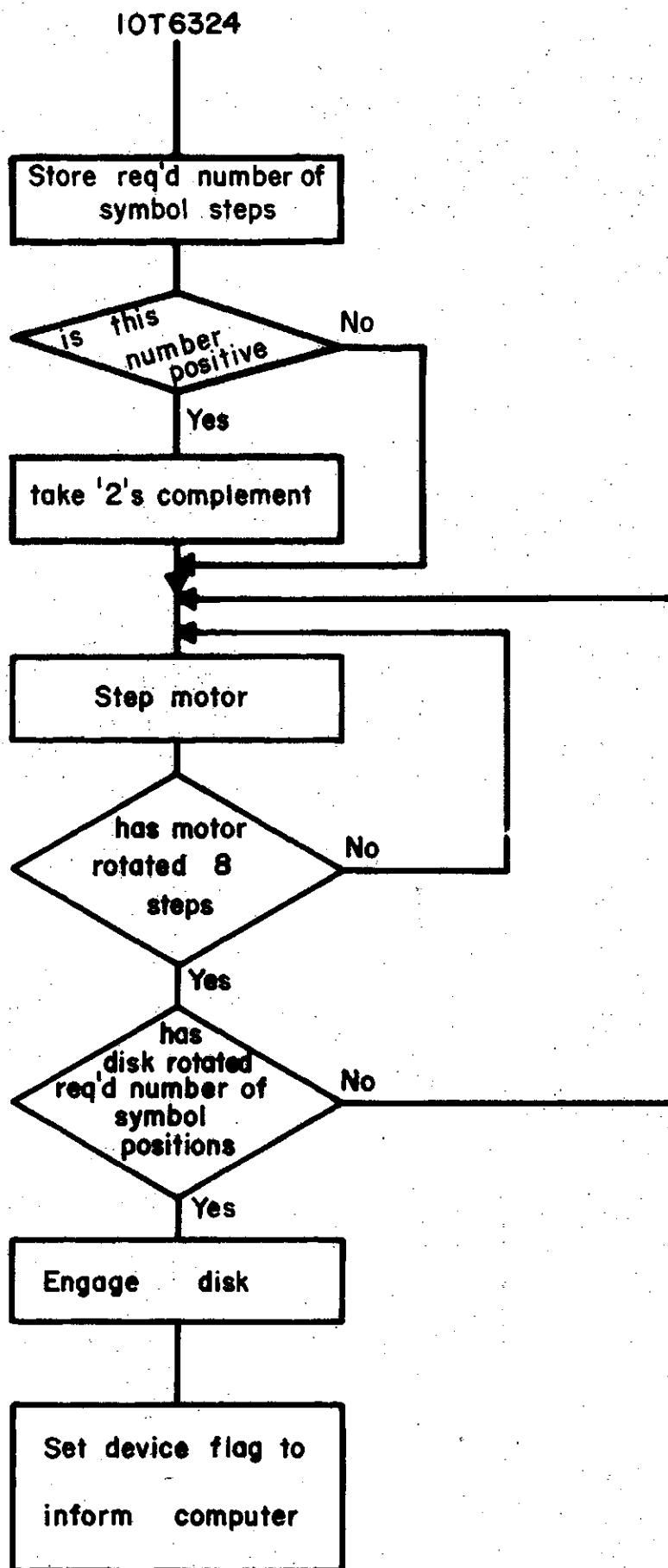


Figure 4.7 Symbol Disk Control Flow Diagram.

the latch solenoid driver switch DR. When it turns on, the latching mechanism disengages from the symbol disk.

A delayed 10T 6324 signal then sets a flip-flop called TOGGLE ENABLE 1 (TG1 ENB: 13; 2/D). This flip-flop enables pulses from a real time clock to be supplied to the stepper motor logic control as well as register STEP. Register STEP is connected as an asynchronous count of 8 circuit; its purpose is to keep track of the number of motor pulses between adjacent symbol positions. Each time register STEP overflows it increments register SYMBOL. Register SYMBOL functions as an asynchronous up-counter storing the remaining number of symbol steps. It overflows when the disk has rotated the required number of steps. When this event occurs, flip-flop LATCH is reset causing the latch solenoid to de-energize. The latch then locates the symbol disk accurately into position. When this has been completed, a flip-flop SYMBOL FLAG (11; 3/A) is set to inform the computer that the hardware operation has terminated.

As in the mechanical slit control, a request for zero symbol steps is considered legal. Normal initiation of the hardware is disallowed by a false ENABLE SET SYMBOL level from gate KLPN (11; 2/C). A true ZERO level enables instruction 6324 to trigger pulse amplifier KLM (11; 3/B). The output of this logic circuit collector sets flip-flop SYMBOL FLAG.

b) Stepper motor driver control logic

The table shown in figure 4.8 shows how stepper motor stator coils were driven to obtain a 7.5 degree step size²¹. A two bit register stores the present switching state of the motor and controls driver switches S1, S2, S3 and S4.

This two bit register called SYMBOL DRIVE consists of flip-flops SYM DR1 and SYM DR2 (13; 3/B). The logic required to implement this register is designed using the same approach as described in section 4.3(c). The transition table for this logic is shown at the top of figure 4.9. The next state of register SYMBOL DRIVE is a function of the present state of flip-flops SYM DR1, SYM DR2 and input variable flip-flop DRTN SYM. The required level gating for this register is summarized at the bottom of figure 4.9.

The driver circuitry used for this control motor consists of four DEC solenoid driver switches. These simple driver switches can be used because current is driven through the stator coils in only one direction.

4.6 Selection of Magnification Lens

a) Basic operation

Machine language instruction 6334 loads the desired magnification lens information from the accumulator into a 2 bit register called TURRET (14; 5/C). The output of this register is decoded momentarily by a delayed 6334 pulse to produce three logic signals. These logic signals control the

Control Reg.	S ₁	S ₂	S ₃	S ₄
00	CLOSED	OPEN	CLOSED	OPEN
01	CLOSED	OPEN	OPEN	CLOSED
11	OPEN	CLOSED	OPEN	CLOSED
10	OPEN	CLOSED	CLOSED	OPEN

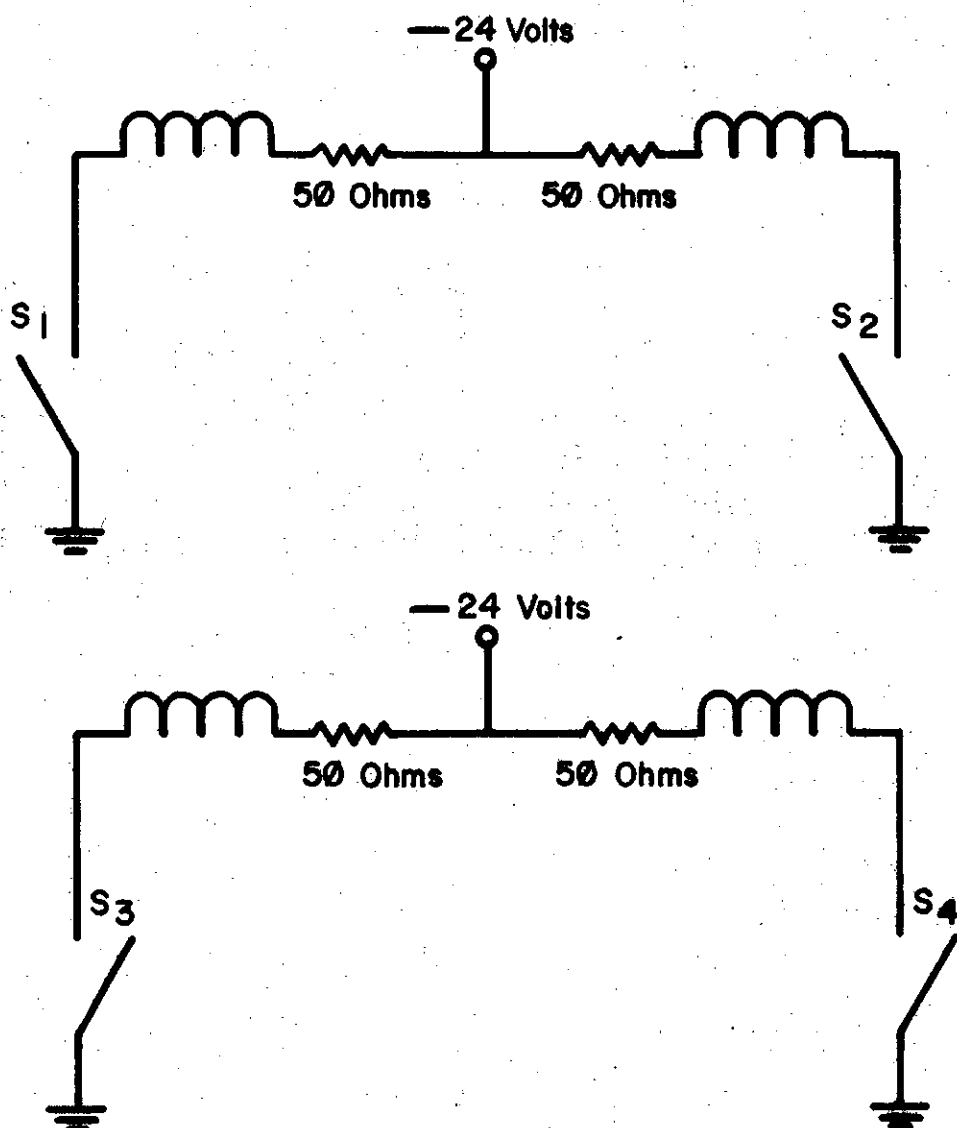


Figure 4.8 Energizing Symbol Disk Stepper.

turret motor driver circuitry. When the desired lens has been selected, a flip-flop called TURRET FLAG (4/B) is set to inform the computer that the hardware operation is completed.

b) Driver circuitry

The synchro torque transmitter is an unusual choice for the turret control motor. Normally it is used in conjunction with a synchro motor. However, for this application it is operated in the same manner as a normal stepper motor. The turret is rotated to the desired position by momentarily energizing the rotor and stator windings of the torque transmitter with the direct current. During this time, the rotor will try to align with the magnetic field set up by the motor's stator windings. Figure 4.10 shows how these stator coils are energized to obtain a 120 degree motor step. The stator motor driver circuits are similar to those described for the rotation stepper motor. (See section 4.2.c.)

4.7 Inner and Outer Light Shutter Control

Flip-flops INNER (15b; 2/B) and OUTER (3/B) control energization of the light head's inner and outer row light shutters. Flip-flop MODE (5/B) stores the operating state of the intensity control (i.e. whether it is set for "line drafting" or "image flashing". See section 4.9 on intensity control for more details.). PDP-8 accumulator bits 0, 10, and 11 indicate what action is to be taken by the control when a machine instruction 6164 is issued. The summary of these details follow:

Turret Lens	Turret Register		Stator		
	Tur 0	Tur 1	Coil 1	Coil 2	Coil 3
X 1	0	0	—	+	OPEN
X 2	0	1	+	OPEN	—
X 3	1	0	OPEN	—	+

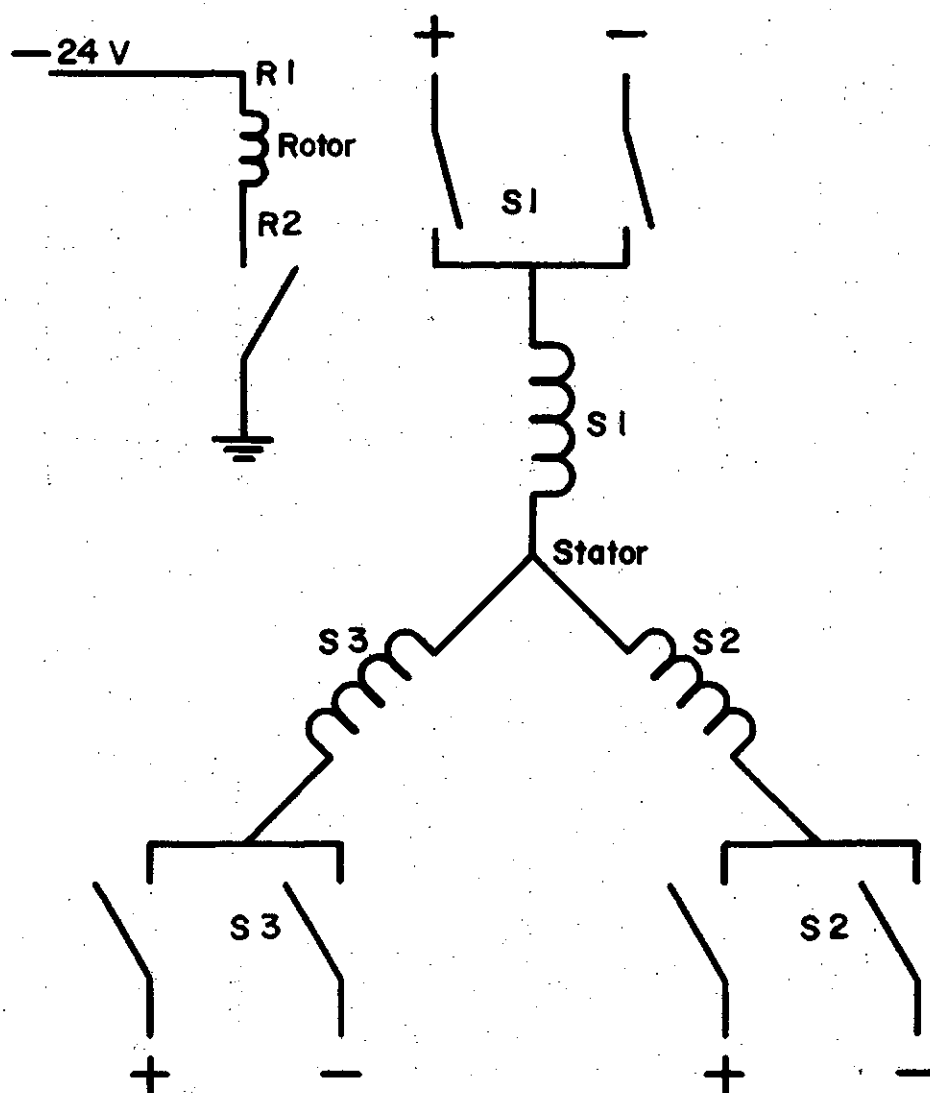


Figure 4.10 Energizing Turret Control Motor.

AC0	= 0	Turn selected shutter on
AC1	= 1	Turn selected shutter off
AC10	= 0	Set state of intensity control to line mode
AC10	= 1	Set state of intensity control to line mode
AC11	= 0	Select inner row light shutter
AC11	= 1	Select outer row light shutter

Machine instruction 6164 normally triggers either delay chain 1 or 2 (15a; top of drawing) to produce signal +1 → SHUTTER (15a; 5/C) which is used to set the controls device flag, flip-flop SHUTTER FLAG (15b; 5/C). The state of flip-flop MODE determines which delay chain is selected. If it is set for "line drafting", then signal ENB LINE will be true allowing delay chain 1 to be triggered (4/A). If it is set for "image flashing", then signal ENB PSYMB will be true allowing delay chain 2 to be triggered. Delay 1 is set to the value of the light shutter delay plus the time it takes to properly expose the end of lines (see section 3.4.6 on light shutter specifications). Delay 2 is set equal to the light shutter opening time.

To ease the burden of programming an additional hardware delay is added to handle the case when the operating mode of intensity control is switched from "line drafting" to "image flashing". This is required to allow the intensity of the projected image to settle to a new value before the light shutter is opened. When this event occurs signal SWTMD is

generated (15a; 4/C) and is used to disable signals ENB PLINE (1/C) and ENB PSYMB. It also enables signal IOTLS to trigger a 30 millisecond delay EFM (15a; 3/B) which is added in series with delay chain 2.

4.8 Interface to PDP-8 Computer

Several processor input/output signals are used to interface the light head control functions to the PDP-8 computer. Some signals have already been mentioned. A list of the signals that are used is summarized below:

a) Input/output transfer pulses and memory buffer bit 3-8

DEC device selector W103 boards are used to convert processor IOP pulses into interface IOT pulses. One W103 board is used for each control. Each device selector is assigned its own individual device code and is programmed to accept computer IOP pulses only if the device code is present on processor input/output MEMORY BUFFER lines 3-8. For example, the device code for the dove prism interface is "34" (see middle two digits of dove prism machine language instruction). This means that the dove prism IOT pulses will be generated from IOP pulses only in the event that code "34" is present on MEMORY BUFFER lines 3-8.

b) Accumulator input and output lines

When programmed data transfers are made to and from the PDP-8 and an interface, they are always done via a twelve bit register in the processor called the ACCUMULATOR (AC). Several AC output lines are utilized to provide each

control with information on the operation being performed. The AC input lines were used to load the status of the control into the computer.

c) INTERRUPT and SKIP line

The INTERRUPT line is used to inform the computer when a control needs servicing. (i.e. A device flag is set.) All interface device flags are connected to this line. The SKIP line is used to allow the processor to identify which device flag is requesting service.

Both INTERRUPT and SKIP lines are connected to the output of an AND/NOR gate RI41 (9; 1/ABCD). This module performs two levels of gating. The first level consists of seven two input negative AND gates. The output of each gate becomes one input to the second stage of this module, which is a seven input negative NOR gate.

d) POWER CLEAR pulse

This negative pulse is generated when the computer is turned on or when the START key on the computer console is depressed. This pulse is buffered by an inverter ML and KJ (09; 3/C) and is used to reset all control device flags.

e) SPECIAL CLEAR pulse

Pulse SPECIAL CLEAR (SPL CLR) is not produced by the PDP-8 processor but has been included in this section because it is often substituted for the POWER CLEAR pulse. It is used in situations where it is not desirable to have clear pulses generated by the computer console START key. A good example

of this is the SYMBOL DRIVE register in the symbol disk rotation control. If this register is cleared during a symbol hardware operation, it is possible that the symbol disk would not stop at a symbol position. The symbol disk would have to be manually rotated to a correct position before another hardware operation could be performed.

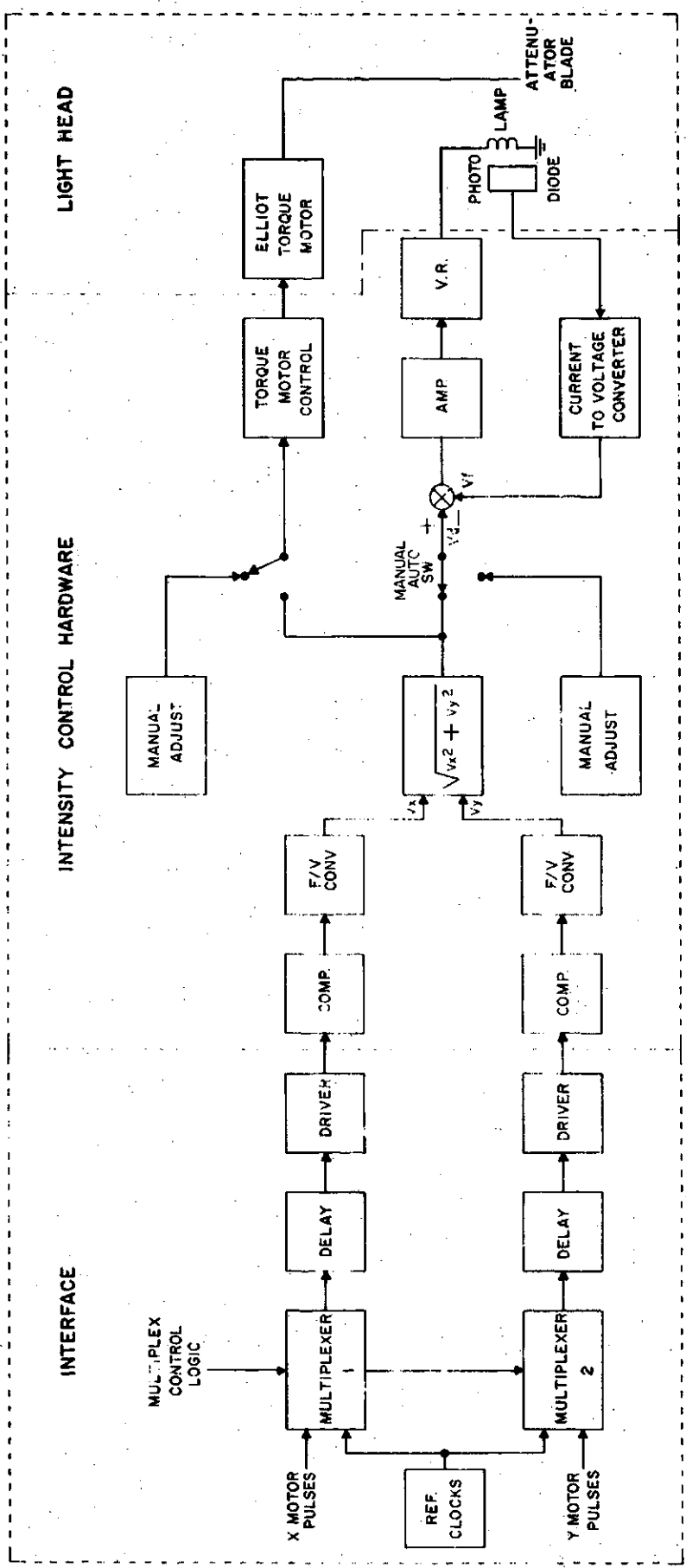
A reed relay (9; 5/B) is used to generate pulse SPL CLR. It is energized by the control logic -15 volt power supply. The normally open contact of this device is fed to invertors HF and ED (9; 5/B). When power is applied to the light head control, it will take some time for the -15 volt supply to charge to its final value due to the capacitance associated with its output. Because of this, the normally open contact of the reed relay will remain momentarily open causing invertors ED and HF to turn on and generate the pulse SPL CLR.

f) SPECIAL CLEAR LINE WIDTH

This pulse is generated when power is applied to the control or in the event of an illegal mechanical slit hardware execution. It is used to reset register LINE which must be clear at the beginning of a line width hardware operation.

4.9 Intensity Control

A basic block diagram of the intensity control hardware is shown in figure 4.11. It consists of a closed loop control for the light source, an open loop control for the attenuator blade, two circuits that produce a



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manually adjustable reference voltage and a circuit that calculates the velocity of the plotter.

The velocity compute circuit electronically calculates the velocity of the travelling light image from existing signals in the drafting system. Both axes of the Gerber plotter are independently driven by stepper motors. Therefore the velocity of either axis can be determined simply by monitoring the frequency of the pulses supplied to its stepper motor control logic. The pulse trains for both X and Y motor axis are sent to the two input channels of the compute circuit where they are converted to an analog voltage which is proportional to frequency. Using the Pythagorean theorem to compute the total velocity from its X and Y components,

$$V_t = \sqrt{V_x^2 + V_y^2}$$

where V_t is the total velocity,

V_x is the X velocity component,

and V_y is the Y velocity component.

The output of the velocity compute circuit serves as the input intensity demand signal for the intensity control loop.

The input channels of the velocity compute circuit are interfaced to digital multiplexer circuits 1 and 2. These circuits allow the intensity demand signal to be produced from other pulse train sources than those for the Gerber plotter. Two other pulse trains are supplied from

real time clocks. The main purpose of the first clock is to ensure that the light source is never completely turned off during the line drafting operation. This is desirable because the response speed of the lamp is limited. The frequency of this clock is set to reflect the start/stop speed of the plotter. The second clock is connected when the projector is programmed for "image flashing". Its frequency is set to reflect the desired intensity for "image flashing".

The closed loop control for the light source consists of error amplifier, adjustable regulated power supply, photodiode and current to voltage amplifier.

The demand signal for this control normally comes from the velocity compute circuit. However, it can be manually switched to an adjustable reference voltage. This facility is useful for conducting exposure tests on film.

The open loop control for the attenuator blade consists of a regulated power supply the output voltage of which can be controlled by either another adjustable reference voltage or by the velocity circuit. The primary purpose of this control is to compensate for different film speeds.

a) Interface to velocity compute circuit

The interface to the two input channels of the intensity control hardware is shown in drawing 23. This interface uses several logic signals produced in the Gerber plotter interface.

- (i) Pulse X SMOOTH This pulse is generated every time the plotter X axis motor increments.
- (ii) Pulse Y SMOOTH This pulse is generated every time the plotter Y axis motor increments.
- (iii) BCLK EN (1) This logic signal will be true whenever the plotter is moving.

The heart of this interface are the digital multiplexer switches that connect the various pulse train sources to two input channels of the intensity control. They consist of pulse amplifiers with DCD input gates. Several logic signals determine which pulse train source is to be connected to the control. The conditions under which each pulse train source is connected are summarized by the logic statements given below.

Source	Logical Condition
Gerber Pulses	$\text{ENB GERB} = (\text{INNER (1)} + \text{OUTER (1)}) \cdot \text{BCLK ENB (1)} \cdot \text{MODE (1)}$
Reference Clock 1	$\text{ENB REF1} = \overline{\text{ENB GERB}} \cdot \text{MODE (0)}$
Reference Clock 2	$\text{ENB REF2} = \text{MODE (1)}$

Note that the Gerber pulses are connected only when the film is exposed to an image and the plotter is moving and the mode of the control is set for "line drawing". If this condition is not true while still in "line drawing" mode, then Reference Clock 1 is connected. If the control

is programmed for "image flashing" then Reference Clock 2 is connected to the intensity control.

The three logic statements shown in this table are generated by gating (23; 1/C) and serve as the enabling inputs for the pulse amplifier DCD input gates. The output pulses produced by the pulse amplifiers are then widened by a delay and fed to the intensity control via bus driver circuits.

b) Velocity compute circuit

The pulses entering the input channels X and Y of the velocity compute circuit are first fed to comparator circuits (24; 2/B and 2/C). The main purpose of these circuits is to remove any pulse ringing that may be present on these input channels. The output of each comparator circuit is then fed to a frequency to voltage converter circuit. This circuit produces an analog voltage that is linearly proportional to input frequency. The frequency to voltage converter circuits that are used are model 3337 modules manufactured by Optical Electronics Incorporated²⁹. This circuit converts every zero crossing at its input into a constant width pulse. These pulses are integrated to produce an analog voltage that is proportional to input frequency.

The total plotter velocity is then computed from its X and Y components by a root sum of squares circuit model 4352 manufactured by Teledyne Philbrick Nexus³⁰. This circuit employs logarithm, antilogarithm and summing amplifiers to obtain the resultant vector voltage from its analog X and Y inputs.

The large signal output response of this velocity circuit was measured to be approximately 30 milliseconds (i.e. 10% to 90% full scale response to a step input).

The positive output voltage from the root of squares circuit is then inverted to negative by amplifier EM (5/B). This extra inverter circuit is required in order to provide the proper polarity demand voltage to the control loop.

c) Manually adjustable references

Normally for automatic operation, the output of inverter EM, is used as a demand voltage for the control loop. However, the demand voltage can also originate from a manually adjustable reference voltage circuit. (The demand voltage source is selected manually by switch S1: 24; 6/B.) A stable reference voltage is obtained from an 8.4 volt temperature compensated zener diode (5/C). This diode regulates the voltage across a 1K Ω potentiometer. The desired reference voltage is set by the wiper arm of the potentiometer and is fed to a noninverting unity gain amplifier. The amplifier acts as a buffer for this voltage reference signal. (i.e. It has a high input and low output impedance.)

d) Light source intensity control loop

The main loop of the light source intensity control consists of a high gain error voltage amplifier stage. The error amplifier is constructed from a Motorola general purpose 1439 operational amplifier (25; 3/B). It amplifies the

difference between demand and feedback signals. Its gain is determined by the ratio of its external components.

The power amplifier circuit is used to increase the drive capability of the voltage produced by the output of the error amplifier. A Motorola monolithic voltage regulator circuit MC1461R and PNP power transistor MJ490 are used to regulate a DC voltage to a value equal to that of the output of the error amplifier. (Approximately 18 volts DC is supplied from an isolation transformer, full wave bridge and filter capacitor.) Since the MC1461R regulator can supply a maximum continuous current of .5 amps, transistor MJ490 is added to increase the capability of the regulator circuit up to two amperes. Only the final unity gain stage of the regulator circuit is utilized. It acts as a control amplifier for the transistor, adjusting its base current (i.e. its effective resistance) so that the output voltage of the regulator will be equal to that requested by the error amplifier.

The feedback signal is produced by a United Detector Technology model PIN5 Schottky silicon pin photodiode which is mounted in close proximity to the light source. A 1/4 inch thick heat shield is mounted in front of it to protect it from the heat generated by the lamp. The photodiode is operated with zero biasing voltage by directly connecting its anode into the inverting input of a Burr Brown 3503A FET input

operational amplifier ($4/C$). Because of negative feedback, the output of this amplifier will adjust to keep the voltage at its inverting input to approximately 0 volts. Hence there is no voltage bias across the diode. Since the input current to the amplifier is negligible, the current flowing through the diode will flow through the amplifier feedback resistor to produce an output voltage which is directly related to diode current.

$$V_o = R_f I_d$$

where R_f is the value of the feedback resistor

and I_d is the current flowing through the diode.

For low frequencies, the diode sees an input impedance of

$$R_i = R_f/A$$

where R_f is the value of the feedback resistor,

and A is the open loop gain of the amplifier.

Because this impedance is very low, the current through the diode and hence the amplifier output voltage will be proportional to the light that is seen by the diode²⁴.

The photodiode is operated with zero voltage bias in order to minimize the effects of changes in temperature. Under these conditions, there is no diode leakage current and so changes in diode current with temperature are due only to shifts in its responsivity. This shift is approximately .3% per degree F.

Operating the photodiode in this mode lowers its

sensitivity but this is not a problem since it is mounted in close proximity to the light source. At the lowest lamp intensity setting (i.e. minimum plotter speed), the diode current is still several orders of magnitude greater than the input bias current of the amplifier. Therefore changes in output voltage due to amplifier input bias drift are negligible. Output voltage changes due to voltage offset drift are also insignificant because the voltage gain configuration of the amplifier is less than unity.

An approximate mathematical model for the control loop is shown in figure 4.12³¹. Several assumptions have been made in this model.

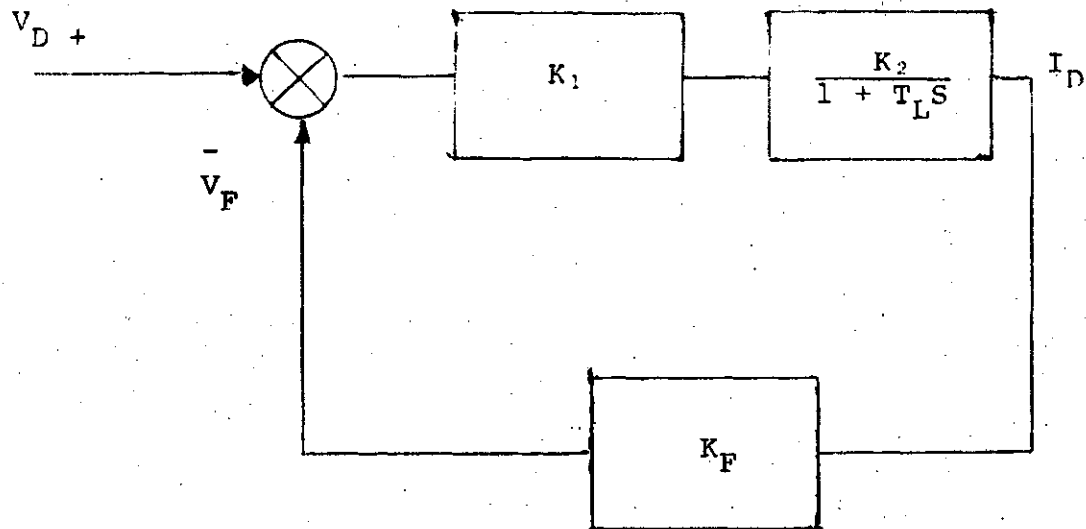
- (i) The relationship between output intensity vs. lamp voltage can be approximated to be a first order transfer function.
- (ii) The value of K_2 is assumed to be constant over the operating region of the lamp.
- (iii) High order poles have been neglected.

On the basis of this model, output lamp intensity as seen by the diode is related to input demand voltage by the following expression.

$$\frac{I_D}{V_D} = \frac{K_1 K_2}{1 + K_1 K_2 K_F} \left(\frac{1}{1 + \frac{T_L S}{1 + K_1 K_2 K_F}} \right)$$

where K_1 is the gain of the error amplifier.

K_2 is proportionality constant relating diode current to lamp voltage.



$$\frac{I_D}{V_D} = \frac{K_1 K_2}{1 + K_1 K_2 K_F} \left(\frac{1 + \frac{1}{T_L S}}{1 + \frac{K_1 K_2 K_F}{1 + T_L S}} \right)$$

if $K_1 K_2 K_F \gg 1$ then the above expression simplifies to

$$\frac{I_D}{V_D} \approx \frac{1}{K_F} \left(\frac{1 + \frac{1}{T_L S}}{\frac{K_1 K_2 K_F}{1 + T_L S}} \right)$$

Figure 4.12 Mathematical Model of Lamp Servo Loop.

T_L is the time constant of the lamp.

K_F is the gain of the current to voltage converter circuit.

This control loop can be approximated to be a type 0 system. Theoretically its gain can be set to infinity; however, this is not found in practice due to the neglected higher order poles in the system. A loop gain setting of 10 to 20 is used.

The bandwidth of the error amplifier was reduced to 10 kilocycles per second to reduce the high frequency noise caused by the frequency to voltage converters in the velocity compute circuit. This was done by adding a 47 picofarad capacitor in parallel with the error amplifier's 220 kilohm feedback resistor.

The response of the control loop was measured by applying a step input voltage and monitoring feedback voltage produced by the current to voltage amplifier. The large signal response of this control was 50 milliseconds (10% to 90% output) both for a positive step input and a negative one.

e) Attenuator blade control

The open loop control that was developed for attenuator blade is shown in drawing 26. It basically consists of an Optical Electronics Incorporated model 9684 power operational amplifier. This device is capable of driving a 5 watt load. Negative feedback has been applied to this device so that its gain will be determined by a ratio of its external components.

The transmission versus voltage characteristic of the attenuator blade shown in figure 4.13 was measured by mounting a photodiode at the output of the PS5 light head. This curve is non-linear at low and high levels of transmission and exhibits hysteresis. The effects of these non-linearities could be reduced by running the attenuator under closed loop conditions. As discussed earlier, this approach was rejected mainly because a fairly major modification would have to be made to the PS5 light head in order to mount a photodiode after the vane.

The full scale response of the vane was measured to be 10 milliseconds (i.e. from 10% to 90% transmission for a step input).

4.10 System Photographs

The interface and control for the PS5 light head is shown in figure 4.14. The DEC chassis shown in figure 4.15(a) houses most of the electronics. The intensity control hardware shown in figures 4.14(b) and (c), was constructed in a Hammond steel instrument case.

Photographs of the basic components of the complete drafting system are shown in figure 4.15. The Potter MT-36 magnetic tape transport and PDP-8 computer are shown in figure 4.15(a). Figure 4.15(b) shows the Barr and Stroud PS5 light head mounted on the Gerber model 32 drafting table.

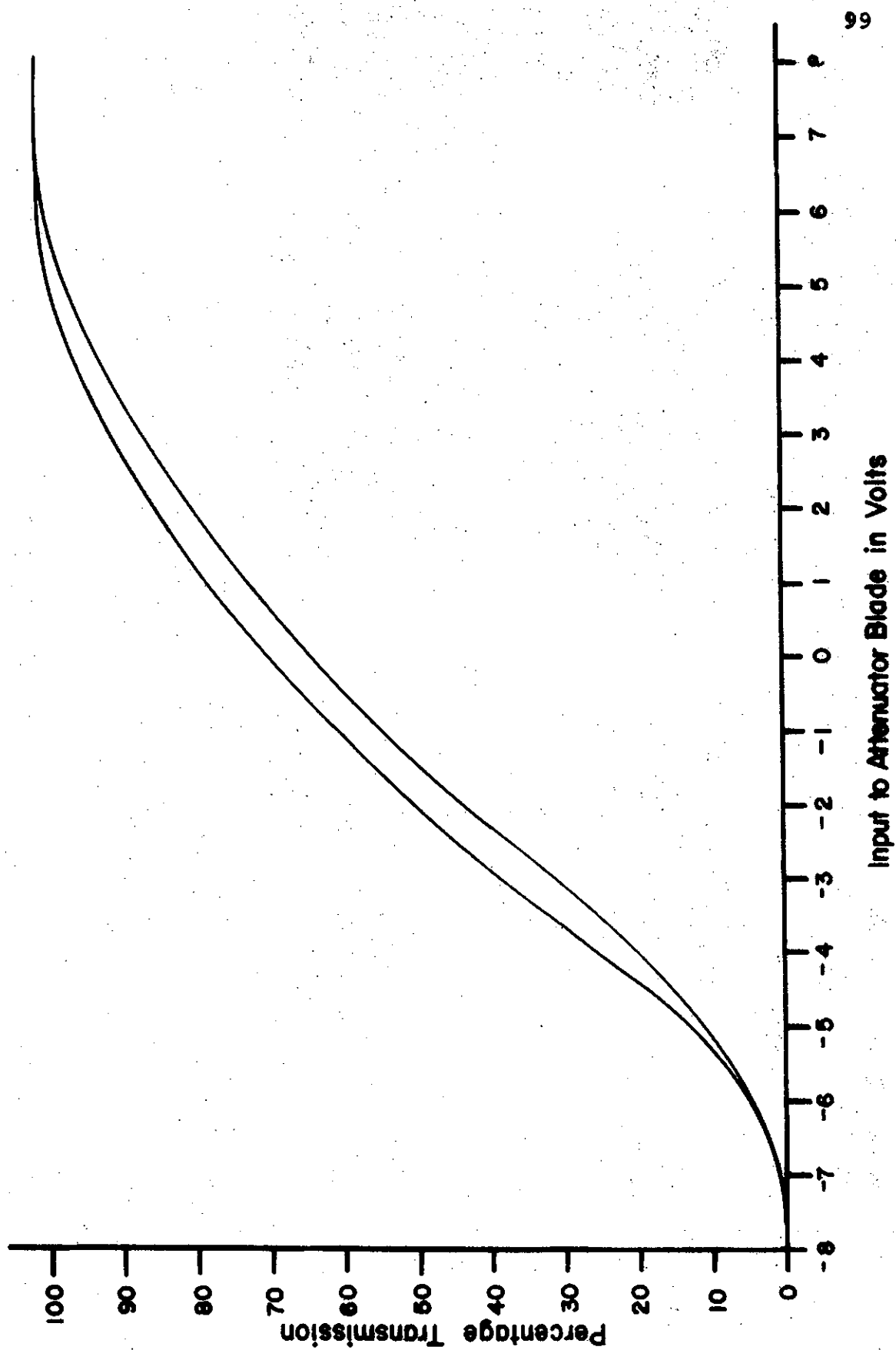
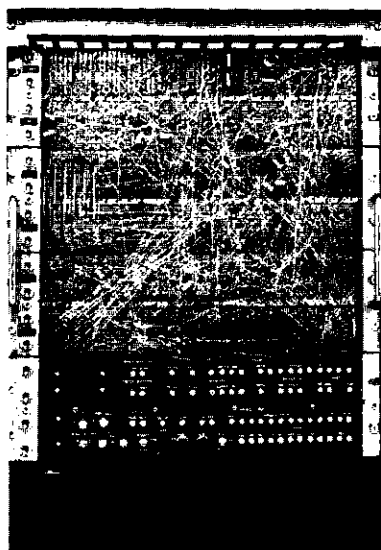
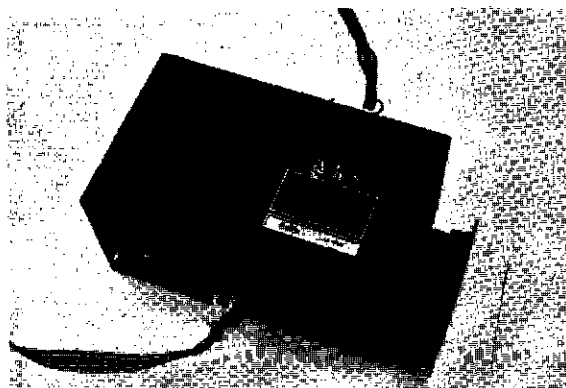


Figure 4.13 Intensity versus Voltage Characteristic of Attenuator Blade



(a) Digital electronics wired on
D.E.C. chassis



(b) Outside view of intensity
control

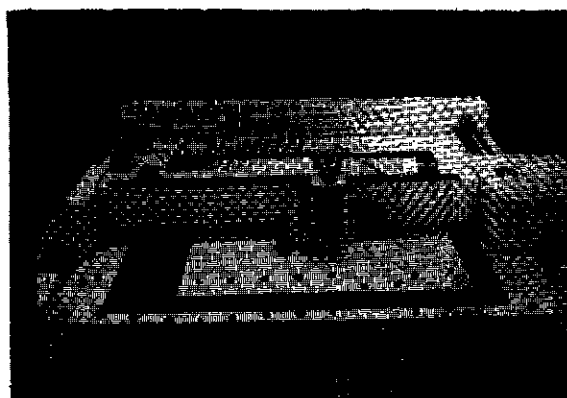


(c) Inside view of intensity
control

Figure 4.14 Photographs of Interface & Control for PS-5 Light Head.



(a) Potter MT-36 transport &
D.E.C. PDP-8 mini - computer



(b) Barr & Stroud PS-5 light
head mounted on Gerber 32
table

Figure 4.15 Photographs of Automatic Drafting System.

		1	2	3	4	5	6	7	8
A	R 201 R 201	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	R 201 R 201	IN	OUT	IN	OUT	IN	OUT	IN	OUT
B	R 202 R 202	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	R 202 R 202	IN	OUT	IN	OUT	IN	OUT	IN	OUT
C	R 203 R 203	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	R 203 R 203	IN	OUT	IN	OUT	IN	OUT	IN	OUT
D	R 204 R 204	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	R 204 R 204	IN	OUT	IN	OUT	IN	OUT	IN	OUT

DATE		TIME	
PROJECT		MODULE LIST	
REV		LSP - 03	
FROM ENG. DATE		LSP - 03 - 1	
PROG	DATE	SHEET	OF

[illegible][illegible]

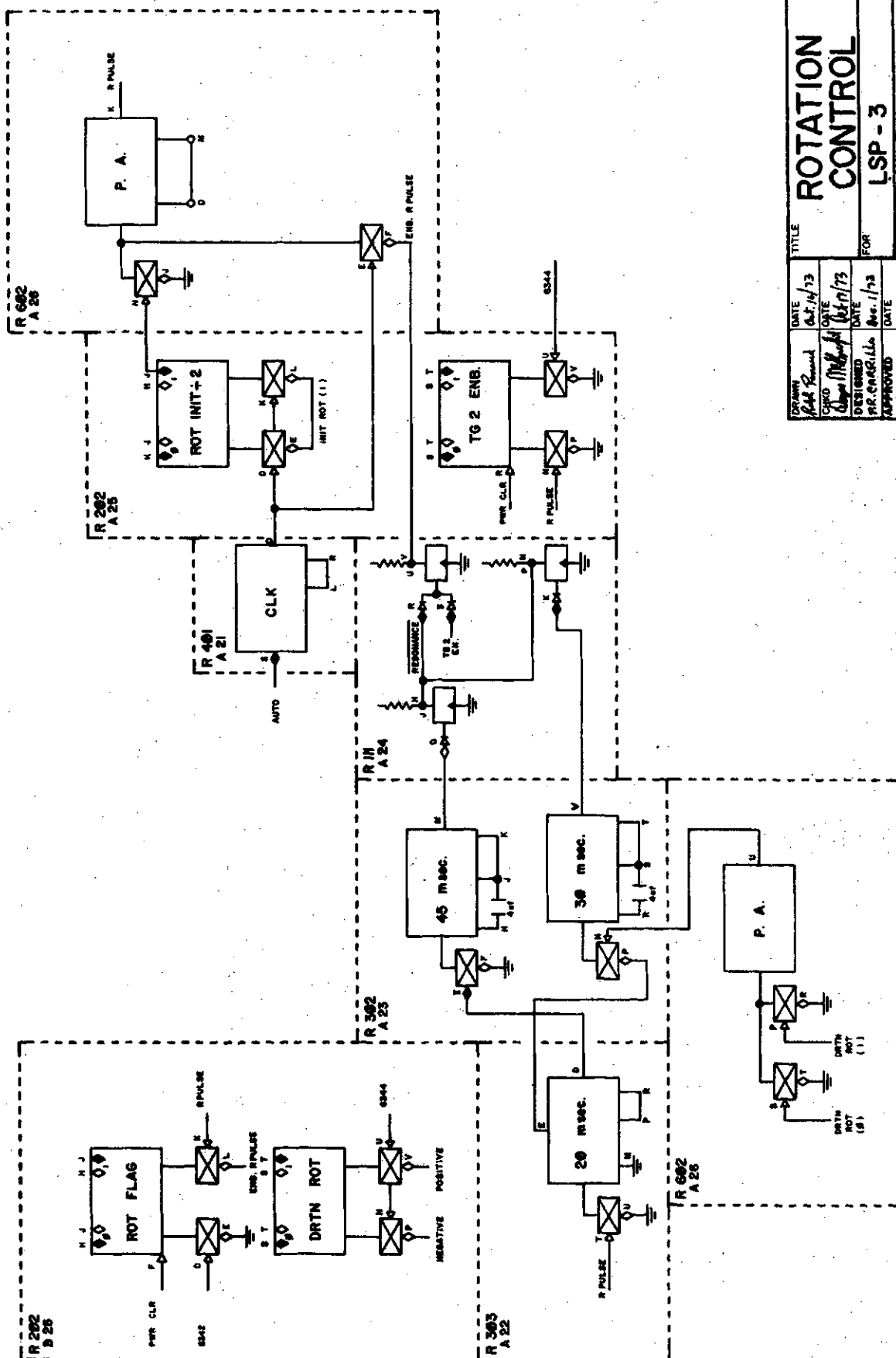
ROTATION CONTROL

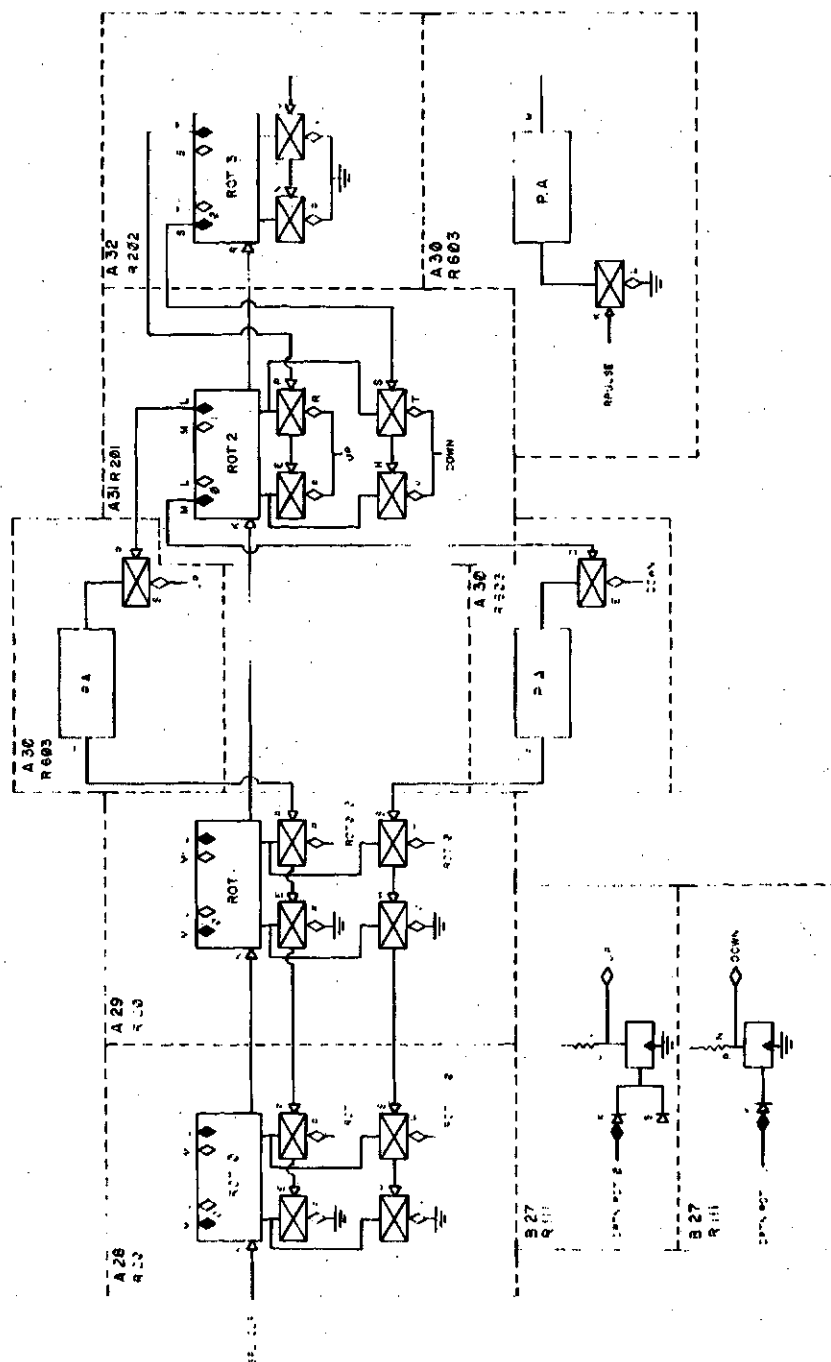
LSP-3

DRAWING NO.

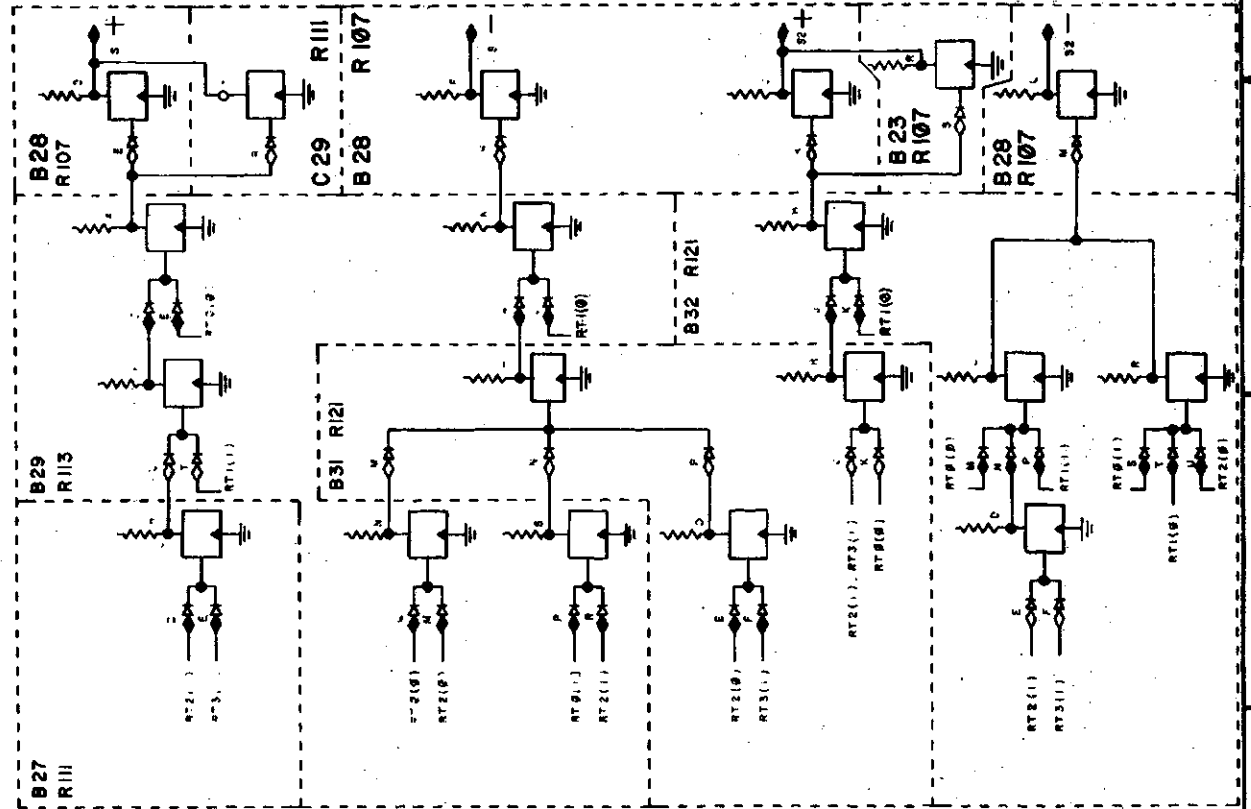
LSP-3-3

DRAWN	DATE	TITLE
Redmond	Oct. 14/73	ROTATION CONTROL
CHKD	DATE	FOR
W. J. McLaughlin	Oct. 17/73	LSP-3
DESIGNED	DATE	DRAWING NO.
W. J. McLaughlin	Oct. 1/73	LSP-3-3
APPROVED	DATE	IMPLEMENTED DATE
SHEET	OF	DIST
5	6	





DESIGN	DATE	UP, DOWN COUNTER FOR ROTATION MOTOR	LSP - 03	DRAWING NO LSP - 03 - 4	DIST
APPROV	DATE				
CHKD	DATE				
DATE	DATE				

[illegible]

6

5

4

3

2

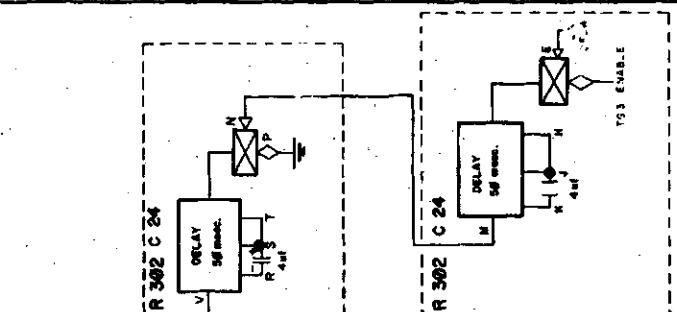
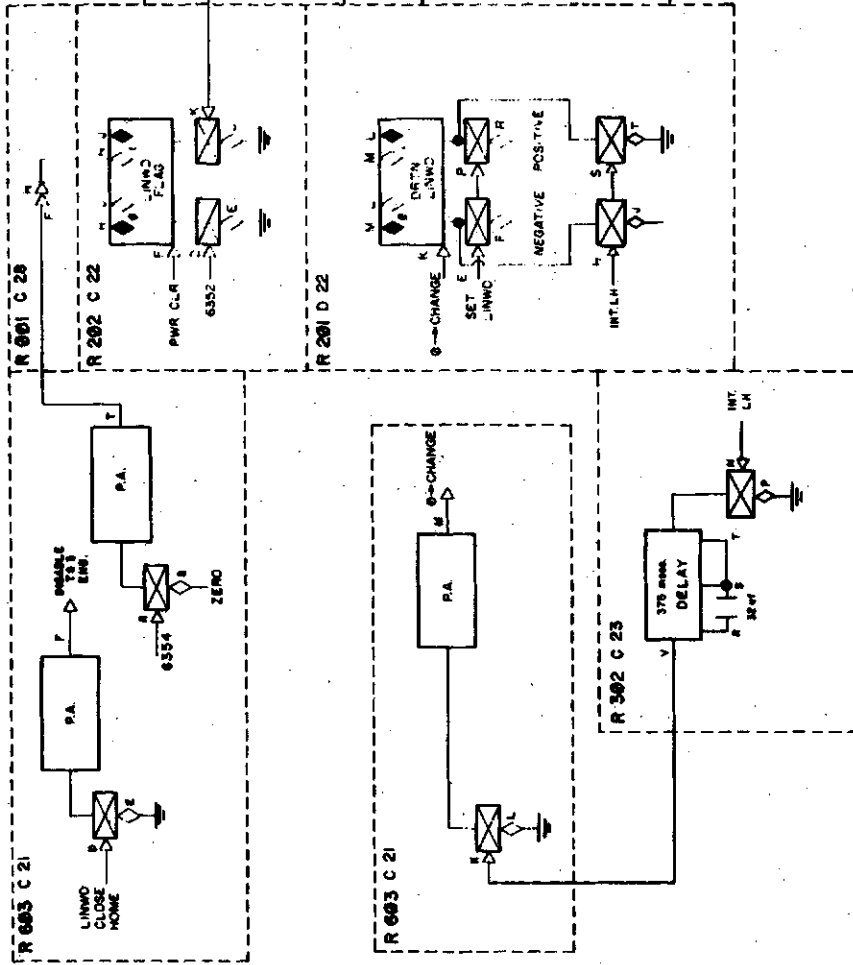
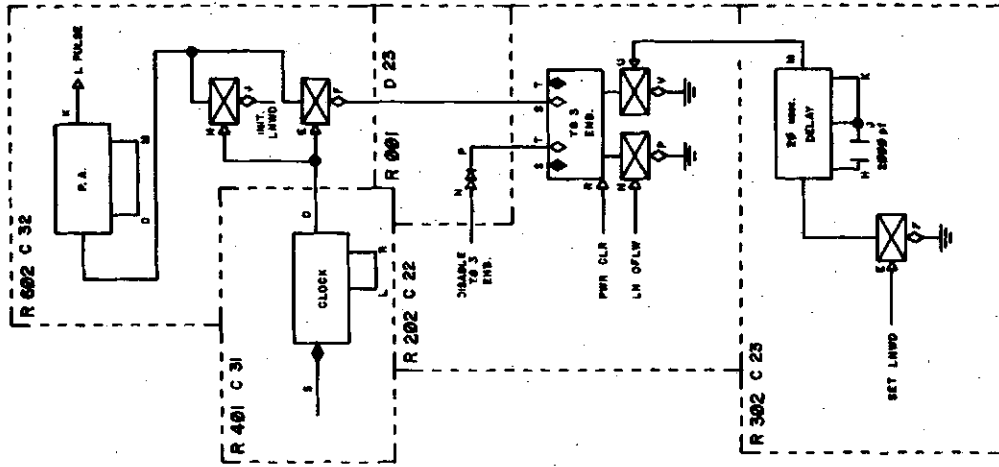
1

A

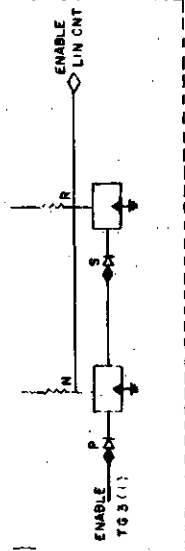
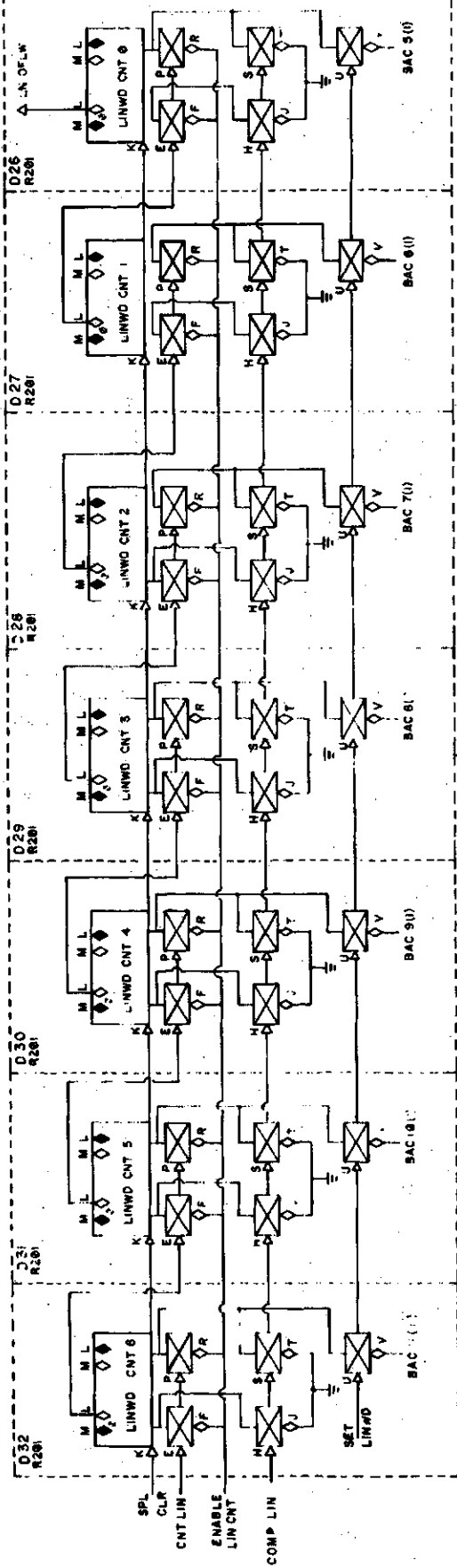
B

C

D



TITLE		DATE	BY
LINE WIDTH CONTROL		01/9/73	RAH
FOR		DATE	BY
LSP-3		01/9/73	RAH
DRAWING NO.		DATE	BY
LSP-3-6		01/9/73	RAH
SHEET		OF	DIST
5		5	6



TITLE	
LINE WIDTH CONTROL	
LINE REGISTER	
FOR	LSP-03
DRAWING NO.	LSP-03-7
SHEET OF	5
DIST	6

DATE	Sept 11/73
DATE	Sept 11/73
DATE	Sept 11/73
DATE	Sept 11/73
DATE	Sept 11/73
DATE	Sept 11/73

6

5

4

3

2

1

A

B

C

D

A

B

C

D

6

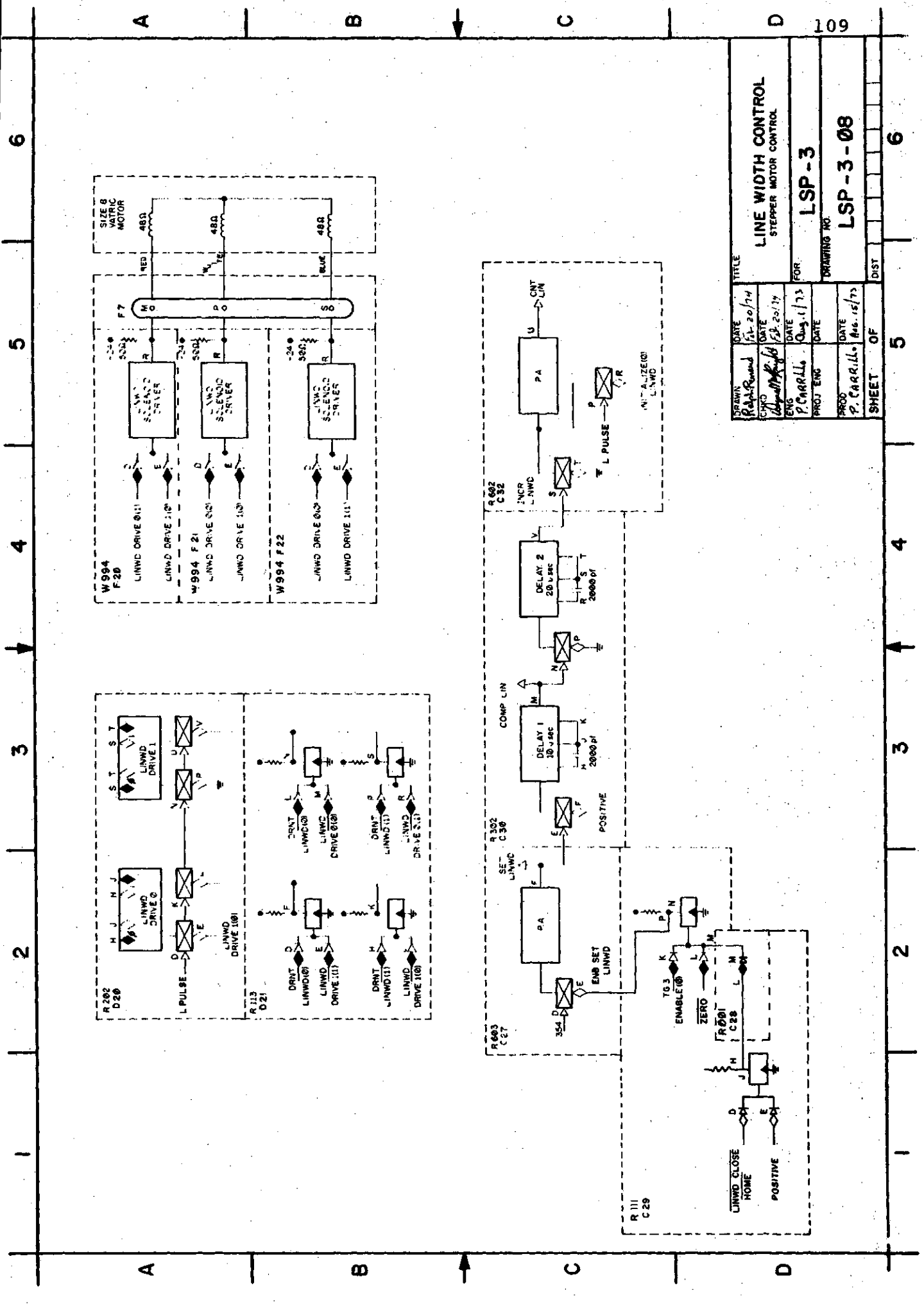
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4

3

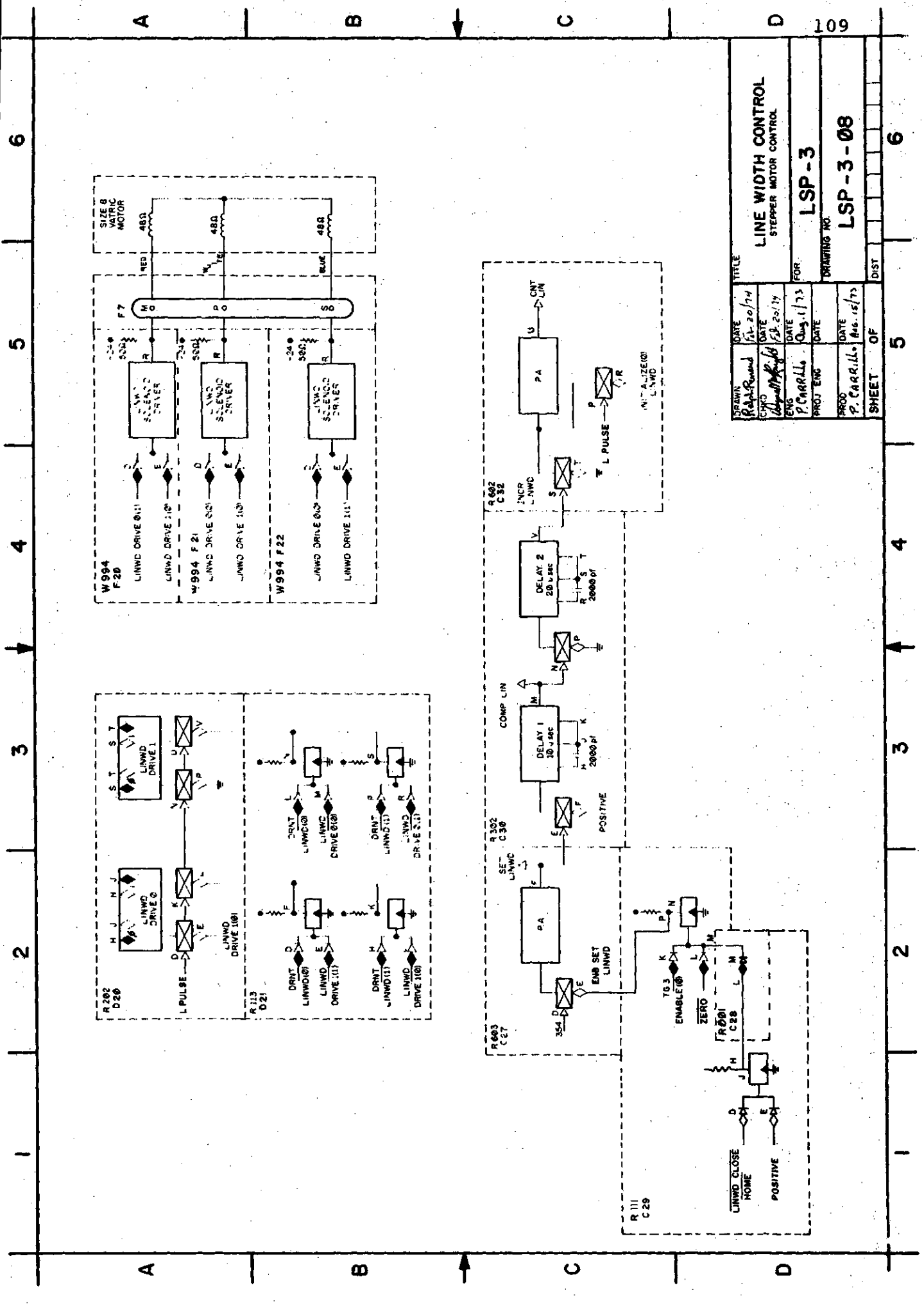
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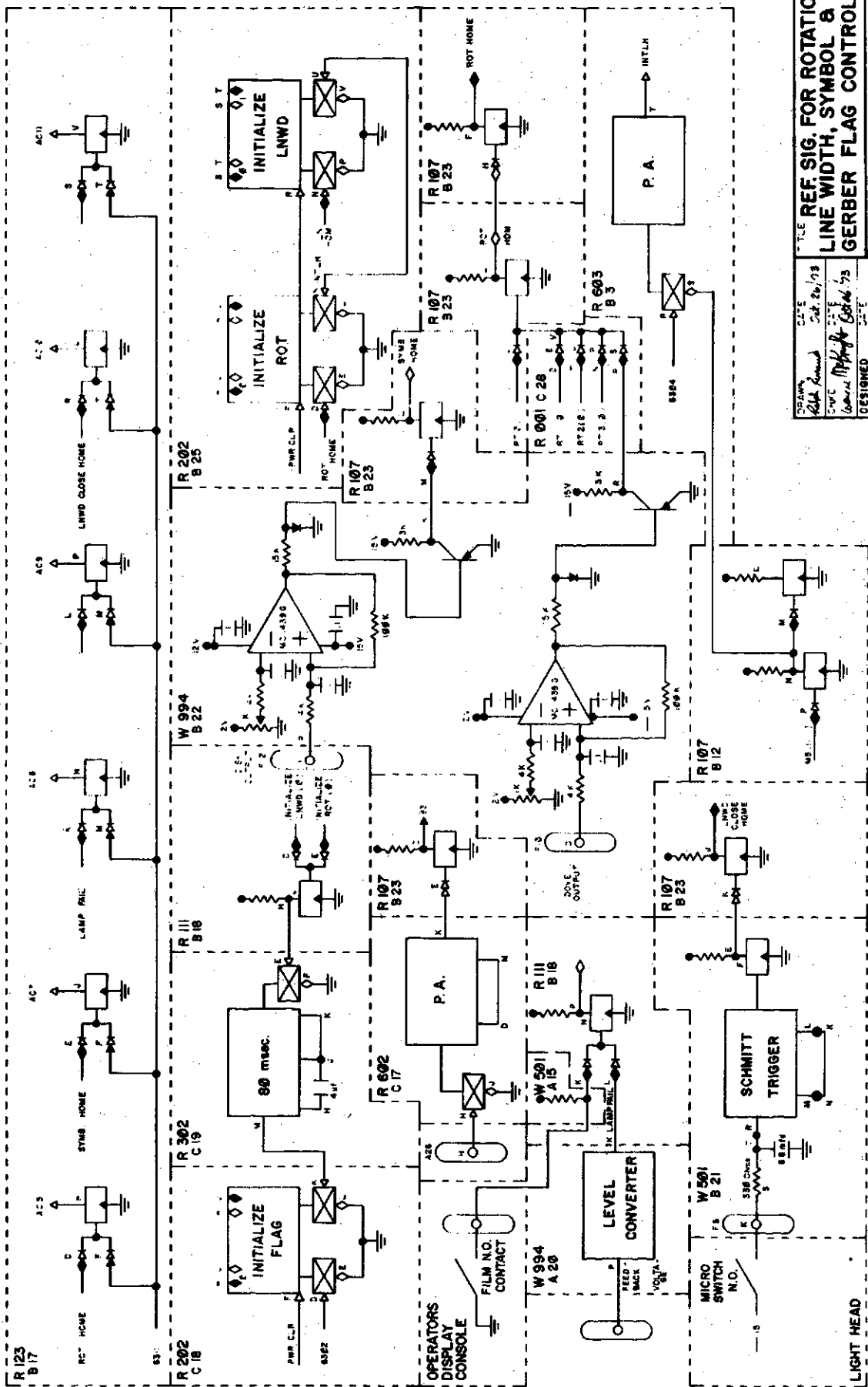
DRAWN		DATE	12-20-74
R. Carrillo		DATE	12-20-74
ENG		DATE	12-20-74
P. Carrillo		DATE	08-11-73
PROJ ENG		DATE	
P. Carrillo		DATE	08-11-73
SHEET		OF	5
DIST			

TITLE
 LINE WIDTH CONTROL
 STEPPER MOTOR CONTROL
 FOR
 LSP-3
 DRAWING NO.
 LSP-3-08



DRAWN		DATE	12-20-74
R. Carrillo		DATE	12-20-74
ENG		DATE	12-20-74
P. Carrillo		DATE	08-11-73
PROJ ENG		DATE	
P. Carrillo		DATE	08-11-73
SHEET		OF	5
DIST			

TITLE
 LINE WIDTH CONTROL
 STEPPER MOTOR CONTROL
 FOR
 LSP-3
 DRAWING NO.
 LSP-3-08



***FILE REF. SIG. FOR ROTATION,
LINE WIDTH, SYMBOL &
GERBER FLAG CONTROL**

3
1
LSP

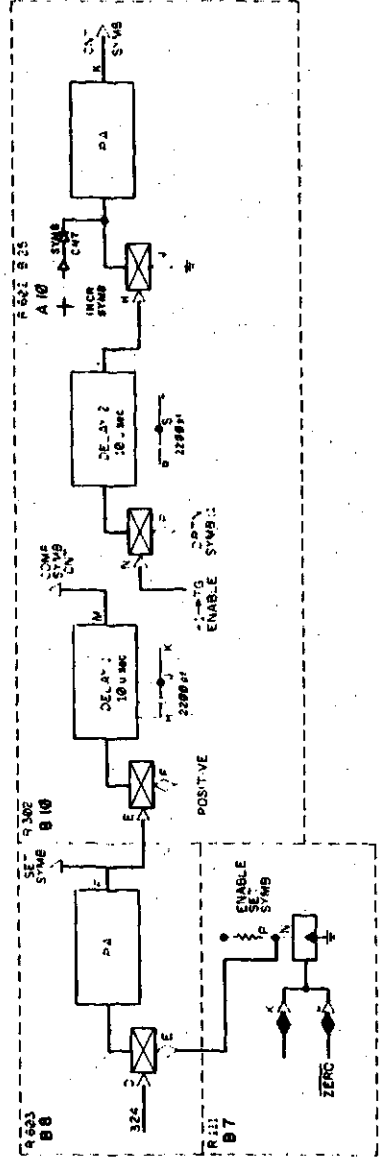
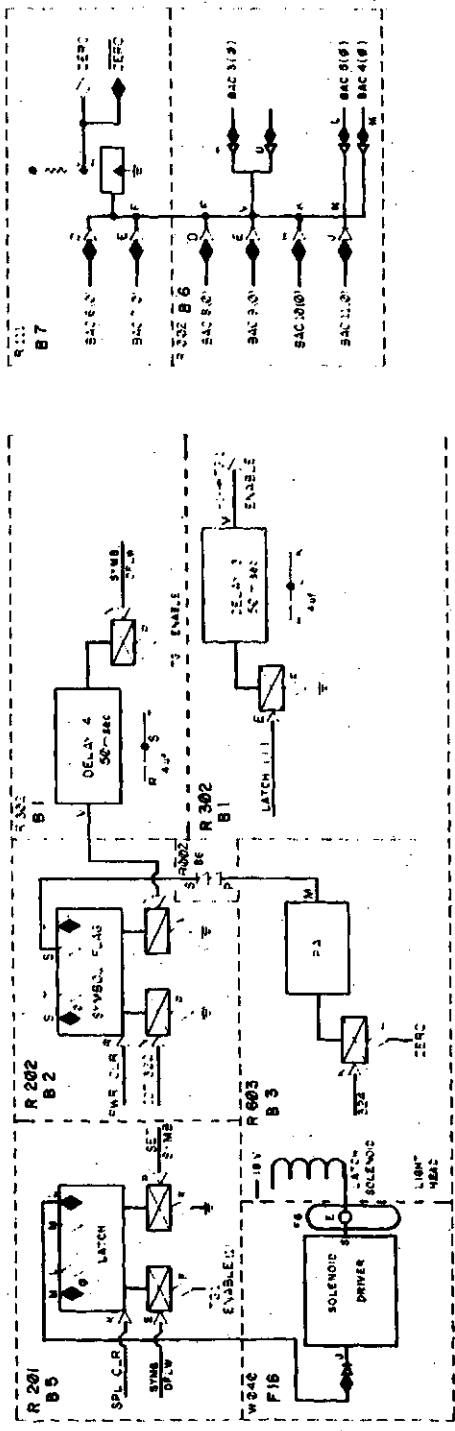
DRAWING NO.

LSP-3-10

150

10 SHEET 1345

10 SHEET 1345



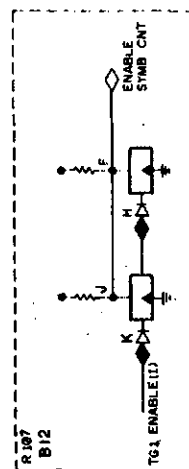
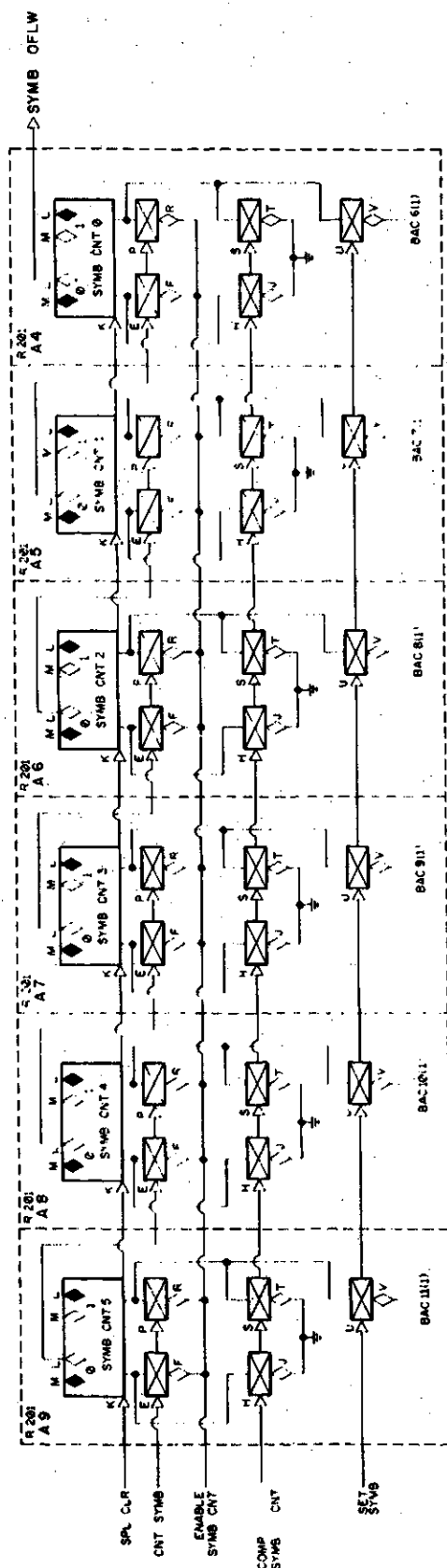
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R 201		10/1/73	SYMBOL DISC CONTROL
R 202		10/1/73	
ENG		DATE	FOR
R 201		10/1/73	LSP-3
PROJ. ENG.		DATE	DRAWING NO.
R 201		10/1/73	LSP-3-11
PROO.		DATE	
R 201			
SHEET		OF	DIST
5		5	6

A

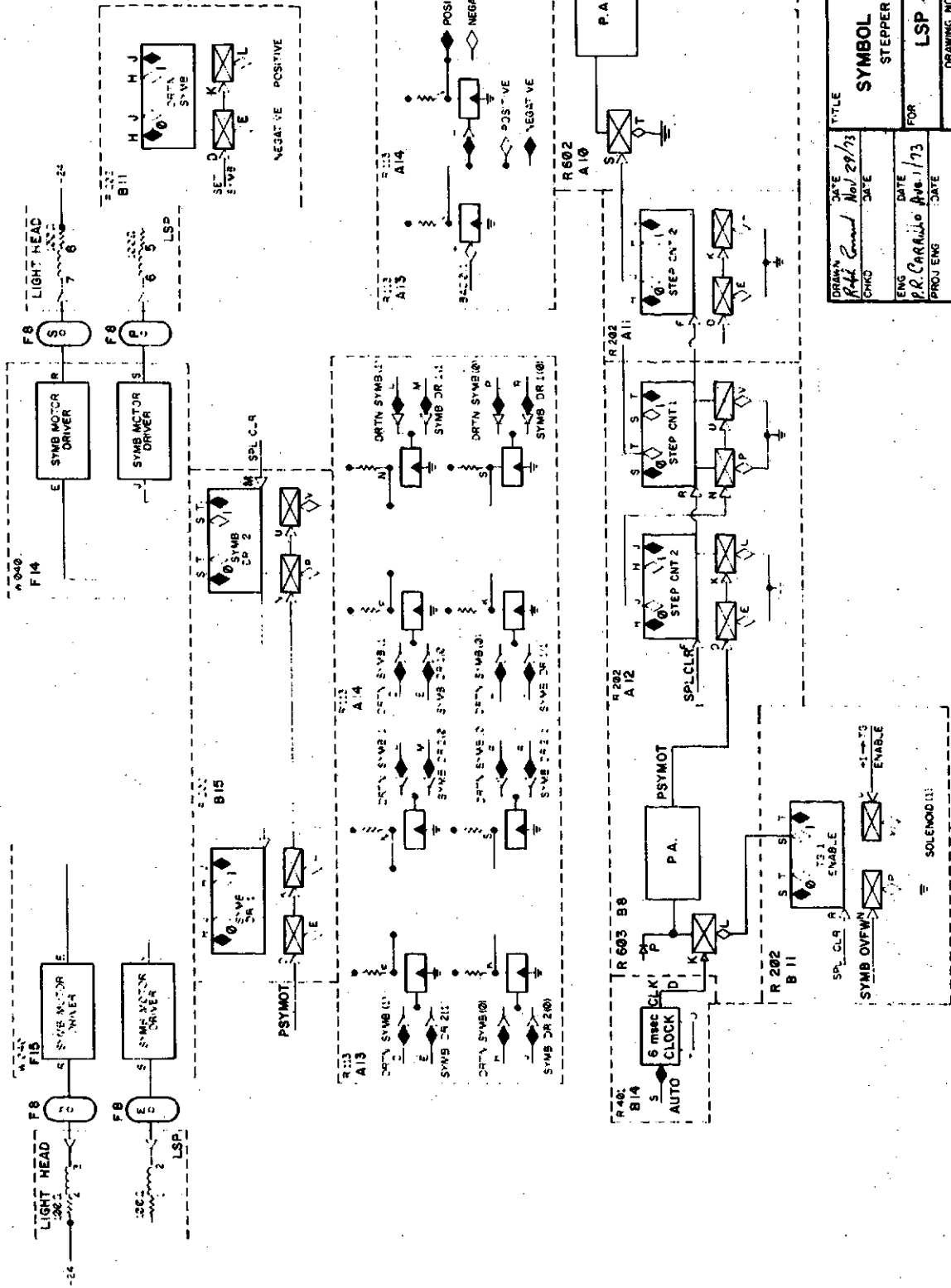
B

C

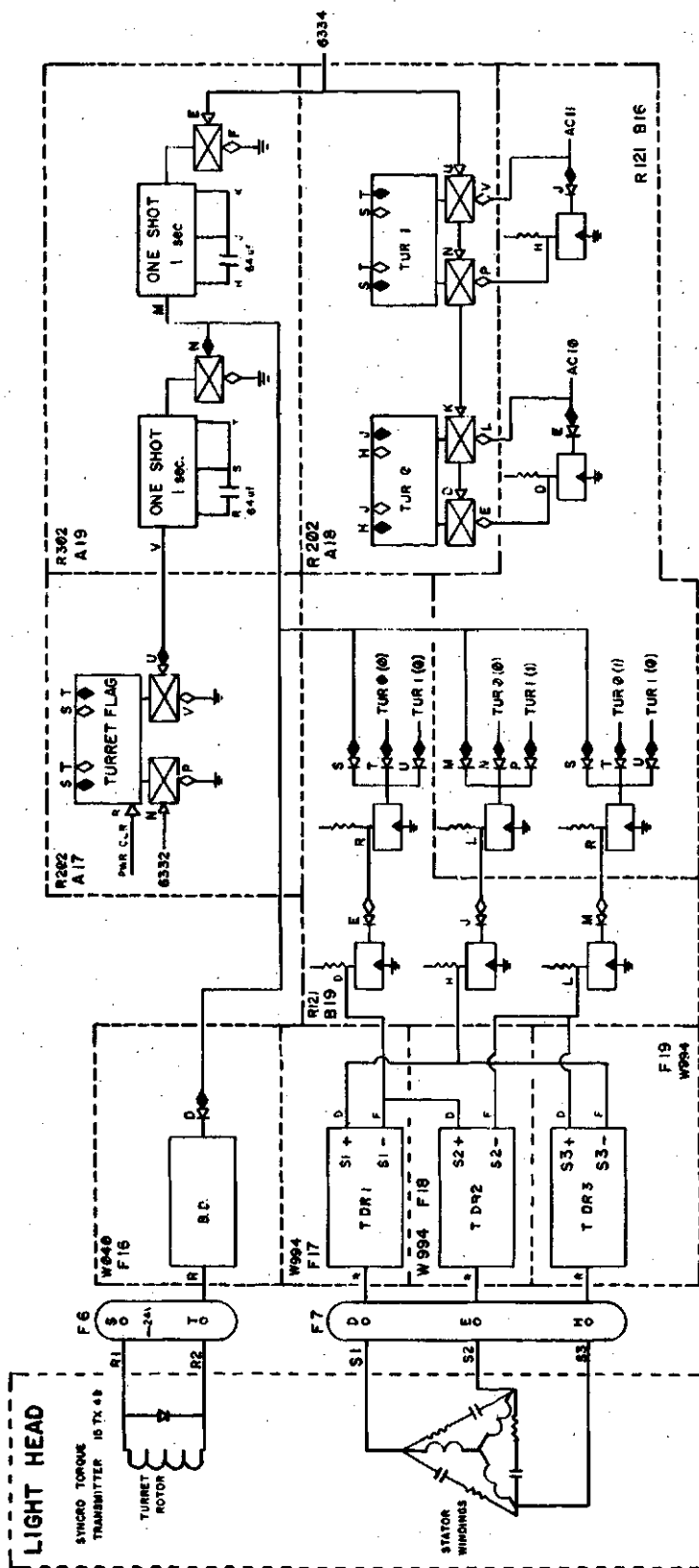
D



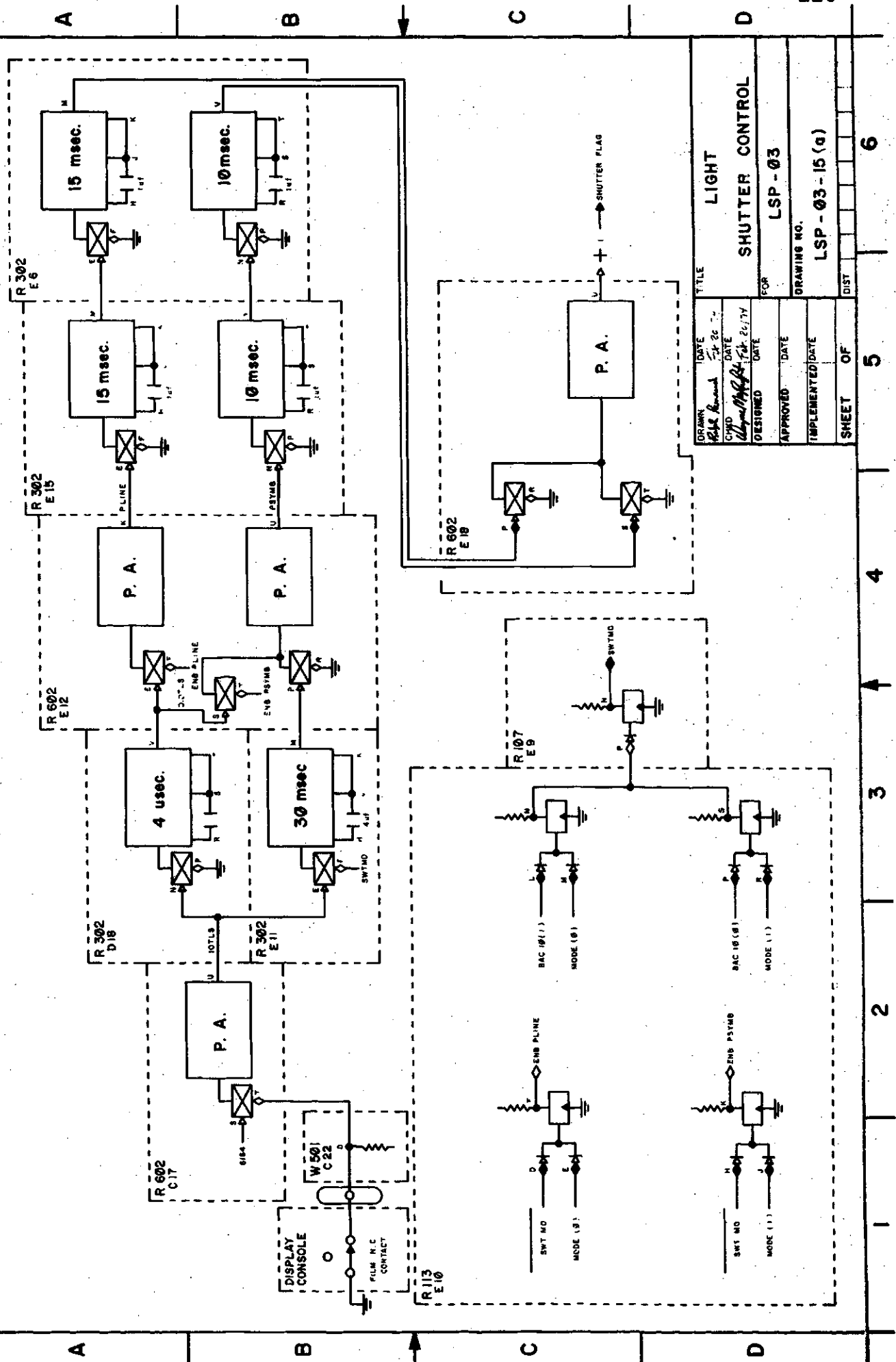
DATE		TITLE	
DATE	May 22/73	SYMBOL DISC CONTROL	
DATE		SYMBOL REGISTER	
DATE		FOR LSP - 3	
DATE	Aug 1/73	DRAWING NO.	
DATE		LSP - 3 - 12	
DATE		SHEET OF	
DATE		DIST	



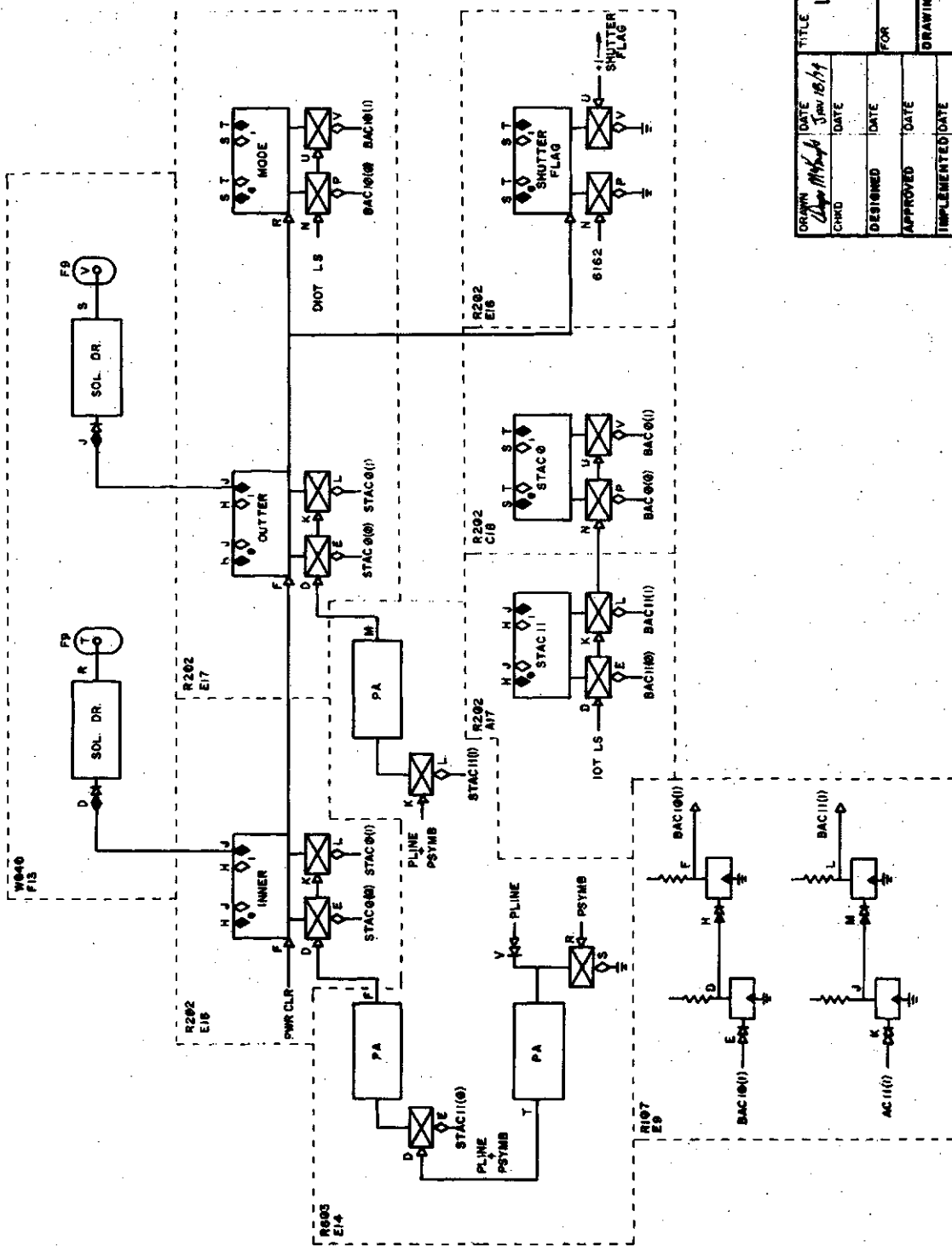
DRAWN		DATE		TITLE	
R 602		Nov 29/73		SYMBOL DISC CONTROL	
ENG		DATE		FOR	
R 602		Nov 29/73		LSP - 3	
PROJ ENG		DATE		DRAWING NO	
R 602		Nov 29/73		LSP - 3-13	
PROO		DATE		SHEET OF	
R 602		Nov 29/73		6	



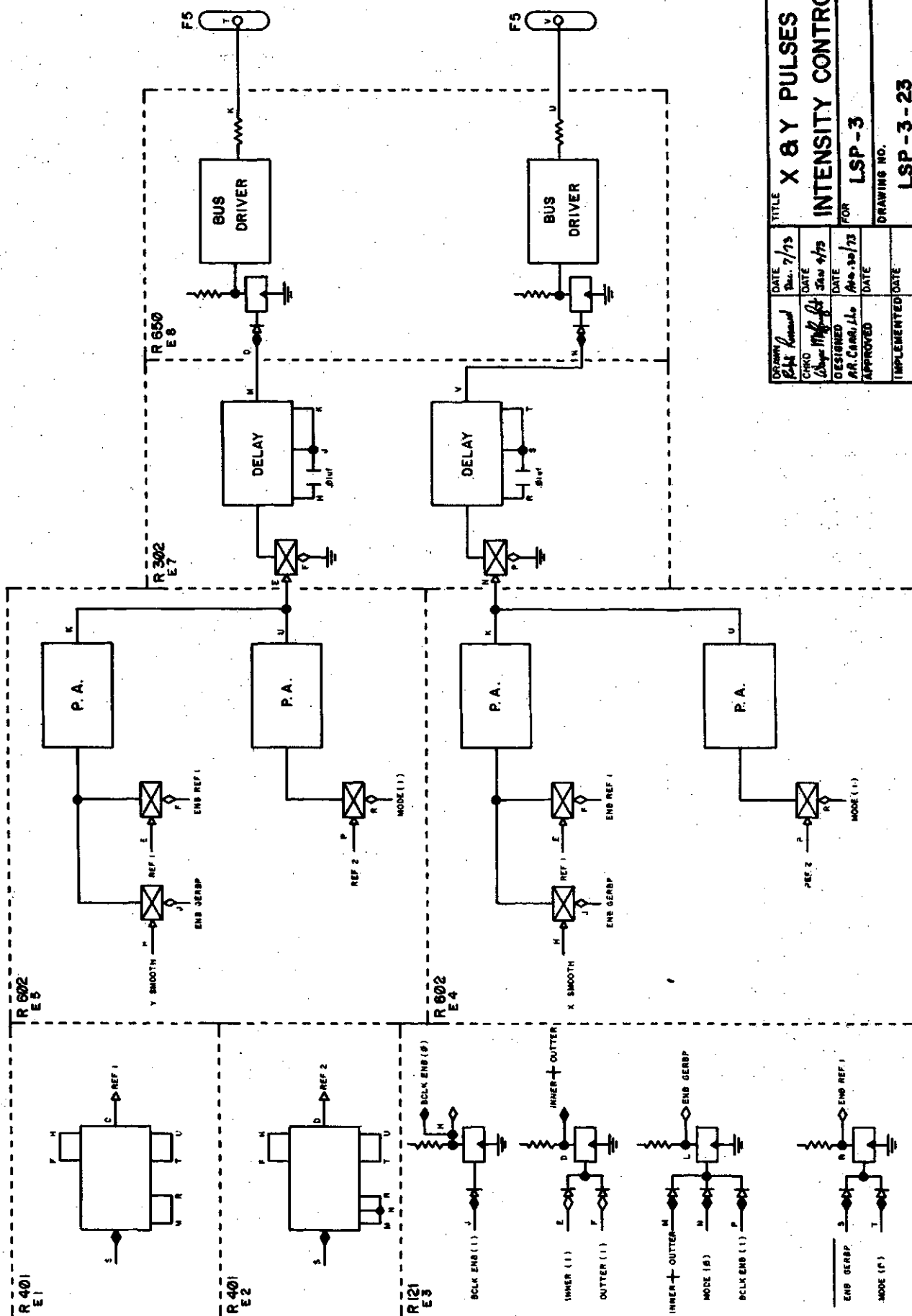
DRAWN		DATE	TITLE
R121 B16		Dec 5/73	TURRET CONTROL
CHKD.		DATE	
W. J. M. / J. M. / J. M.		Jan 9/73	
FOR		DATE	
R. E. M. / L. O.		Dec 5/73	
DRAWING NO.		DATE	
LSP-3			
SHEET		OF	
5			



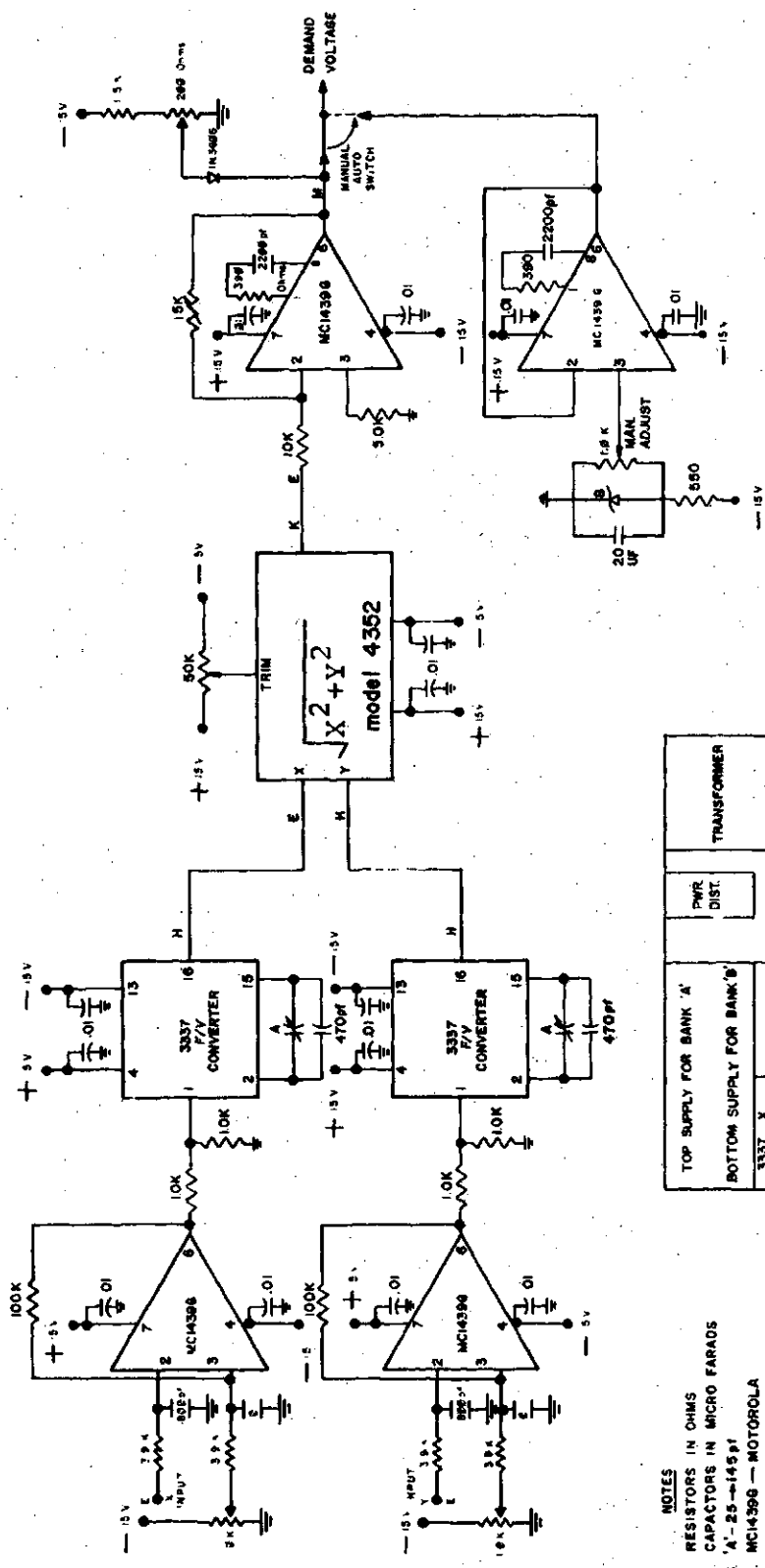
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R. L. R. R.		26/7/74		LIGHT SHUTTER CONTROL	
DESIGNED		DATE		FOR	
R. L. R. R.		26/7/74		LSP - 03	
APPROVED		DATE		DRAWING NO.	
R. L. R. R.		26/7/74		LSP - 03 - 15 (a)	
IMPLEMENTED		DATE		DIST	
R. L. R. R.		26/7/74		6	
SHEET		OF		5	



DRAWN		DATE		TITLE	
J. M. M. M.		Jan 18/54		LIGHT SHUTTER CONTROL	
DESIGNED		DATE		FOR	
				LSP-03	
APPROVED		DATE		DRAWING NO.	
				LSP-03-15b	
SHEET		OF		DIST	
5		5		6	



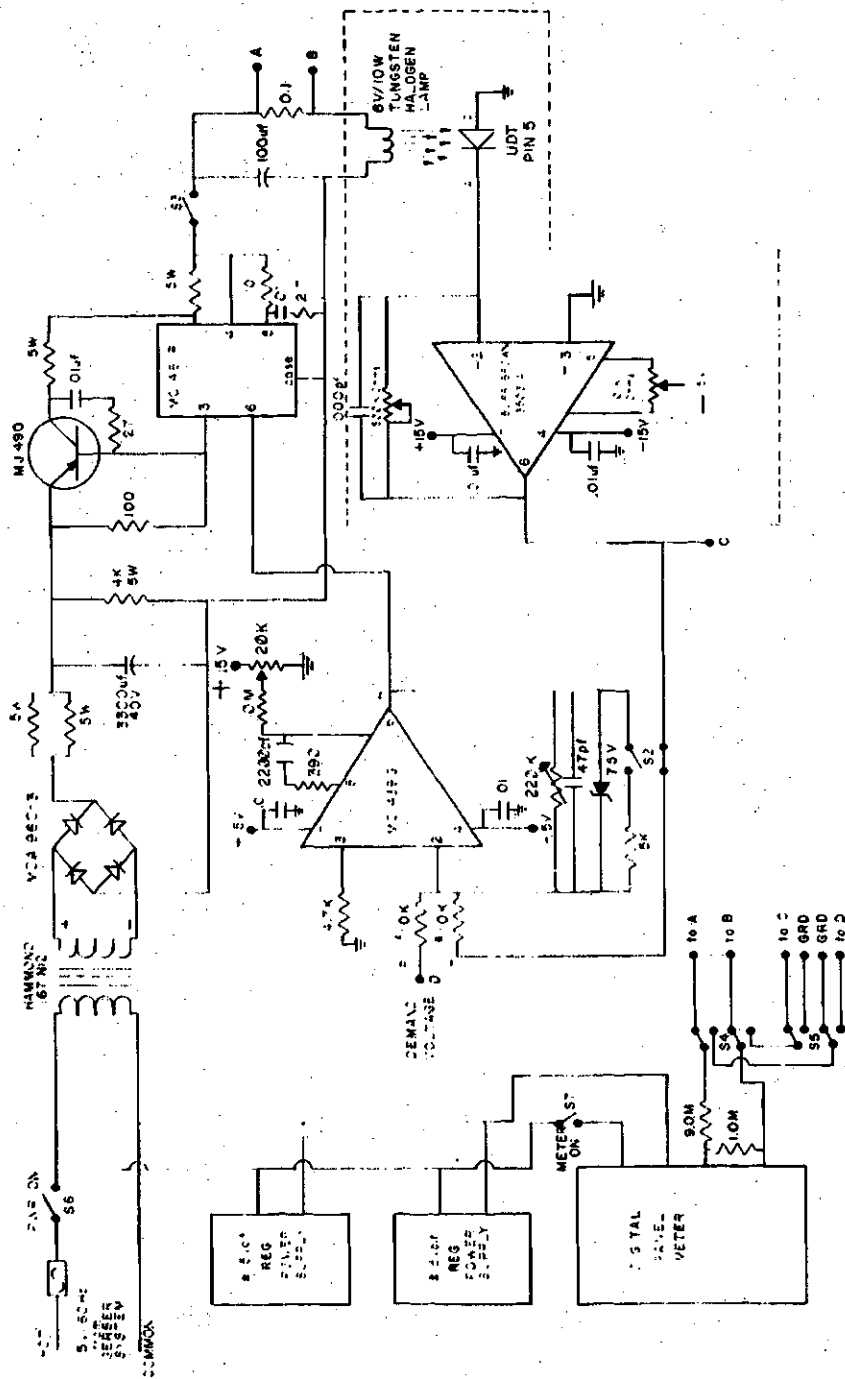
DRAWING	DATE	TITLE
844 Revised	Dec. 7/73	X & Y PULSES for INTENSITY CONTROL
CIRCUIT	DATE	FOR
Design MFG-60	Jan 4/73	LSP - 3
DESIGNED	DATE	DRAWING NO.
AAR. CRANI, LLC	Aug. 30/73	LSP - 3-23
APPROVED	DATE	
IMPLEMENTED	DATE	
SHEET	OF	DIST.



- NOTES**
- 1 RESISTORS IN OHMS
 - 2 CAPACITORS IN MICRO FARADS
 - 3 'A' - 25-1451
 - 4 MC1396 - MOTOROLA
 - 5 3337 - OPTICAL ELECTRONICS
 - 6 4362 - PHILBRICK NEXUS
 - 7 'B' - MOTOROLA IN358A T.C.

TOP SUPPLY FOR BANK 'A'		DWR DIST.	TRANSFORMER
3337 X			
BOTTOM SUPPLY FOR BANK'S		POWER SUPPLY	VR
3337 Y	IN/OUT		
	INW & SUM AMP		
MANUAL REF			PT

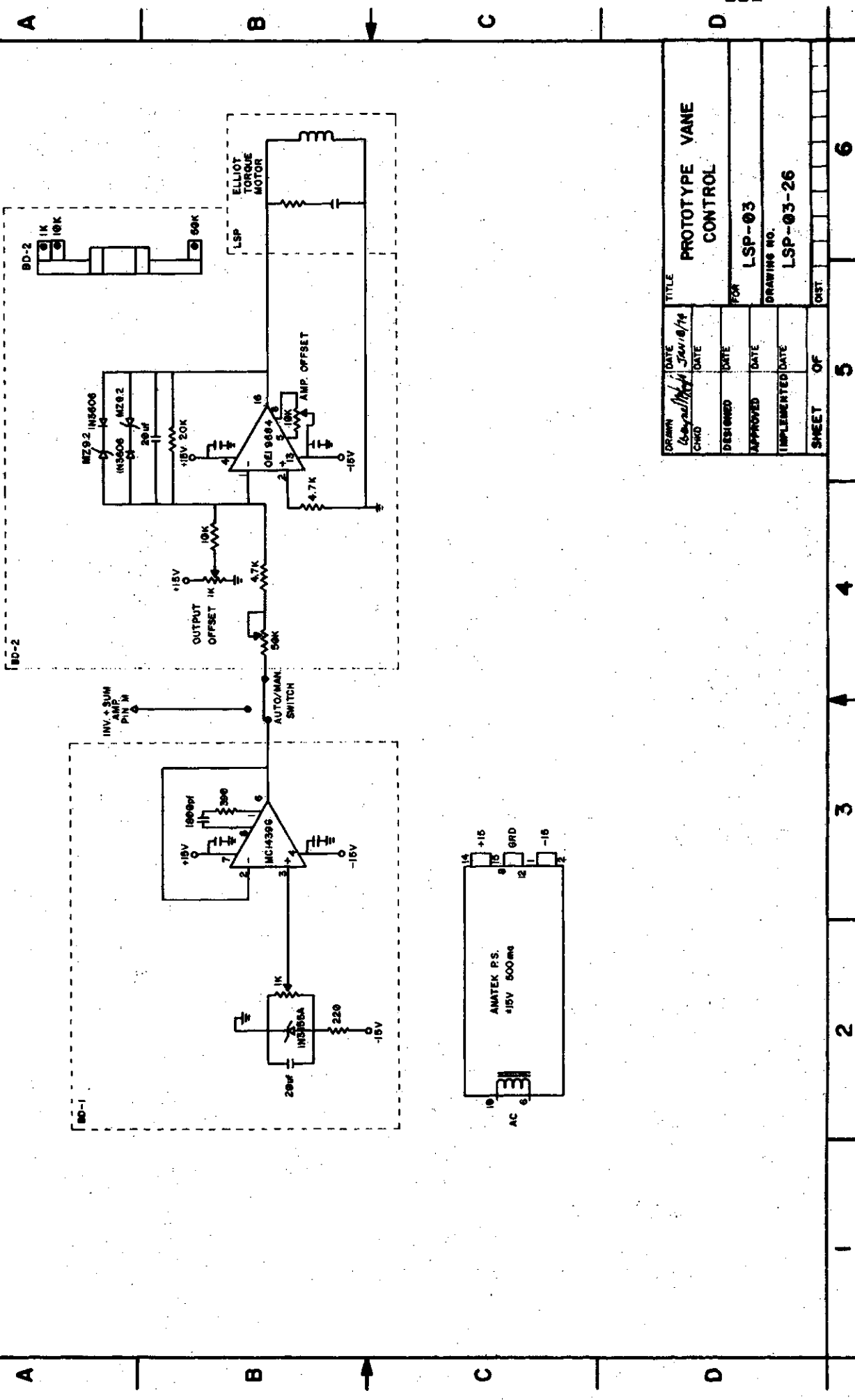
[illegible]



NOTES

- NOTES**
- 1 ALL RESISTANCES IN OHMS
 - 2 ALL CAPACITANCE IN UF
 - 3 * - PRECISION RESISTORS
 - 4 ALL SEMICON. IC'S - MOTOROLA
 5. OPEN LOOP - CLOSE LOOP - DPOT
 6. SS - LAMP ON - OFF - SPST
 7. 54 - CURRENT - VOLTAGE - DPOT
 8. 55 - DEMAND - FEEDBACK - DPOT
 9. 56 - AC ON - OFF - SPST
 10. 57 - METER ON - OFF - SPST

DRAWN	DATE	TITLE
R.H. Leonard	MAY 1974	INTENSITY CONTROL LOOP
CHECK	DATE	FOR
GARY SWANDE	MAY 1974	LSP - 3
PR CARRELO AUG / 73	DATE	DRAWING NO.
	DATE	LSP-3-25
SHEET OF	DIST	



DATE	TITLE
12/18/74	PROTOTYPE VANE CONTROL
DATE	FOR
12/18/74	LSP-03
DATE	DRAWING NO.
12/18/74	LSP-03-26
DATE	DESIGNED
12/18/74	LSP-03
DATE	APPROVED
12/18/74	LSP-03-26
DATE	IMPLEMENTED
12/18/74	LSP-03-26
SHEET	OF
5	6

5 SYSTEM PERFORMANCE

5.1 General

This chapter discusses the performance of the PS5 light head and associated hardware presented in earlier chapters. Firstly, the control and interface are examined to determine whether they have met the hardware requirements set out in Chapter 3. This is followed by a discussion of the line drawing and symbol projecting performance of the light head on plastic based Ortho film. This film is then compared with other plastic based films that could be used. Finally, several sample film plots are shown to illustrate the type of drawing that is produced by this automatic drafting system.

5.2 Interface and Control

5.2.1 Digital hardware

Most of the interface and control is constructed from digital circuitry. This type of electronics is stable and requires very few adjustments.

Several control exerciser programs were written for the PDP-8 computer to evaluate the operation of the controls with reference feedback (i.e. dove prism, mechanical slit and symbol disk controls). Each hardware operation is determined by the bit pattern of a word in computer memory. The program cycles through the complete 4K memory of the PDP-8, decoding each word for the time and type of each hardware operation. It also remembers where the reference origin

position of the control is with respect to its present position. After a predetermined number of hardware operations, the program instructs the control to move to its reference position for a hardware check. Such a program will not detect all hardware faults since only reference feedback is provided by the control. An example of such an event would be if two hardware faults occurred between reference position checks such that the second faulty operation cancelled out the first. However, the probability of such an event occurring would be very low.

The final test of any control is to study how well it functions in its real working environment. The PDP-8 plot control program used in the automatic drafting system is designed so that several checks are made against dove, symbol disk and mechanical slit reference origin positions during the course of a plot. These controls plus the other remaining ones can also be checked by closely examining plots of known graphical data. These tests showed that all digital hardware could be run reliably over long periods of time.

The dove prism hardware control presented, by far, the greatest difficulty in its early stages of development. The main problem was to obtain reliable stepper motor operation for a continuous range of speeds up to the maximum required image rotation rate. Also, the method used for detecting the dove home position was unreliable.

In subsequent models of the PS5 light head, the

problem of "stepper motor resonance" has been reduced because of the increased amount of damping available in the system. Reliable stepper motor operation can be obtained up to a maximum image rotation rate of 600 degrees per second.

5.2.2 Analog hardware

A significant portion of the intensity control is constructed from analog circuitry. This circuitry has to remain stable if film exposure conditions are to be held constant. The feedback and demand voltages to the lamp servo loop were noted periodically during tests and were found to be stable. This was mainly attributed to the use of negative feedback in the control and because of the relatively constant temperature environment.

It was not found necessary to make any adjustment to this control during the lifetime of the lamp or even when it was replaced. This was believed to be due to several reasons. Firstly, it was found that the voltage intensity characteristic of the lamps used did not change significantly over their lifetime because of the presence of halogen gases surrounding the lamp filament. Secondly, the characteristics of each lamp were closely matched to one another. Thirdly, the negative feedback employed in the lamp servo loop provided some compensation for the varying intensity-voltage characteristics of the lamps. Finally, small changes in exposure conditions were not noticeable on the developed film

due to its large exposure latitude.

As explained earlier, the open loop control for the attenuator blade was also tested as an alternative method to controlling the intensity of the projected image. This is discussed in the next section. The attenuator blade is presently being used to compensate for the different film speeds. Under existing conditions it must be set to fully open for drafting on Ortho film with a .004" fixed dimension rectangle. It is for this reason that no data is available on the long term stability of this open loop control.

The latest PS5 light head models are supplied with a 6 volt 20 watt tungsten halogen light source. However, the present intensity control has yet to be updated to provide for the extra drive capability.

The performance of the intensity control over the range of plotting speeds is discussed in the next section.

5.3 Drafting on Ortho Film

5.3.1 General

Much emphasis was placed on evaluating the PS5 light head from the cartographic user's point of view, that is its ability to draft on film to a very high standard. Special test patterns were drawn on Dupont and Kodak Ortho plastic based films. An attempt was made to identify all variables that could have a significant effect on the quality and accuracy of results.

5.3.2 Line drafting

Most of the line drawing tests were conducted with a rectangular shaped image although a circular one was also evaluated. Several variables were found to affect the quality and accuracy of the line work; the more important ones are discussed in the next few sections.

a) Film

As explained in section 3.4.7, one of the reasons why Dupont Cronar Ortho Sensitive film was selected for this drawing system was that well-defined lines could be drawn over a wide range of exposure conditions. This means that good line quality could be obtained without the need for a precise intensity control.

Film processing conditions represent another factor that affects the width and density of developed lines. The film was processed under similar conditions to those recommended by the manufacturer. It was developed for three minutes ± 15 seconds in Kodalith developer stored at a temperature of 70 degrees, ± 2 degrees F.

Since development time and temperature are the two most critical factors in the developing process, an experiment was conducted to determine what effect they had on results. In the first test developer temperature was held constant at 70 degrees F, ± 2 degrees F, and development time was varied from 2 to 4 minutes. This test was performed on a .005" wide line. The width of the line increased

slightly as a function of development time. The overall increase in width was measured to be less than .0005".

The density of the line decreased appreciably for development time values of less than 2 minutes 30 seconds. In the second test, development temperature was varied from 60 degrees F to 80 degrees F. The results obtained with this test were very similar to the first. The overall increase in line width was less than .0005" while line density decreased significantly for developer temperatures of less than 65 degrees F.

The conclusions made from these experiments were that for lines drawn with a rectangular image the development time and temperature could be varied by ± 18 seconds and ± 7 degrees F without significantly affecting the developed line width and density.

b) Intensity control

When drafting lines, the intensity control must adjust the intensity of the projected image proportionally to its velocity to maintain constant exposure conditions. This is accomplished by varying the current through the light source under closed loop conditions. The lines obtained with this control appeared to be excellent even when viewed through a 40 power microscope. Edges were well defined, line width variation was less than .0003" and there was no noticeable variation in density either across the width or along the length of a line. The control was set so that a line was

given approximately 1 1/2 times the minimum required exposure to allow for any variations in the intensity control and film processing conditions.

As discussed in Chapter 5, the intensity control has its limitations since no attempt was made to closely match the spectral characteristics of the photodiode to that of the film. A test was conducted to determine approximately how well the control worked over the operating speed range of the plotter. The lamp servo loop was set to its manual operating mode (i.e. a manually adjustable voltage serves as the demand signal to the lamp servo loop). A series of .005" wide lines were drawn, all at one selected speed. The exposure time of each line was varied by manually adjusting the intensity of the projected image. The purpose of this test was to determine the minimum intensity required to produce an acceptable line at this speed. Figure 5.1 shows a sample of the results of such a test conducted at several plotter speeds. Illustrated is a series of straight lines that have been drawn with a .005" wide rectangle at speeds of .05, .1, .5 and 1 inches per second. Lamp current, servo demand and feedback voltages as well as exact width are indicated for each line. The minimum values required for proper exposure of a line are circled for each speed. Note that the feedback voltage indicates approximately how the intensity of the projected image is changing since it is monitoring the intensity of the light source. For a given

SPEED IN/SEC	DEMAND VOLTAGE	FEEDBACK VOLTAGE	LAMP CURRENT	Width in inches
1 in/sec	2.40	2.29	1.65	
	2.50	2.38	1.66	
	2.60	2.49	1.67	.0045
	2.70	2.58	1.68	.0045
	2.80	2.68	1.69	.0045
	2.90	2.78	1.70	.0045
	3.00	2.89	1.71	.0048
	3.10	2.99	1.72	.0048
.5 in/sec	1.30	1.19	1.49	
	1.40	1.30	1.51	
	1.50	1.39	1.52	
	1.60	1.50	1.54	.0045
	1.70	1.59	1.55	.0048
	1.80	1.69	1.57	.0048
	1.90	1.79	1.58	.0049
	2.00	1.89	1.60	.0049
.1 in/sec	.38	.29	1.25	
	.40	.31	1.26	
	.42	.34	1.27	
	.44	.36	1.28	
	.46	.38	1.29	.004
	.48	.40	1.30	.0044
	.50	.41	1.31	.0047
	.52	.43	1.32	.0048
.05 in/sec	.22	.14	1.17	
	.24	.16	1.18	
	.26	.18	1.19	
	.28	.20	1.21	
	.30	.22	1.22	.004
	.32	.24	1.23	.0046
	.34	.25	1.24	.0048
	.36	.27	1.25	.0048

set of lines it will be approximately proportional to exposure time.

The intensity control was then switched to automatic mode and run as under normal plotting conditions (i.e. the intensity of the light source was varied proportionally to the drafting speed). Similar lines were drafted at the speeds selected in the previous test. Once again lamp current, demand and feedback voltage were noted and compared to those obtained in the previous test.

Figure 5.2 shows a plot of minimum required servo demand voltage versus drafting speed. Ideally this curve should vary linearly with drafting speed as does the actual demand voltage which is also shown. However, it is not linear especially at lower velocities.

There are two plausible explanations for this. Firstly, it can be attributed to a mismatch in spectral response of the photodiode and film. As plotting speed is decreased, the intensity of the light source decreases and hence its spectral output shifts in the direction of the longer wave lengths. The photodiode sees this light but the film is insensitive to it. Secondly, it is possible that this non-linearity is caused by a phenomenon known in photography as the reciprocity law of failure. Briefly this law states that maintaining a constant product of intensity and time does not ensure that the total energy absorbed by the

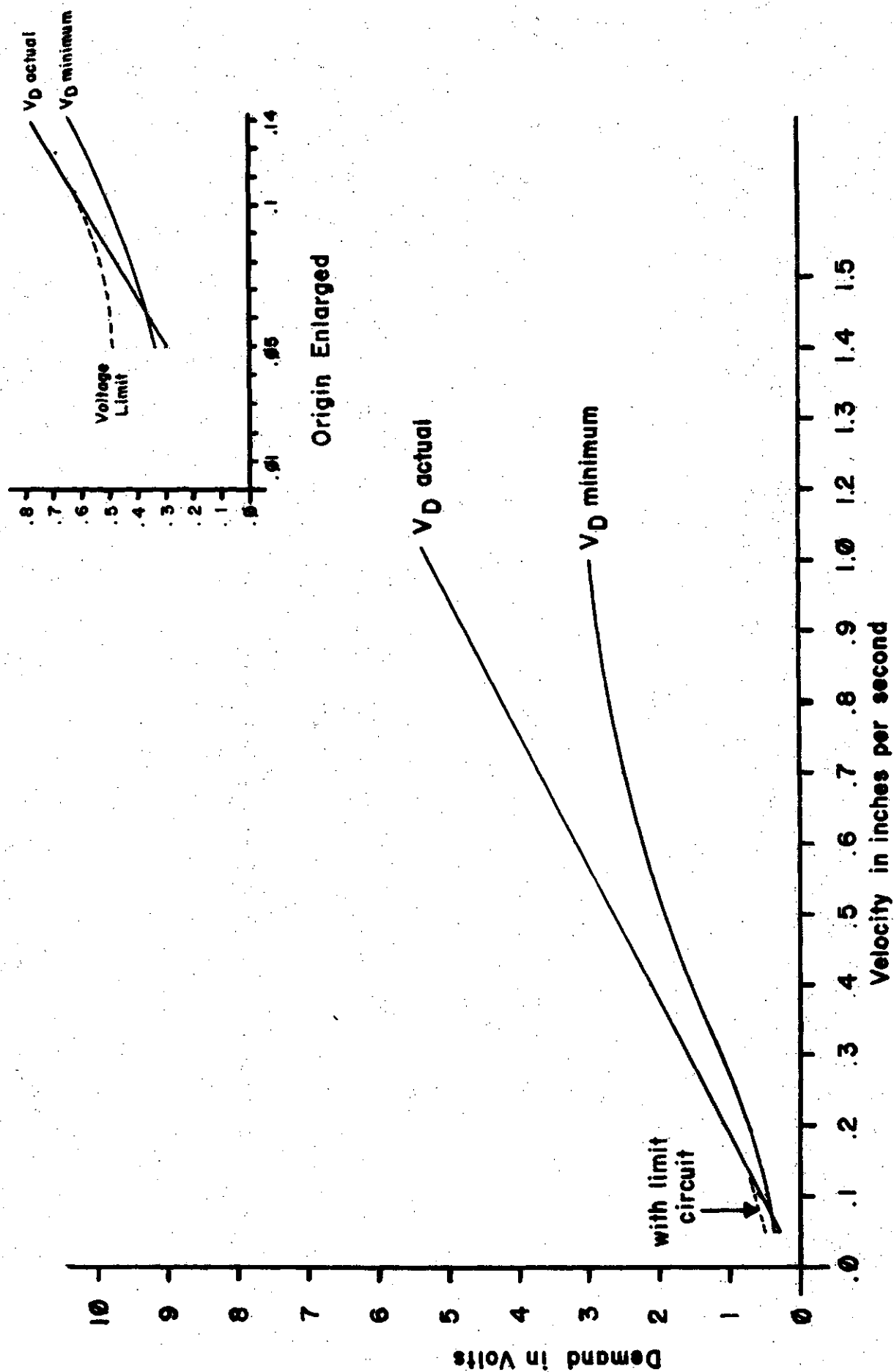


Figure 5.2 Demand Voltage versus Drafting Speed.

photographic emulsion will remain constant. This effect can usually be neglected in cases where variations in time and intensity are small. However, in this case it must be considered, since intensity and time vary by up to 28 times.

The non-linear characteristics of the intensity control do not adversely affect the quality of lines produced for the range of drafting speeds used. The operating point of the control (see actual voltage demand curve) is set high enough to ensure proper line exposure for low speeds. The excess amount of intensity that is present at higher speeds is allowable because of the large exposure latitude of the photographic film that is used. However this does place a limit on the dynamic operating range of the intensity control.

One way of increasing this range is to match the shape of the servo demand voltage curve to that of the minimum required demand. A significant improvement can be made by using a diode clamping network to limit the minimum demand voltage to the system. (See Chapter 4 drawing 24; 6/B.) The modified demand voltage curve is shown in figure 5.2.

A more precise approach to measuring the accuracy of the intensity control was attempted by making use of a device called a densitometer. This instrument is used to measure film density. The aim of the first step of this experiment was to obtain the film's "characteristic curve" (i.e. log film density vs. log exposure time). This was

done by drawing a series of straight lines each with a different exposure time. The densitometer was then used to measure the density of each line. The film's characteristic curve was then plotted from this data.

The intensity control was then operated in automatic mode for the second stage of this test. The intensity of the projected image was set so operation of the characteristic curve was in the region of the greatest density change. Straight lines were plotted at different selected speeds. The density of each line was measured and referred back to the characteristic curve to obtain variations in exposure time.

The high contrast nature of the film made it difficult to obtain valid results from the test. Any slight variation of illumination across the width of the line produced significant changes in density. Consequently, it was difficult to obtain consistent densitometer readings. However, the test did substantiate the findings of the previous test.

As mentioned earlier, the open loop control of the attenuator blade was also tested for possible use as an intensity control. The results obtained with this device were not as good as those obtained from the lamp control loop. This was mainly attributed to the non-linearity and hysteresis of its transmission versus voltage characteristic. Since the dynamic speed range of the plotter was 28:1, operation in

this non-linear region of this curve is unavoidable. The net result is that there is a noticeable increase of line width at lower speeds.

The conclusion made from these experiments was that this open loop control was unacceptable mainly because of the large operating range required. As noted in an earlier discussion the dynamic operating range of the attenuator could have been extended by running it under closed loop conditions.

The attenuator blade with its present form of control can still provide the useful function of varying the operating point of the lamp servo loop to accommodate for different film speeds.

Figure 5.3 shows the type of line quality that can be obtained with the PS5 light head and Gerber plotter. This figure, called a rotating square, was selected mainly because it provides an excellent check on the overall positional accuracy of the plotter and on the quality and width tolerances of a line drafted at a variety of angles. The width of most lines shown are $.0055" \pm .00025"$. The width of lines drawn from the centre of the square are slightly larger because they have been doubly exposed.

c) Shape of projected image

As was discussed in Chapter 2, a rectangular shaped image was selected over the circular one for line

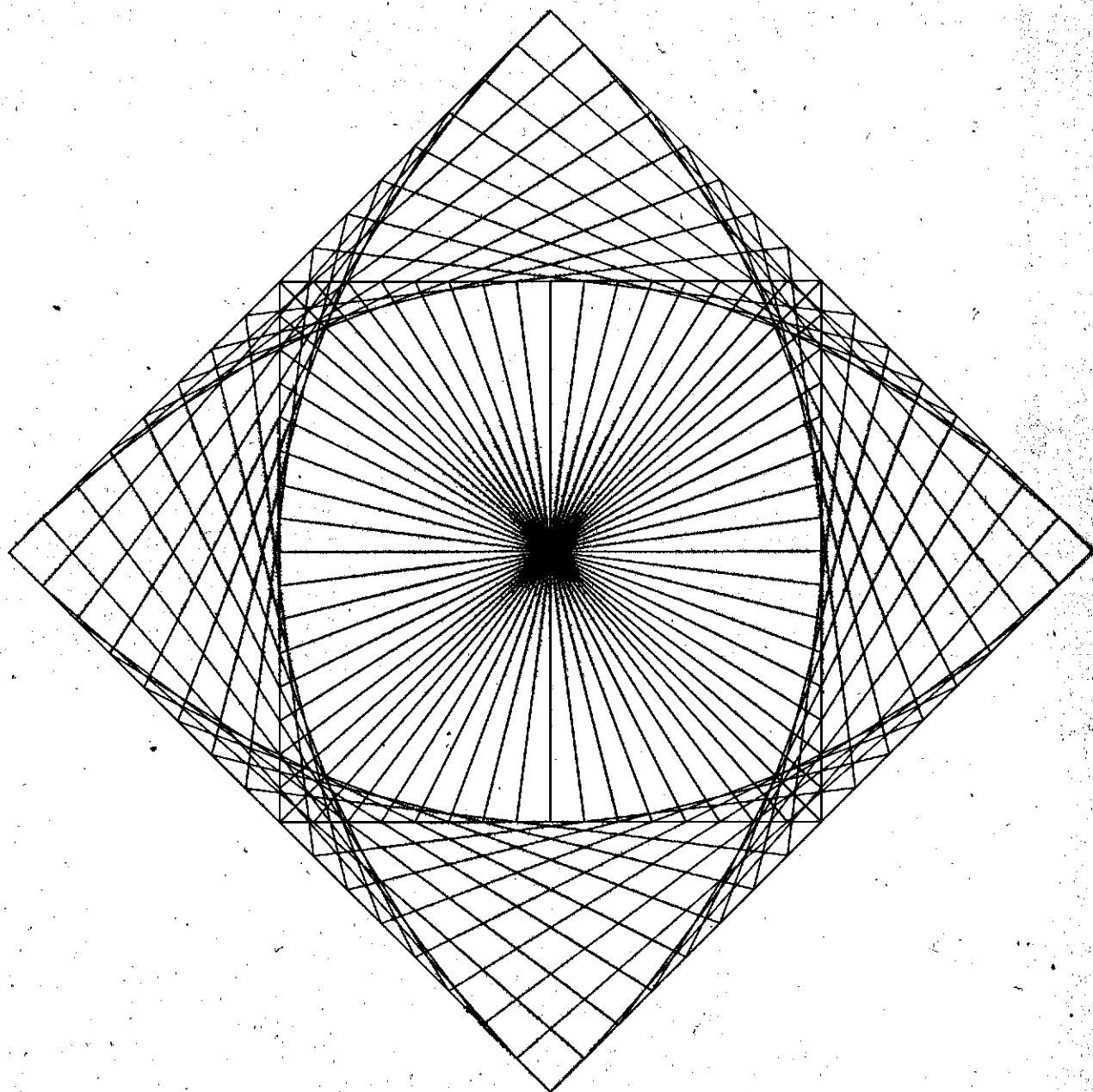


Figure 5.3 Rotating Square

drawing. One dimension of the rectangle remains fixed at .004" while the other was varied to obtain the different line widths.

Several tests were conducted with the circle in order to compare its performance to that of the rectangle. In one test, a series of straight lines were drafted all at constant velocity but each at a different intensity. Each individual line was first drawn with a rectangle and then with a circle. A range of line widths were tested.

Several general conclusions were made from this test. Firstly, both images produced good quality lines. Secondly, for small line widths (.005" -.015"), the intensity for the circle must be increased with respect to that for the rectangle, in order to sharply define its edges. Thirdly, in general, the exposure latitude for the circle is less than that for the rectangle and decreases as a function of diameter. For example, the exposure latitude of a .005" dot is slightly less than three while for the rectangle it is greater than 3. However, if the dot is increased to .015" its exposure latitude is reduced to less than 2 while that for the rectangle remains the same. Finally, the circle cannot be used for drawing line widths of greater than .020" unless some means is introduced to compensate for the excessive exposure produced at its centre.

Both the circle and rectangle were used to draft some of the various types of lines required on a nautical

chart. The conclusion made from these tests was that the rectangle should be used for straight lines and smooth curves. What is questionable, however, is whether the rectangle has any advantage over the circle for drawing irregularly shaped small width lines such as shoreline and contours. The reason for this is that the rectangle must be rotated in an irregular manner and in some cases is unable to follow the abrupt changes in direction of the line. As a result, the edges of the line become jagged and there is noticeable thinning at sharp corners. This is not evident when the circle is used because it does not have to be rotated.

d) Light head

Several components in the PS5 light head have an important bearing on the quality of line work. Firstly, the optical system of the light head must be designed so that image spread with increased intensity is minimal; this allows a greater exposure latitude. As stated earlier line spreading is also a function of the shape of the projected image and photographic film. For straight lines drawn on Ortho film with a rectangular image, line spreading was less than .001" for a three times increase in light intensity.

Secondly, all optical components must be aligned accurately. For example, if the axis of the dove prism is not properly aligned to the rest of the optical system, errors in rotation will result. This is of particular importance for line drawing with a rectangle because its

image must be rotated about its centre. Errors in rotation also occur if the centre of the symbol does not align with the optical system of the light head. The error in rotation for the current PS5 light head was measured to be less than .001" when using the one times magnification lens.

Thirdly, in order to avoid improper exposure at the beginning and end of lines, it is desirable to use light shutters with fast opening and closing times. Then, the exposure for the beginning and end of lines can be adjusted in the light head control. The speeds of the light shutters in the PS5 light head were measured to be approximately 20 milliseconds from the time of energization and de-energization of the shutter solenoids. These opening and closing speeds were found acceptable for drafting on Ortho film.

To obtain optimum performance from the PS5 light head, it must be properly focussed. If this is not done, the projected rectangular image loses its shape. It was found through experience that line ends become rounded and line edges were not well-defined. Perhaps more important was the loss of exposure latitude. This point is illustrated in figure 5.4. This series of curves was obtained by drawing a set of constant velocity straight lines at different projector heights. Line width was then plotted as a function of absolute projector height. A family of curves was obtained for different image intensities. Note that line

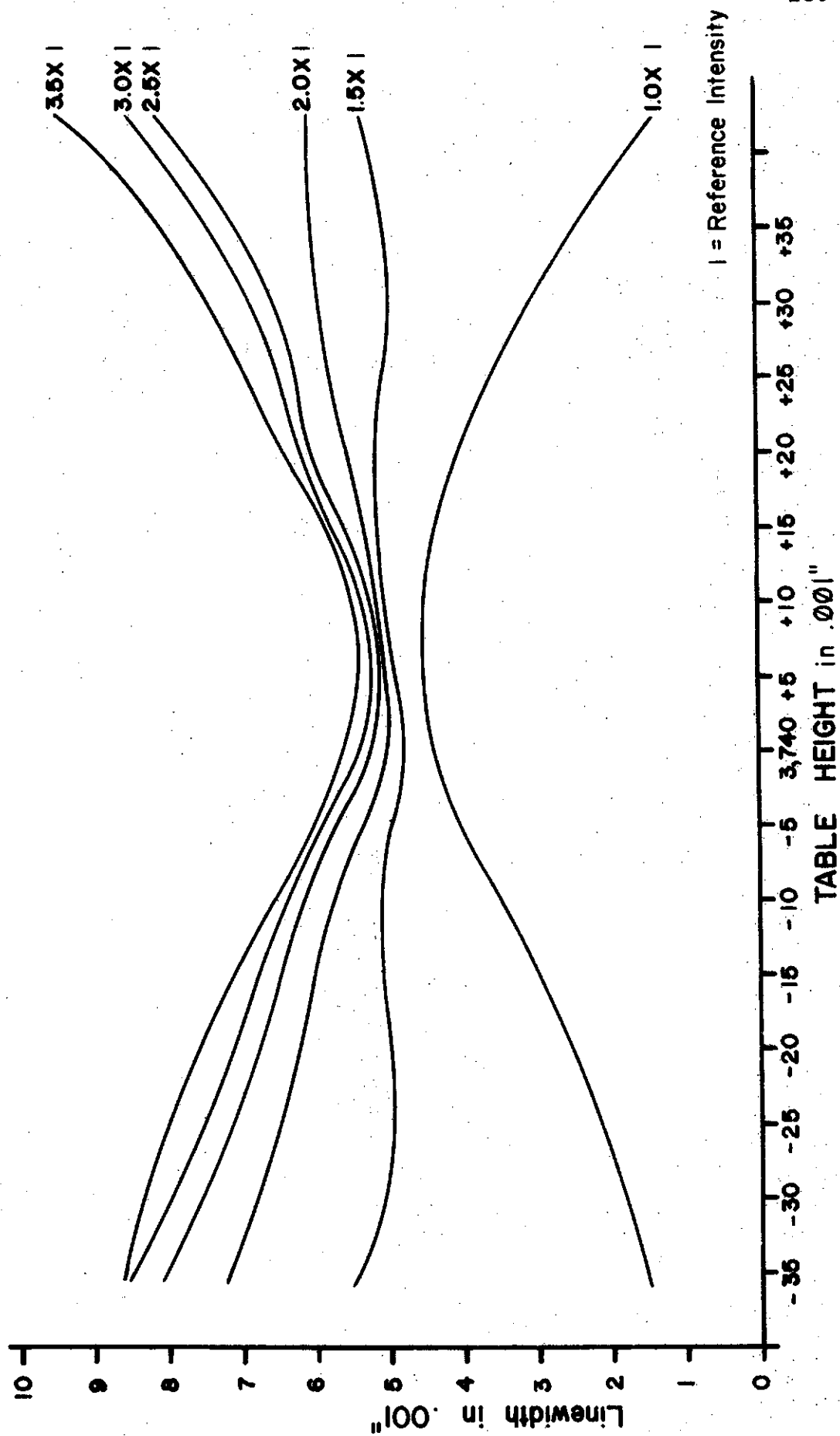


Figure 5.4 Linewidth verses Absolute Projector Height

width variation with intensity is minimal in the region of focus of the projector.

The reader will note that the region of focus of this projector is extremely critical (.010"). The approximate theoretical value for depth of field for the PS5 light head is

$$D_f = \frac{F_o D_d}{E_p} \quad 5.1$$

where E_p is the diameter of the exit pupil,

F_o is the focal length of the objective lens,

and D_d is the acceptable dot size of the projected image.

Substituting known values of $E_p = .30"$, $F_o = 1.54"$, $F_d = .0005"$, the depth of field becomes $D_f = .0025"$. This figure compares favourably with the curves shown in figure 5.4. However, this value is somewhat less than that obtained in practice because equation 5.1 does not take into account the film's response to different image intensities.

Examination of equation 5.1 indicates that the depth of field can be increased either by increasing the focal length of the objective lens or by decreasing the diameter of the exit pupil. Increasing the focal length of the objective lens will decrease the demagnification factor relating disk mask size to projected image as well as increase optical alignment errors.

Decreasing the diameter of the exit pupil can be

done only at the expense of decreasing the intensity of the projected image. The depth of field varies inversely with diameter of the exit pupil, while the intensity of the projected image varies proportionally with its square. For example if the diameter of the exit pupil were reduced to half, the depth of field would be increased by a factor of two, whereas, the intensity of the projected image would be decreased by a factor of four. Selection of the most desirable exit pupil, therefore, involves a trade-off between the desired image intensity and depth of field.

5.3.3 Image flashing

"Image flashing" is a simpler process than "line drafting" since the plotter is stationary. All symbols are projected at one constant intensity. Shutter opening and closing times are controlled to obtain the correct exposure for the different magnification lenses.

The variables that affect the quality of symbols are similar to those described for line drawing. Tests on Ortho film showed that good quality symbols could be obtained with as much variation as $\pm 25\%$ of the optimum exposure time.

The errors associated with "symbol projecting" are due to the inaccuracy of placement of each mask on the symbol disk combined with those of dove rotation and selection of magnification lens. The combined symbol placement errors in the current PS5 light head were measured to be less than .003".

Figure 5.5 shows a sample of several hydrographic symbols projected at the three different available magnifications.

5.4 Drafting on Other Films

Several other plastic based films were evaluated. Much of the evaluation was devoted to comparing the exposure latitude and dimensional stability of each film. As explained earlier, films with a high exposure latitude are desired because they relax the requirements for a precise intensity control. Dimensional stability of the drawing material must be emphasized mainly so all colour overlays can be properly registered to produce the final chart. Most of the films tested were manufactured by Dupont or Kodak.

a) Exposure latitude

The line drawing capability of each film was compared by using the same technique as described in section 5.3.1(b). A series of straight .005" wide lines were drawn all at the same speed but each with a different intensity. Relative values of intensity were obtained by noting the feedback voltages produced by the photodiode and amplifier mounted close to the projector light source. The films were compared by plotting measured line width versus logarithm of feedback voltage. The logarithm of feedback voltage was used so that films would be compared on the basis of line spreading versus relative exposure change. This is more meaningful when attempting to compare films

.	.	.	.	.	.	4	5	4	5	4	5
.	.	.	.	.	.	3	6	3	6	3	6
.	.	.	.	.	.	2	7	2	8	2	7
.	.	.	.	○	.	1	8	○	9	1	8
.	0	.	.	○	0	0	9	○	0	0	9
.	2	.	.	◇	2	.	<	◇	2	.	<
■	3	.	.	⊠	3	■	*	⊠	3	■	*
□	4	■	.	□	4	□	+	□	4	□	+
○	5	.	.	○	5	△	⊠	○	5	△	⊠
.	6	-	*	△	6	-	*	△	6	-	*
.	7	-	+	-	7	-	+	-	7	-	+
.	8	.	⊠	⊠	8	9	⊠	⊠	8	9	⊠

Figure 5.5 Sample of Hydrographic Symbols.

of different speeds.

Only a rough comparison could be made because of limitation in the accuracy of intensity and line width measurements. Generally, films with comparable speeds had the same slope. Dupont Halftone Litho, the fastest film tested, had the most gradual slope while Kodak High Speed Duplicating film, the slowest film tested, had the steepest slope. The results of these exposure tests are summarized in table 5.1. The film, manufacturer, speed, and exposure latitude are indicated in columns 1, 2, 3 and 4. The figures given for film speed are relative to the intensity required for the reference film, Kodak Ortho 3, which has a speed rating of ASA 6. The criterion used for exposure latitude was based on the relative increase in intensity that produces a line width increase of less than .001". The figures given for speed and latitude are approximate.

It is interesting to note that all films tested, with one exception, are used to produce a drawing positive, that is, those areas exposed to light appear black when developed. In the case of High Speed Duplicating film, the opposite effect takes place; this is due to a phenomenon called "solarization"⁹. This film is useful in cases where a drawing negative is desired instead of a positive.

b) Dimensional stability

An experiment was devised to study the effects of environmental and processing conditions on the dimensional

Manufacturer	Film	Speed I Ref refers to amount of intensity required to expose film with ASA speed rating of 9.	Approximate Latitude i.e. amount of increase intensity from minimum for increase in line width of .001"
Kodak	Ortho S - .007"	I Ref.	> 3X
Dupont	Cos - .007"	I Ref	> 3X
Kodak	Kodaline .007"	1.5 x I Ref	3X
Dupont	CBS .007"	1.5 x I Ref	3X
Kodak	High Speed duplicating film .007"	8 x I Ref	2X
Dupont	CHL .007"	$< \frac{I \text{ Ref}}{2}$	5X

Figure 5.6 Summary of Exposure Latitude Test.

stability of several plastic based films. In the test conducted, an attempt was made to simulate, as much as possible, the environmental conditions normally encountered in practice. (Note that, at present, both processing and plotting areas have a temperature control. There is no humidity control in the processing area and only an inexpensive humidifier in the plotting area.) A series of crosses were projected onto film, spaced apart at known distances. The film was developed and remeasured under the same environmental conditions. It was then placed in a relatively uncontrolled environment for ten months and finally remeasured again.

The results of this experiment are of limited value mainly because of the lack of a good humidity control for both film exposure and processing environments. In all cases the errors measured were small and comparable to the positional accuracy of the plotter. The maximum error measured was .02% (i.e. an .008" increase on a 40 inch line). It was therefore difficult to make a fair comparison of the films tested.

However, several general conclusions were made from these tests. Firstly, the films with synthetic emulsions such as Dupont Cronar Ortho S and Kodak Kodaline were the most stable of those tested. As explained earlier, the manufacturers have substituted stable resins in place of the animal gelatin that is normally used in emulsions. Secondly, all films tended to shrink slightly after a period

of time. Thirdly, and most important, this test proved that in most cases it is unnecessary to use a sophisticated humidity control when drafting on these stable films. Only an inexpensive humidifier can be used to match the humidity conditions of the plotting and processing environments.

5.5 Sample Film Plots

The PS5 light head and associated hardware is now part of an operational automatic drafting system intended to be used to draw nautical charts. Most production work done to date has been for "mathematically based" line data, that is graphical data that can be generated from a computer program as opposed to field survey data. Examples of this are chart borders, projections and lattices used in conjunction with radio navigation. Figure 5.7 shows a sample of a Mercator projection with a fully graduated border. A sample of a Loran hyperbolic lattice is shown in figure 5.8. All line work in these two figures has been done with a rectangular shaped image.

Much experimental work has been conducted with plotting field survey sheets and chart bases. Figure 5.9 shows a sample plot of some shoreline and soundings. In this figure, the shoreline has been done with a circular shaped image.

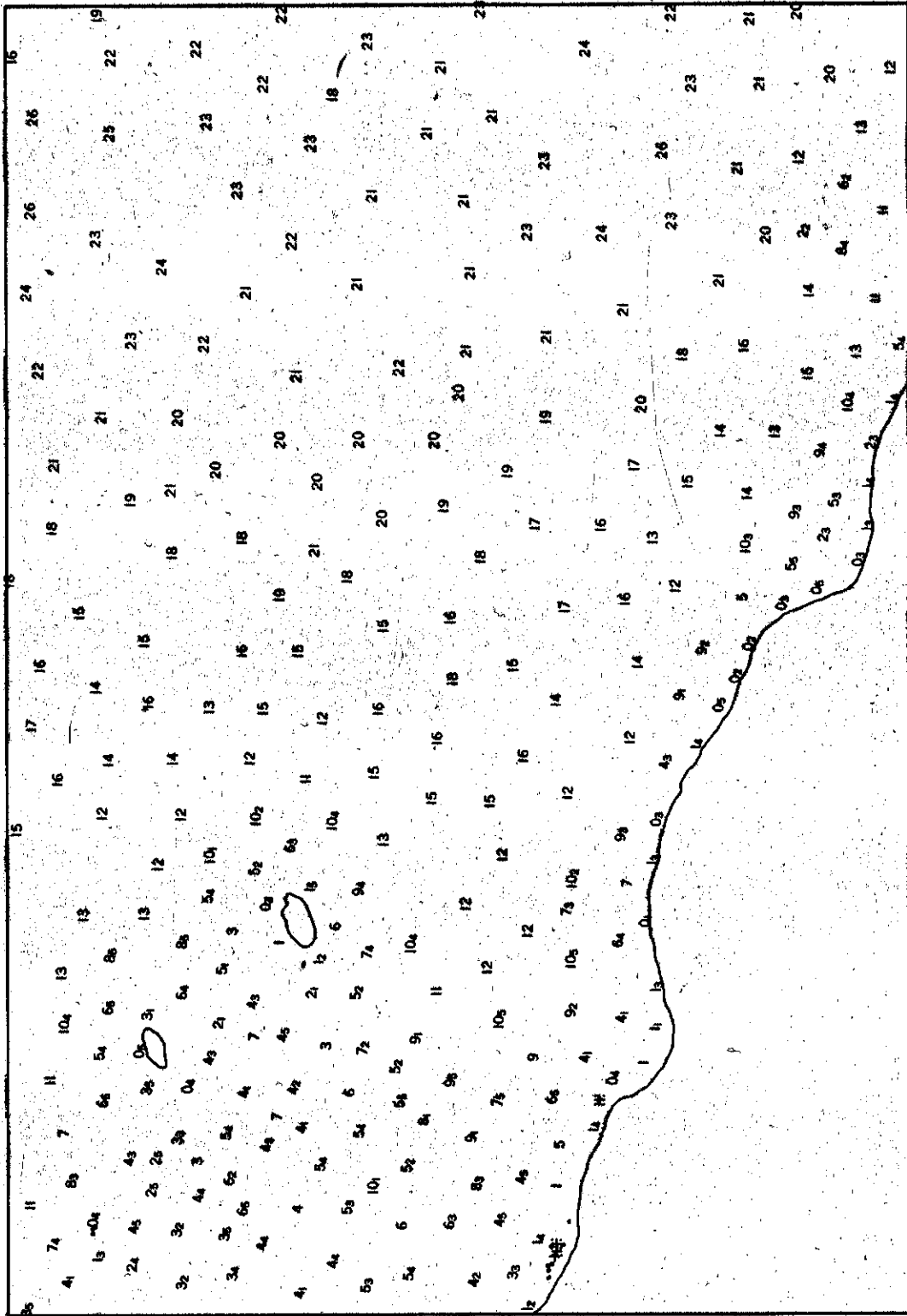


Figure 5.9 Sample of Shoreline & Soundings.

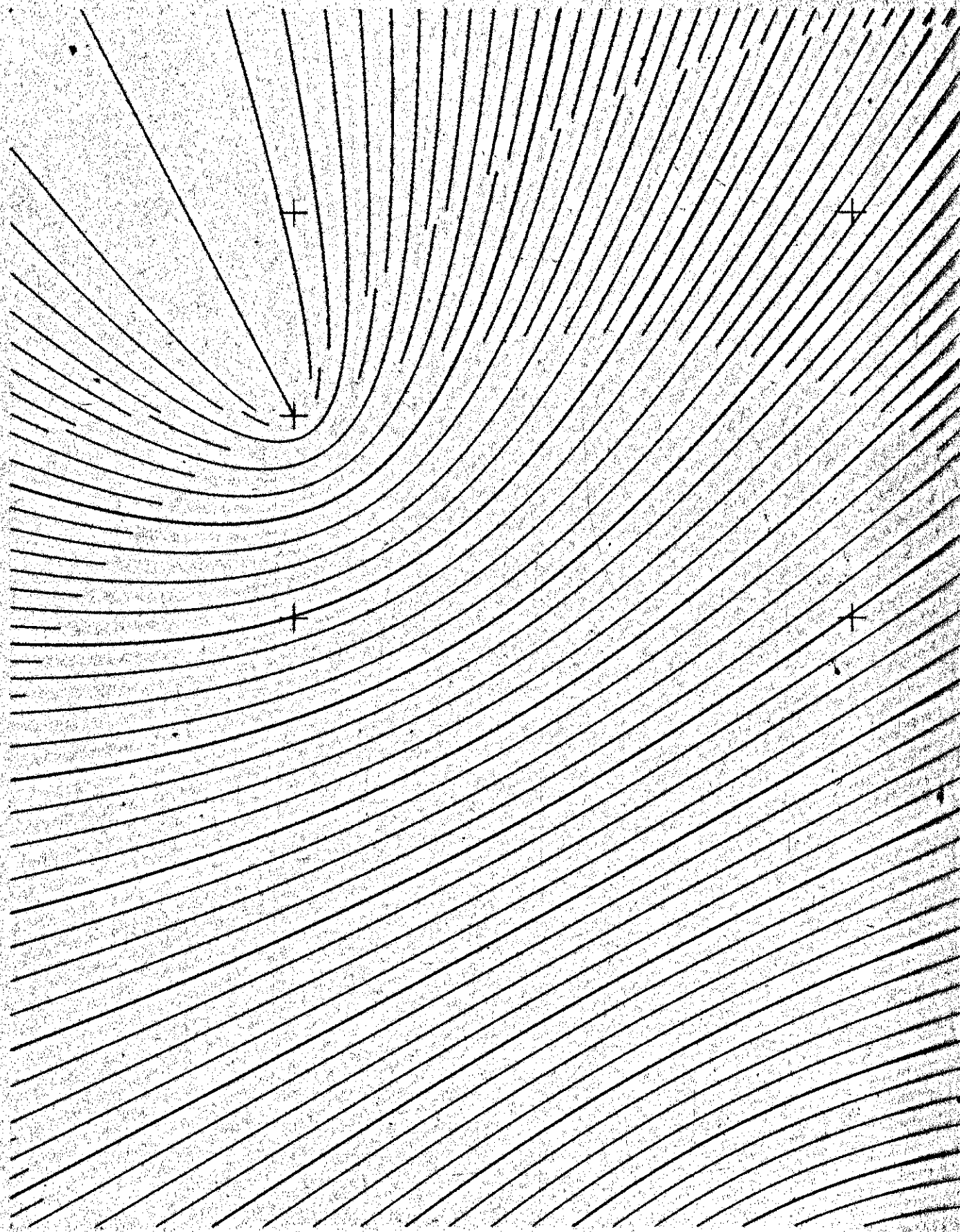


Figure 5.8 Sample of LORAN Hyperbolic Lattice .

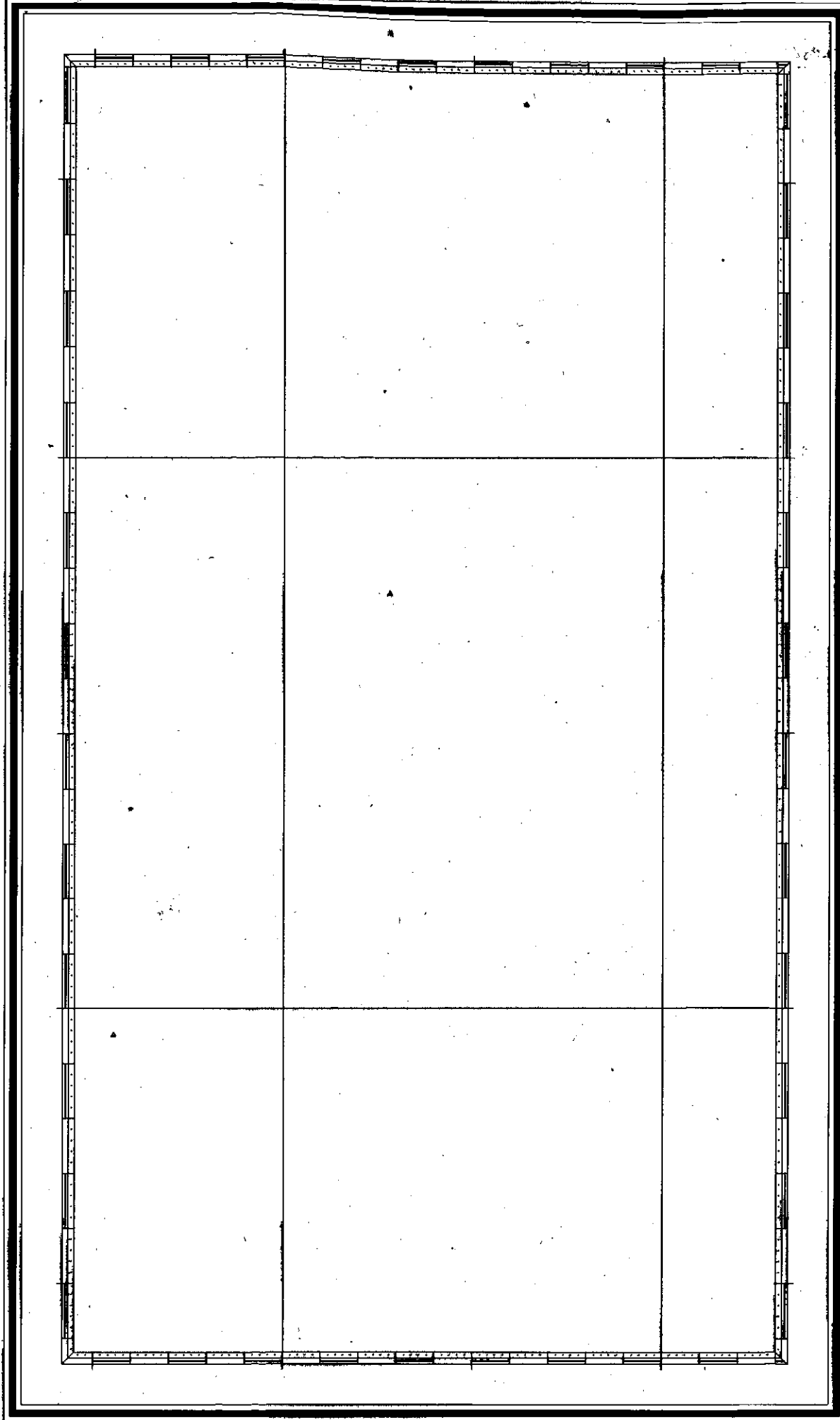


Figure 5.7 Sample of Fully Graduated Mercator Border.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The purpose of this work was to select and implement the most suitable drafting device for an automatic drafting system intended to be used to draw nautical charts. This system consisted of a Potter MT36 magnetic tape transport, a Digital Equipment PDP-8 mini-computer and a Gerber model 32 precision drafting table. The main requirements for this drafting instrument were that it produce high quality and accurate drawings, that it be versatile so that a large number of line widths and symbols could be drafted, and that it require a minimum amount of operator attention.

Drafting directly onto photographic film with a light beam was selected over the pen on paper and scribing on mylar techniques because it best met these requirements. The rectangle and circle were selected from several possible image shapes that could be used for drafting lines. The rectangle was preferred because it most easily met the requirement for squared corners and several line widths with tight width tolerances.

Different ways of producing a beam of light were considered. The conventional opto-mechanical method of using a light source, set of mechanical masks and optical system was selected because of its simplicity and also due to the availability of commercial units. The Barr and Stroud

PS5 light head was chosen from other instruments mainly because it offered a larger number of automatically accessible symbols, combined with the ability to set the angular orientation of any image projected onto film. This latter feature was essential for both "line drafting" and "image flashing".

A control and interface unit was developed for the PS5 light head so that most of its functions could be programmed by a PDP-8 mini-computer. Controls were developed to set image orientation, to vary one dimension of a rectangle used for drafting different line widths, to select the desired symbol for projection, to select one of three possible image magnifications, to open and close inner and outer row light shutters and to control the intensity of the projected image for both "line drafting" and "image flashing".

Most functions required some form of positioning control. An open loop control utilizing a "stepper motor" was employed where possible because of its simplicity and compatibility with digital circuitry.

The intensity of the projected image was controlled by varying the current through the light source. This light source was run under closed loop conditions in order to obtain the necessary linearity and speed of response. This simple form of control was adequate mainly because of the large exposure latitude of the photographic films that were used.

An attenuator blade was also evaluated for possible use as an intensity control. It was rejected mainly because of the non-linearities in its intensity versus voltage characteristics. Nevertheless, it still provided a convenient means of compensating for a large range of film speeds.

The PS5 light head with associated interface and control was carefully evaluated to ensure that all design goals had been met. Special PDP-8 programs were written to exercise several of the control functions continuously. The PDP-8 drafting control program was designed so that periodic checks could be made on its major functions during the course of a film plot. These tests proved that all hardware operated reliably for long periods of time.

Much effort was devoted to the important evaluation of the performance of the PS5 light head on plastic based Ortho film. The purpose of these tests were threefold. The foremost was to ensure that the PS5 light head was capable of meeting the required drafting standards. This was done by drafting graphical data as required on a nautical chart as well as by the use of special test patterns. The results were studied carefully with a 40 power microscope. These tests conclusively proved that the required drafting standards had been met.

Secondly, an attempt was made to identify and study the variables affecting both "line drafting" and "image

flashing". Some of the more important variables studied were film exposure latitude, film processing, intensity control, shape of projected image, the region of focus and positional accuracy of the PS5 light head. A series of film tests was devised to determine how variations of each parameter affected results. Most of the tests were conducted on Dupont Cronar Ortho S and Kodak Ortho 3 films.

These tests pointed out the limitations of this drafting system. Firstly, for line drafting, the required demand voltage for the intensity control servo had non-linear characteristics especially for low plotting speeds. This factor limits its operating range. It can be increased by introducing the attenuator blade into the light head optical system. Secondly, the focussing region of the PS5 light head is narrow (.010") and therefore an accurate height adjustment and a flat drawing surface are essential for operation.

These film tests also proved that a circular light spot can be used to produce high quality small width lines. This configuration should be seriously considered as an alternative to the rectangle for drafting curved lines since this eliminates the need for dynamic rotation.

Finally, several other plastic based films were evaluated for possible use in the automatic drafting system. Experiments were conducted to compare the exposure latitude and dimensional stability of each film. The results obtained

from these tests were not conclusive because of the limitations of the environmental control and test instruments. However, they did indicate that there are several films available that are comparable in performance to Cronar Ortho S and Kodak Ortho 3 film.

6.2 Recommendations

In the writer's opinion, there are several features in the light head that could be improved to make it more useful to the Canadian Hydrographic Service. Firstly, the number of automatically accessible symbols is still not great enough. At least 150 symbols are required to plot the chart base.

Secondly, although there is a facility for varying the magnification of projected symbols, it would be desirable to have a continuously variable magnification system. The light head could then also be considered for use as a name placement device.

Thirdly, the narrow region of focus of the PS5 light head make height adjustments critical and limits its use to flat table surfaces. This focussing problem has been overcome in later models of the PS5 light head with the introduction of an air bearing. This ensures that the final lens in the light head's optical system remains at a fixed distance from the surface of the film.

Finally, it was found through the experience gained with the PS5 light head that it was difficult to

replace many of the components that wear out through normal operation. In the writer's opinion, some of the compactness of the light head should be sacrificed in order to facilitate the replacement procedure for the user.

The writer questions the choice of the three phase stepper motor used for the rotation control. The circuitry required to implement a 30 degree step size is fairly complicated.

This control could be greatly simplified if a multiple stepper with "bifilar" windings had been used. In a stepper motor of this type, each stator coil is split into two sections. One half of the coil is wound in the opposite direction to the other half. This eliminates the need for a bidirectional drive circuit since the desired flux is obtained by driving either one of these coils.

The multipole magnetic rotor eliminates the need for a large number of logic states to develop a small motor step size.

One of the main limitations of the opto-mechanical method of producing a light beam is the limited number of automatically accessible symbols and the fact that additions and modifications cannot be made easily. Some manufacturers have tried to overcome these problems by increasing the number of symbols and by making it possible to interchange each symbol individually. However, this is done at the expense of making such a light head more bulky and expensive.

This still does not solve the problem of easily producing new symbols.

As suggested in Chapter 2, these problems can be overcome by using an electronic means to produce the symbol. Both the cathode ray tube and matrix of light emitting diodes should be investigated for this purpose. Such a device could project an unlimited number of symbols in a large variety of sizes.

It is the opinion of the writer that in the light of today's high level of technology such a system could be developed that would compete in price with commercial opto-mechanical units.

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APPENDICES

Appendix A: Relative Exposure Expression for Rectangles, Circles and Annulars,

A.1 General

This appendix contains the derivations of the general expressions for the relative exposure across a line drafted with a rectangular, circular or annular image. This is a function of the image shape used and the radius of curvature of the line being drawn. The exposure time as a function of position across the line is first calculated. This expression is then normalized, by dividing it by the exposure time obtained for a straight line drafted with a rectangle whose fixed dimension is .004". It is assumed that the intensity of all projected images is the same.

A.2 Rectangle

In the case of the rectangular image, it is assumed that the rectangle is being rotated smoothly so that one of its dimensions is always facing in the direction of travel. The relative exposure expression is derived in terms of the following variables:

$2L$ = length of the rectangle,

$2W$ = width of the rectangle. This sets the line width,

R_c = radius of curvature to centre of the rectangle,

V_t = tangential velocity of the centre of the rectangle.

Three different relative exposure expressions are required

for the rectangle as depicted in figure A.1. Each region is defined in terms of the distance from the centre of the radius of the line being drawn.

$$\text{region 1 } (R_c - W) \leq R \leq R_1.$$

$$\text{region 2 } R_1 \leq R \leq R_2.$$

$$\text{region 3 } R_2 \leq R \leq R_3.$$

Where R_1 , R_2 , R_3 can be defined in terms of the input variables

$$R_1 = \sqrt{L^2 + (R_c - W)^2},$$

$$R_2 = R_c + W, \text{ and}$$

$$R_3 = \sqrt{L^2 + (R_c + W)^2}.$$

(a) Region 1

The expression for exposure time is

$$E = It \tag{.1}$$

where I is the intensity,

and t is the time

$$\text{Also } S = Vt$$

where S is the distance

V is velocity,

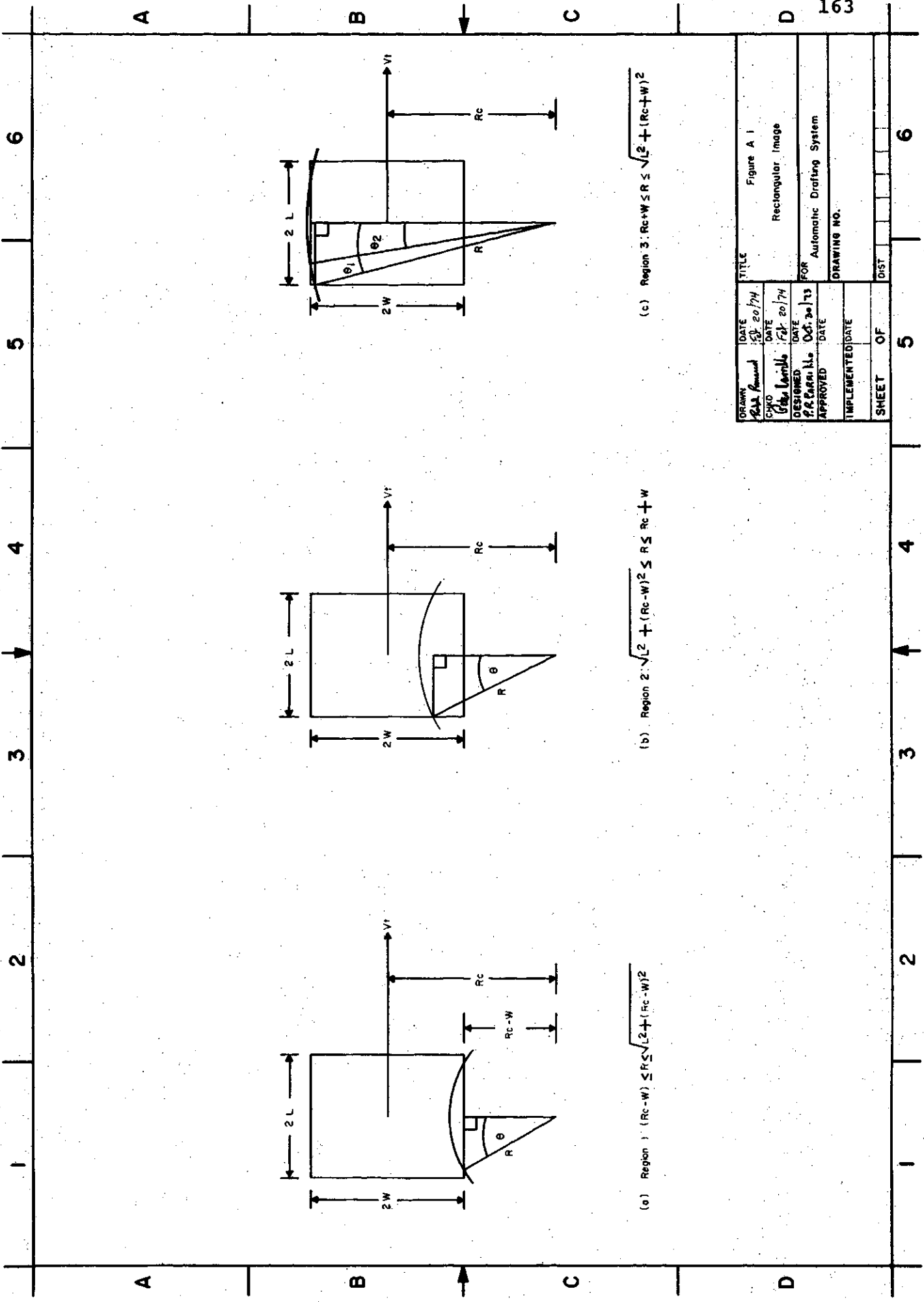
and t is time.

Solving for time

$$t = \frac{S}{V} \tag{.2}$$

Substituting 2 into 1

$$E = \frac{IS}{V} \tag{.3}$$



DRAWN	DATE	TITLE
John Smith	20/74	Figure A 1
CHECKED	DATE	
John Smith	20/74	Rectangular Image
DESIGNED	DATE	
J.R. Smith	20/74	FOR Automatic Drafting System
APPROVED	DATE	
		DRAWING NO.
IMPLEMENTED	DATE	
SHEET	OF	DIST
5	6	

Referring to the Figure A.1(a)

$$\cos \theta = \frac{R_c - W}{R}$$

$$\theta = \cos^{-1} \left(\frac{R_c - W}{R} \right) \quad .4$$

The length S can be calculated from the following expression

$$A = 2 \theta R \quad .5$$

Where A is the arc length,

θ is the angle in radians,

and R is the radius

substituting 4 into 5

$$A = 2R \cos^{-1} \left(\frac{R_c - W}{R} \right) \quad .6$$

the expression for tangential velocity is

$$V_t = \omega R_c$$

where V_t is the tangential velocity at the centre of the rectangle,

ω is the angular velocity of rotation,

and R_c is the radius of curvature.

Solving for ω

$$\omega = \frac{V_t}{R_c} \quad .7$$

the velocity of any point at a radius R from the centre of a curvature is

$$V = \omega R \quad .8$$

Substituting 7 into 8

$$V = \frac{V_t}{R_c} R \quad .9$$

Substituting 9 and 6 into 3, the expression for exposure becomes

$$E = \frac{I}{V_t} 2R_c \cos^{-1} \left(\frac{R_c - W}{R} \right) \quad .10$$

(b) Region 2

Refer to figure A.1(b). Similar logic can be used to derive all other expressions for exposure time. Therefore an abbreviated derivation will be presented.

In this case

$$\theta = \sin^{-1} \left(\frac{L}{R} \right) \quad .11$$

Substituting 5, 11 and 9 into 3

$$E = \frac{I}{V_t} 2R_c \sin^{-1} \left(\frac{L}{R} \right) \quad .12$$

(c) Region 3

Refer to figure A.1(c).

$$\begin{aligned} \theta &= \theta_1 - \theta_2 \\ &= \sin^{-1} \left(\frac{L}{R} \right) - \cos^{-1} \left(\frac{R_c + W}{R} \right) \end{aligned} \quad .13$$

Substituting 5, 13 and 9 into 3

$$E = \frac{I}{V_t} 2R_c \left(\sin^{-1} \left(\frac{L}{R} \right) - \cos^{-1} \left(\frac{R_c + W}{R} \right) \right) \quad .14$$

(d) Normalizing

The exposure time for the centre of a straight line can be obtained by substituting $R_c = \infty$ into the exposure time expression for region 2

$$\lim_{R_c \rightarrow \infty} \frac{I}{V_t} \frac{2R_c}{\sin^{-1} \left(\frac{L}{R_c} \right)} = \frac{I2L}{V_t} \quad .15$$

For the case where the fixed dimension of the rectangle is .004" (i.e. $2L = .004$ ") the normalized expressions for exposure become

$$\text{Region 1} \quad (R_c - W) \leq R \leq \sqrt{L^2 + (R_c - W)^2}$$

$$E_{nr1} = \frac{R_c}{.002} \cos^{-1} \left(\frac{R_c - W}{R} \right) \quad .16$$

$$\text{Region 2} \quad \sqrt{L^2 + (R_c - W)^2} \leq R \leq (R_c + W)$$

$$E_{nr2} = \frac{R_c}{.002} \sin^{-1} \left(\frac{L}{R} \right) \quad .17$$

$$\text{Region 3} \quad (R_c + W) \leq R \leq \sqrt{L^2 + (R_c + W)^2}$$

$$E_{nr3} = \frac{R_c}{.002} \left[\sin^{-1} \left(\frac{L}{R} \right) - \cos^{-1} \left(\frac{R_c + W}{R} \right) \right] \quad .18$$

A.3 Circle

Refer to figure A.2. In this case the expression for relative exposure is derived in terms of the following variables

r is the radius of the circle, where

$$R_c - r \leq R \leq R_c + r$$

R_c is the radius of curvature to the centre of the circle,

and V_t is tangential velocity of the centre of the circle.

The cosine law is used to find θ

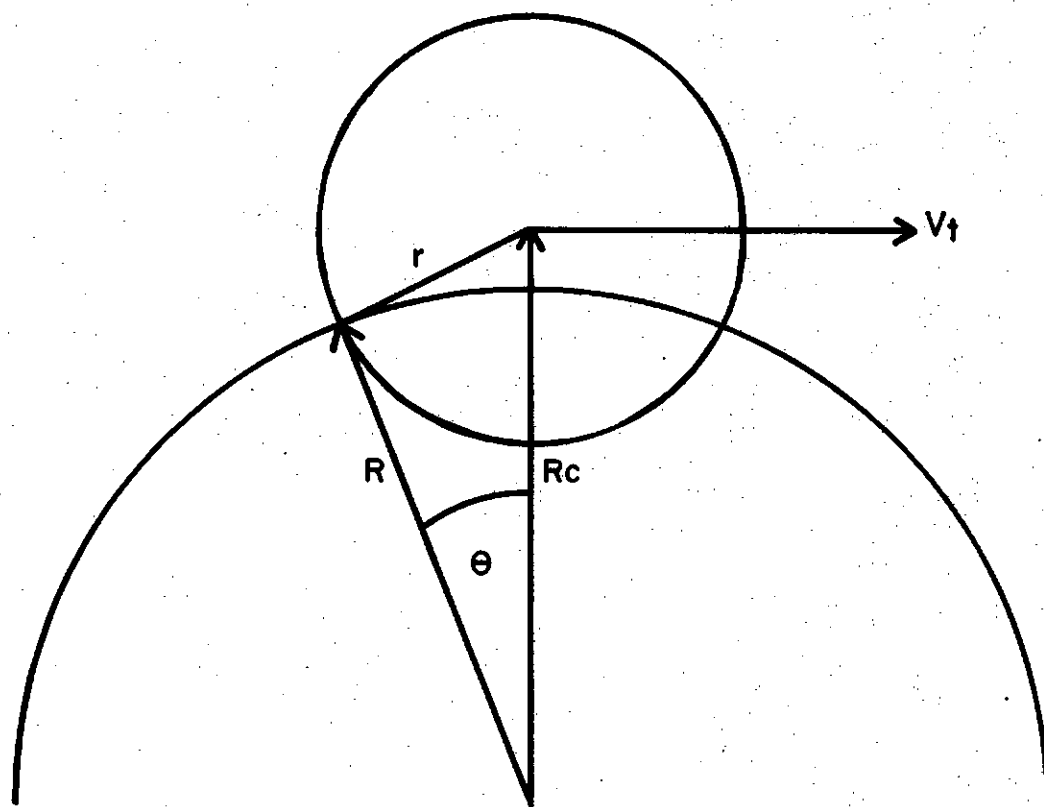


Figure A.2 Circular Image.

$$r^2 = R^2 + R_c^2 - 2RR_c \cos \theta \quad .19$$

$$\text{Solving for } \theta = \cos^{-1} \left(\frac{R^2 + R_c^2 - r^2}{2RR_c} \right) \quad .20$$

combining this expression with 5 and 9 of the previous section and putting in 3, the expression for exposure becomes

$$E = I \frac{2R_c}{V_t} \cos^{-1} \left(\frac{R^2 + R_c^2 - r^2}{2RR_c} \right) \quad .21$$

Normalizing this expression with respect to exposure time obtained for a straight line that has been drawn with a rectangle whose fixed dimension is .004" (see equation 15)

$$E_{nc} = \frac{R_c \cos^{-1} \left(\frac{R^2 + R_c^2 - r^2}{2RR_c} \right)}{.002} \quad .22$$

where $R_c - r \leq R \leq R_c + r$

A.4 Annulus

In the case of the annulus, the expression for relative exposure is derived in terms of the following variables (Refer to figure A.3(a))

r_o outer radius of annulus,

r_i inner radius of annulus,

r_t tangential velocity of the centre of annulus,

and R_c radius of curvature of line being drawn.

As with the rectangular image, the annulus has to be divided into different regions.

region 1: $\{R_C - r_o\} \leq R \leq R_1$ and $R_2 \leq R \leq \{R_C + r_o\}$

region 2: $R_1 \leq R \leq R_2$

where $R_1 = R_C - r_i$

$R_2 = R_C + r_i$

(a) Region 1

Refer to figure A.3(a)

The derivation of this expression is identical to that for a circle (see equation 21)

$$E = \frac{I}{V_t} 2 R_C \cos^{-1} \left(\frac{R^2 + R_C^2 - r_o^2}{2RR_C} \right) \quad .23$$

(b) Region 2

Refer to figure A.3(b)

$$\theta = \theta_1 - \theta_2$$

again using the cosine law

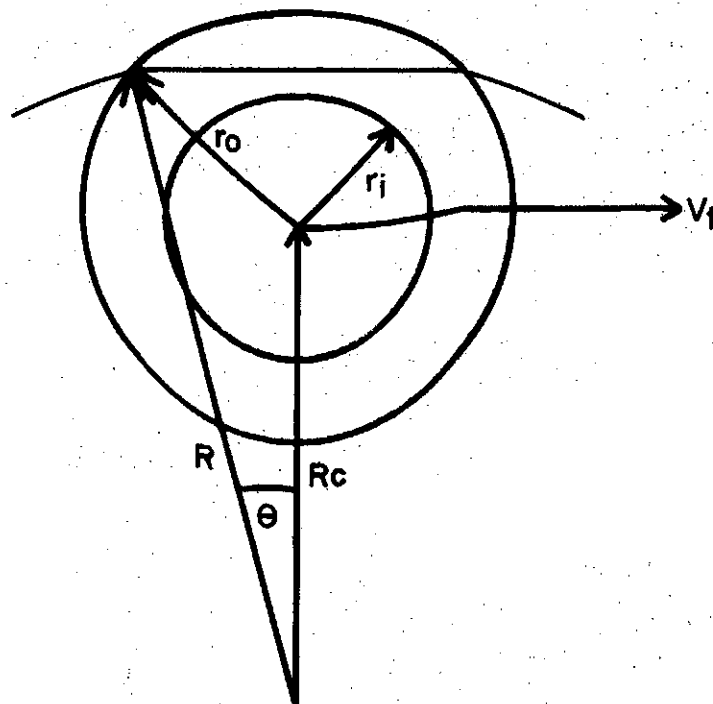
$$\theta = \cos^{-1} \left(\frac{R^2 + R_C^2 - r_o^2}{2RR_C} \right) - \cos^{-1} \left(\frac{R^2 + R_C^2 - r_i^2}{2RR_C} \right) \quad .24$$

combining this expression with 5 and 9 of the previous section and putting into 3

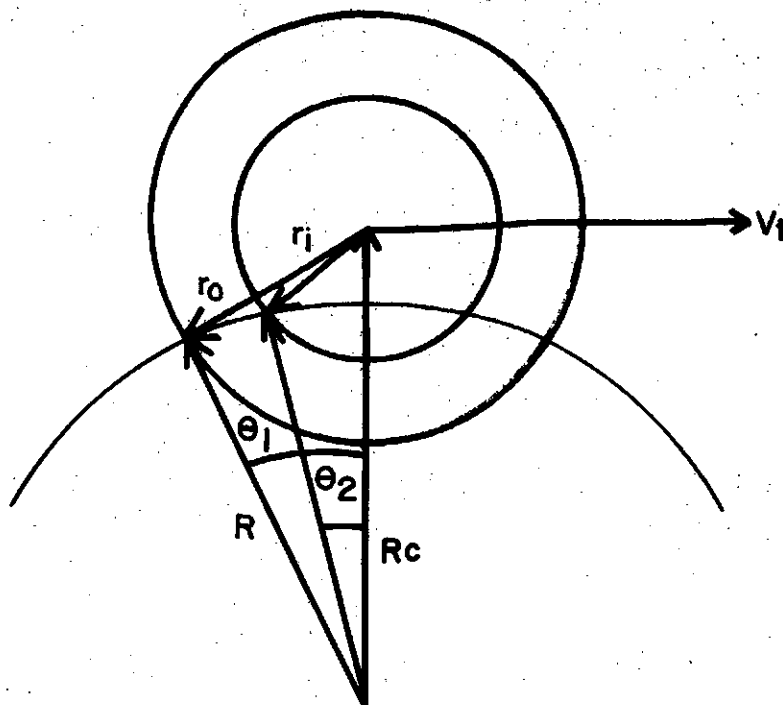
$$E = \frac{I}{V_t} 2 R_C \left[\cos^{-1} \left(\frac{R^2 + R_C^2 - r_o^2}{2RR_C} \right) - \cos^{-1} \left(\frac{R^2 + R_C^2 - r_i^2}{2RR_C} \right) \right] \quad .25$$

(c) Normalizing

Normalizing the expressions for regions 1 and 2 with respect to the exposure time obtained for a straight line that has been drawn with a rectangle whose fixed dimension is .004" (see equation 15)



(a) Region 1 : $R_c - r_o \leq R \leq R_c - r_i$ & $R_c + r_i \leq R \leq R_c + r_o$



(b) Region 2 : $R_c - r_i \leq R \leq R_c + r_i$

Figure A.3 Annular Image.

$$\text{Region 1 } E_{na_1} = \frac{R_c}{.002} \cos^{-1} \left(\frac{R^2 + R_c^2 - r_o^2}{2RR_c} \right)$$

$$\text{where } (R_c - r_o) \leq R \leq (R_c + r_i)$$

$$\text{and } (R_c + r_i) \leq R \leq (R_c + r_o)$$

Region 2

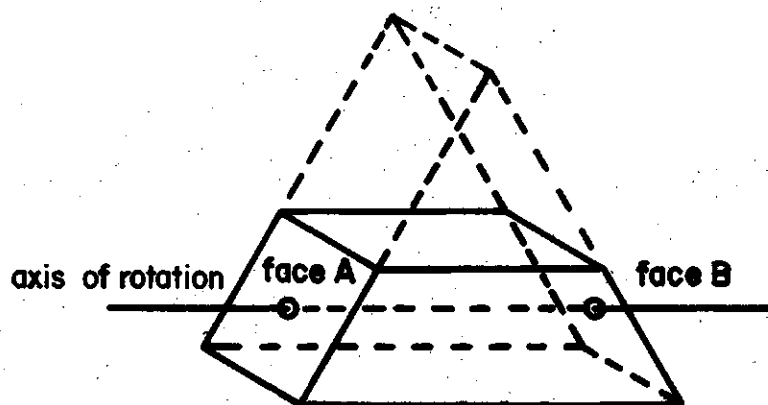
$$E_{na_2} = \frac{R_c}{.002} \cos^{-1} \left(\frac{R^2 + R_c^2 - r_o^2}{2RR_c} \right) - \cos^{-1} \left(\frac{R^2 + R_c^2 - r_i^2}{2RR_c} \right)$$

$$\text{where } (R_c - r_i) \leq R \leq (R_c + r_i)$$

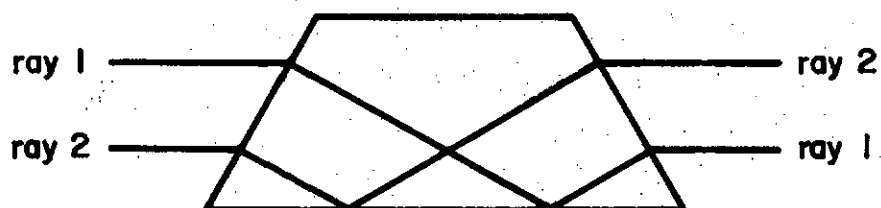
Appendix B: Operating Principle of Dove Prism

A sketch of the dove prism is shown at the top of figure B.1. It is shaped so that light rays entering face A will be refracted and bent downwards, striking the bottom face of the prism at an angle which is greater than the critical angle. (The critical angle is "the smallest angle of incidence, in the medium of greater index, for which light is totally reflected".) Theoretically then, all light rays are internally reflected and exit out of face B.

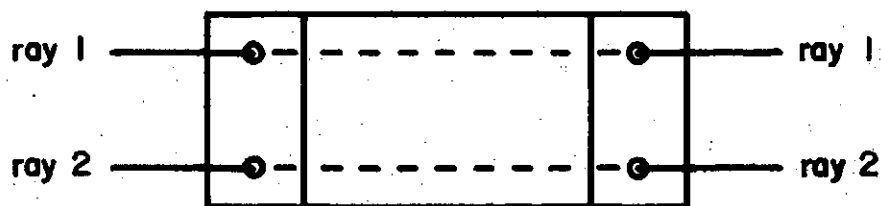
The dove prism is sometimes referred to as the inverting prism because it interchanges light rays passing through it. This is illustrated at the top of figure B.1(b). Two parallel rays 1 and 2 enter the left of the prism. Both ray 1 and 2 are refracted and then reflected. Ray 1 travels a longer distance than ray 2 before it is reflected and consequently it exits the prism below ray 2. The bottom of figure B.1(b) shows the same light rays only this time the dove prism has been rotated 90 degrees about its axis. Note that for a 90 degree revolution of the dove prism, the output rays appear to have rotated 180 degrees.



(a) Sketch of Dove Prism



Dove Prism Set to 0 Degrees



Dove Prism Set to 90 Degrees

(b) Operation

Figure B.1 Operation of Dove Prism.

Appendix C: DEC "R" Series Logic

C.1 General

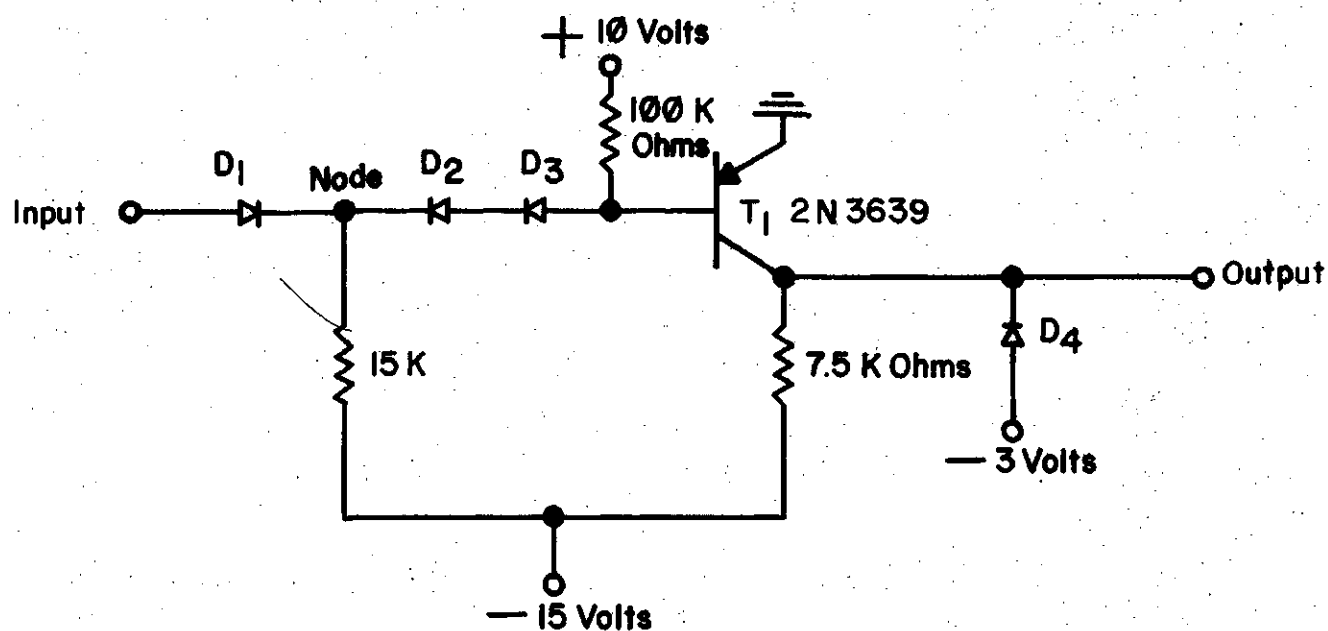
The digital electronics used in the PS5 interface and control was constructed mostly out of Digital Equipment Company (DEC) "R" series flip-flop modules. These modules are based on the diode transistor logic family and can be operated up to speeds of 2 megahertz. This appendix gives a brief explanation of this logic family^{16,17}, followed by an explanation of the logic convention used in the system drawings for the PS5 interface and control.

C.2 Basic Building Block

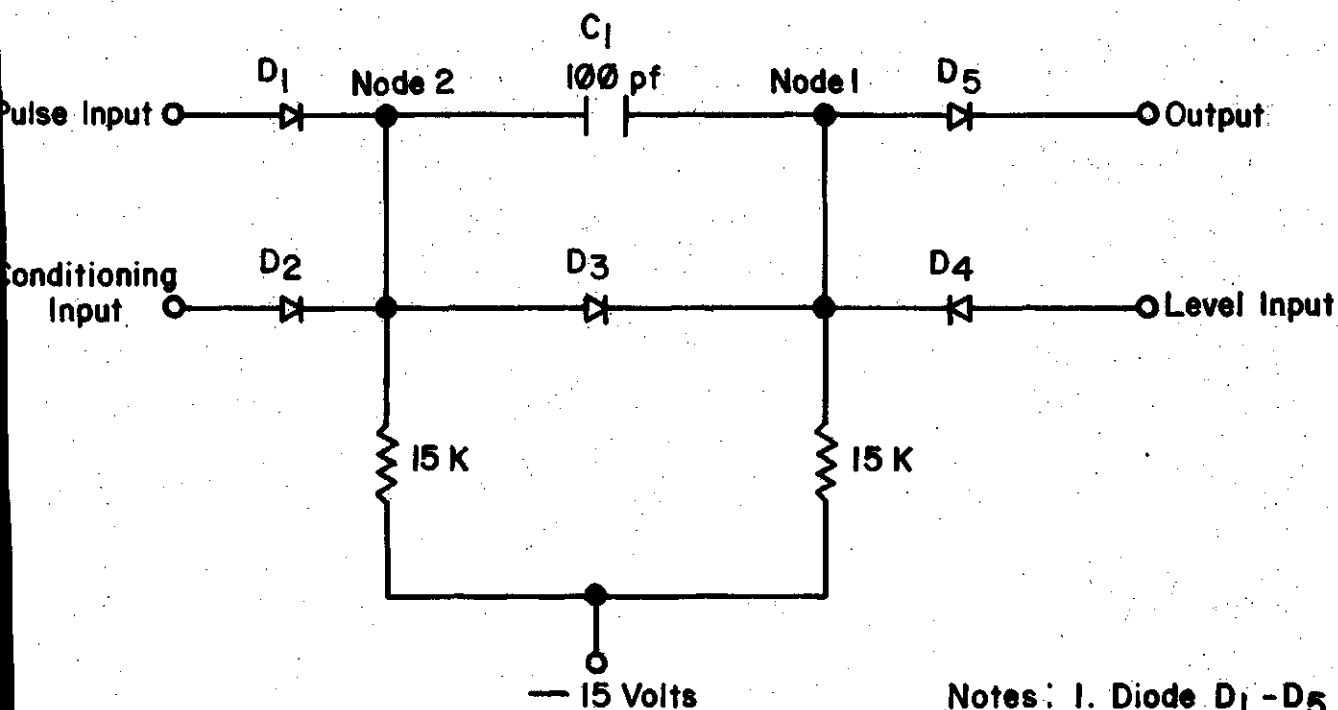
The basic inverter circuit used in the DEC "R" series logic is shown in figure C.1. When INPUT to diode D₁ is tied to ground, transistor T₁, is turned off. Diode D₄ becomes forward biased and clamps the OUTPUT, collector of transistor T₁, to -3 volts. If the INPUT is tied to -3 volts, the base-emitter junction of transistor T₁ will become forward biased causing it to go into saturation. Its output will therefore go to approximately ground.

Diodes D₂ and D₃ are added to the base path of Transistor T₁ to increase its DC noise margin.

The INPUT terminal of this circuit draws one milliampere when it is at ground. When it is at -3 volts, diode D₁ is reverse biased and so it draws only the leakage current of the diode. When transistor T₁ is turned on it



(a) Basic D.E.C. 'R' series inverter



Notes: 1. Diode D_1 - D_5
-IN3606

(b) DCD gate

Figure C.1 Basic 'R' Series Inverter & DCD Gate.

is capable of supplying a total of 20 milliamps of current. Two milliamps is required for the collector load resistor; the remaining 18 milliamps can be used to drive external loads. Many of the required logic elements can be constructed from this simple circuit. For example, the negative NAND gate is made simply by adding more diodes in parallel with diode D_1 . An R-S type flip-flop can be constructed by cross coupling the outputs of two negative NAND gates.

C.3 Diode Capacitor Diode Gate

One of the unique features of DEC "R" series logic is a circuit called a diode capacitor diode (DCD) gate, shown at the bottom of figure C.1. This circuit enables many of the logic elements to be AC coupled. It performs a logical AND operation on PULSE and LEVEL inputs. A positive pulse or positive going level transition applied to PULSE input will cause it to trigger if the LEVEL input is held at ground. Because of the presence of capacitor C_1 , the circuit is able to "remember" what the condition of the LEVEL input was prior to the pulse. It is therefore possible to trigger it and simultaneously change the level input. This feature is extremely useful when implementing logical functions. For example, any flip-flop that has DCD input gates can be sampled and loaded simultaneously.

When the LEVEL input is tied to ground, node 1 charges to 0 volts. Node 2 is clamped to -3 volts by

the CONDITIONING input. When a -3 volts to ground transition is applied to the PULSE input, node 2 goes to ground and node 1 goes to +3 volts. This +3 volt pulse is used to initiate the turn-off of a transistor (not shown) and is directly connected to its base through diode D_5 .

If LEVEL input is held to -3 volts, node 1 will charge to -3 volts. When node 2 goes to ground, node 1 will be raised from -3 volts to ground. This is not sufficient to forward bias diode D_5 and hence no pulse is transmitted to the OUTPUT.

The CONDITIONING input to this circuit is sometimes used in pulse steering applications. This enables flip-flops with set and reset DCD input gates to be connected to operate as JK flip-flops. The reset gate is conditioned by the "1" output of the flip-flop, the set by the "0" output. The PULSE inputs of both gates are tied together. The CONDITIONING input steers the triggering pulse to the desired DCD gate. If for example, the flip-flop is in the one state, only the reset gate can be pulsed. The flip-flop will be reset by a clock pulse if the reset level input is at ground.

C.4 Logic Symbology

The conventions used in the logic drawings presented at the end of Chapter 4, are similar to the old conventions used by DEC for their R series modules. This

convention was adopted so that these drawings would be compatible to the rest of the logic drawings for the automatic drafting system.

A mixed logic convention is used, that is, -3 volts can represent a logical "1" or "0". The assertion levels for each gate are always shown. It can normally be assumed that if the asserted inputs to a gate are negative it is performing a logical NAND operation and if they are positive it is performing a logical NOR. In cases where this is not true the logical function of the gate is indicated by placement of "." (AND) or "+" (OR) or "A" (INVERTED) within the logic symbol of the gate.

The assertion level of each signal name corresponds to the level of the input gate. Sometimes an H (ground) or L (-3 volts) is placed after a signal name to indicate its asserted level.

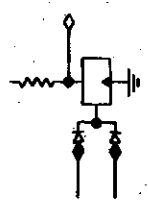
The symbols used for each logical element are summarized in figure C.2. The standard level and pulse symbols are shown in C.2(a). C.2(b) shows the symbol for the DCD gate although it is never seen alone. Note that this gate is triggered by a positive going edge of a pulse or level transition. The inverter, negative NAND and positive NOR gates are shown in figures C.2(c), (d), and (e). The symbol for a flip-flop is shown in figure C.2(f); in this case it is shown with two DCD gates although several possible other combinations are available. The other commonly

- Ground level for assertion
- 3 volts level for assertion
- Ground pulse or positive going level change
- Negative pulse or negative going level change

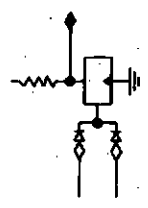
(a) Standard levels and pulses



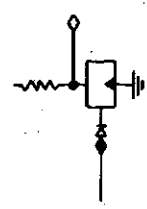
(b) DCD gate



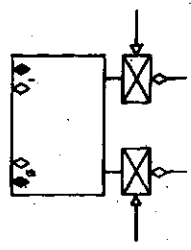
(d) Negative NAND gate



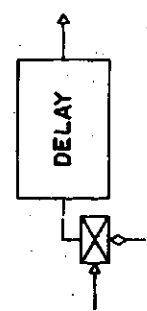
(e) Positive NOR gate



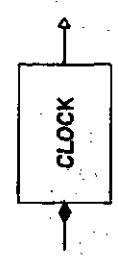
(c) Inverter



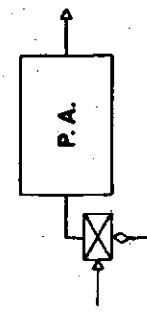
(f) Flip-Flop



(g) Delay



(h) Oscillator



(i) Pulse amplifier

DRAWN RJA	DATE Oct 30/78	TITLE Figure C.2
CHKD RJA	DATE Oct 30/78	D.E.C. 'R' Series Logic Symbol
DESIGNED RJA	DATE Oct 30/78	FOR Automatic Drafting System
APPROVED	DATE Oct 30/78	DRAWING NO.
IMPLEMENTED DATE		
SHEET	OF	DIST

used logical elements, the monostable, oscillator and pulse ampligier are shown in C.2 (g), (h) and (i). The symbols for other less frequently used logic elements can be found in the 1968 "DEC" "R" series handbook.