AUTOMATIC LINE FOLLOWER

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"AUTOMATIC LINE FOLLOWER"

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ABSTRACT

This thesis describes the design and construction of an automatic line follower to digitize line data from cartographic charts with a minimum amount of operator participation.

An electromechanical line sensing head is combined with the positive stepping qualities of a digital type servo system and digital control logic to produce a simple and reliable automatic line follower. In the course of the design study, a mathematical model of a stepping motor is developed and verified. This model is then applied to show the effect of varying different circuit parameters on the stepping motor multi-step response. The problem of resonance in the stepping motor is investigated and methods of improving the dynamic performance are derived.

The results from experimental tests on the prototype of the automatic line follower are described. In addition, results are included to demonstrate the performance of the prototype in digitizing a sample chart.

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LIST OF PRINCIPAL SYMBOLS

I_o	reverse current of photodotector
I	stepping motor operating current
K_T	torque constant of stepping motor
K_V	constant relating induced voltage and stepping motor rotor velocity
ω_n	system natural frequency
ζ	system damping ratio
K_{RT}	constant relating electrical radians and mechanical radians
θ	rotor position in electrical radians
α	rotor position in mechanical radians
J	stepping motor rotor inertia
D	stepping motor viscous damping

1. INTRODUCTION

1.1 General

The advent of the inexpensive and compact digital computer has caused an appreciable revision of ideas in the areas of control systems, data handling, and data storage. The basic advantage of the digital computer is the simplicity with which mathematical manipulation and processing can be carried out, the amount of data which can be handled and stored, and the ease with which the data can be modified.

In cartography it was realized that these advantages could be applied to create a system of automatic cartography superior to that using traditional manual methods. Previous methods required laborious manual tracing and scribing every time a chart was updated, and much calculation if either the scale or the projection were altered. If all the data were available in computer storage, the calculation and manipulation could be carried out by the computer and the final product drawn by a draughting machine on line to it. The problem in implementing the concept was that all data were traditionally stored in chart form and would need to be digitized to convert it to a suitable form for the digital computer. New data from the field would be recorded digitally, but there remains the problem of digitizing the vast amount of existing cartographic records. Hence digitizers are necessary to see the automatic cartography project through the transition stages.

Information on maps and charts falls into two categories. Firstly, there is line and point information, and secondly, there is symbolic and written information. The two categories of data differ so greatly that two entirely different devices are required to digitize them. This thesis only deals with devices which will digitize line and point information.

It is generally accepted that the accuracy of existing charts is ± 0.004", with a minimum line width of 0.004". These tolerances are dictated by the practical limitations of the production methods. In specifying the line follower accuracy it has to be understood that the inaccuracy of the digitized data is the inaccuracy of the original line on the chart plus the inaccuracy of the digitizing device. From practical considerations, the acceptable accuracy for the prototype line follower designed in this thesis was within ± 0.004". This gives an overall accuracy of ± 0.008". There is no reason why a higher accuracy could not be strived for, but this might require a more sophisticated system.

The resolution of a system can be defined in a number of different ways. Two definitions are used in this text, giving information about two different properties of the line following and digitizing system. First the resolution is defined as how close two parallel lines on a chart can be positioned such that the line follower will still be able to follow one of them without being influenced by the presence of the other. The other definition of resolution is defined as the radius of the smallest circle which can be followed, keeping within the accuracy specification. These definitions of resolution apply to the line sensing head rather than to the remainder of the system.

In approaching the design of the automatic line follower it is desirable to minimize complexity and cost. It is convenient in an automatic cartography project, and almost essential in other applications, that the mechanism of the automatic line follower be able to operate independently of a digital computer. This has the additional advantage of allowing the basic system, that is the line sensing head and associated logic, and the servo system to be developed without the cost of a digital computer. If desired at a later time, when the problems of the basic system are known, the control logic may be replaced by an interface, serviced by a digital computer.

There are two different types of logic systems used for control in line follower devices: analog and digital. A digital signal is one which is limited to a number of discrete values within a specified range. Normally the digital signal is limited to two values, making it very stable in operation. To take advantage of this stability, the prototype automatic line follower was designed to use digital control logic and a digital position servomechanism.

The specifications outlined in this last section provide a basis for discussing the different types of line digitizers and the operating systems available, and to give justification for choosing the particular model designed in this thesis.

1.2 Digitizers for Cartographic Applications

Having established the requirement for a device for digitizing analog hard copy, it is necessary to investigate the different modes of operation of the line follower and the hardware involved in each method. There are four possible modes of operation: manual, semi-manual, semi-automatic and automatic.

Manual operation requires the operator to position the stylus manually on a series of points on the line being digitized and visually read the X and Y co-ordinates from position indicators. The semi-manual mode is similar to the manual system except that the co-ordinates of the points on the line are read out automatically from position encoders and recorded on tape or other media whenever the operator depresses a switch. On the other hand, the semi-automatic system only requires the operator to position the device at the beginning of the line to be digitized and indicate to the system the direction in which the line has to be followed. The system will then automatically follow the line on the chart, generating and recording the co-ordinates of points along the line as often as required until the operator intervenes. An automatic line following system would be one in which the machine would search for a line, digitize it completely and then search for the next one automatically until the job was finished.

Manual digitizing is not a practical proposition where a large amount of data is involved mainly because of the effort demanded of the operator in order to position the stylus accurately. Another drawback is the tedious and error-prone job of transferring,the co-ordinates of the stylus, given by the position indicators to a permanent record.

The semi-manual system[1] is only slightly better because the operator is still required to position a stylus to within ± 0.004" of the centre of the line in order to maintain sufficient accuracy. It is an extremely demanding process and the precision of the operation tends to diminish after extended periods of digitizing.

The semi-automatic digitizing system[2,3,4,5] reduces much of the operator error and effort, as the operator is only required to position the line sensing head at the start of the line and at ambiguous points. Continuous concentration is not required.

Automatic digitizing requires even less operator participation. If taken to the limit, it would only be necessary to mount the chart on the machine and the system would complete the digitizing unaided. It would negotiate intersections according to some predetermined plan and when finished one line, it would automatically search for the next.

The system design described in this thesis is of the semi-automatic type. This follows from a decision to do as much as possible with simple hardware design. When describing the operation of the different types of digitizers, the terms semi-automatic and automatic were used in describing the different types of line followers. However in the literature available, the semi-automatic system as described in this thesis is normally referred to as an automatic line follower or ALF. This practice will be adhered to in the remainder of the thesis.

Some of the practical difficulties encountered when digitizing a chart with an automatic line follower, are illustrated in Figure 1.1. Shown in this figure is the intersection of a river with a contour line and the coast line, both of which create ambiguous areas. The automatic line follower will lose accuracy when approaching these points as it will be unable to differentiate between the two intersecting lines and on leaving, the path taken will be indeterminate. The contour lines are broken to make space for height values and place names. These

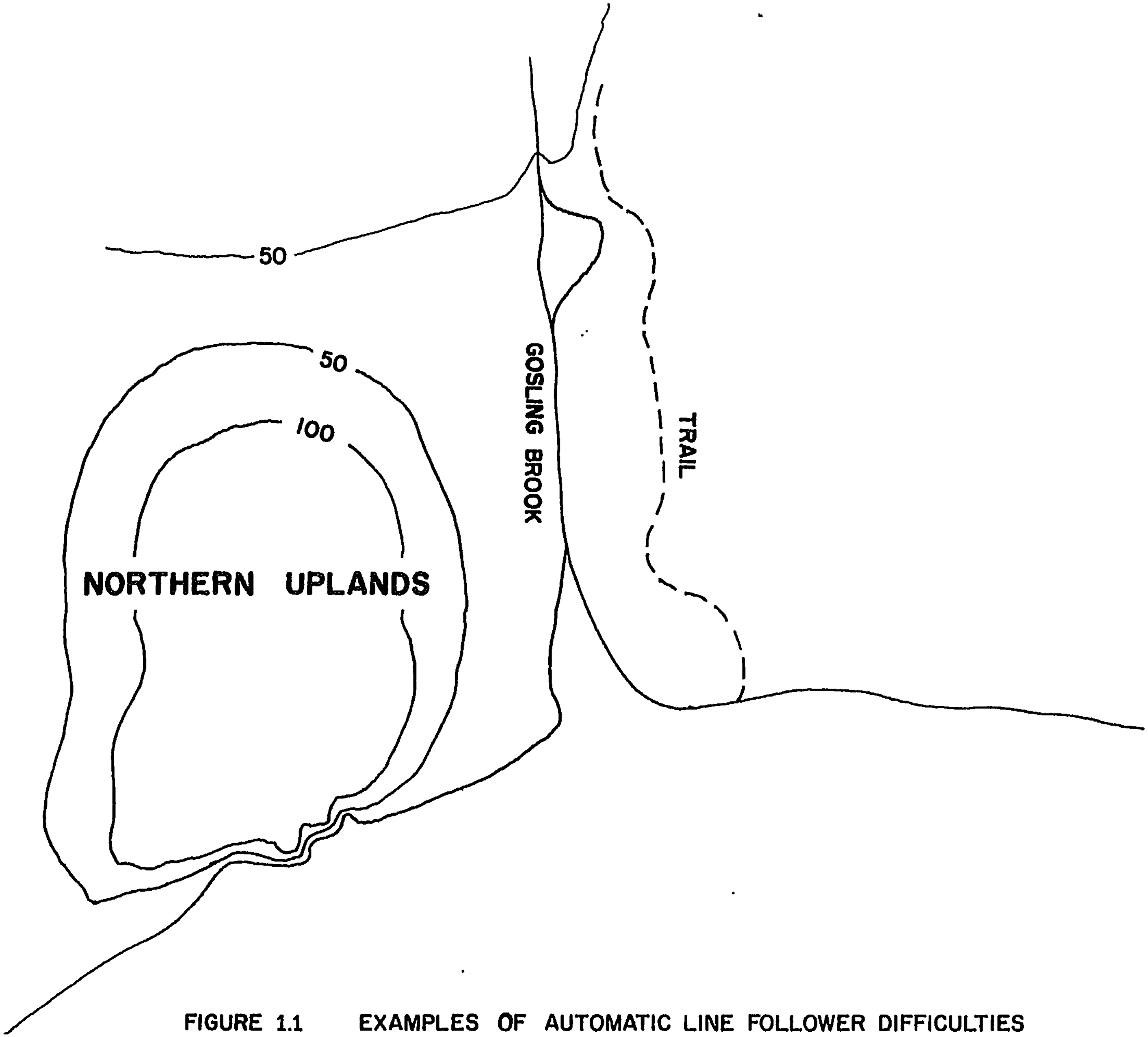


FIGURE 1.1 EXAMPLES OF AUTOMATIC LINE FOLLOWER DIFFICULTIES

interfere with line following. To negotiate these areas the operator has to steer the line follower system manually. He has also to move the system from the end of one line to the beginning of the next.

A method which would make the proposed automatic line follower completely automatic is to interface it with a digital computer to allow a 'director' tape to control the automatic line follower. The 'director' tape would have been previously made on a semi-manual digitizer, where the path to be followed has been partially traced, manually by the operator. All the starts and ends of lines would have been accurately digitized. At intersections and other ambiguous areas, the operator could have digitized possibly several inches of line. This 'director' tape, when complete, enables the automatic line follower to digitize the entire chart rapidly and automatically, under the control of the digital computer and independently of the operator.

This thesis describes the design and contruction of a prototype line follower built to satisfy the basic performance characteristics dictated by the form of conventional chart records. In addition, an assessment is made of the performance of the prototype, and conclusions and recommendations are set forth as a result of the experience gained in this project.

The next chapter describes the operation of an analog automatic line follower. This leads to a discussion of automatic line follower systems.

2. SYSTEM REQUIREMENTS

2.1 General

The operation of a typical automatic line follower can be described in the following manner. The line follower has essentially two axes of control, as shown in Figure 2.1. The X axis and Y axis systems operate independently of one another from a common input signal which is derived from the line being followed on the chart. Under steady state conditions both control axes are held on the line by the action of their respective position feedback loops. A drive voltage, or forcing input, is applied to the system to make it follow the line. This voltage is resolved into X and Y components by a resolver whose angular position tracks the slope of the line. The X and Y drive components make the system follow the line in the required direction and any error is corrected by the position loops of the two control axes. Whenever the forcing input is removed, the system holds its present position. When following a line, the error to be corrected by the individual position loops is small, as the forcing input has been resolved into X and Y components. The speed of following is determined by the magnitude of the forcing input.

It is of first importance that the system always operates within the required accuracy of ± 0.004" of the centre of the line. Therefore the position error must be less than 0.004". The velocity error must also be less than 0.004" at the maximum following speed. In the system just described, the following error should be zero as the forcing input supplies the drive to maintain the two axes at the

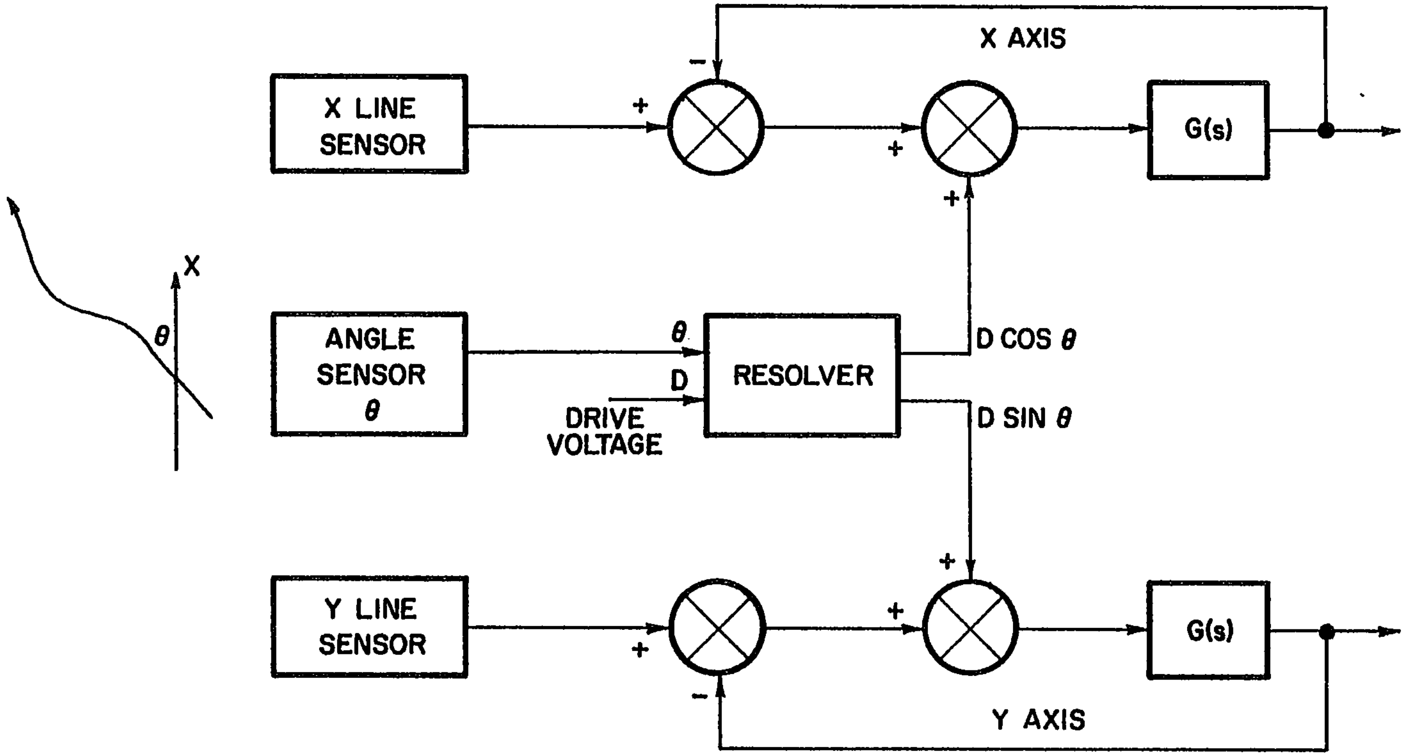


FIGURE 2.1 ANALOG LINE FOLLOWER

required following speed. Neither the position error coefficient nor the velocity error coefficient give much information about the system when it is subjected to a sudden change in the line direction, for example, a right-angled corner. The performance of the line follower when negotiating a right-angled corner is related to the natural frequency of the system. In order to obtain an indication of the required system natural frequency to follow an irregular line on a chart to within the desired accuracy, it is useful to consider the worst case condition, a right-angled corner.

Later it will be shown that the position servo of the prototype automatic line follower is a second order system. Puckle and Arrowsmith[6] derive an approximate expression for the overshoot, for a step change in velocity for a second order positional servo.

$$\epsilon = v\tau \qquad 2.1$$

where: ϵ is the overshoot
v is the velocity in inches/second
ζ is the damping ratio
τ is the system time constant $(1/\zeta\omega_n)$
ω_n is the natural frequency of the system.

Assuming a following speed of 0.1 inches/second and a typical value for ζ of 0.707, it is found that the natural frequency of the positional servo must be greater than 3.8 Hz or 25 radians/second, for the overshoot to be less than 0.004". This determines the minimum servo bandwidth required for the automatic line follower. It must in fact be greater, since the total error from all sources has to be less than 0.004".

Reliability is a desired feature in any equipment and is dependent on the system design and components. A good design will allow for component tolerances when new and variation with temperature and age. In considering any design, the final choice should be made on the grounds of performance, reliability, simplicity of design and cost. The separate parts of the automatic line follower system are now discussed bearing in mind the points mentioned above. A review of the methods available for generating line information from a chart is given first.

2.2 Line Sensing Devices

There are two possible methods of generating line information from a chart. These are fixed scan and programmed scan. Fixed scan implies that the device always scans along a fixed path, normally a circular path. With the programmed scan, the scanning path depends only on the set of conditions existing at that instant. As a method, the programmed scan is much more adaptable and efficient but requires the device to be on-line to a computer; it could be limited in speed by the time taken in computation. As the fixed scan method was simpler and required less hardware, it was the method used in the prototype automatic line follower.

The next choice was between an electromechanical and an electronic scanner, for example a television camera. The electromechanical scanner is simpler in operation and uses fewer components; the stability of the electromechanical scan is good as it is only dependent on the stability of the mechanical assembly.

The electron beam scanners have several advantages. They have high resolution and high sensitivity. The disadvantages are that they are expensive, complex and bulky and require electromagnetic or electrostatic fields for beam deflection and focussing, and more circuitry for synchronizing the scanning waveforms. Careful control of potentials is essential to achieve stable operation. Accurate scanning geometry is difficult to obtain as characteristics change with time, scanning velocity and gun alignment. A hot cathode is employed for electron emission; it ages and has a limited life.

A matrix of photodiodes was considered as the line sensor but it hasa number of disadvantages without giving any balancing advantages. It lacks definition and requires an appreciable number of high gain, high stability amplifiers. The output of the photodiode matrix is difficult to process into an error signal to drive a servomechanism.

A simple method used in digitizing charts recorded on strip chart recorders is to illuminate the line and focus the reflected light onto photocells with a semi-cylindrical lens[5]. The two photocells are mounted very close together and their outputs fed to a differential amplifier (see Figure 2.2). When the line on the chart is midway between the cells a null is obtained. If the chart being digitized is driven forward in the longitudinal axis, and the cross-axis servo fed by the diode pair, the system will track the line. Normally an analog output is obtained. The accuracy of the method is limited and is difficult to improve upon. The main problem is that as the angle between the line being digitized and the longitudinal axis increases, the accuracy diminishes.

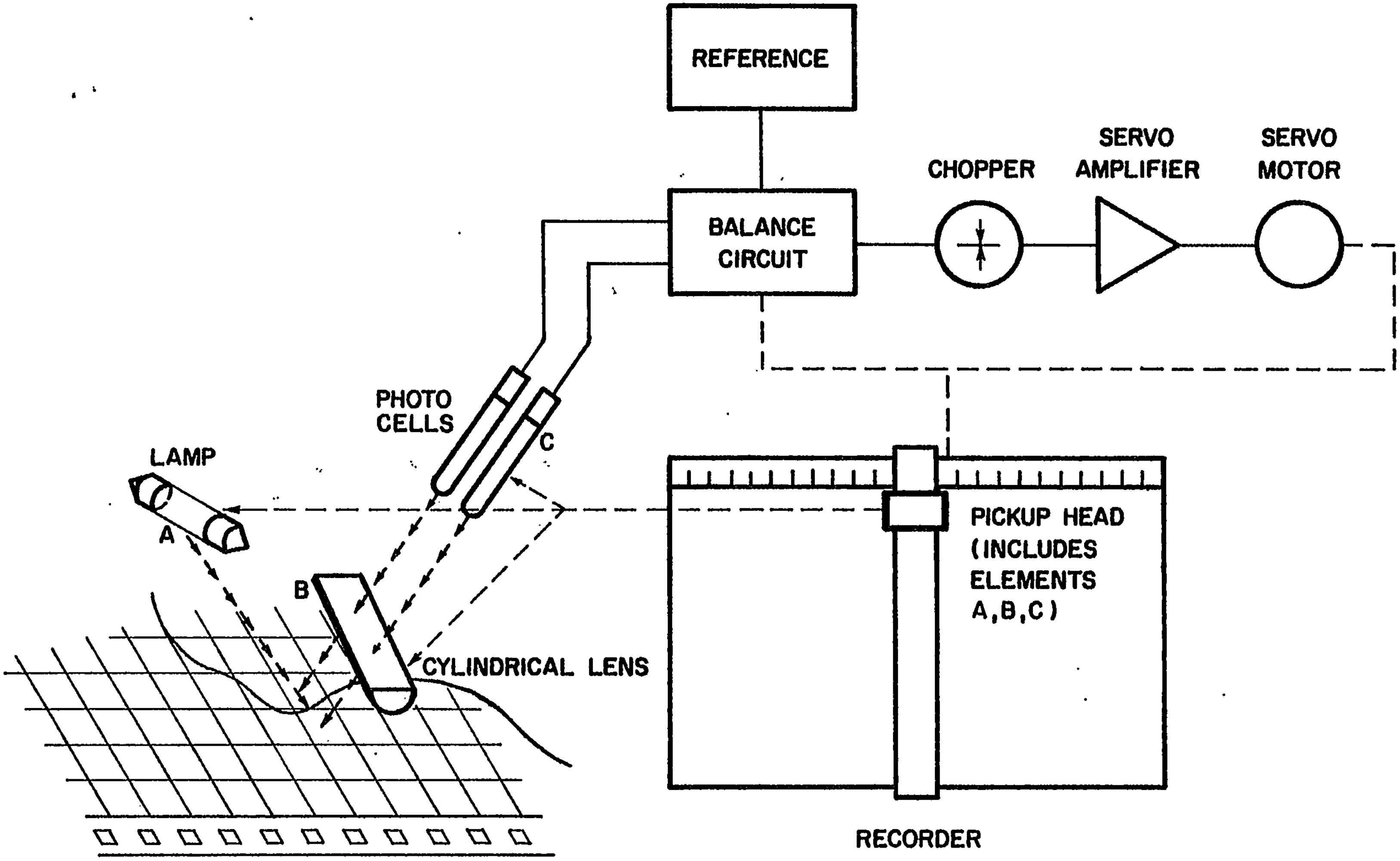
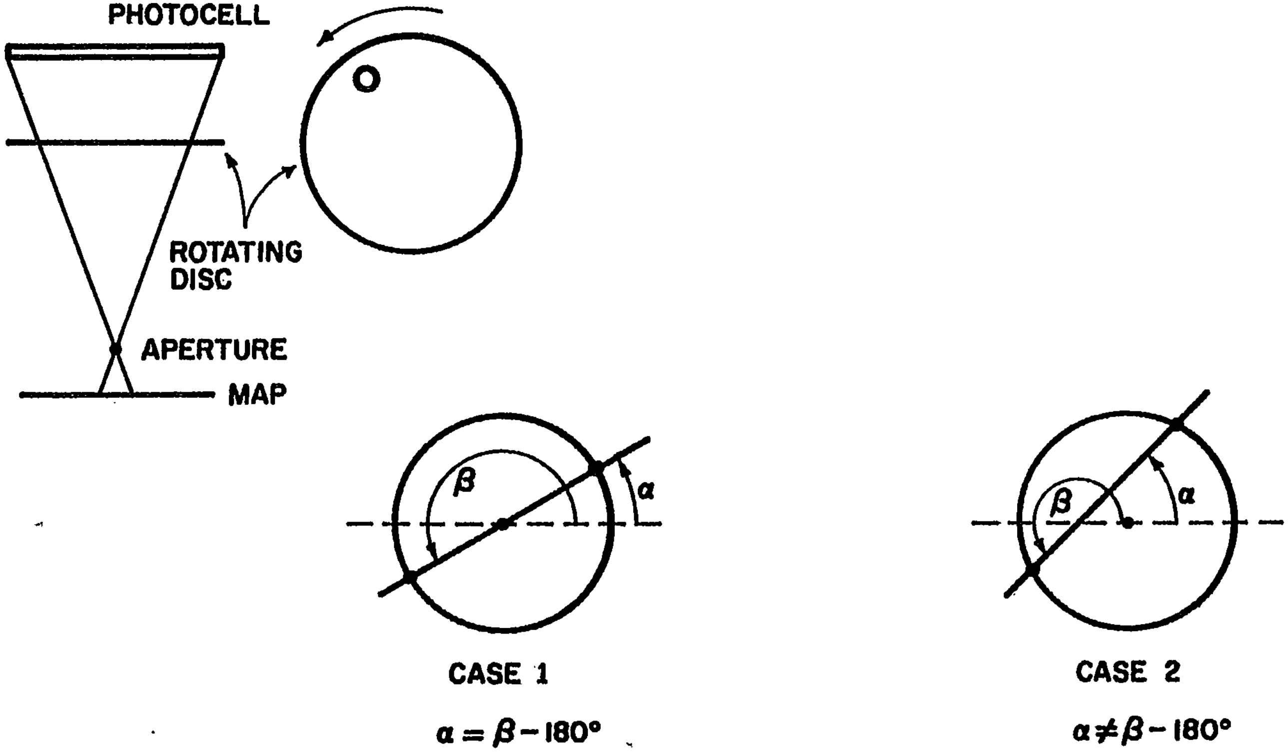


FIGURE 2.2 STRIP CHART LINE FOLLOWER

Another method of tracking a line might be an adaption of a method used for measuring the position of a spot of light using a special purpose photodiode. United Detector Technology manufacture a range of diodes giving voltages proportional to the co-ordinates of the centroid of the spot of light on the diodes active area. These diodes allow the position of the spot of light to be measured anywhere in an area of up to 1.5" diameter. Unfortunately the scale factor of the device is dependent on the amount of light flux contained in the spot. If a line is projected onto the diode surface the diode output will be dependent on the area of the line in the field of view as well as the position of the line. In order to use this type of photodiode, some means of keeping constant, the area of the line seen by the diode, would have to be found.

The electromechanical fixed scan was chosen as the best method for the present application. A circular scan is the easiest electromechanical scan to implement. It can either be a spot scan or a half moon scan. The spot scan[7] shown in Figure 2.3 was not used as it was thought that it would be easily affected by dirt or irregularities on the paper surface and is less sensitive to the line input. It gives a digital output but this is not readily processable to a form suitable to drive a servomechanism.

The rotary half moon scan integrates the brightness of half the scanned area at any instant, and as a result it is less affected by surface irregularities and a larger output is obtained. The output of a half moon chopping system is shown in Figure 2.4. It does not give a sine wave output directly but as a bandpass amplifier is used,



$$\text{SLOPE} = \frac{\alpha}{2} + \frac{\beta}{2} - 90°$$

$$\Delta x = \frac{r}{2}(\cos\beta - \cos\alpha)$$

$$\Delta y = \frac{r}{2}(\sin\alpha - \sin\beta)$$

FIGURE 2.3 ELECTRO MECHANICAL SPOT SCAN

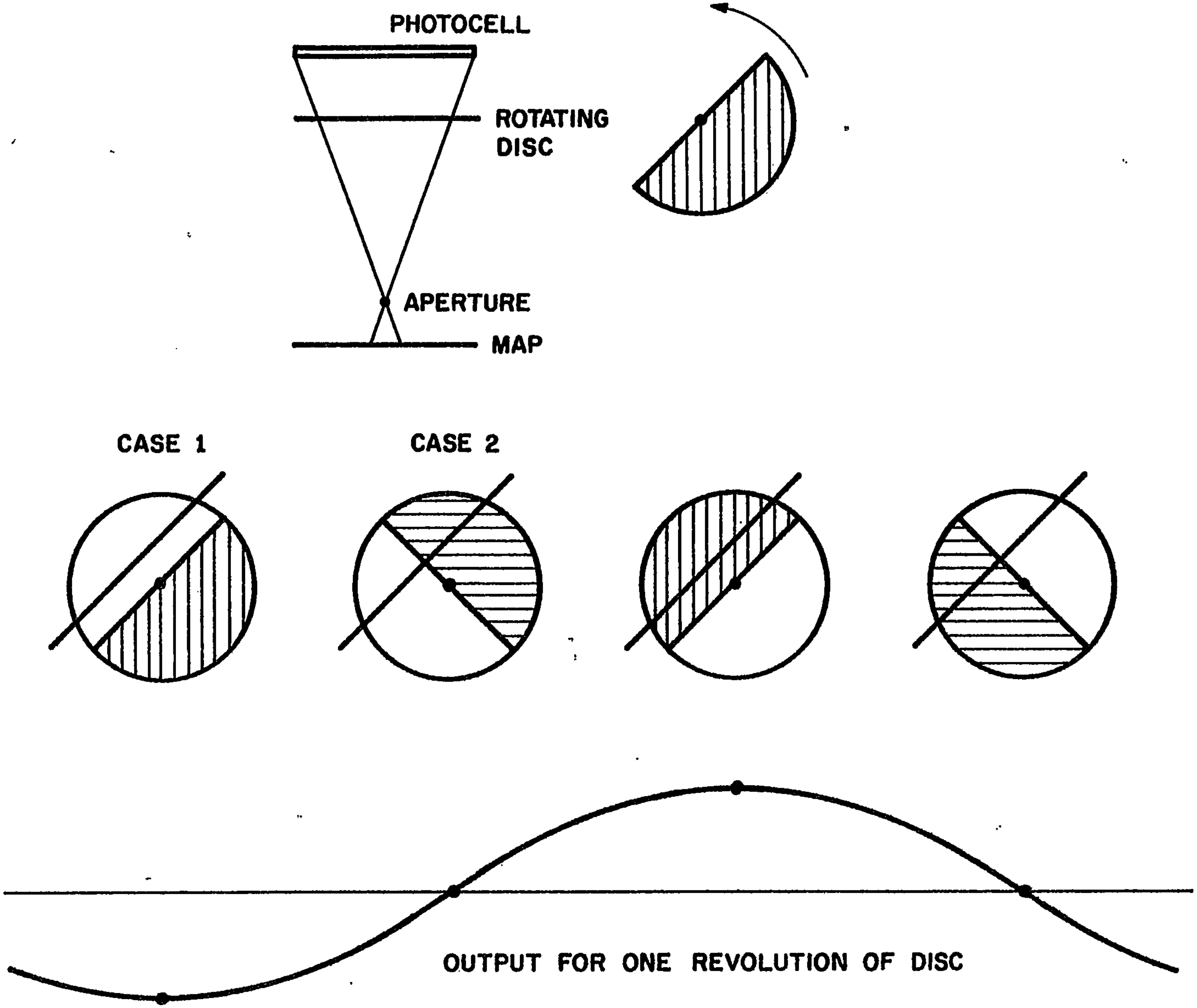


FIGURE 2.4 ELECTRO MECHANICAL HALF-MOON SCAN

the harmonics are filtered out, and in practice it can be approximated to a sine wave. The amplitude of the sine wave increases linearly with position error until a maximum is reached, when the centre of the line sensing head is on the edge of the line. Further increase in error causes the amplitude of the sine wave to fall off according to a nonlinear law. The above characteristic is only approximate as it is dependent on the precision of the construction of the scanning system. An inspection of Figure 2.4 shows that the slope of the line determines the phase of the sine wave. The construction of a prototype automatic line follower using this line sensing head is given in subsequent chapters.

2.3 A Comparison of Analog and Digital Servomechanisms

Having selected a line sensing head, no restriction has yet been put on the rest of the system; it may be analog or digital. The analog automatic line follower described in the introduction to this chapter has been implemented commercially using a 400 Hz two phase carrier system. Using the figures of merit outlined, the theoretical performance of this system is good. The position error is zero since it is a type 1 system. There is a velocity error but this is effectively cancelled by the forcing inputs. These supply the drive to the two axes to move them at the desired speed. The position loop is only required to correct for minor deviations and acceleration.

A factor not taken into account in the analysis is that analog characteristics are susceptible to change with temperature and voltage fluctuation. To compensate for these variations, continual adjustment is required. Another difficulty encountered in an analog servo is low motor torque for small errors. This, together with stiction, causes deadzones, loss of accuracy and random oscillation when stationary; hunting when following ramp inputs is another possibility owing to variations in the open loop gain. All these features are undesirable. To overcome them it was decided to investigate the feasibility of a digital type servo.

The digital system is based on the use of a digital stepping motor as the prime mover. For every pulse applied to the stepping motor, the output shaft increments by one step. It can be indexed clockwise or anticlockwise without restriction. The step size is accurate to ± 3% of the step. Any error is noncumulative. The motor develops its maximum torque even when moving only one increment. It appeared that if a digital stepping motor were used much of the uncertainty of the analog servo could be eliminated and the stability and reliability increased. The positive stepping features of the motor would decrease the deadzone and any random oscillation. The discrete movements of the stepping motor give another advantage; no position encoders are required to measure the carriage position. Instead, if the pulses driving the stepping motor are summed in a counter, the relative position of the carriage will be given by the number in the counter. This enhances the digital system as the position encoders required in an analog system are expensive, complex and troublesome.

In the first chapter, the role of the automatic line follower in the automatic cartography system was outlined. After weighing the relative merits of the analog and digital type line followers, it can be appreciated how much easier it is to integrate a digital line follower into a digital system.

However, the stepping motor introduces many nonlinearities and discontinuities into the system. The small signal mathematical model can be approximated by a second order system. This model although valid for a single step input is not adequate when considering the multi-step performance of the motor. The analysis of the nonlinear system is a formidable problem, but it can be tackled in many different ways. All involve a large amount of effort and as various approximations have to be made, the results are dubious. In approaching this aspect of the work it was decided to take the simplest analysis and use experimental verification whenever possible. The describing function technique was used as it is relatively easy to apply, and the results obtained using this technique proved beneficial in assessing the performance of the system. The inherent inaccuracies of the describing function technique have to be accepted and allowed for when using the results of the method.

In the next chapter the individual components in the prototype automatic line follower are discussed separately, and then the overall system performance is assessed from theoretical considerations and compared with the experimental results obtained from tests on the prototype.

3. SYSTEM DESCRIPTION

3.1 The Overall System

The proposed digital automatic line follower system is shown in block schematic form in Figure 3.1. It consists of an XY mechanism carrying the line sensing head and a digital control unit. The operation of the system may be described as follows. The X axis is incremented by the master oscillator at a constant rate. The control logic determines the direction and magnitude of the correction required in the Y axis to keep the line sensing head positioned on the line. Another block schematic, giving more detail of the error correcting Y axis, is given in Figure 3.2. In this block schematic, the line sensing head and its immediate control logic is represented by a relay with deadzone. If the error is within a specified tolerance there is no output from the relay. However, if the error is outside the specified tolerance, the relay gives the direction of correction needed to reduce the error. The output of the relay, together with the master oscillator output are applied to the logical AND gates which generate the pulse trains fed to the stepping motors. These move the XY mechanism so that it follows the line on the chart and keeps the following error at a minimum. The individual components are described in detail in the subsequent sections, before continuing with a description of the overall system performance of the designed model.

3.2 The Line Sensing Head

3.2.1 General

In an earlier chapter the reasons for using an electromechanical,