

COMPUTER SYSTEM DEVELOPMENT AND
INVESTIGATION OF A DIGITAL
CONTROL TECHNIQUE

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by

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To -

MY FAMILY

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SYNOPSIS

A control software system was developed for a mini-computer system. The system enables an operator to set up plant conditions, such as actuator settings, controlled by digital-to-analog converters and to monitor plant conditions, using analog-to-digital converters, while the plant is off-line. The operator can also establish parameters necessary for on-line control, and can generate reports on the present status of such parameters. Such activities would include selection of appropriate filtering for the sampled variables, and establishing controller characteristics for various control loops.

Multiple control loops may be catered for. In addition loops may be cascaded, a primary loop providing some relatively simple control function, the set point for this controller being provided in turn by a secondary control loop.

In order to achieve this, the system is interrupt driven, events being scheduled using the real-time clock.

The design of each control loop uses an algorithm developed by E.B. Dahlin and I.D. Higham. The method uses Z-transforms to provide a DDC scheme which is easy to implement and in particular has the ability to cater for process dead time and delays.

An investigation of the system was carried out on a "web process", where material in sheet form, such as a roll of paper, is passed over a system of rollers. The web system in

this case was an experimental one, the material being a continuous roll of towelling.

The control system provided lateral position control of the material on the rollers, position being detected by photocells, and a roller, pivoted on its main axis and pneumatically operated under control of an electrical signal from the computer, providing position actuation.

The operation of a primary loop was investigated using photocells close to the actuating roller, so that time delay was minimal.

A cascaded system, using results derived for the primary controller, was developed for photocells some distance from the actuating roller.

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1. INTRODUCTION

This thesis concerns the implementation of direct digital control, using a PDP/8F minicomputer. The project has been undertaken to gain a better understanding of certain aspects of the control theory used, and also the effective use of the minicomputer. The use of this system in the laboratory for the control of a typical system is described.

Direct digital control (DDC) is becoming increasingly important and is often replacing analog means using three-term controllers. Digital control is applied to a continuous process, which is sampled and processed as discrete time data. The z-transformation procedure is especially convenient and useful in the analysis of these systems.

The design method used has already been developed independently by E.B. Dahlin [7,8] and J.D. Higham [16,17]. This has been applied successfully in paper making and cement industries [9]. It has been chosen for its ease of implementation and ability to cater for process dead time, as well as its proven performance.

The objective is to establish an effective digital feedback control system utilizing the above design. Thus the variable feedback signal is compared with the desired set point value. The difference which is the error signal then passes to a digitized compensator which implements the desired control strategy and sends a signal to an actuator. This in turn controls the process element.

The above-mentioned design demonstrates the direct digital concept and is applied in a laboratory situation to the control of a web processing pilot plant. The objective of web process control is to establish an automatic guiding system to control the path of any material in sheet form with uniform width and straight edges running over a series of fixed rollers. This includes materials like paper, plastic, cloth or metal in sheet form. The pilot plant web material is a continuous roll of towel.

The automatic guiding system will thus incorporate the following basic components:-

- (a) Sensing devices (photo cell) which detect the web edge position on the roller,
- (b) A controller (minicomputer) which processes an error signal.
- (c) The actuator which drives the pneumatic guiding equipment, moving an adjustable roller which has been pivoted about an axis perpendicular to and halfway along its length. The guiding equipment turns the roller about the axis deflecting the roller to the right or left and so changing web position.

The controller used is a 12-bit word-length, 8K PDP/8F minicomputer. A manufacturer-supplied floating point software package is used to assist in providing the basic multiplication and division operations. The entire Executive Program utilizes almost 4K of core storage and provides a real-time operating system. This includes an interactive system for setting process parameters and monitoring plant conditions

under interruptable procedures.

The performance and accuracy of the system is directly dependent on the quality of measurement of the controlled process variables. Therefore, the design of digital filtering is necessary to avoid excessive noise distortion of the signal which is transmitted over a distance. The digital filter is implemented in the software Executive Program of the PDP/8F system.

Two control schemes have been investigated. The first, when the web position is monitored by the photo cell which is mounted close to the adjustable roller (see Fig. 3.3). This controller has been proved to be simple and its application is very effective. The second scheme is more complex. Web position is monitored by a photo cell which is mounted further from the adjustable roller after having passed across an intermediate fixed roller. For this system, a two level control structure proves necessary in order to achieve satisfactory results.

Further details regarding hardware and software involved, application of DDC to the web mechanism and discussions of the experimental results are reviewed in later chapters.

The need to improve process efficiency and profitability has produced a demand for improved control over process operations and this in turn has led to the introduction and utilization of computers in the development of the control.

It is hoped that the mentioned design method [9] and its implementation will show that it is possible to achieve a satisfactory digital computer control suitable for application to industrial users since the project is being

directly related to such processes. Thus the constant requirements of certain industries for higher production rates, better quality control work and lower operating costs can hopefully be achieved.

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2. CONTROL SYSTEM DESIGN

The initial section of this chapter introduces a brief review of certain aspects of control technology and Direct Digital Control. This leads to the System Design Method which examines the Process Dynamics of the web and the controller design method. In addition to these, the filter design method is also described.

2.1 Brief Review of Relevant Control System Technology

Computer process control may be defined as the technique of utilizing digital computers to control an overall process, associated equipment, and operating procedures in order to attain performance and economic objectives [1,23].

In contrast, conventional control utilizing regulators and instrumental controllers, attempts to regulate individual process variables with the objective of attaining accurate and stable regulation over a wide range of operating conditions. Thus computer process control is a much broader form of control than conventional control.

The role of the computer in process control applications falls into one of two categories - a supervisory or a control function.

2.1.1 Supervisory Function

For the supervisory function, the operator is still an essential part of the control loop. The computer assists him by providing accurate information on which he can base his decisions. These decisions are made by the operator and not by the computer which has an entirely passive role,

2.1.2 Control Function

For the control function, there are many different methods by which the computer can exercise control. In general the computer will signal to an external device when it requires action by that device. The signal can be interpreted in one of several ways.

- (a) It can represent separate on/off commands for separate devices.
- (b) It can be a representation of an analog voltage. The required voltage is obtained from a digital to analog converter and then used to control equipment.
- (c) It gives the count of the number of pulses to be sent out in a pulse train [3, 4, 12].

2.1.3 Reasons for Computer Control

The advance in computer implementation of control is due in part to the following reasons:-

- (a) Computer systems ensure easy development of control concepts. This follows from the flexibility a computer provides for control experimentation and for ready analysis of data collected in digital form.
- (b) Computer systems using DDC provide instructions directly to plant actuators and embody a higher order of intelligence into the control decisions than is possible with other controllers [28].

In the system described later, interest is focussed on Feedback control, where it is necessary to bring the value of an output variable to some required level. Information is fed back to adjust the values of the input variables. This method of control is particularly appropriate to continuous

processes.

Dynamic Systems are time-varying systems and descriptions of their behaviour make use of differential equations with time as the independent variable. These linear differential equations can normally be solved by the classical approach but this becomes increasingly difficult as the order of the equation increases. The operational techniques based on Laplace Transformation are used instead to simplify the derivation of equations rather than obtain the solution, since the equations are transformed from differential to algebraic equations [13,19].

It must be emphasized that DDC is sampled data control of a continuous process. A powerful, yet simple numerical method for the direct computation of the transient response of feedback systems containing time delays is the use of the Z-transforms [19].

2.1.4 *Concept of Direct Digital Control (DDC)*

The basic function of a process computer is to collect input data from the processes it is to monitor and control. Input may be digital or analog information. The analog information is a voltage which is functionally related to a physical quantity such as pressure or position. The analog data is converted into digital data for computational purposes.

For continuous flow operations, the values of the process variables are read into the computer at regular intervals usually through a multiplexed Analog to Digital Converter. These values are checked against their set points and if there is a difference then the computer calculates

what action it is required to take to remove the discrepancy, It then initiates the action, if necessary using Digital to Analog converters [22].

DDC utilizes the computer as a feedback element in the plant, replacing conventional analog control devices. PID analog controllers are now replaced by a single computer system which is time-shared among many loops. By choosing conventional scanning of analog and digital inputs, the appropriate data is available for processing by the control equation. The result from the equation is then output to the control device [15].

Figure 2.1 shows a block diagram of a DDC system. The control computer communicates directly with the process, not only to obtain input information, but also to issue output commands directly to valve actuators and other process controls and to oversee the execution [26].

The measurement of analog electric signals from transducers is accomplished in the signal conditioning and analog-to-digital converter sections. Keyboards and switches permit the operator manually to enter and request data for individual control loops, such as set points, filter constants, process variables and tuning adjustment gain terms. The display of data for the operator is available in a variety of forms from the computer, including graphic plotting against time and other variables, printed messages and numerical data.

The only remaining functions of the control loop in the figure are computational. These include the calculation of the error between set point and measured variable, the

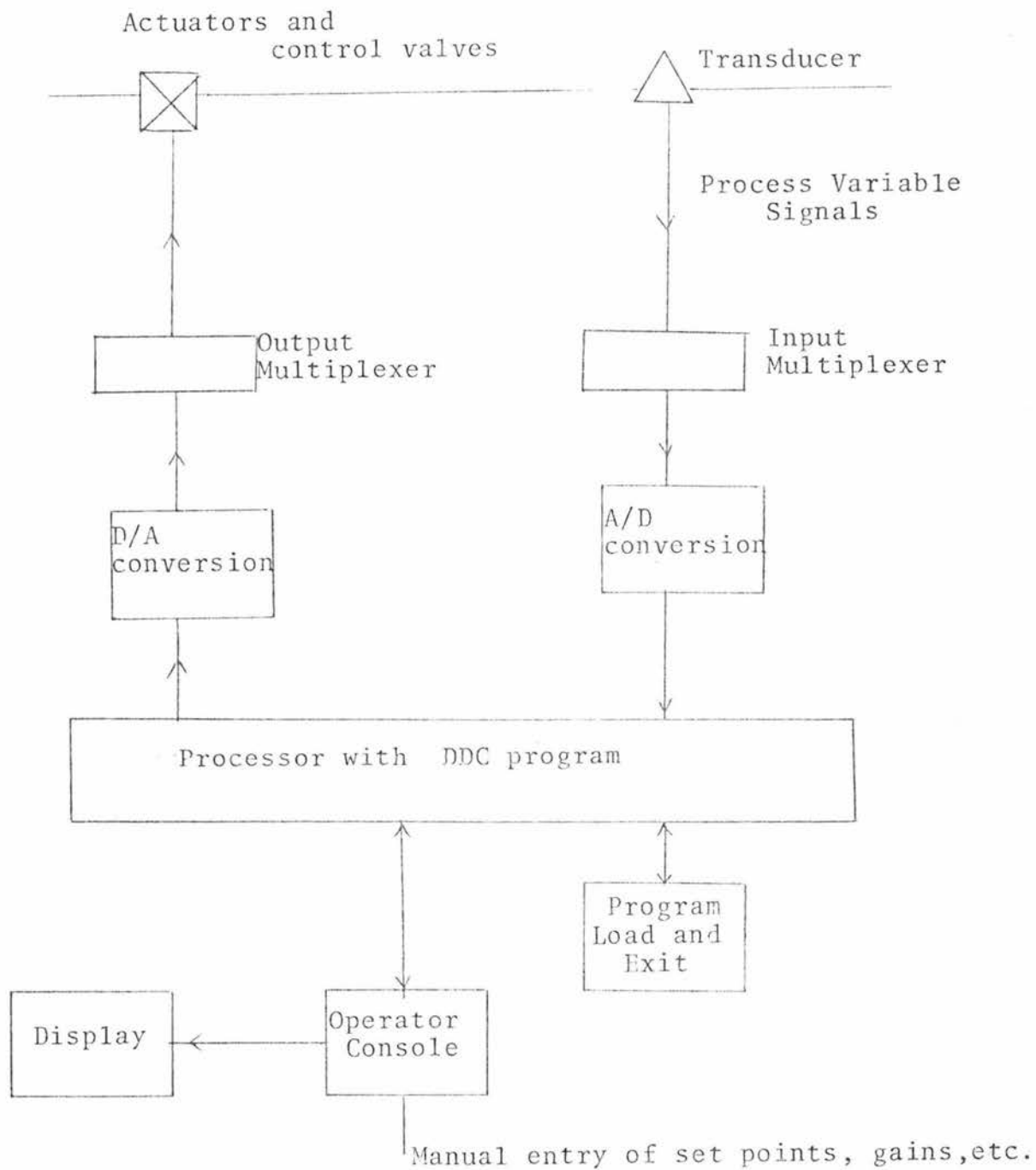


Fig. 2.1 The Direct Digital Control Concept

calculation of valve position from a control equation, and limit checking. All data necessary for these computations such as set points, limits, adjustment-term values, error value, and the equations themselves may be stored in the computer rather than in individual analog elements duplicated for each loop [3, 4, 26].

2.2 Control System Design Method

2.2.1 Process Dynamics

The Web-Handling system can be described by differential equations with time as the independent variable. The dynamic behaviour consists of small deviations of a process variable from steady operating points. This type of behaviour can be described by Laplace Transformations. Thus part of the process can be described by a Mathematical function and is independent of the type of forcing signal applied to the system.

The elements in a web processing system are "first order transfer stages", the dynamics of which are described by an equation of the form:

$$T \frac{dy}{dx} + y = Kx(t)$$

where

t = time

T = time constant of the stage

y = output signal or response

x = input or forcing signal

K = any constant

Figures 2.2 and 2.3 show the displacement of the web on rollers and the time constant for a displaced web respectively, D is the distance between the two rollers, and V is the web speed.[14.]

Figure 2.2

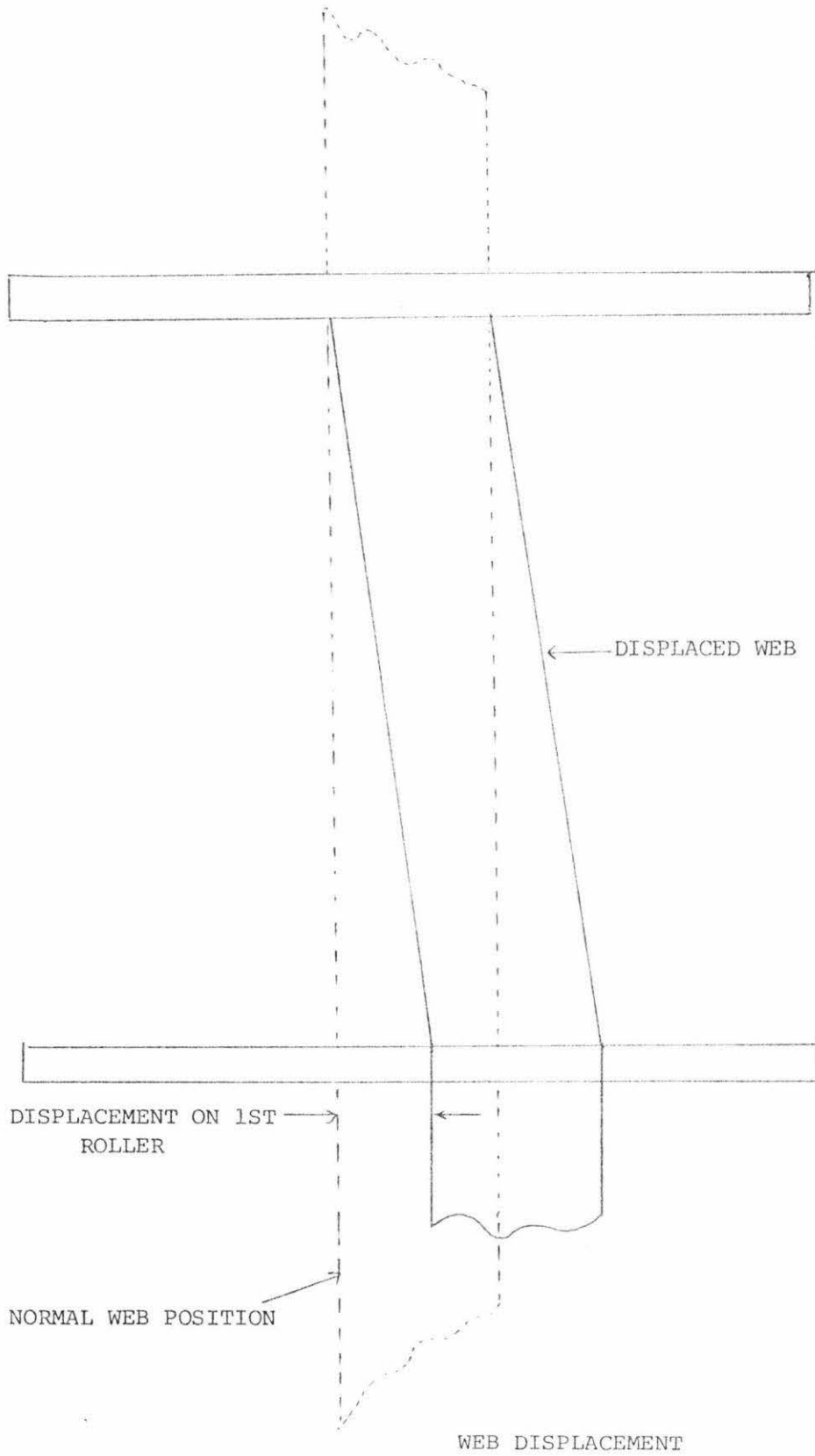
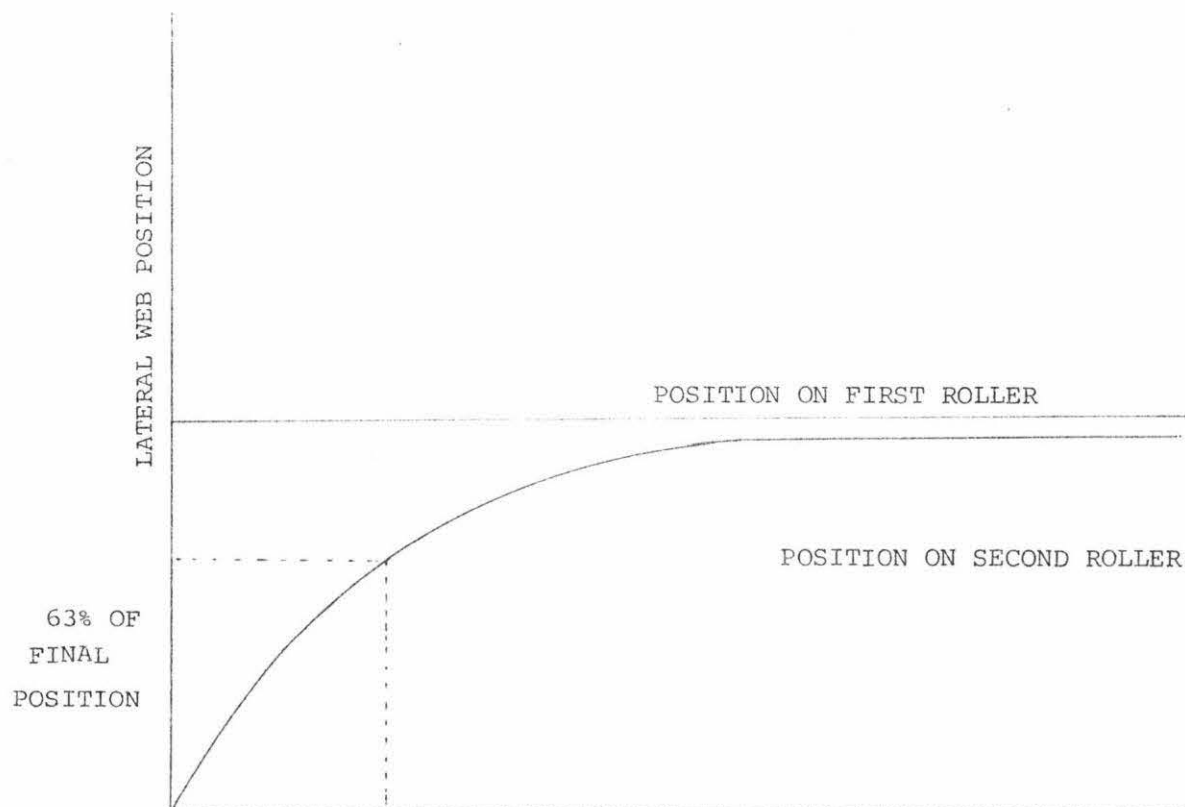


Figure 2.3



$$T = D/V$$

If y = lateral displacement on the second roller
 x = lateral displacement on the first roller

Then $\frac{dy}{dx} = V \frac{x - y}{D}$

Rearranging:

$$\frac{dy}{dt} + \frac{V}{D}y = \frac{V}{D}x$$

$$\therefore \frac{D}{V} \frac{dy}{dt} + y = x$$

Since $T = \frac{D}{V}$

Then $T \frac{dy}{dt} + y = x$

Which is the general form of a first order equation.

Applying Laplace Transformations to this to solve for Y:

$$TsY(s) + Y(s) = X(s)$$

$$\therefore \frac{Y(s)}{X(s)} = \frac{\text{response}}{\text{forcing variable}} = \frac{1}{Ts + 1}$$

$$G(s) = \text{Transfer function} = \frac{1}{Ts + 1}$$

The result for a step input i.e. $X(s) = \frac{X}{s}$ is depicted in the Fig. 2.3 as an exponential rise given by the equation

$$y(t) = X (1 - e^{-t/T})$$

2.2.2 Controller Design Method

Nomenclature:

$G(s)$ Laplace Transform of Process Dynamics

$H(s)$ Laplace Transform of Computer/process interface

$G(z)$ Z transform of interface and process

$D(z)$ Z transform of controller

$K(z)$	Z transform of a closed loop dynamics
R	Set point
C	Controlled variable
W	Disturbance variable
E	Error, $E = R - C$
T_d	Process Dead Time
T_p	Process 1st order time constant
G	Process Gain
T	Control interval
N	Nearest integer of T_d/T
T_r	Required closed loop 1st order time constant.

2.2.2.1 Design Theory

Single Input - Single Output Controllers [9].

Consider a general control loop where variables and dynamic elements are in sampled data form (Z transforms).

Fig.2.4.

The computer/plant interface is modelled as a 1st order sample and hold, $H(s)$, which generates a staircase function $X(s)$ as input to the continuous process transfer function $G(s)$. The 1st order sample and hold is an adequate representation of the interface.

The closed loop transfer function, $K(z)$, which relates process output to set point is then:

$$K(z) = \frac{C(z)}{R(z)} = \frac{D(z) \cdot G(z)}{1 + D(z) \cdot G(z)}$$

$$[W(z) = 0]$$

Equation 1.

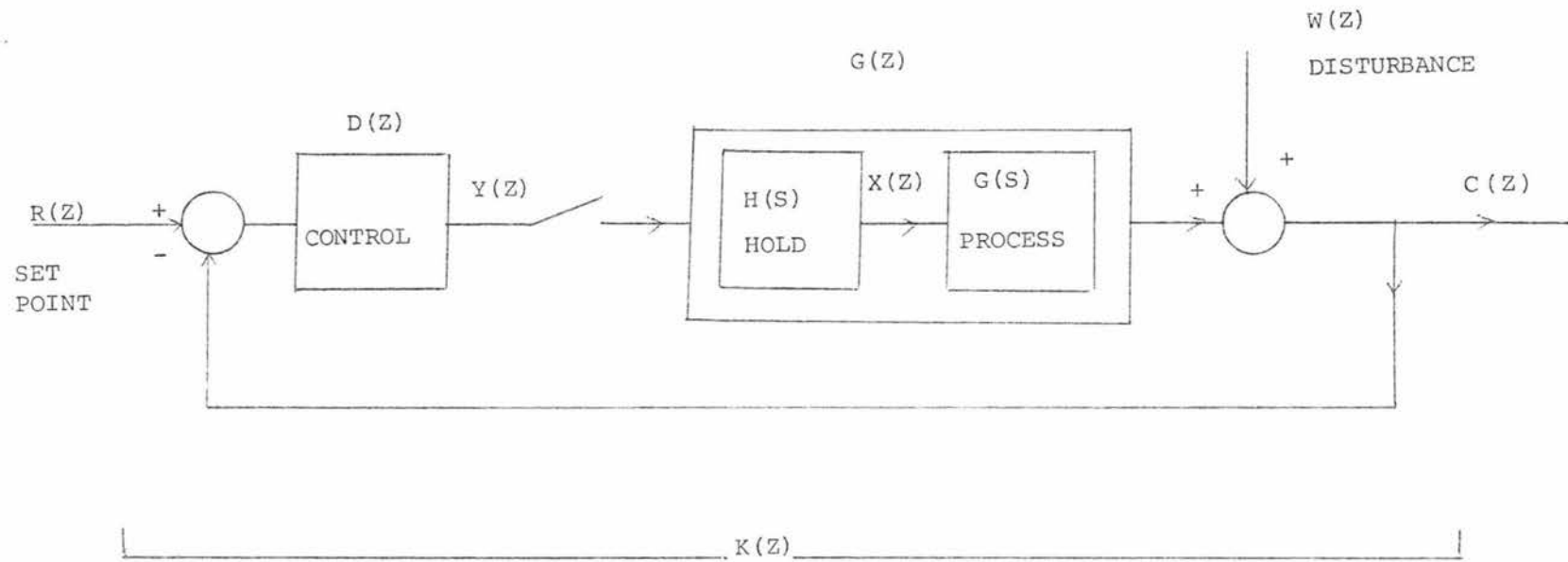


Fig. 2.4 General Control Loop

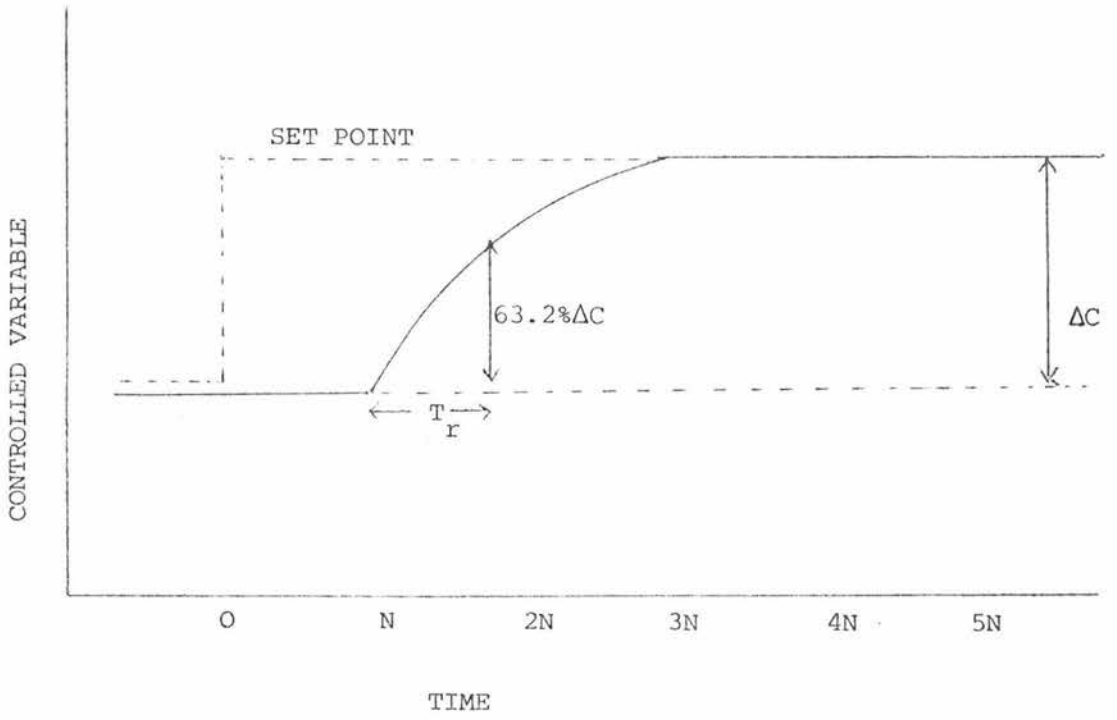


Fig. 2.5 *Set Point Response*

If $K(z)$ is specified, one can solve for the controller transfer function $D(z)$

$$D(z) = \frac{1}{G(z)} \cdot \frac{K(z)}{1 - K(z)} \quad \text{Equation 2.}$$

This general synthesis formula is the origin of many controller designs. The power available to the controller will limit K (at $K = 1$, D is infinite) and no predictive elements (positive powers of Z) can be present in D .

For the Dahlin/ Higham design [7, 8], $K(z)$ is chosen so that the controlled variable shows a delayed exponential approach, to a new set point value.

For a continuous system:

$$K(s) = \frac{\exp(-ST_d)}{1 + T_r \cdot s} = \frac{C(s)}{R(s)} \quad \text{Equation 3.}$$

The response in each case is governed by the parameter Q so that the closed-loop transfer function of the system in Z transform of K is then:

$$K(z) = \frac{z^{-(N+1)} Q}{1 - (1-Q)z^{-1}}$$

$$Q = 1 - \exp(-T/T_r) \quad \text{Equation 4.}$$

T_r is the time constant of the change to a new set point. The delay z^{-N} in $K(z)$ is necessary to cancel the process dead time, T_d , and avoid predictive elements in $D(z)$. The objective is to find the controller $D(z)$ which will achieve this closed-loop response.

Substituting $K(z)$ in the synthesis formula Equation 2 yields the controller transfer function.

$$D(z) = \frac{1}{G(z)} \left[\frac{Q \cdot Z^{-(N+1)}}{1 - (1-Q)Z^{-1} - QZ^{-(N+1)}} \right] \quad \text{Equation 5.}$$

Thus the control algorithm, $D(z)$ contains the parameter Q and the reciprocal of the process transfer function. It is obvious that $K(z)$ will depend on how accurately one knows $G(z)$. For a system where rapid and large changes are made in the control output X , mismeasuring $G(z)$, especially the dead time, can cause poor control and ultimately instability. To overcome this, one has to decrease Q .

For the process transfer function, $G(z)$, the web-processing control loop can be adequately represented by a general dead time plus a first order lag i.e.

$$\begin{aligned} G(s) &= G \cdot \frac{\exp(-ST_d)}{(1 + T_p \cdot S)} \\ &= G \cdot \frac{\exp(-SNT)}{(1 + T_p \cdot S)} \end{aligned}$$

Including the plant/computer interface and transforming to the Z domain,

$$\begin{aligned} G(z) &= Z[H(s) \cdot G(s)] \\ &= Z \left[\frac{1 - \exp(-ST)}{S} \cdot \frac{G \exp(-SNT)}{(1 + T_p \cdot S)} \right] \\ &= \frac{G \cdot L \cdot Z^{-(N+1)}}{1 - (1-L)Z^{-1}} \quad \text{Equation 6.} \end{aligned}$$

$$\text{Where } L = 1 - \exp(-T/T_p)$$

Substituting for $G(z)$ in (5) yields -

$$\begin{aligned} D(z) &= \left[\frac{1 - (1-L)Z^{-1}}{GLZ^{-(N+1)}} \right] \cdot \left[\frac{Q \cdot Z^{-(N+1)}}{1 - (1-Q)Z^{-1} - QZ^{-(N+1)}} \right] \\ &= \frac{1}{G} \left[\frac{Q/L - Z^{-1}Q(1-L)/L}{1 - (1-Q)Z^{-1} - QZ^{-(N+1)}} \right] \quad \text{Equation 7.} \end{aligned}$$

It is usually more convenient to calculate a change in control output rather than the absolute value, i.e. to acquire

$$\begin{aligned}\Delta Y_R(z) &= Y_K(z) - Y_{K-1}(z) \\ &= (1 - Z^{-1})Y_K(z) \\ \Delta D(z) &= \frac{\Delta Y_K(z)}{E(z)} = (1 - Z^{-1}) \cdot \frac{Y(Z)}{E(Z)} \\ &= (1 - Z^{-1}) \cdot D(z)\end{aligned}$$

There is a factor $(1 - Z^{-1})$ in the denominator of $D(z)$ which cancels

$$\Delta D(z) = \frac{1}{G} \left[\frac{Q/L - Z^{-1} \cdot Q(1-L)/L}{1 + QZ^{-1} + QZ^{-2} + \dots + QZ^{-N}} \right] \quad \text{Equation 8.}$$

The above equation is the general form of the control algorithm used for the design of the web processing control system. The correct form for $N=0$ (no dead time) is -

$$D(z) = \frac{1}{G} [Q/L - Z^{-1}Q(1-L)/L] \quad \text{Equation 9.}$$

2.2.3 Aim of Control

The web-processing system is a dynamic system. It is changing with time and is also regarded as an information processing system. That is it receives, digests and generates information as signals of various kinds. The objective of any control system is economic i.e.:-

1. Less labour is required for the process
2. Higher speeds of operation
3. Higher and more consistent quality of products.

The basic control system is depicted in Fig. 2,4. The reference or set point R is normally decided by the operator. In this particular control case, the web edge position, the feedback signal C is the measure of the variable we wish to control. The difference between R and C is the error signal that is $E = R - C$.

This error signal passes to the controller (PDP/8F) which sends out a signal which in turn passes to a control element such as an actuator. This will then control the process by monitoring the web position change to the desired set point value and manipulating the adjustable rollers.

The sensing device detects the web edge position and sends a signal for comparison with the set point reference. The system is most suitable for edge guiding of opaque material.

In the first control scheme, web position is monitored by the photocell which is mounted close to the adjustable roller (see Fig 3.3). This system will require a controller design with no time delay.

The second control scheme introduces time delay into the system. Web position, in this case is monitored by the photo cell which is mounted further from the adjustable roller (see Fig. 3,3). It is necessary to implement a two level control system in order to achieve satisfactory control.

To design and implement the controllers for the control schemes, it is necessary to establish certain essential parameters. These will include identifying open loop

time and gain constants. Careful selection of appropriate filter constant, control intervals and response time constants are required to achieve satisfactory control.

2.3 *Filter Design*

Instrument systems provide information that represents the value of measured variables. Unfortunately, these measurements are subject to error, due to interference or noise introduced by the physical environment. Random disturbances can seriously affect the accuracy of the experimental results. Thus much attention is needed in the design of signal transmission systems to minimize noise-caused uncertainties. Filtering data properly for transmission may help to eliminate noise problems [10,11].

It is better to prevent noise at its source than to remove it later. However, practical constraints such as measured variables being inherently small have limited such engineering practice. More significantly, digital filtering is implemented in the software using programmable logic. In this case, digital filtering or averaging, is frequently desired in order to obtain a single representative value of a signal.

Algorithms are devised that accept the description of operating characteristics and automatically produce the desired filter. If the filter is implemented in software, one can apply several alternatives to the same set of data, inexpensively and quickly to see which gives the most satisfactory result. Hence, the ideal filter for effective performance can be selected by observations of the experimental results.

The filter constant α is designed from the following:-

$$\hat{Y}_{\text{new}} = \alpha \cdot Y_{\text{raw}} + (1-\alpha)\hat{Y}_{\text{old}}$$

Where \hat{Y}_{new} = new filtered value

\hat{Y}_{old} = previous filtered value

Y_{raw} = raw value

and $0 < \alpha \leq 1$

Rearranging the above equation yields

$$\hat{Y}_{\text{new}} = \hat{Y}_{\text{old}} + \alpha (Y_{\text{raw}} - \hat{Y}_{\text{old}}) \quad \text{Equation 10.}$$

The filter constant α can be changed on-line by entry via the teletype. Since it has to be a value between 0 and 1, the design algorithm for this filtering subroutine allows the operator to enter any character from 0 to 8 for the filter constant α according to the equation

$$\hat{Y}_{\text{new}} = \hat{Y}_{\text{old}} + \frac{\alpha}{8} (\hat{Y}_{\text{raw}} - \hat{Y}_{\text{old}}) \quad \text{Equation 11.}$$

This equation has the same effect as restricting the filter constant between $0 < \alpha \leq 1$. The maximum value of 8 instead of 10 is used in order to simplify programming procedure in the conversion of octal or decimal units.

The desired filter constant can be selected by observing the experimental results in later applications.

3. HARDWARE & SOFTWARE

This chapter describes the process computer control equipment involved in the system. It deals with both the control hardware which is associated directly with the process, and the control software system which can be described as everything over and above the hardware required in order for the computer control system to function [27].

The first part of this chapter describes the details of the computer apparatus involved. The second part describes the details of the web system. The real time software system is explained in the final section of this chapter.

3.1 *Computing Apparatus.*

The process computer used in this system is the PDP/8F minicomputer manufactured by Digital Equipment Corporation [see fig. 3.1]. The system has 8K of core memory. For the PDP/8F, the 12 bit word length allows addressing through 4K of memory. Additional 4K memory fields are catered for by extended memory addressing, which adds 3 bits to the memory address register, allowing 8 fields of 4K, thus providing a total maximum capacity of up to 32K of core memory.

The standard set of instructions for the PDP/8F includes eight basic instructions. The memory reference instructions require a nine bit operand to specify the address of the location to which the instruction refers. To make the best use of the available nine bits, the PDP/8F utilizes a logical division of memory into blocks (pages) of 200 octal locations each [18]. In summary, the PDP/8F has the limitations of:-

- 1, 12 bit words
- 2, Fixed pages,
3. Limited instruction set.

Bearing in mind these limitations, the lowest 4K field of the PDP/8F core memory has been used for the programming of the Executive System, To use anything more than 4K will require an address of more than 12 bits and hence extended memory addressing.

The Assembly Language is used for the programming simply because no suitable higher level languages are available which will run on the existing system with the restriction to 8K of core.

Terminal Input/Output operations are provided by a 10-character per second combined paper tape reader/keyboard/printer/paper tape punch - the Teletype ASR 33, Fig [3.1].

I/O operations can utilize the data break, interrupt facilities, or may examine device flags, using a skip facility, under program control. The program interrupt facility allows certain external conditions to interrupt the computer program. It is used to speed the processing of I/O devices or to allow certain alarms to halt program execution and initiate another routine. The one bit register interrupt request flag normally contains an 0, but it is set to 1 whenever a device requires servicing, [18].

Programming for the PDP/8F is assisted by the Cassete Programming System (CAPS-8) which uses a TU-60 dual cassette unit [see Fig. 3.1]. It is designed around the use of cassettes for program storage and replaces paper tape completely. It also provides the user with a keyboard monitor, I/O facilities at monitor level and a library of system programs.



Fig. 3.1.

The photograph shows the ASR-33 teletypewriter console at the extreme left. Beside it, is a TU 60 dual cassette drive unit with the PDP-8/F Programmer's console on the top of the unit.

The CAPS-8 cassette is a magnetic tape device [2].

A real time clock uses a crystal oscillator to provide interrupts at selectable intervals from 20 μ sec to 1 sec.

The clock interrupt signal is counted down to yield an interrupt every one second (1Hz) for the present studies. The period between interrupts is not program selectable, and must be preselected by a hard-wired modification.

The A/D converter system enables the user to sample analog data and to store the equivalent digital value in the memory of the PDP/8 for subsequent processing. For the PDP/8F system, the A/D converter is the ADS-EA, a 10-bit successive approximation converter with sample and hold circuits, conversion circuits, an input buffer and control logic. It is used with the AMS-EA multiplexer boards to perform conversions on up to 8 channels and permitting full-scale inputs of ± 1 volt [21].

The digital-to-analog (D/A) converters that exist at the output line have the task of converting computer determined set points to electrical analog signals and maintaining the signal while the computer performs other computations.

Two D/A channels have been used. One channel provided the activation signal for the system under control, while the other provided an analog output of the measured system response. Both these channels were displayed on a National two pen recorder.

A block diagram of the system's general organization is illustrated in figure 3.2.

3.2 *The Web System.*

The pilot plant for the web process has been designed and constructed in the IME laboratory at Massey University. The unit is designed to show the important aspects of web

General Organization of Computer System

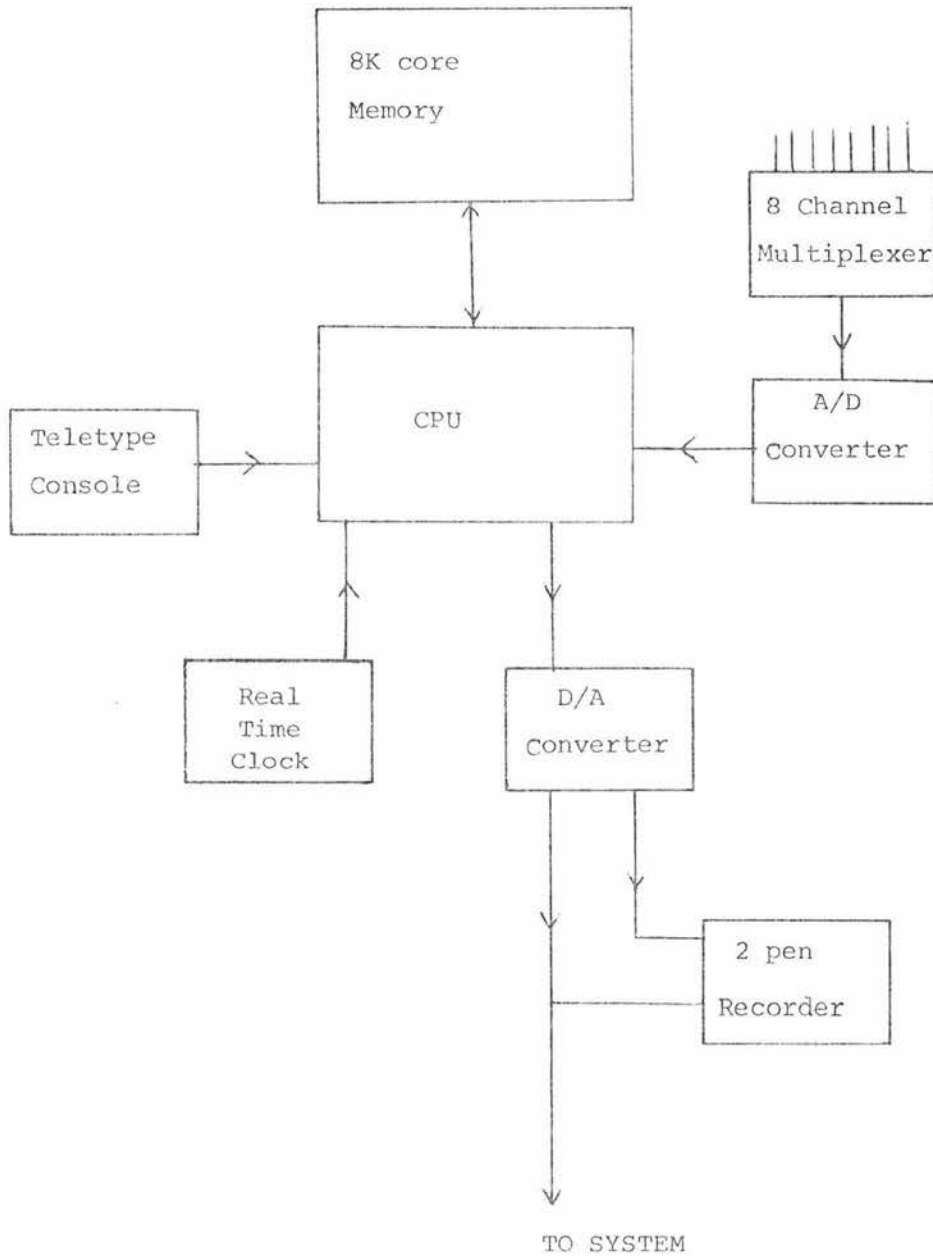


Fig. 3.2

processing especially in guiding techniques. This unit is illustrated in Fig 3.3,

It is seven feet in height by twelve feet in length and consists of a basic frame on which many attachments can be placed and moved at will to show any particular aspect of web handling. These components include unwind and rewind stands, idler rollers, adjustable roller, web guides, photo-electric sensors and an assortment of other electronic control elements.

Web processes are used in the winding and/or unwinding of a plain web such as a sheet of paper, felt, any textile or plastic - anything in sheet or web form, running over a curved roll. In this illustration (Fig 3.3) the sheet is a towel. The ends of the towel are joined to form a continuous sheet. It is permanently stretched along the rollers. The equipment is used in the development of an automatic guiding system to control the path of the web, compensating for the errors in the lateral position of the material as it passes over the rollers.

Nowadays, guiding systems are sophisticated and have been designed mainly for automatic control. This demand has resulted because of faster machine speeds, higher quality requirements, increased material costs and high labour costs.

A variety of guiding techniques are available, varying in reliability and cost. In most guiding systems, the web approaching a roller does so perpendicularly to the axis of the roller. The automatic guiding system will thus incorporate the following basic components:

- (a) A sensing device which detects web edge position.
- (b) A controller which processes an error signal,
- (c) The guiding equipment which is moved by an actuating device. [14.]

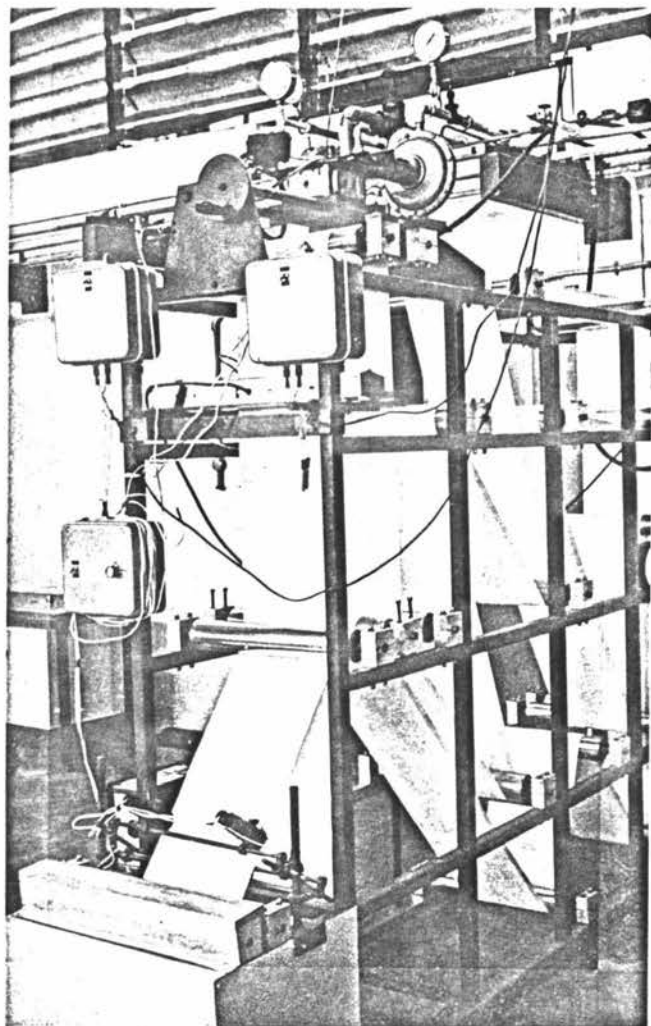


Fig. 3.3

The photograph shows the pilot-plant web processing equipment. The web is an entire piece of towel, joined at the ends. The bottom left corner shows the second set of photo-electric sensors. Located at the same side along the top of the frame is the other set of sensors.

The performance and accuracy of the system is directly dependent on the quality of measurement of the controlled process variables. All measuring and control instruments involve the transmission of signals which are electrical in this case, back to the controller. Digital filtering has been introduced to assist in avoiding excessive noise distortion of the signal after it has been transported over a distance. The basic guiding techniques involve the following:

- (a) Initially, the electronic sensing device detects the web edge position.
- (b) This information is fed into the computer. The signals are converted from analog to digital form at the computer. A binary actuating signal is calculated by the computer, converted to a voltage by a digital-to-analog (D/A) converter, and transmitted to an actuator.
- (c) The actuator now drives the pneumatic guiding equipment which in turn adjusts the web position by turning the adjustable roller in the appropriate direction.

The sensor detects the position of the web as it travels through the processing line. The sensing head must be able to detect errors instantaneously and send the signal to the computer unit. The latter then decides how to activate the system to compensate for any displacement error that has been detected.

The particular sensor used in this system is the photo electric type. It is especially useful for edge guiding of opaque materials. Two photo electric cells monitor the position of each edge of the roller and are excited by a controlled light source. Their outputs are combined differentially to provide a signal which changes as the towel moves

from one side to the other,

Any lateral movement of the towel will result in action from the controller to adjust the moveable roller, shifting the towel and restoring the set point signal level.

The sensing device must be accurate, sensitive and consistent because web processing is a high speed operation.

A schematic diagram of the web process system is illustrated in Fig 3.4. As observed, the idler rollers fixed to the frame merely help to give the tension control to the web to provide a smooth running process. The unwind and rewind stands are replaced by idler rollers since the towel is a single sheet joined at both ends to provide a continuous loop for the research demonstration.

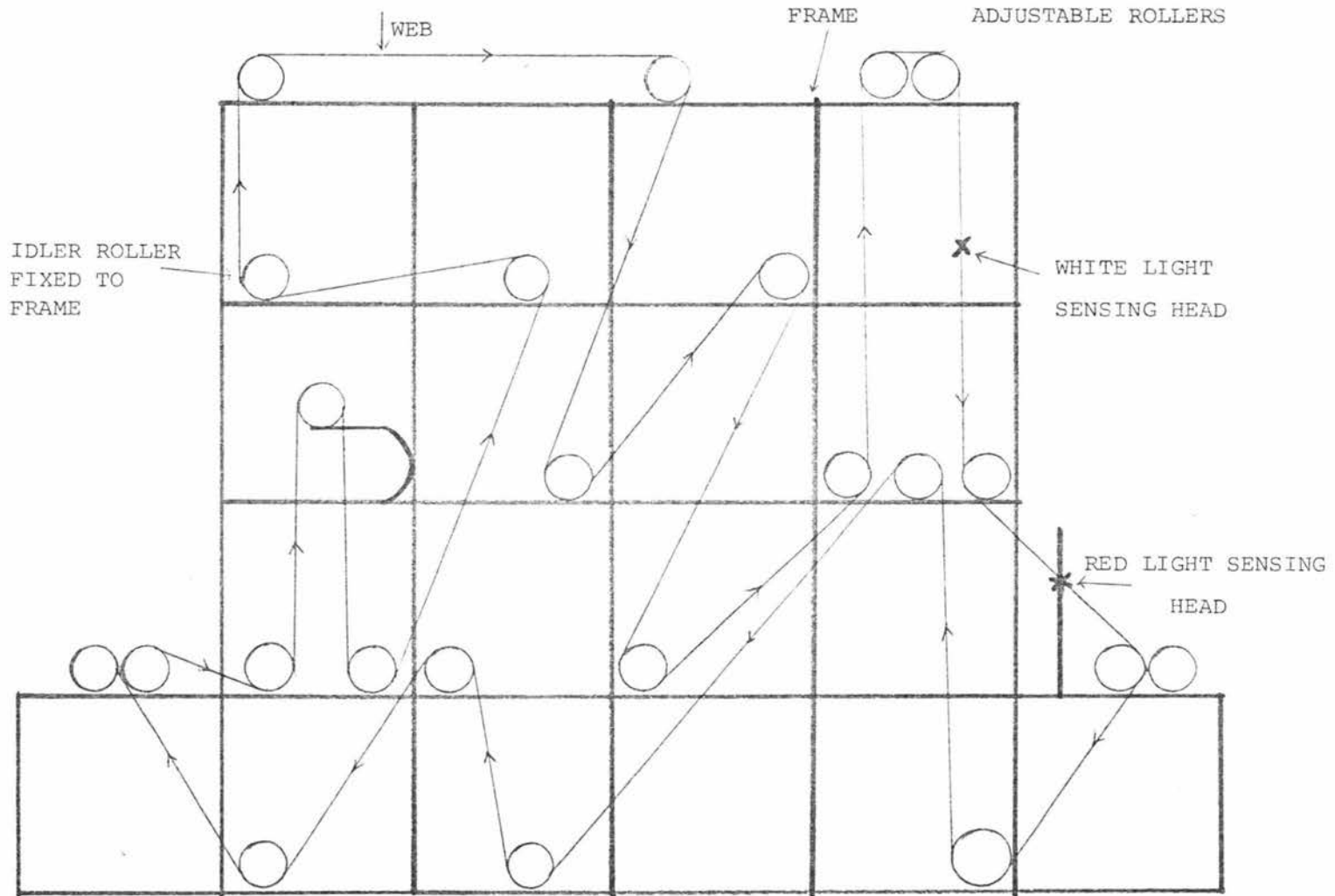
3.3 *Real Time Computer Software System.*

The computer system has been installed to provide Real-time computing facility in the research laboratory. This involves on-line data acquisition and the analysis and display of process control activities. The system is a PDP/8F mini-computer. The aim of the project is to develop a real-time operating system for the PDP/8F with special emphasis on simplicity, efficiency and avoidance of superfluties.

A typical process control software system consists of a number of programs which operate together to control some external process. The program which co-ordinates the execution of these programs is called the operating or executive system [6].

A complete process control system is made up of many different programs, some of which are executed at fixed intervals and some at the occurrence of external events as signalled to the computer through its interrupt structure.

Fig. 3.4. Schematic Diagram of the Web System.



One useful way to consider an operating system's role in a process control environment is that the operating system is responsible for the control of the computer itself, allocating that computer to the various programs necessary to control the process. The operating system controls the computer while the computer controls the process.

A real time computer system is defined as one which controls an environment by receiving data, processing them and taking action or returning results sufficiently quickly to affect the functioning of the environment at that time [24].

Real time computing systems are of major importance in automatic control process applications, where a number of rapidly changing variables must be monitored, analysed and controlled continuously to produce an optimum result.

For this particular operating system the Executive is described as the Simple Mainline routine which is directly dependent on the console switches. All routines relinquish control either directly or indirectly to the switcher, and the switcher in turn routes control to the appropriate routine. This procedure is based on the continuous scanning of the switches to determine if there are any changes that require the initiation of different routines. The problem is relatively independent of time. The various routines assigned to the individual console switches are listed in Appendix 1.1.

The operator activates program sequences by depressing the appropriate program select switch. A typical sequence of events following a program request is as follows:-

- (a) Mainline Routine acknowledges the receipt of the request and initiates the selected program.
- (b) The Program prompts the operator with a message.
- (c) Operator types a response which is returned to the

requesting program,

(d) Program proceed as directed.

The entire procedure for entering the systems program is given in Appendix 1. The starting address for this mainline or background routine is at location #200(octal). In addition to scanning the console switches, the background routine also checks for fault conditions. Error messages associated with the process are printed out if an "OVERRUN" condition does occur in the system. The key to the error messages is given in Appendix 1.2 and the "OVERRUN" conditions are defined in the same Appendix.

The basic flowchart of the Mainline Routine is illustrated in Appendix 2.1.

Virtually all process control computers require a real time clock. The purpose of the clocking routine "CLSTAT" is to use the periodic interrupt of the hardware clock to control and initiate all operations which are time dependent. This includes updating a counter which is accessible to all tasks such as one which interrupts the A/D routine at a specified interval. Once the mainline routine is in progress, the clock start can be easily initiated by depressing console switch 3. Other routines that can be interrupted at specified intervals are illustrated in the flowchart of Appendix 2.2.

The operating system caters for both open and close loop control of the process. The computation of the arithmetic involved in the process is done using the supplied floating point package. This package occupies almost half the 4K of core store used with 1553 (decimal) words. Neglecting page zero and final page which contains the bootstrap loader and binary loader programs, there are only

$$[4096 - (1553 + 128 + 128)] = 2287 \text{ (decimal)}$$

words left available for programming the operating system [5].

Computation is performed in binary units and hence a conversion procedure that caters for the entry of decimal numbers from the keyboard is preferred. This involves programming the PDP/8F to allow for entry of the ASCII characters which are converted to digestible binary units. With the aid of the floating point arithmetic package, it is possible to convert these units to the appropriate decimal form for computation in the control algorithm.

The reverse which converts the decimal computed value to binary form is assisted by the same package. The entire procedure for the conversion and the subroutine involved is given in Appendix 3.

In order to introduce the control function of the system, it is necessary to enter the control interval values for the appropriate intervals as illustrated in Appendix 3.5. Switch \emptyset has been assigned to this routine named "ININT". In response to the message "VALUE?", the control interval is chosen as integer multiples of the basic service interval and entered via the teletype. The procedure for entering these interval values is explained in Appendix 3.5.

To display the interval values at anytime, the operator has to initiate the routine "PINT" via switch 11. The print out of this message is illustrated in Appendix 3.5. Before designing the closed loop control algorithm for the process, it is necessary to obtain certain open loop characteristics of the system. To do this, it is necessary to interface the computer with the process. For this particular system, the web remains stationary and a step change in response is introduced into the system. The output of the step change is recorded and the open loop gain and time

constant estimated from the result. In order to introduce the step response it is necessary to design the open loop control algorithm for the process. The entire program is initiated in the normal way. Then a step change is introduced into the system by entering a new set point value via the routine "INDAC".

The procedure is explained in detail in Appendix 3.3. Once the program is initiated via switch 1, the operator can select the choice of entry to either channel X or Y of the D/A converter. In response to the question "VALUE?", the operator will enter the desired step change value.

Valid entries range from +511 to -511 (decimal). At any time, the operator may initiate routine "PDAC" to print out all the values associated with the two channels respectively. Switch 9 is allocated to this routine and the entire procedure is found in Appendix 3.4.

In addition to the digital to analog converter, there is the analog to digital converter. The purpose of the A/D routine is to control all data sampling performed with the A/D converter. The A/D routine is entered at specified intervals according to the clocking interrupt routine. An analog scan routine scans all the eight channels periodically. The routine is illustrated in Appendix 2.

In order to keep track of the current values of all the 8 channels (0 to 7) of the ADC, it is necessary to activate the routine named "PADC". This routine, once initiated will list the appropriate values stored in the channels at the requested time. The print out message can be examined in Appendix 3.6.

The open loop constants obtained from the system can then be used to design the closed loop control algorithm,

As observed from the equations 13 and 14 the parametric constants need to be entered via the teletype initially for Direct Digital Control action. The routine "FLIN" caters for the entry facility and the explanation for the entire procedure is found in Appendix 3.7. The routine enables the operator to enter all integers in the form of an exponent E and mantissa M. To this effect, the operator is required to type in any 4 digits with a decimal value less than 2047 in response to both letters E and M, which are prompts from the computer.

In addition to supplying these parametric constant values, the control interval values, selected filter constant, set point values and plotmark are to be supplied initially before introducing any control function.

The filter constant value can be changed directly by initiating the routine "FLOUT". The entire entry procedure is explained in Appendix 3.8. In response to the query "VALUE?", the operator is limited to enter value from 1 to 8 for the filter constant.

The same routine "FLOUT" also caters for the operator to enter set point values for both the controllers. In response to "%" the operator types 1 if a set point relating to a value from the sensors nearer the guiding roller is to be entered, and 2 if the alternate sensors are to be used. This is followed by entering the set point value in response to the question "VALUE?"

In addition to these, "FLOUT" also caters for operator

selection of the appropriate plotmark to display the desired output response, Character 4 has to be typed in response to "%" followed by the appropriate number from 1 to 4. The resulting display is described in Appendix 3.8. When all these parametric constants have been entered through the appropriate routines via the respective switches, the operator can now initiate the control function.

It is necessary to operate switch 4 for the Primary Controller to activate process control. When the system is performing satisfactorily, the Secondary Controller is introduced with the time delay case. This can be activated by operating switch 3.

The routine named "INBIT" allows the operator to enter bit status for the desired output register. The programmer may assign this output register as he wishes e.g. this function may be used for switching operations via the Digital Output interface.

This routine has not been used in the system but has been included should any need for its use arise. The Appendix 3.1 describes this procedure in more detail. To inspect the input/output bit register status, it is necessary to refer to the routine named "PIOS". This routine, when initiated will print out all bits of the status registers for both input and output at any time. Print out may be observed in Appendix 3.2.

If the operator needs to know which routine is associated with the appropriate console switch, he has only to activate the routine "SWITCH" by operating switch 7. When initiated, the routine will print out all the switch numbers and the various routine names associated with them. A listing

of this print out is illustrated in Appendix 3,9,

Thus, with the capability of the operating system as described, the operator can now proceed to apply this program to the web system.

-ooOoo-

4. APPLICATION OF DIRECT DIGITAL CONTROL TO THE WEB MECHANISM

This chapter describes the connection of the PDP/8F computer to the pilot web process. The design and implementation of control systems to position the moving web is discussed. Two control schemes are investigated. For the first, web position is monitored by the photo cell which is mounted close to the adjustable roller (see Fig. 3.3). This controller proves to have a simple structure and the application is very effective. The second control scheme is more complex. Web position, in this case, is monitored by the photo cell which is mounted about four feet from the adjustable roller. The web has to pass across an intermediate roller before position is monitored (see Fig. 3.3). A two level control system structure proves necessary in order to achieve satisfactory control at this point.

4.1 *Filtering measurements*

When the web is moving on the rollers, the signals recorded at the computer from the photoelectric devices are very noisy. This is because the edge of the web is not uniform and in certain patches rather jagged. To obtain a reasonable estimate of the average position of the edge of the web, it is necessary to incorporate the exponential filter of equation 11. The degree of noise requires the selection of filter constant α of about 1 second. This value has been arrived at simply by observing the filtered

measurements and choosing the smallest value of time constant which is effective in smoothing the original noisy signal.

4.2 *Step Response of Process*

To design a control system, using the methods outlined in Chapter 2, it is necessary to obtain an estimate of the process gain and time constant. This has been achieved by injecting a step input into the process, i.e. step adjusting the position of the movable roller, and monitoring the response of the web position. It is important, in such an experiment, that the filtered measurement is inspected so that the dynamics of the filter are accounted for in the evaluation of the process characteristics,

The first experiment is concerned with the evaluation of web behaviour at the photocell close to the adjustable roller (see Fig. 3.3). At this point, response is immediate following an adjustment of roller position. The web, in this case may be maintained stationary on the rollers. This avoids the difficulty that can result if the web drifts from side to side as it moves past the monitoring point. Such drifts can make the step response characteristics difficult to interpret. The photocell position is so close to the roller that the system response is identical whether or not the web is in motion.

The computer provides a step change to the activation signal and the resulting response is recorded. The system is identified as a first order system from its step response. Fig. 4.1 illustrates such a typical step response. The figure displays the step input variable and the controlled variable output of the system with respect to a common time base,

Fig. 4.1 Loop Characteristics Identification.

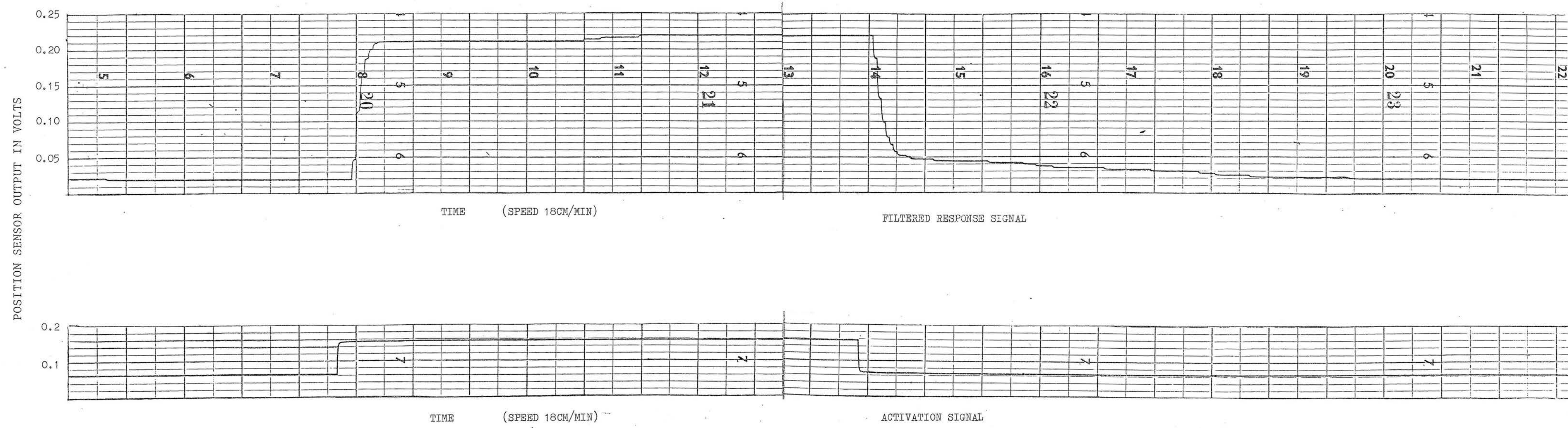
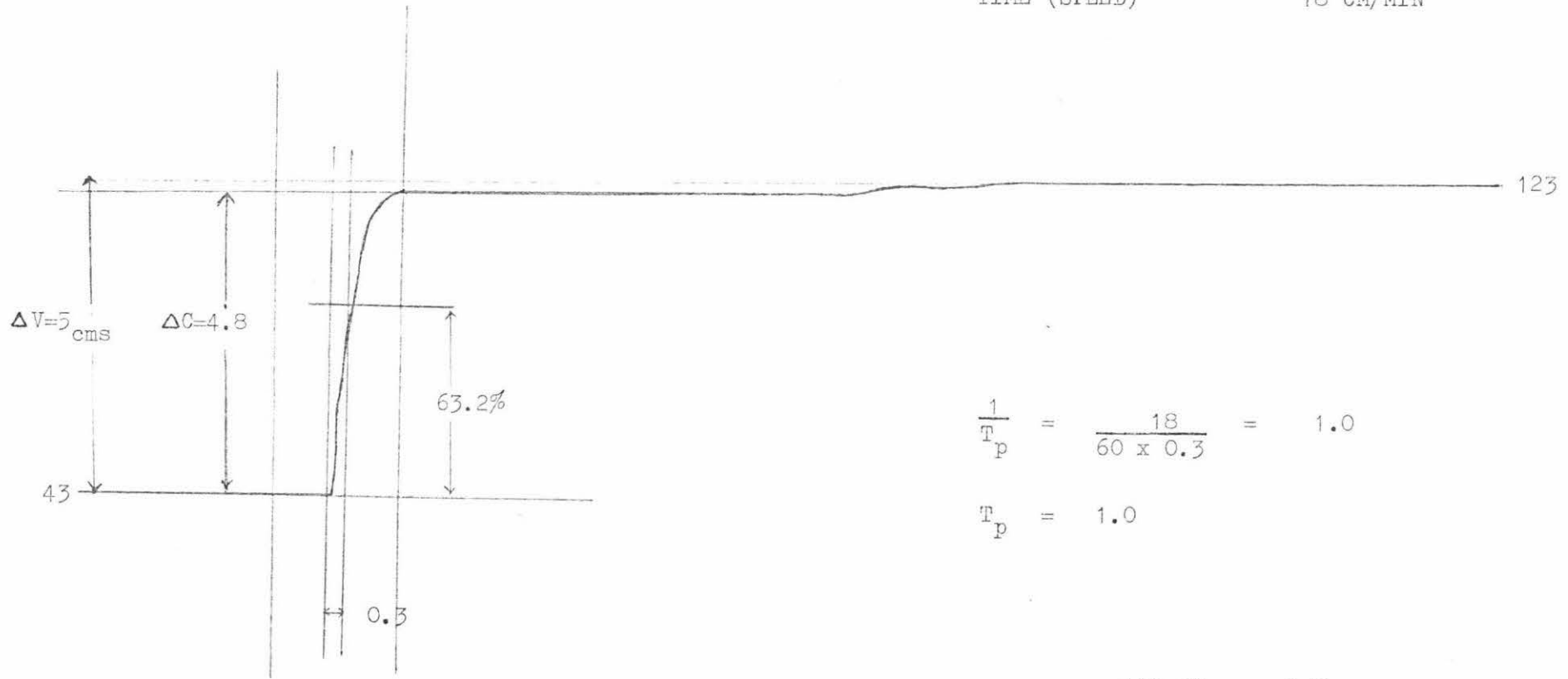


Fig. 4.2

Loop Characteristics Calculations.

DAC VALUE	160 → 80
ADC FILTERED VALUE	123 → 43
TIME (SPEED)	18 CM/MIN



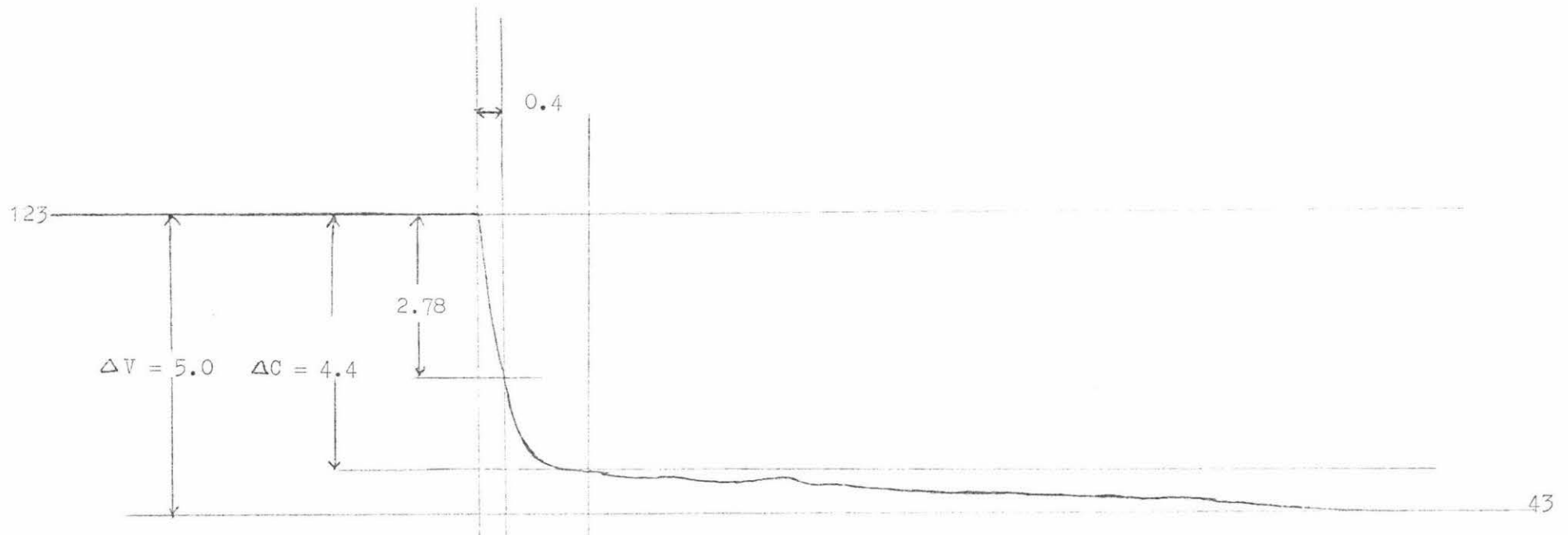
$$\frac{1}{T_p} = \frac{18}{60 \times 0.3} = 1.0$$

$$T_p = 1.0$$

$$\text{Gain} = \frac{123-43}{160-80} \times \frac{4.8}{5} = 0.96$$

Fig. 4.3

Loop Characteristics Calculations



$$\frac{1}{T_p} = \frac{18}{60 \times 0.4}$$
$$\therefore T_p = \frac{24}{18} = 1.33$$

$$\text{Gain} = \frac{123-43}{160-80} \times \frac{4.4}{5} = 0.88$$

A tangent has been drawn through the steepest point on the step response graph. Where this cuts the line of the initial value of the response gives the approximate dead time T_d . In this case T_d is zero since the non-time delay case is considered.

The time at which 63.2% of the rise is complete gives the process time constant T_p . The value of the gain as shown in Fig. 4.2 is given as gain $K = \Delta C / \Delta V$. The tracings from Fig 4.2 and Fig 4.3 enable the calculation of the open loop gain and time constants for the system to be made. From the experimental data, the average values are selected as follows:-

$$\text{Dead Time, } T_d = 0 \text{ second}$$

$$\begin{aligned} \text{Gain, } K &= \frac{1}{2}(0.88 + 0.96) \\ &= 0.92 \end{aligned}$$

$$\begin{aligned} \text{Process Time Constant, } T_p &= \frac{1}{2}(1.00 + 1.33) \\ &= 1.16 \text{ seconds} \end{aligned}$$

4.3 Control of Process without time delay

The data obtained from the open loop characteristics experiment (section 4.2) on the web processing system are now utilized to design the controller without time delay. The equation 9 (Chapter 2) requires the selection of the five appropriate parametric values namely gain K , control interval T , process dead time T_d , process time constant T_p , and response time T_r . These values will assist in deriving the constants A , B and C to be entered via the teletype into the controller algorithm of the form (overleaf)

$$\Delta U = AY_{sp} - BY_o + CY_1 \quad \text{Equation 12}$$

as derived from the controller equation 9 of Chapter 2.

The values arrived at by keeping $T_d = 0$, $K = 0.92$ and $T_p = 1.16$ constant while varying T and T_r before they are selected,

From experimental observations and taking into account the speed at which the computer is processing the controller, the control interval has been selected as $T = 0.5$ second.

As suggested in [9] that, a set point change to a controller, for which $T_r = T_p$ should be accomplished by one change in controller output. However, in this experiment, when $T_p = T_r$ is introduced, the system does not respond as suggested. Instead, instability appears to set in endlessly with a set-point change to the system. This is depicted by the random oscillating output responses. Since $T_r = T_p$ does not give adequate set-point response, selecting another suitable value of T_r is necessary.

T_r has been progressively manipulated until satisfactory operation is achieved. The final value arrived at is being reduced to $T_r = 0.5$ (compare with $T_p = 1.16$ initially). Smaller values of T_r eventually tend to cause instability as depicted in the earlier experiment with $T_r = T_p$.

It is essential to determine the working range for set-point changes. Hence, the saturation limit for the adjustable rollers to deflect right or left has to be predetermined. This can be performed by injecting step-responses to the stationary system with no controller and recording the data as in Appendix 5. Reference to these experimental values show that appropriate set-point ranges

are best selected around DAC values of 0 - 200 to permit satisfactory results for a linear system.

The response in Fig. 4.4 is the best obtained after a large number of observations. The controller is able to respond very rapidly to any set-point changes and maintain the system in a satisfactory manner.

The typical values selected for the system are $K = 0.92$, $T_p = 1.16$, $T_r = 0.5$, $T = 0.5$ and $T_d = 0$. Using these data, the controller algorithm as designed from equation 9 yields the controller of the form:

$$\Delta U = 0.73Y_{sp} - 1.96Y_0 + 1.23Y_1 \quad \text{Equation 13}$$

the calculation of which is found in Appendix 4.1 and the computer algorithm for this controller is in Appendix 4.

The typical output response to a set-point change is depicted in Fig. 4.4. It is clearly observable from the response that there are variations about the set point. The variations are distributed fairly evenly with a defined upper and lower bound limit.

There is however, the exception of a prominent disturbance as indicated. This is caused by the poor joint of the towel (see Appendix 6). The ends of the towel are joined so that it forms a continuous loop for the purpose of the laboratory experiment.

The prominent disturbance feature appears at every cycle of the loop and has to be tolerated by the system.

Noise, which has been filtered as described earlier in section 2.3 is still a disturbance contributing factor, although to a lesser degree.

Other factors that can account for the variations

CONTROLLED VARIABLE OUTPUT IN VOLTS

Fig. 4.4 Set-point changes under first set of sensors with controller in action when web system is in progress.



ACTIVATION SIGNAL IN VOLTS

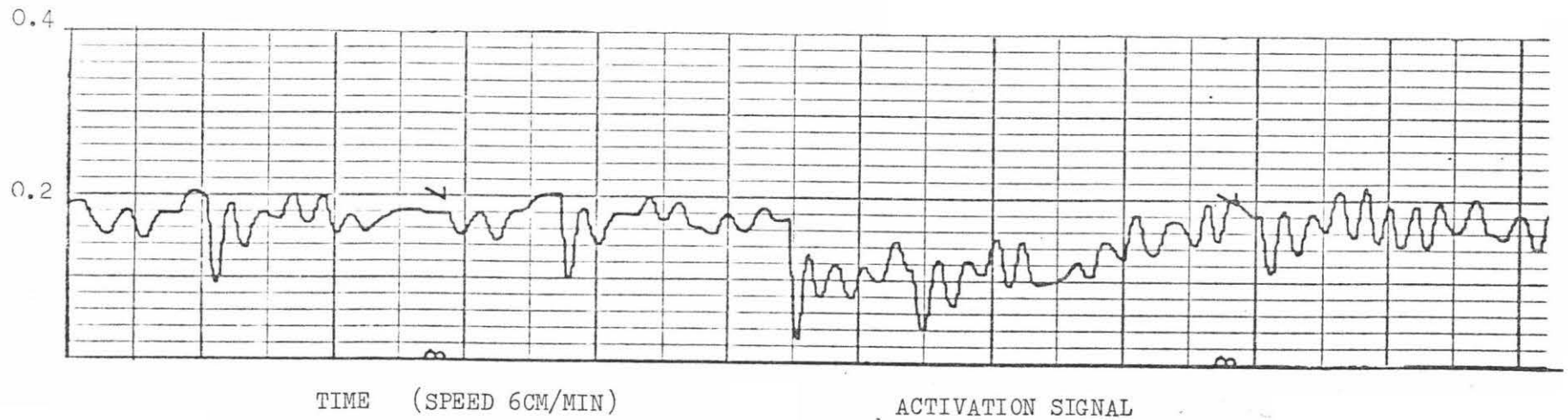
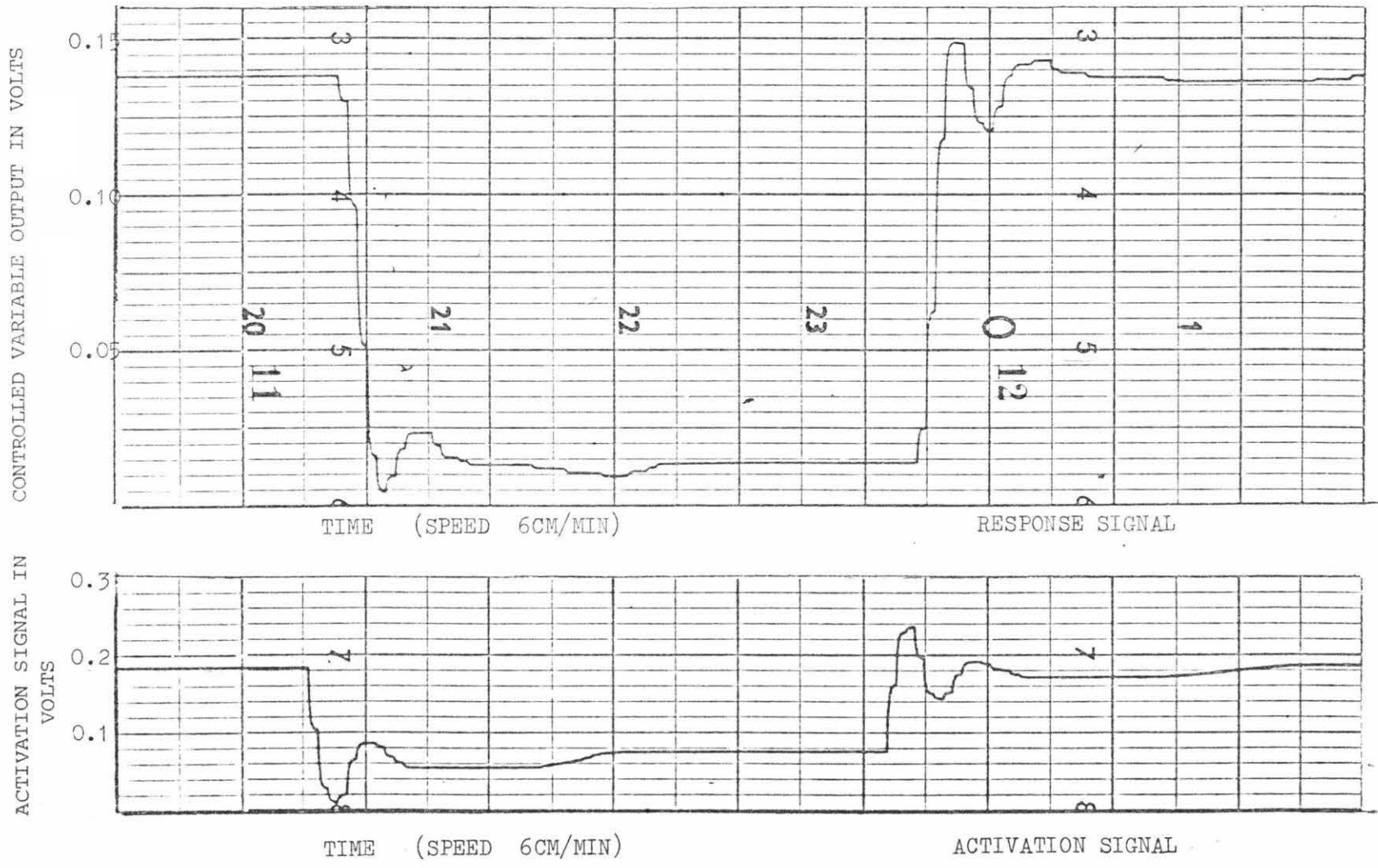


Fig. 4.5 Set-point change with controller in action but the web stationary.



are described below.

The towel being not uniform in width has jagged edges (see Appendix 6). The towel has to be located as centrally as possible to allow for efficient edge guiding. Any deviation, caused by jagged edges, deflection of towel to one side, and other errors will activate the controller to cause the necessary corrective action.

Tension control is fairly important although not attended to in this respect. It must be emphasized that without tension, the web will be limp and cause slipping. Slipping is accompanied by a sideways sliding on the extremely smooth surfaces of the rollers when the process is operating at a fast speed. Some rollers may rotate faster than others and will help to intensify slippage. Even a slight gust of wind on the limp towel will add to the slippage effect thus causing disturbance.

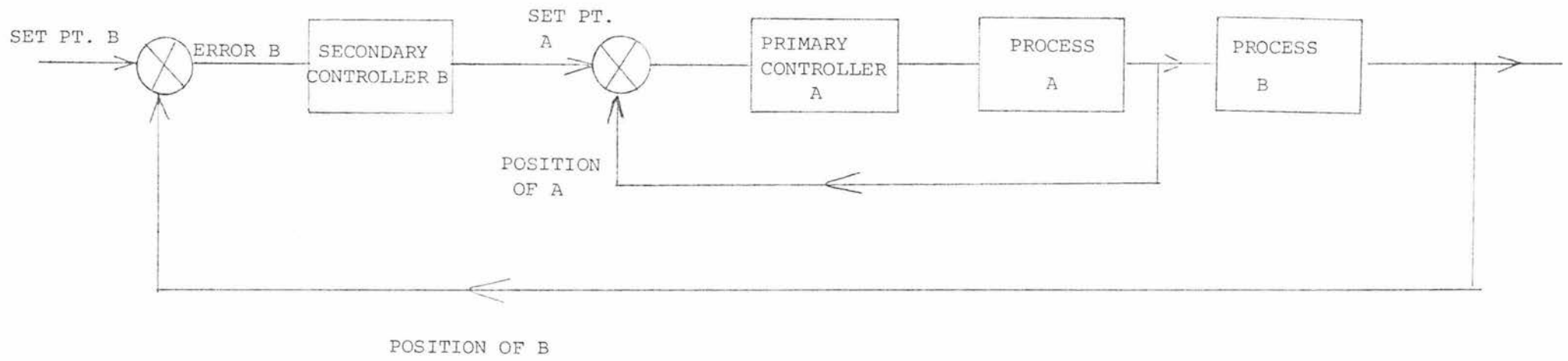
The improvement of these factors have to be considered if a much better response is required. For the purpose of this exercise, the system is performing satisfactorily and it is appreciated that the digital controller is responding rapidly enough for corrective action.

4.4 *Two Level Control System*

A system incorporating time delay is introduced in the second control scheme. In this case, the web position is monitored by the photo cell further away from the adjustable roller (see Fig. 3.3).

For the purpose of the laboratory experiment, the web is made to traverse from the first cell to the second cell via an intermediate roller in a period of a second. The system time delay is then estimated as described and can be

FIGURE 4.6



introduced later into the controller design.

When using the single level control algorithm and incorporating time delay as proposed utilising the second photo cells as guide sensors, difficulty was experienced in trying to achieve a satisfactory control. This is observed by the random endless oscillations with the process never catching up to the actual desired set point of the system. This is probably due to the nature of the process.

An approach which avoids this problem uses a more complex two-level control system. The approach is developed from the cascade control concept. It will be shown that the scheme improves the basic performance of the loop. It is really a feedback loop within a loop as shown in the block diagram (Fig. 4.6).

The real advantage of this system becomes evident when the disturbances are considered. Disturbances enter both the inner and outer loops. The application of digital filtering has assisted in the compensation of the disturbances entering both loops. While major disturbances entering the primary controller have been filtered, the compensation of disturbances entering the secondary controller is greatly improved in the case of the two-level control scheme.

For the web process design, the cascade control has a single primary controller. The set-point of the primary controller is adjusted by a secondary controller. The value is compared with the desired set-point and the error is fed back to the primary controller. The process output from this inner loop sends the signal output to the transducer which in turn sends a signal back to the secondary controller.

The following sections will describe the procedure for

Fig. 4.7 Set-point change to determine time delay for the second set of sensors (further from the adjustable roller). The system is under control using first set of sensors.

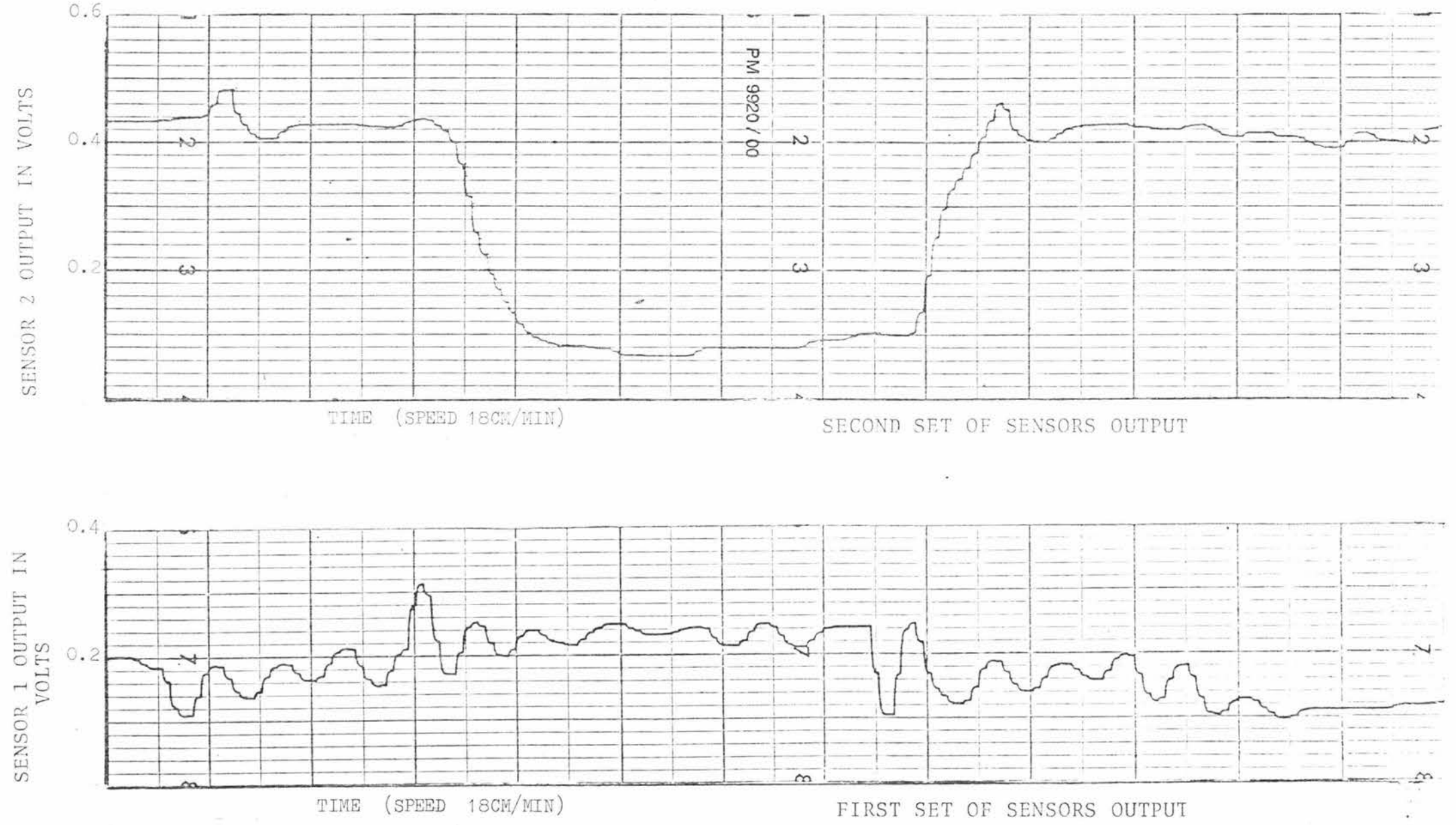
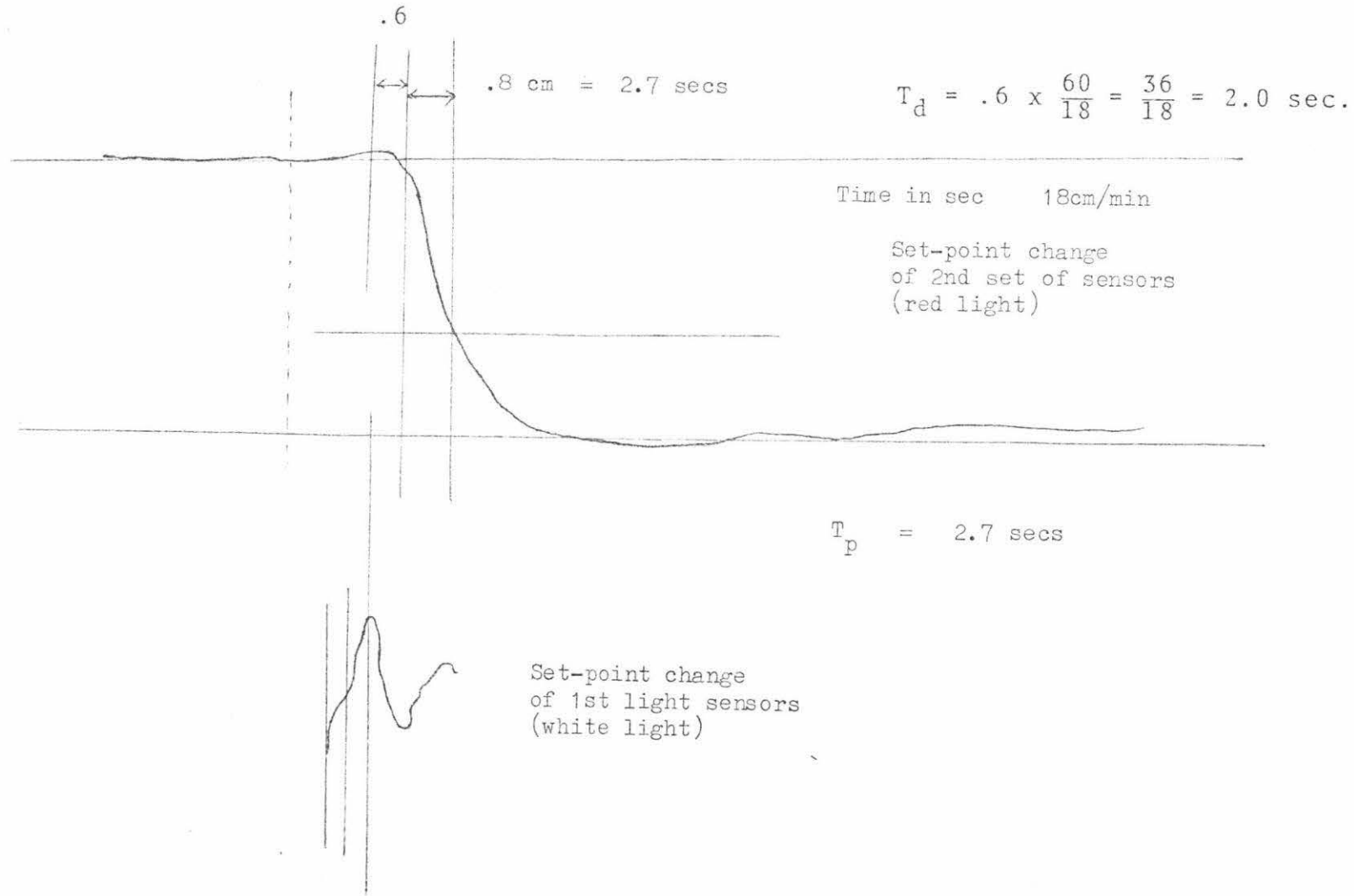


Fig. 4.8 Tracings from Graph 4 to determine process time constant and time delay.



the controller design,

4.4.1 *Step Response*

In this case, the primary loop controller is designed using the photo-cell nearest the adjustable rollers as guide sensors. The parameters already obtained in Section 4.3 are re-used for the primary controller design. The system applying the primary controller is allowed to run until it settles with a satisfactory response. Then a step to the set-point of the primary controller is introduced into the system. The output responses on both sets of photo-cells are recorded simultaneously as shown in Fig. 4.7.

By careful tracings depicted on Fig 4.8, that is, superimposing one graph on to the other, it is possible to determine the time delay constant T_d of the system. From the calculations, the time delay is found to be $T_d = 2.0$ seconds (see Fig. 4,8).

As observed from Fig. 4.7, the gain and process time constants are not readily measured. They have to be estimated in order to establish the controller algorithm from equation 8 for the time delay case. It is appropriate to examine the estimation of such parametric constants.

4.4.2 *Control Process*

The design procedure for this two level system requires that the primary controller maintains satisfactory response initially with the aid of the first set of photo-cells as guide sensors. Then the secondary controller is introduced and the various parameters pertaining to the secondary controller estimated to determine the best values for satisfactory performance.

In section 4.4.1, the value of the time delay has been estimated to be $T_d = 2.0$ seconds. The other parametric constants namely gain K , response time T_r , process time T_p and sampling time interval T , are estimated as follows:-

For the cascade control system to function properly and effectively, the inner loop is to cycle much faster than the outer loop especially when major disturbances alter the inner loop first [27]. Hence the sampling time interval for the secondary controller for the system is longer than for the primary controller. If this rapid cycling condition for the primary controller is not met, it is generally not possible to satisfactorily tune the secondary controller [27].

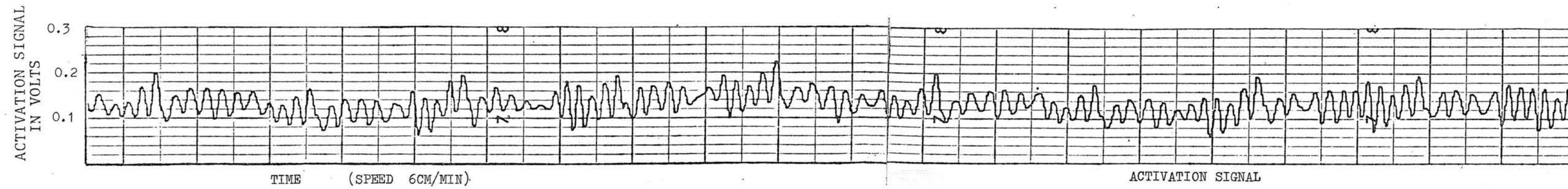
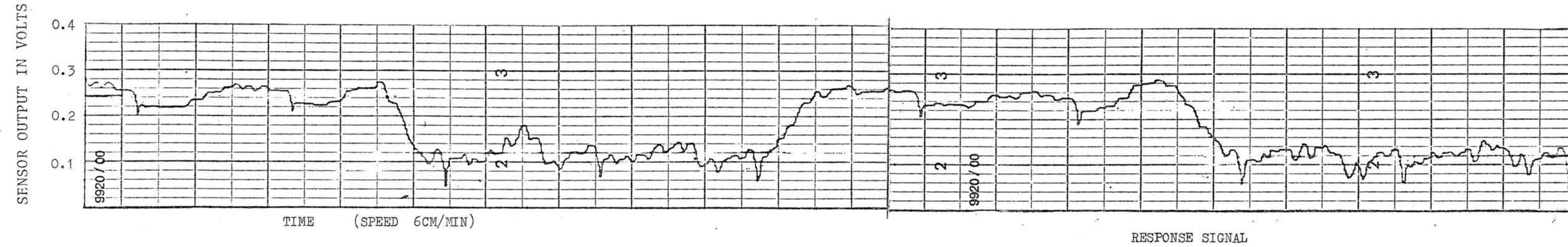
By considering the capability of the PDP/8F and observing the estimates of the various sampling time interval actions, the value arrived at for the secondary system is $T = 2.0$ seconds while the primary loop uses a sampling time interval of $T = 0.5$ seconds.

Initially the gain value for the secondary controller was varied while maintaining the other parameters constant. It was observed that no satisfactory control resulted. The values of the gain and process time constants have to be varied simultaneously (i.e. vary K and T_p). The final outcome resulted with the gain as $K = 2.9$ and $T_p = 3.1$ seconds, contrasting with values of 0.9 and 1.1 for the primary controller.

Keeping these parameters constant, the final value of the response time T_r was estimated. As recommended in [9] the case where $T_r = T_p$ was examined but with unsatisfactory results. It was found that satisfactory control can be

Fig. 4.9

Set-point Change under Cascade Control.



achieved only for values of T_r greater than T_p . If T_r is made too small, the system will oscillate randomly, not returning to the desired set point.

By careful observations, the final estimate of the response time was obtained as $T_r = 8.0$ seconds which permitted satisfactory set-point change responses. The estimates for secondary controller parameters giving a satisfactory response can be summarized as

Time delay, T_d	=	2.0 seconds
Sampling time interval, T	=	2.0 seconds
Process time constant, T_p	=	3.1 seconds
Gain, K	=	2.9
Response Time, T_r	=	8.0 seconds

Substituting these values into the equation 8 gives the following equation for the secondary controller:

$$U_o = 0.78U_1 + 0.22U_2 + 0.158E_o - 0.082E_1 \quad \text{Equation 14}$$

The calculation is shown in Appendix 4.3 and the computer algorithm for this controller is included in Appendix 4.2.

The typical step response for this two level control scheme is depicted in Fig. 4.9.

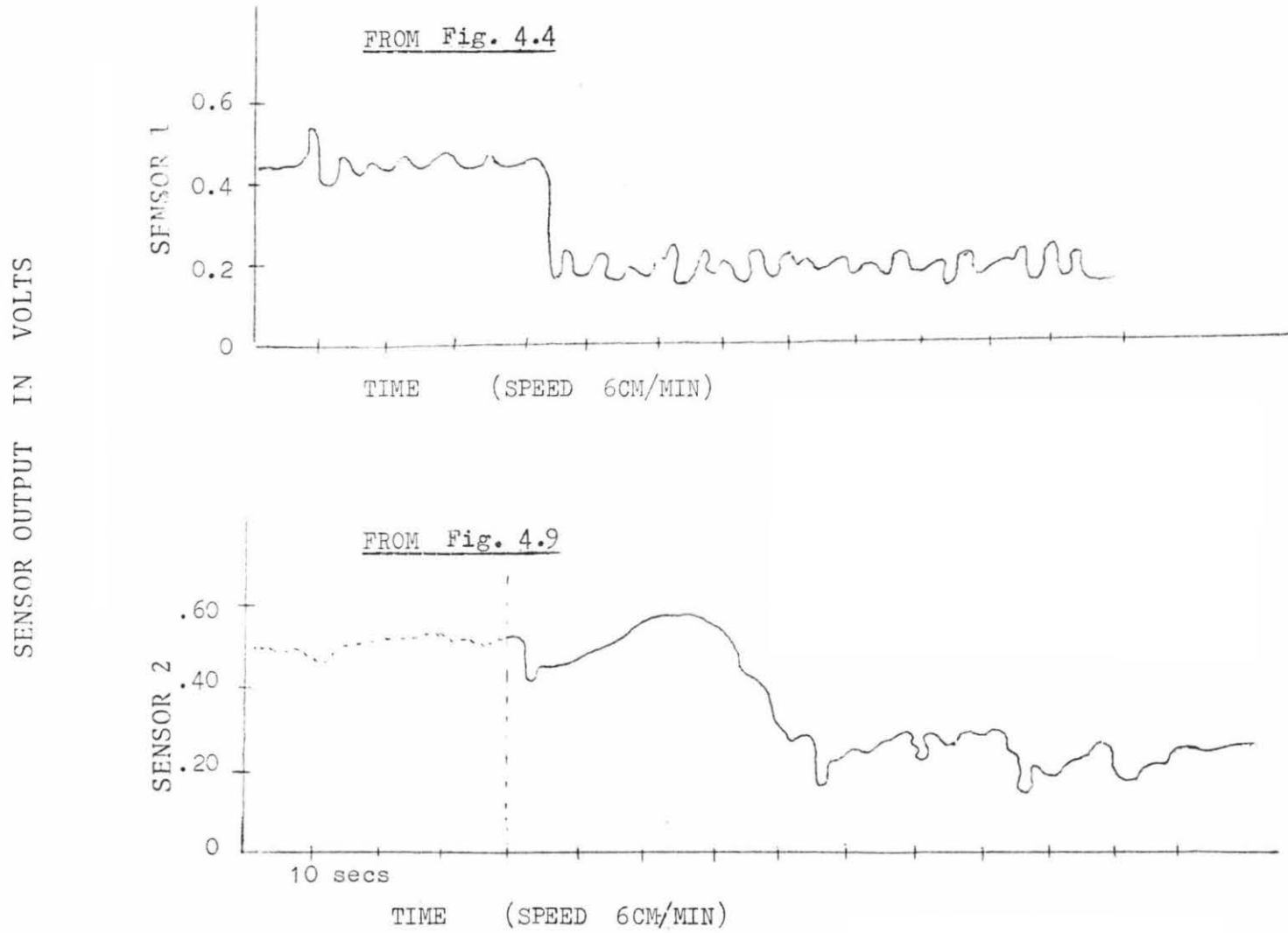
4.5 Discussion of Results

There is satisfactory control using the two level control scheme for the time delay system. This may be seen from the response of the system to a set point change shown in Fig. 4.10.

As observed from the diagram, the response to a step change is more sluggish for the two level control scheme when

Fig. 4.10

A Comparison of the Set-point Change Responses.



compared with the single level system. However, this two-level scheme has provided a satisfactory response performance.

In spite of careful digital filtering, noise disturbances are still apparent in the plot. However, for disturbances that enter the system, the secondary controller starts corrective action before the process output shows any deviation. By using the same filter constant in both cases, it is observed that these noise disturbance errors for cascade control are smaller than with a single controller.

The diagram of Fig. 4.10 shows that the error variations apparent when using a single controller are more distinct than when using the cascade controller. The reasons for the causes in both cases have been discussed earlier. The prominent disturbance caused by the poor joint of the towel is still evident in both cases.

This research has demonstrated that by carefully designing the primary controller and then experimentally selecting values for the secondary loop parameters, a good response to a set point change may be obtained even when the system has a time delay.

The two level control resulted in a process time constant for the secondary controller of $T_p = 3.10$ seconds in comparison with that of the primary controller $T_p = 1.16$ seconds.

The sampling time interval for the secondary controller has been increased to 2.0 seconds so that the primary controller can cycle rapidly using $T = 0.5$ seconds.

If the value of the secondary loop gain is lower than

the primary gain value, it tends to upset the system response and actually result in instability. Leaving both primary and secondary loop gains at the same values will not help to improve the system. Increasing the primary gain while secondary gain remains constant has little effect in satisfactory performance. Therefore it is clearly an advantage to have a high secondary controller gain. The estimated value for the primary controller is $K = 0.92$ and for the secondary controller is $K = 2.9$.

It has been suggested by the DSIR report [9] that T_r must be less than T_p to achieve good performance. This is possible for the primary controller, but not so for the secondary controller when a two level control scheme is used. Experimenting with different values showed that this controller required T_r larger than T_p to give satisfactory response performance.

The time response T_r selected for the secondary controller is 8.0 seconds in comparison with 0.5 for the primary controller in the development of the two level control system. The longer rise time resulting from increased response time implies a slower overall response. However, lower values of response time for the secondary controller will cause more offsets, instability and increased noise disturbances and hence system upsets. Higher values than 8.0 seconds for the secondary controller will cause more overshoot and instability.

Once the parameters have been correctly chosen, the two level scheme gives encouraging results. The scheme is suitable for implementing on a mini-computer or micro-

processor of limited capacity and avoids the need for very expensive instrumentation.

~ooOoo~

5. CONCLUSION

As illustrated in this research project, relatively recent advances in control theory, coupled with the flexibility of digital control have made it desirable to replace some existing analog systems with digital controllers which can be used in a wide variety of situations. Control computers find their application where relatively simple operations must be performed, requiring reliability and repeatability, rapidity (often because of a multiplicity of loops) and accuracy.

The increasing complexity and sophistication of modern industrial plant may lead to growing requirements for better system control. In this situation, the digital computer is an essential tool for use by modern engineers in achieving advanced control objectives.

A lot of DDC equipment is programmed to implement the classical ideas of the three mode control theory. With DDC systems, the digital computer along with pneumatic measuring instruments and control valves are used to implement some desired control policy.

Satisfactory controllers have been designed and applied to the web processing system. Realistic models of industrial control systems involve complicated non-linear relationships which make a straight forward application of modern control theory difficult. Usually, some simplifying assumptions are made to reduce the cost of the system design and implementation.

The Dahlin/Higham methods used for the controller design have been found to be suitable for the process under study. It is shown that sampled-data control may be simplified by the use of the Z-transform. Two control schemes using this method have been investigated,

The first controller design monitors the web position with the photo-cell nearest the adjustable roller. This controller proves to have a simple structure and the result is very effective. As observed in Fig. 4.4 the controller is able to respond very rapidly to any set-point changes and maintain the system at the set point in a satisfactory manner.

The second control scheme is introduced with the time delay design and is more complex. The web position is monitored by the photo-cell further from the adjustable roller (see Fig. 3.3). It is necessary to implement a two level control scheme in order to achieve satisfactory control. This scheme is developed from the cascade control concept involving both primary and secondary controllers. Section 4.4 describes the control scheme in more details.

However, for both schemes, it is essential to select appropriately the various parametric constants namely process and response times, gains, time interval and delay in order to achieve the desired responses.

The single controller parametric constants have been estimated to be

$$\begin{aligned} T_r &= 0,50 \text{ seconds} \\ T_p &= 1,16 \text{ seconds} \end{aligned}$$

$$\begin{aligned}
 T &= 0,50 \text{ seconds} \\
 T_d &= 0 \text{ seconds} \\
 K &= 0,92
 \end{aligned}$$

These values are used for the primary controller in the two level scheme while the secondary controller parametric constants are estimated as

$$\begin{aligned}
 T_r &= 8,00 \text{ seconds} \\
 T_p &= 3.00 \text{ seconds} \\
 T &= 2,00 \text{ seconds} \\
 T_d &= 2.00 \text{ seconds} \\
 K &= 2,90
 \end{aligned}$$

From the dynamic estimation point of view, the web process presents a difficult problem because

- a. compared with some processes, response times are fast, hence a high sampling rate must be used. The PDP/8F has a limited capacity, which is heavily utilized in this problem.
- b. Inherent noise levels are high for the process and digital filtering has been introduced to reduce this noise
- c. The jagged edges resulting from the non-uniform width of the towel have produced endless variations about the set-point as observed from the system output response. The prominent peak of these variations caused by the poor joint is also distinct, and has to be tolerated by the controller.

- d. Tension control causes additional problems, As observed, without tension, the web will be limp and slippage may easily occur,

An improvement to the response may be possible if additional secondary controllers are developed for the present system. These may involve investigating the following fields [14]:-

Web Tension Control

As mentioned earlier, tension control is necessary to prevent the limp web from slipping and rolling during the process. Tension control may assist in providing a more uniform control, less slippage and less variations in the set point.

Registration Control

This is to ensure that a certain position on the towel face remains in the same position each time the sensor is activated. Instead of detecting the jagged edges of the web with the photo cell, the registration control method can be introduced. It can be done by sensing the special indicators of narrow stripes drawn on the inside of the web edges. This will ensure correct positioning of the web with uniformity in the control system. The endless variations along the set-point may hopefully be minimized because the registration control now ensures that the photo-cell is sensing the same width of the towel along the two uniform stripes instead of the jagged non-uniform edges.

Guiding Techniques

The present system uses a sensor to detect web position and control it by the use of a steering guide. However, other possible methods of guiding may be examined. These may include displacement guides, bar guiding, crown roller guiding, roll flange guiding and centre guiding.

A less important field of interest may include control of static electricity caused by the rapid process of the system. It is also of importance to observe the uniformity of the motor speed in order to provide a uniform control.

However, the object of the laboratory research project is to present an investigation of modern digital computer control. Hence the above factors have not been investigated, with the exception of the web-guiding control that has been described.

In summary, direct digital control offers an opportunity to apply the largely theoretical solutions of control problems to affect major improvements in industrial process control. Improvements can be measured not only in nett return from higher control performance, but also in making possible the design of lower cost plants which can be erected more rapidly and which require less maintenance and are safer to operate than conventional plants [25,26].

An engineering evaluation of the true reliability requirements for each application and good system design will permit direct digital control with most on-line digital computers. These requirements, combined with those for any other computer applications in the same plant, will then determine the most economical machine configuration to satisfy the total system requirements [10,20].

Thus, with the advent of digital computers and their ability to handle large quantities of information, engineering horizons have been dramatically extended [11,26].

~ooOoo~

APPENDIX 1

The procedure for loading the Program is as follows:-

1. Set Switch Register (SR) to 0000 and press EXTD ADDR LOAD,
2. Set SR to 7777 and press ADDR LOAD.
3. Press CLEAR first and then press CONT on the computer console.
4. Set SR to 0002 and press ADDR LOAD.

Make sure that BIN is in CORE, that is when the tape stops, the console SR should read 7402.

If it does not, reload BIN and start over as in Step 1 above.

5. Then set SR to 0003 and press ADDR LOAD to load in the Executive Program.
6. When tape stops with SR reading 7402, check to see if accumulator (AC) equals zero. If it does not, reload all over as at Step 1 above,
else
7. Set SR to 0200(Starting address of Executive) and press ADDR LOAD, then press CLEAR, CONT and the whole Executive is in progress.

APPENDIX 1.1

Routine Names

The routines assigned to the various console switches are listed as follows:-

<i>Switch Number</i>	<i>Routine Name</i>	<i>Task to Perform</i>
0	ININT	Input to Interval Values
1	INDAC	Input to DAC Values
2	INBIT	Input to Bit Status
3	CLSTAT	Clock Start
4	CHANGE	Program Start
5	FLIN	Input Constants
6	FLOUT	Input Filter Constants
		Set pt & plot mark.
7	SWITCH	Output Switch List
8	PIOS	Output Bit Status
9	PDAC	Output DAC Values
10	PADC	Output ADC Values
11	PINT	Output Interval Values

-ooOoo-

APPENDIX 1.2

Overrun Messages

The alarm messages that are associated with the process can be printed out as:-

"OVERRUN 1"

This implies that input/output is updating too fast

"OVERRUN 2"

The ADC is updating too fast

"OVERRUN 3"

Primary calculation is cycling too fast

"OVERRUN 4"

Secondary calculation is cycling too fast

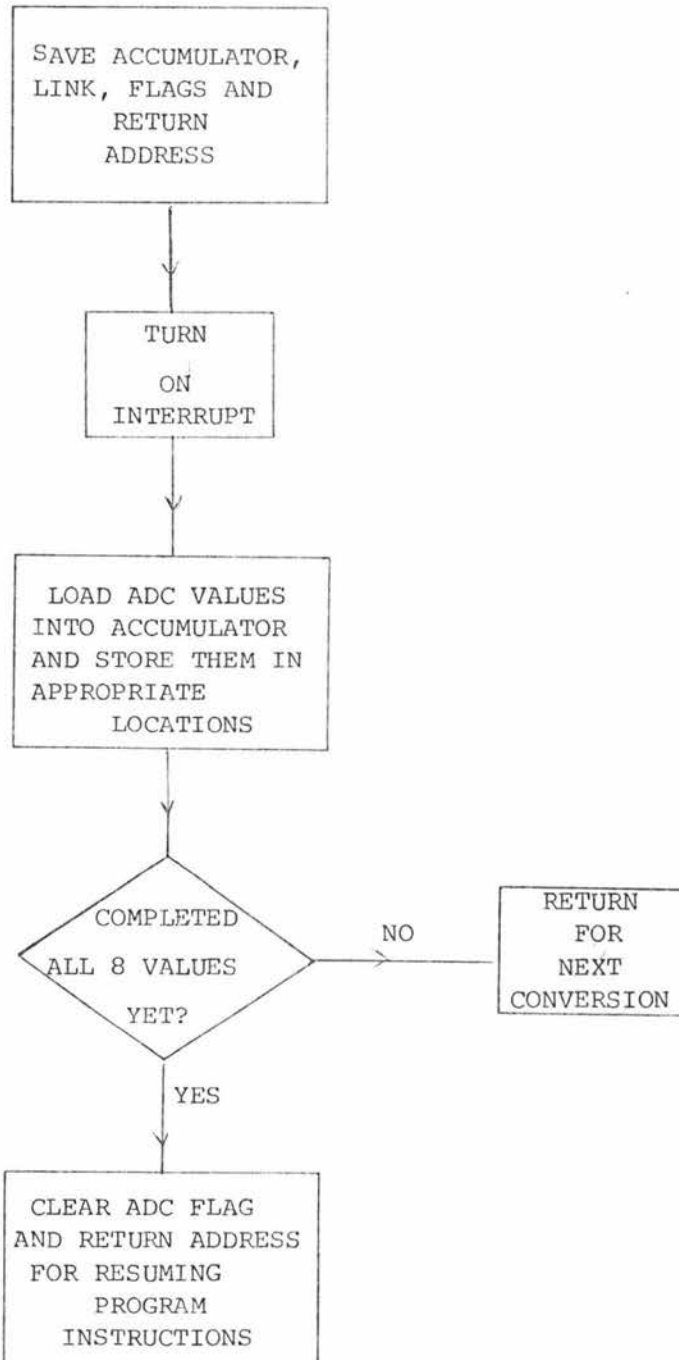
-ooOoo-

APPENDIX 2

The A/D routine is entered at specified intervals according to the clocking interrupt routine. Initially, the routine "IADIN" is activated. The routine merely sets storage locations for accepting the values from channels 0 to 7. It will then enable the ADC interrupt register flag and initiate subroutine "IADC" which selects the appropriate channel for conversions:

```
IADC, 0
      CLA CLL
      TAD I IR3
      6531      / select channel and load multiplexer
      6532      / start conversion
      JMP I IADC
```

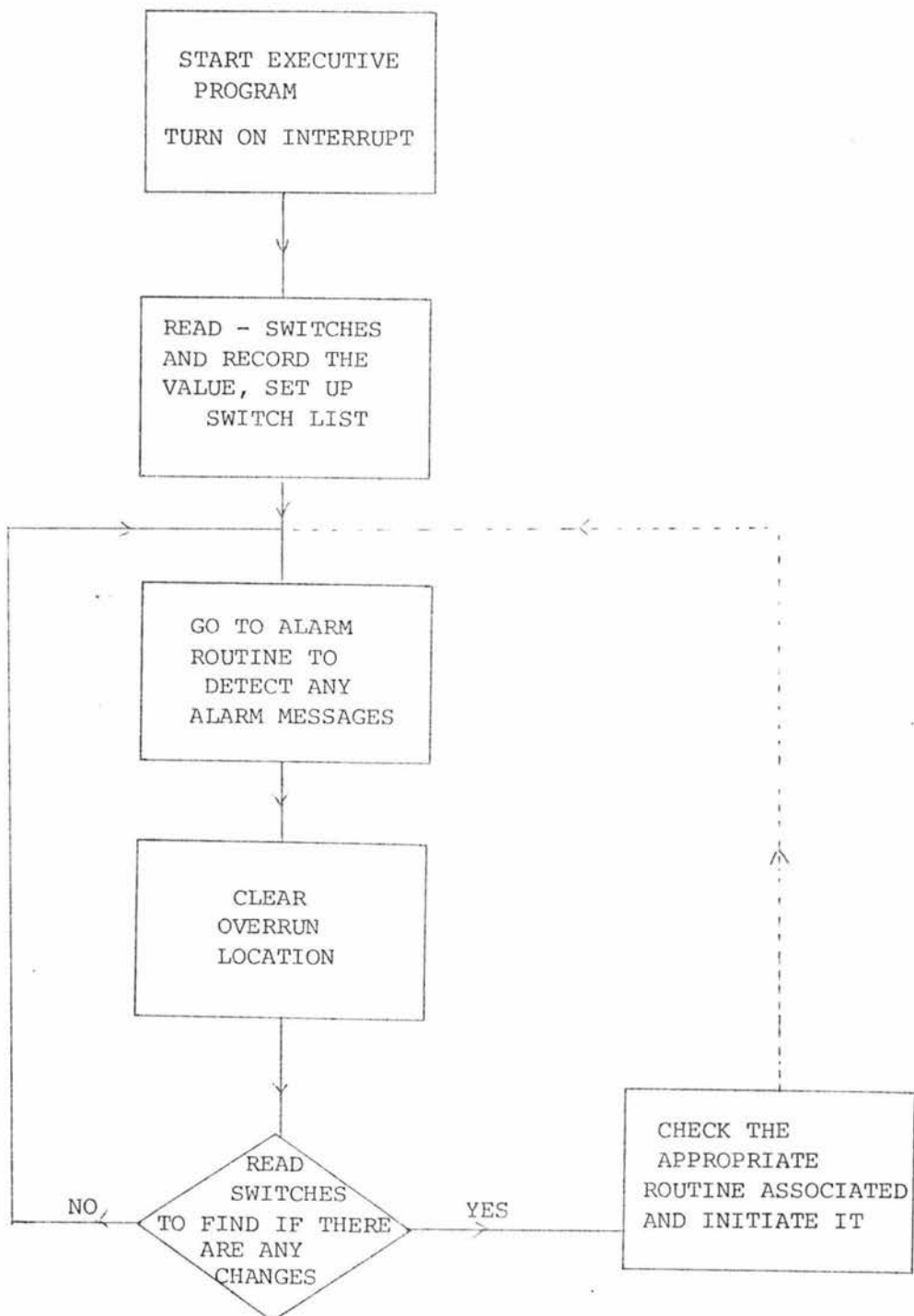
These routines can be examined in the program listing. When servicing the interrupt, the accumulator, link, flags and return address are saved. Then the interrupt is turned back on and the A/D values from the eight channels are read in and stored in the appropriate locations. On completion, the reverse procedure returns the CPU to the interrupted routine.

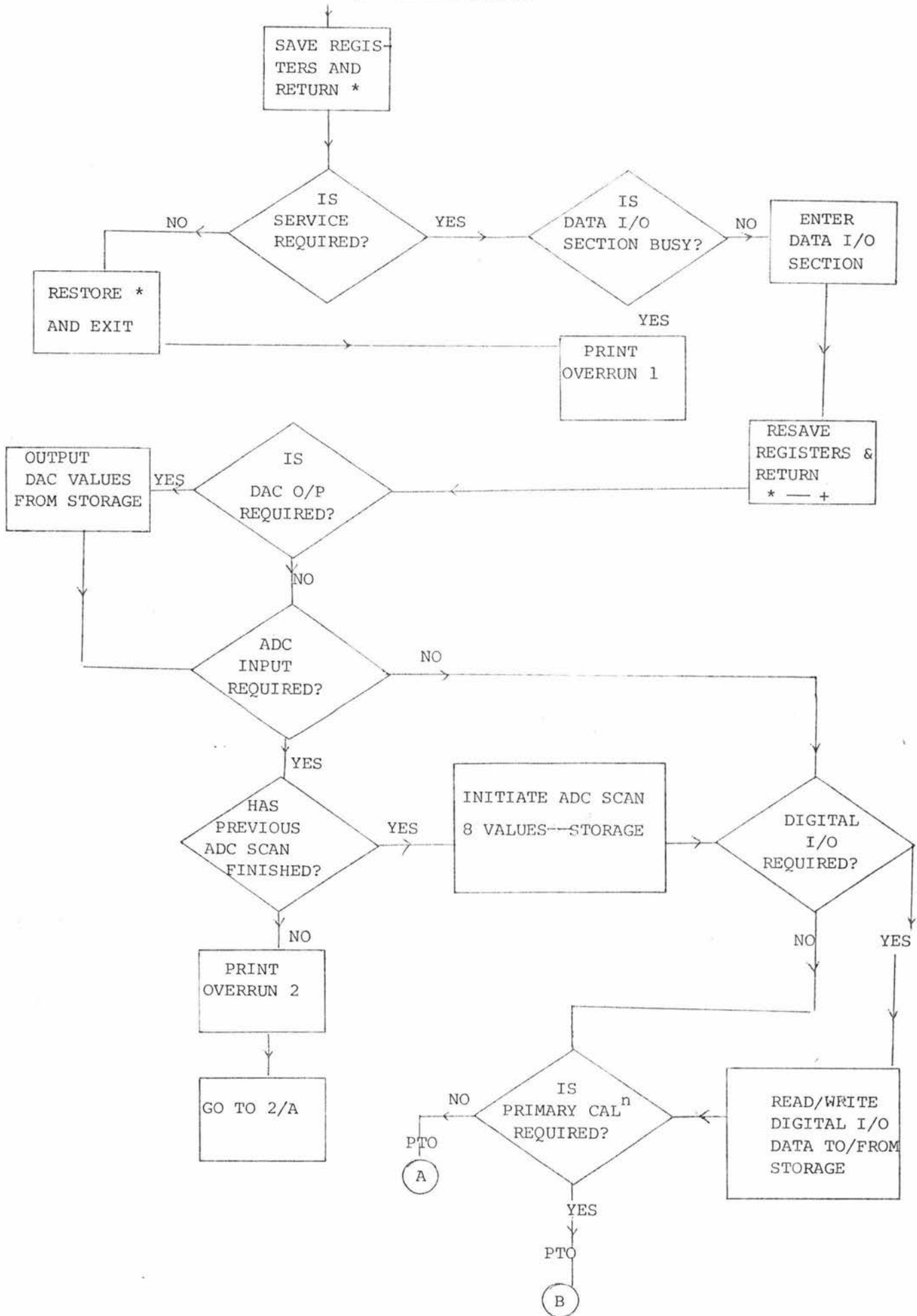


APPENDIX 2.1

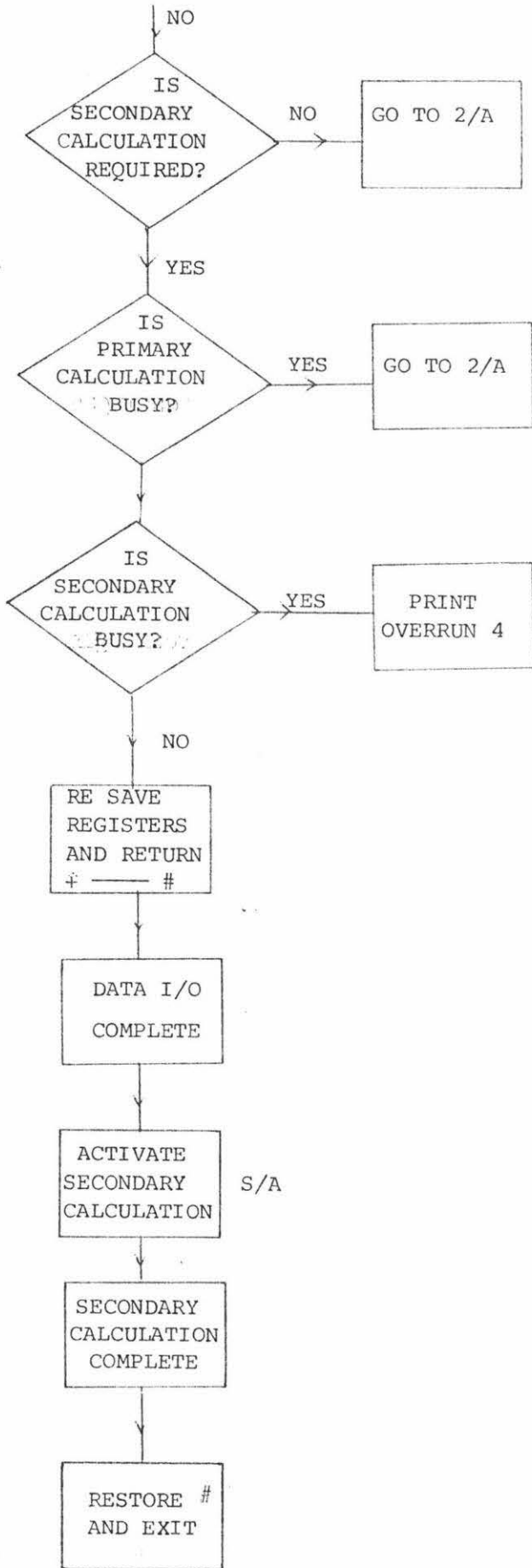
Mainline Routine

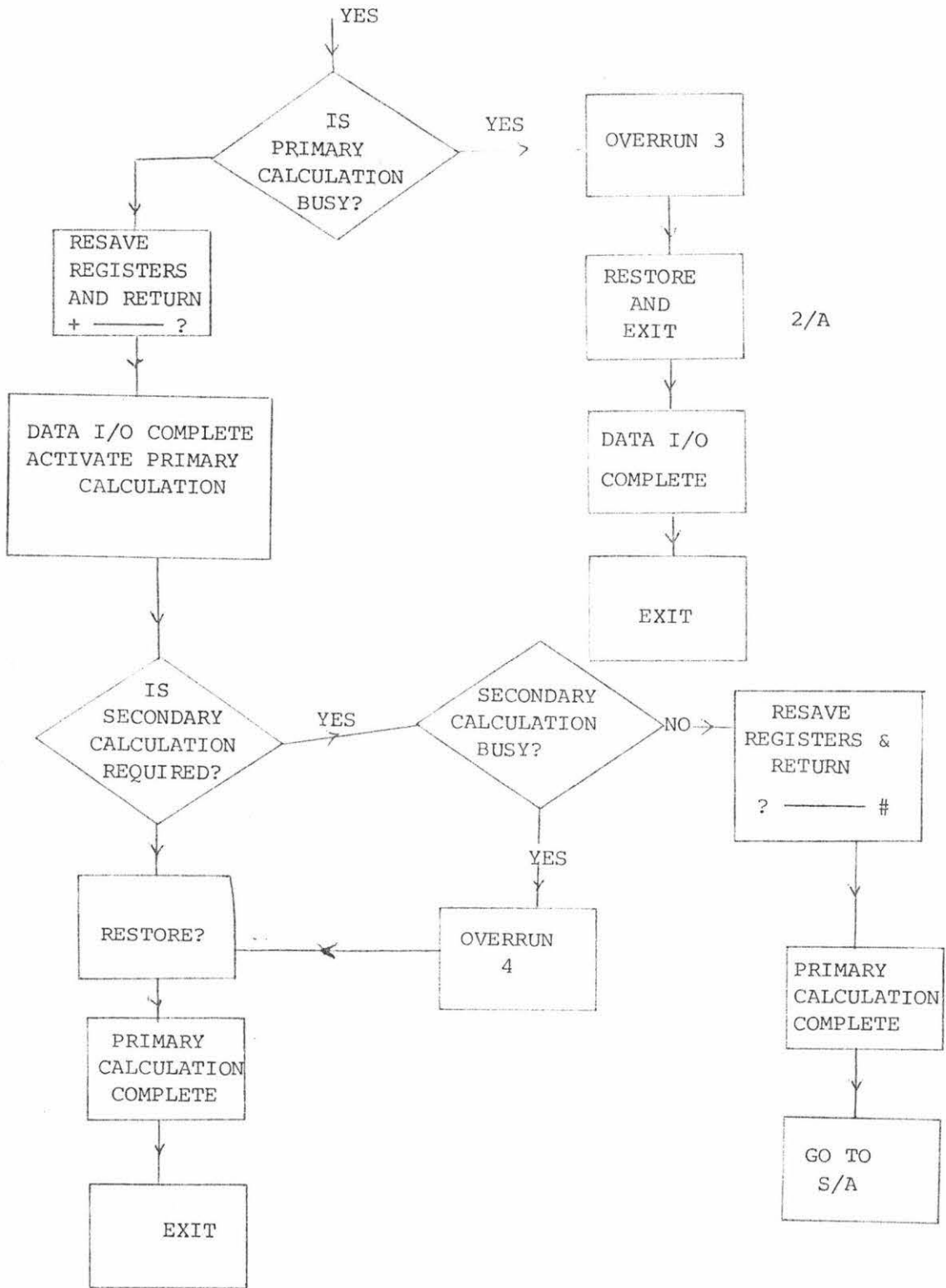
The basic flowchart of the Mainline Routine is





A





APPENDIX 3

Computation is performed in binary units and hence a conversion procedure is required if decimal input is preferred. The usual procedure allowing input of ASCII characters is followed. These are converted to digestible binary units for further conversions. The process involved is as follows:-

Assuming the digit read in is in the range of 0 to 9. Multiply it by ten and add on to the next incoming digit until the maximum of four digits are read. Then store the converted decimal number. The programming is illustrated in the subroutines names "INPUT" and "PACK" in the listing.

The reverse is true when the printing of the number has to be in decimal form. In this case, the number is divided initially by 1000 and the dividend is printed first. It is followed by the division of 100 and 10, thus giving a four digit decimal number output. The program is assembled as the subroutine named "OUTPUT" in the listing.

-ooOoo-

APPENDIX 3,1

"INBIT" Routine

INBIT is the name assigned to switch 2. It can be entered by depressing switch 2 to initiate the routine. Once the routine has been effected, the program queries the operator with a message:

"O/P BIT NO?"

In response to this question, the operator may type the desired output bit status number from 0 to 11. The program will immediately reply with another question

"VALUE?"

The operator must then type the status value of 0 or 1 followed by a carriage return.

-ooOoo-

APPENDIX 3.2

"PIOS" Routine

"PIOS" is the routine name assigned to switch 8. It can be initiated by depressing switch 8 to effect the routine. The program will print out all bit status numbers with the respective Input/Output status value associated with it as follows:-

S	0	1	2	3	4	5	6	7	8	9	10	11
I	0	0	1	0	0	1	0	0	0	0	1	0
O	0	0	0	0	0	0	0	0	0	0	0	0

- I - This register is determined by bit input by the operator to the CPU. It is associated with an output operation from the CPU.
- O - This register is determined by a read operation by the CPU from some external device (e.g. digital input from on/off sensors).

-ooOoo-

APPENDIX 3.3

"INDAC" Routine

Switch 1 has been allocated to routine INDAC which allows the operator to enter DAC values. As soon as the routine is initiated, it will request:

"DAC CHANNEL (X OR Y) ?"

The operator can select either channel by typing the appropriate response i.e. X or Y. This will be followed by another question:

"VALUE?"

The operator will type the desired decimal value ranging from - 511 to +511 followed by the usual carriage return.

-ooOoo-

APPENDIX 3.4

"PDAC" Routine

PDAC routine is associated with switch 9. This routine is easily initiated by manipulating switch 9 at any desired time. The routine will print out the values of both channels as follows:-

DAC VALUES

X	Y
+0165	-0007

-00000-

APPENDIX 3.5

"ININT" Routine

Switch 0 is assigned to the input routine ININT which allows the operator to allocate the various interval values. When it is initiated, the program queries with

"INTERVAL VALUE (0 to 6)?"

to which one can respond by typing the appropriate interval value.

The numbers associated with the routine numbers are as follows:-

1. Basic Interrupt service interval
2. Interval for DAC update
3. Interval for ADC update
4. Interval for digital I/O update
5. Interval for Primary calculation
6. Interval for Secondary calculation

Interval values from 2 to 6 are multiples of the basic service interval. In response to the question

"VALUE?"

the operator can type in any desired decimal value associated to the intervals.

Associated with this is the print out routine "PINT".

Switch 11 is assigned to start the print out messages. Once initiated, the print out will follow as:-

INTERVAL VALUES

1	2	3	4	5	6
+0005	+0002	+0001	+0001	+0001	+0001

-ooOoo-

APPENDIX 3,6

"PADC" Routine

"PADC" is associated with the listing of the ADC values of all the 8 channels of the multiplexer. This can be activated by depressing switch 10. The routine, once initiated, will print out the following message: e.g.

ADC VALUES

0	1	2	3	4	5	6	7
+0201	-0004	-0004	+0257	-0003	-0004	-0004	+0000

-oo0oo-

APPENDIX 3,7

Routine "FLIN"

"FLIN" is the routine assigned to switch 5. This routine, when initiated, will permit the operator to enter the values of the constants required for the control algorithm of the system. The program will ask the operator for the value of the constants. In response to the mantissa letter M, the operator will type any 4 integer number less than 2047 (decimal). This will be followed by the exponent E, to which the operator responds with an exponent value less than 2047 (decimal).

-ooOoo-

APPENDIX 3.8

Routine "FLOUT"

Switch 6 is allocated to the routine "FLOUT". This routine allows the operator to enter the required filter constant value. It also caters for one to select the appropriate plotmark to plot the set point or measured values of either of the light sensors. When the routine is initiated, it responds with

%

The operator must type any integer from 1 to 4 appropriately. The numbers associated with the functions are as follows:-

1. To enter the set point for the light source nearest the guiding roller (A).
2. To enter the set point for the light source further from the guiding roller (B).
3. Filter constant.
4. Plotmark to decide whether to plot
 - (i) set point for light sensor A
 - (ii) set point for light sensor B
 - (iii) measured value of light sensor A
 - (iv) measured value of light sensor B

Thus, if the operator decides to enter the filter constant, he will have to type 3 following the query %. In response to this another query

"VALUE?"

will appear, and the operator will type in the appropriate value of the filter constant. Value 8 will imply no filtering, while 1 implies maximum filtering.

A similar procedure may be followed for the other options.

-ooOoo-

APPENDIX 3.9

"SWITCH" Routine

"SWITCH" is allocated to the switch number 7. When initiated, it will print out all the switch numbers and the various routines associated with them.

SWITCH

0	1	2	3	4	5
INTV/IN	DAC/IN	BIT O/P	CLOCK/INT	PROG/START	SET/PT
6	7	8	9	10	11
FILTER/NO	SW/INSTR	I/O BIT	DAC/OUT	ADC/OUT	INTV/OUT

-ooOoo-

APPENDIX 4

The primary Controller is established using algorithm described in Section 2.2.2.1.

The program accepts the filtered ADC value from channel 0, which is compared with the set point. The error is then inserted into the algorithm. Any deviation from the desired set point value has to be remedied immediately by the output signal. The program is listed within the routine "RDOSEC" where "PRIGO" is the actual Primary Controller section. Reference is made to the listing.

-ooOoo-

APPENDIX 4.1

The results obtained from the characteristics of the open loop experiment on the web processing system can be used to design the primary controller. From the experimental data, it is better to select an average of the time and gain constants as follows:-

$$\begin{aligned} \text{Take } T_p &= \frac{1 + 1.33}{2} \\ &= 1.16 \text{ seconds} \end{aligned}$$

$$\begin{aligned} K &= \frac{0.88 + 0.96}{2} \\ &= 0.92 \end{aligned}$$

$$\text{Choose } T_r = 0.5 \text{ second}$$

$$T = 0.5 \text{ second}$$

The controller design as from [9] gives

$$\begin{aligned} Q &= 1 - e^{-T_p/T_r} \\ &= 1 - e^{-1} \\ e^{-1} &= 0.37 \\ \therefore Q &= 1 - 0.37 \\ &= 0.63 \\ L &= 1 - e^{-0.5/1.16} \\ &= 1 - 0.65 \\ &= 0.35 \end{aligned}$$

$$\begin{aligned}
 (U_0 - U_1) &= \frac{Q}{KL} [E_0 - (1 - L)E_1] \\
 &= \frac{0.63}{0.92 \times 0.35} [E_0 - 0.65E_1] \\
 &= 1.96E_0 - 1.23E_1
 \end{aligned}$$

∴ Control entries

$$(U_0 - U_1) = 0.73Y_{sp} - 1.96Y_0 + 1.23Y_1$$

The algorithm for this primary controller is thus designed as

$$\Delta U = A Y_{sp} - B Y_0 + C Y_1$$

where A, B and C are entered via the teletype.

-ooOoo-

APPENDIX 4,2

A secondary controller is incorporated in the routine to form the cascade control system. The algorithm is derived with the inclusion of the time-delay element.

The secondary controller is programmed as an extension of the Primary Controller. The routine "SEGGO" in the listing is associated with the Secondary Controller.

-ooOoo-

APPENDIX 4.3

The parametric constants as derived from section 4.4.2 are

$$\begin{aligned}
 T_p &= 3.1 \text{ seconds} \\
 T_r &= 8.0 \text{ seconds} \\
 T_d &= 2.0 \text{ seconds} \\
 T &= 2.0 \text{ seconds} \\
 K &= 2.9
 \end{aligned}$$

The following calculations utilizing these parametric constants lead to the secondary controller algorithm as follows:-

$$\begin{aligned}
 N &= T_d/T = 2/2 = 1 \\
 Q &= 1 - e^{(-T/T_r)} \\
 &= 1 - e^{(-2/8)} \\
 &= 1 - 0.78 \\
 &= 0.22 \\
 L &= 1 - e^{(-T/T_p)} \\
 &= 1 - e^{(-2/3,1)} \\
 &= 1 - 0.52 \\
 &= 0.48
 \end{aligned}$$

$$D(Z) = \frac{Q}{L, K} \left[\frac{1 - (1-L)Z^{-1}}{1 - (1-Q)Z^{-1} - QZ^{-2}} \right]$$

$$= \frac{0.22}{0.48 \times 2.9} \left[\frac{1 - 0.52Z^{-1}}{1 - 0.78Z^{-1} - 0.22Z^{-2}} \right]$$

$$\frac{U_o}{E_o} = 0.158 \left[\frac{1 - 0.52Z^{-1}}{1 - 0.78Z^{-1} - 0.22Z^{-2}} \right]$$

From this the algorithm is therefore

$$U_o = 0.78U_1 + 0.22U_2 + 0.158E_o - 0.082E_1$$

The algorithm for this controller is depicted in the routine "SECGO". This can be reviewed in the listing.

-ooOoo-

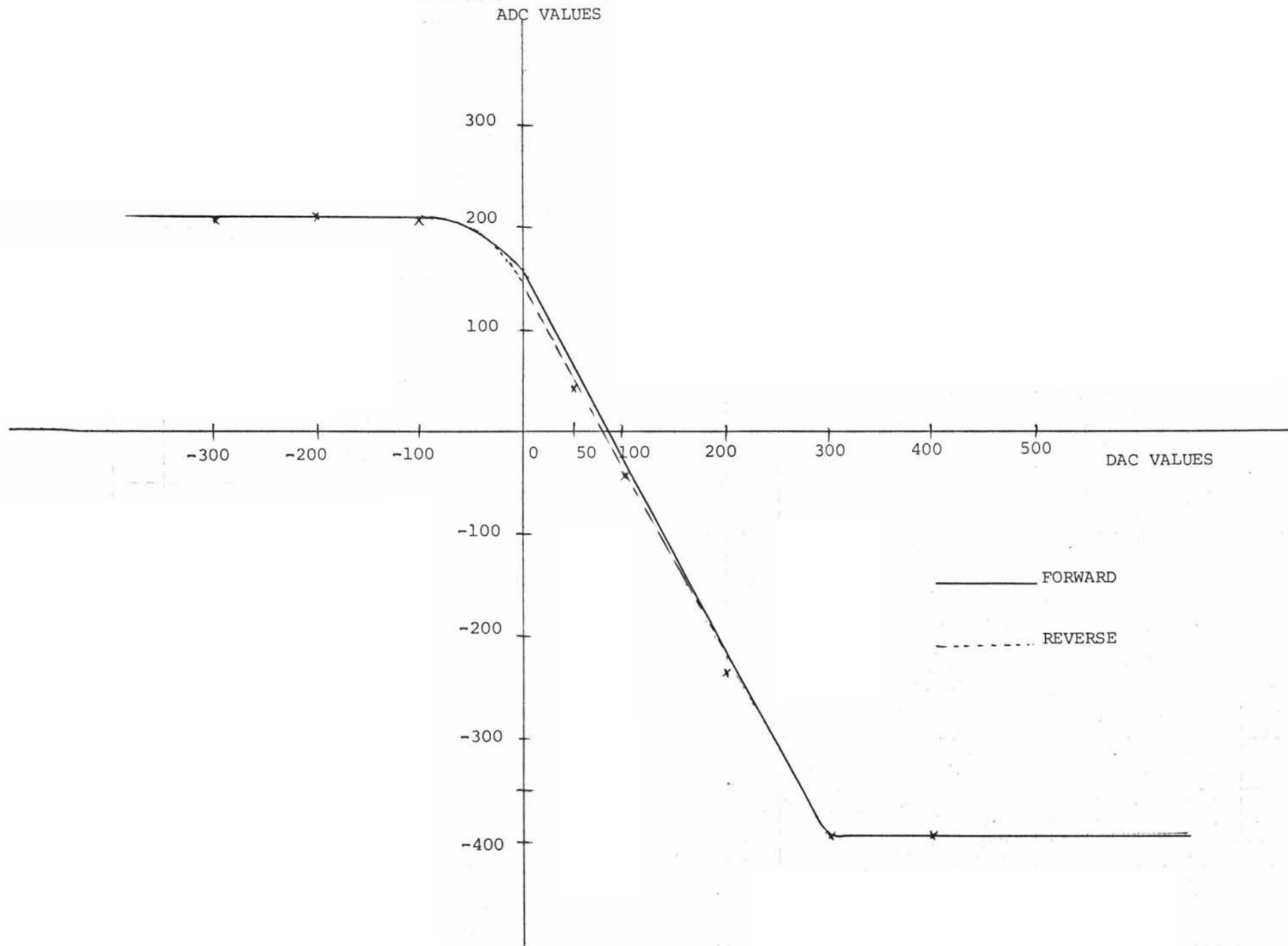
APPENDIX 5

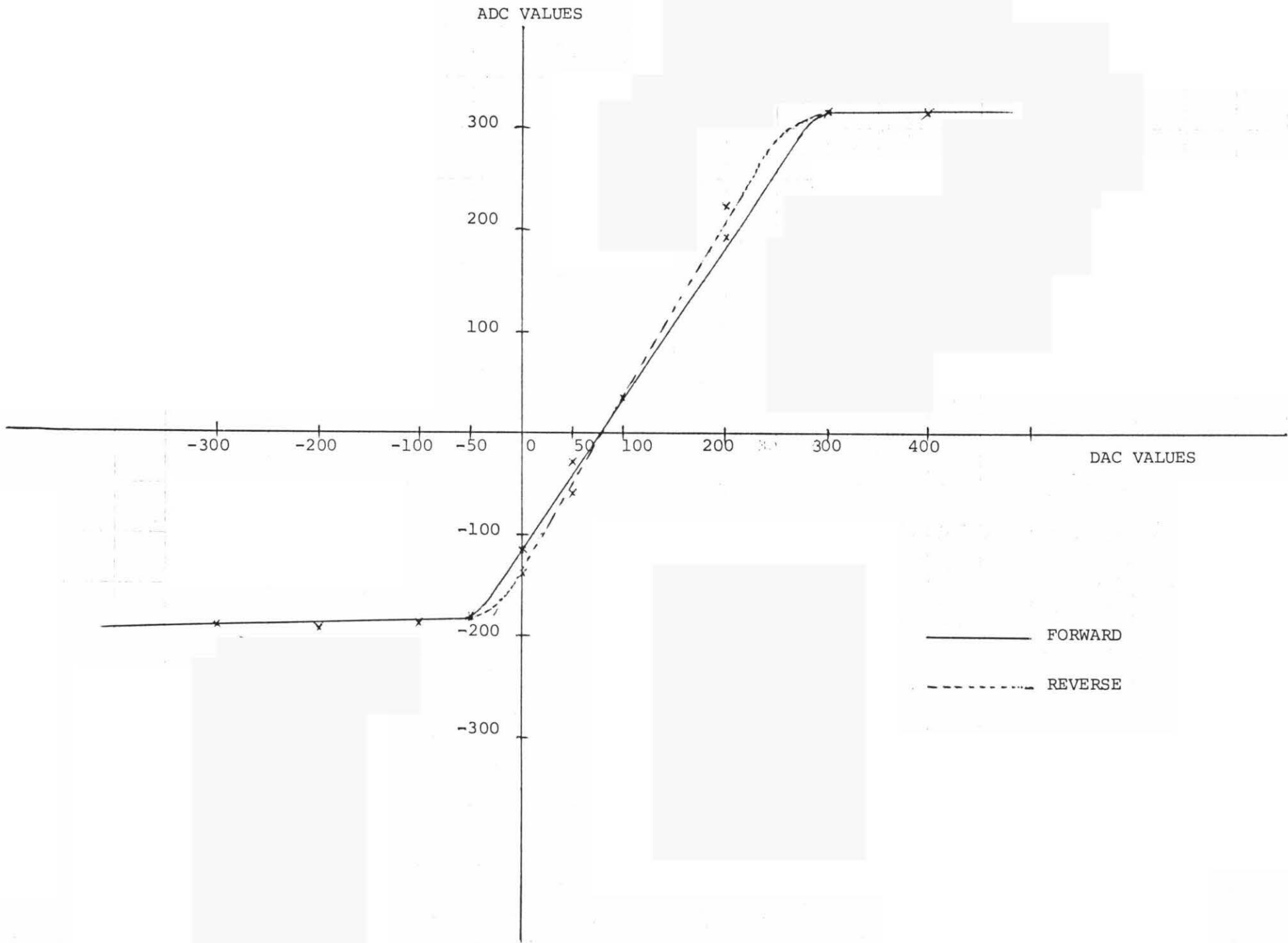
It is essential to determine the working range for the set-point changes. This can be determined by injecting step responses to the stationary system with no controller. The saturation limits for the adjustable roller to deflect left or right are recorded and the most suitable range of values selected from the following plots. Reference to these experimental values show that the most appropriate DAC values of 0 - 200 will permit satisfactory results

-ooOoo-

EXPERIMENTAL VALUES OBTAINED
FOR DAC/ADC VALUES

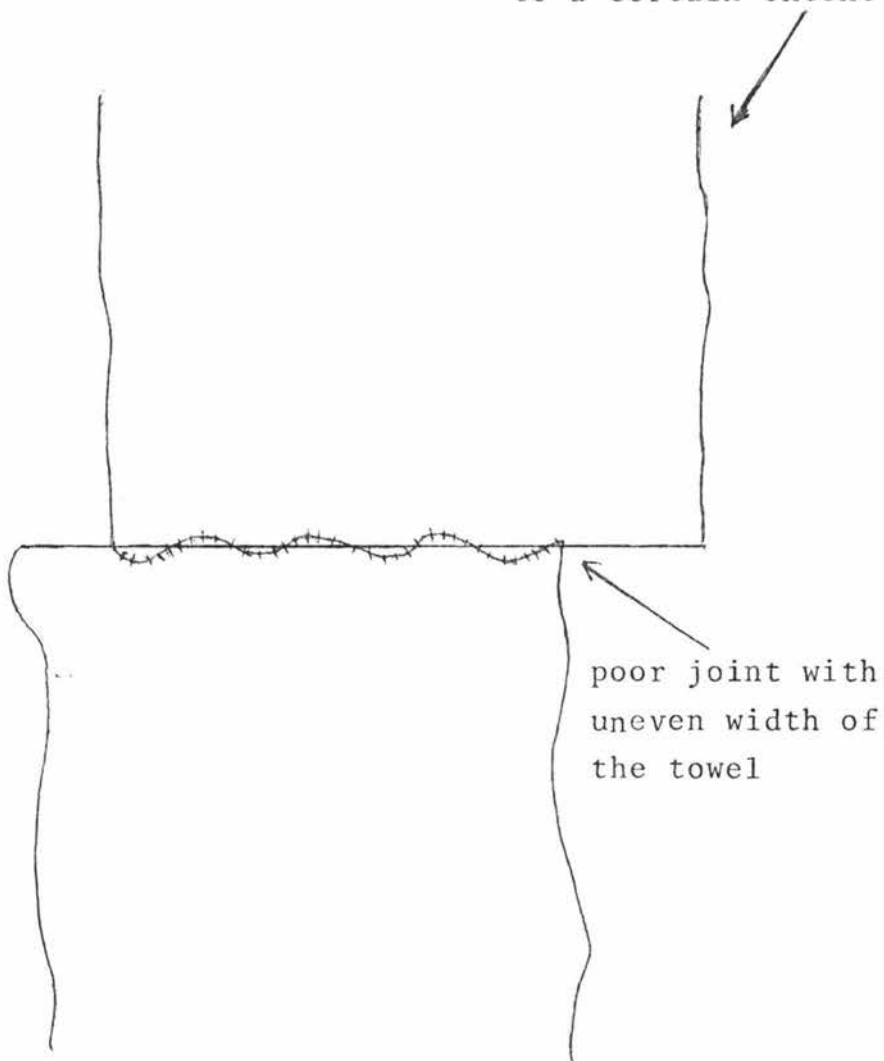
DAC	ADC		REVERSE	
	FORWARD			
-300	-188	-180	-190	-191
-200	-193	-180	-191	-172
-100	-188	-168	-183	-170
- 50	-192	-172	-189	-178
0	-131	-154	-171	-121
+ 50	- 27	- 25	- 61	- 60
+100	+ 27	+ 39	+ 58	- 60
+200	+189	+201	+236	+239
+300	+318	+323	+324	+310
+400	+317	+325	+335	+321





APPENDIX 6

Towel edges are jagged
to a certain extent



Both ends of the towel are poorly
joined.

BIBLIOGRAPHY

1. BOWDEN, T.
"Computers and Process Control", *Automation and Control*, N.Z. July, 1972 pp 15-16
2. CASSETTE PROGRAMMING SYSTEM
Users Manual, Digital Equipment Corporation.
Maynard, Massachusetts. 1974
3. CHORAFAS, D.N.
"Control Systems functions and Programming Approaches"
Vol. A. Academic Press, New York, 1973.
4. CHORAFAS, D.N.
"Control Systems functions and Programming Approaches"
Vol. B. Academic Press, New York, 1973.
5. COGGAN, G.C. AND WILSON, J.A.
"On-line State estimation with a small computer",
Computer Journal, *Vol. 14*. 1971, pp 61-64
6. CORY, F.F.
"A practical guide to Minicomputer Applications"
IEEE Press, New York, 1972.

7. DAHLIN, E,B.
"Designing and Tuning Digital Controllers, Part 1",
Instruments and Control System, Vol 41. June, 1968,
pp 77-83
8. DAHLIN, E,B.
"Designing and Tuning Digital Controllers Part 2",
Instruments and Control System Vol 41. July, 1968
pp 87-91
9. DAVIS, P.R.
"Primary Controls for a falling film milk evaporator",
DSIR Report 511, March 1976, NZ.
10. GOFF, K.W.
"A systematic Approach to DDC Design", *ISA Journal*,
Dec, 1966
11. GOFF, K.W.
"Estimating Characteristics and Effects of Noisy
Signals", *ISA Journal*, Nov. 1966.
12. GRUENBERGER, F,J.
"Computing", an introduction.
Harcourt, Brace, and World Inc, N.Y. 1969.

13. HARRIOTT, P.
"Process Control", McGraw-Hill, N.Y. 1964
14. HEATH, G.F.
"Web Processing and Control",
Dept of IME. Massey University, Palm. Nth. NZ. 1972
15. HENZEL, R.A.
"Direct Digital Control", *Computers*, Sept./Oct. 1971
p.9
16. HIGHAM, J.D.
"Single Term Control of First and Second Order Processes
with Dead Time", *Control*, Feb. 1968 pp 136-140
17. HIGHAM, J.D.
"Dynamic computer Regulation of a dry process cement
kiln", *Proc IEEE*, Vol. 118, No 3/4. March/April, 1971.
18. INTRODUCTION TO PROGRAMMING
PDP 8 Handbook Series, Maynard, Mass. 1973.
19. JOHNSON, E.F.
"Automatic Process Control", McGraw-Hill, N.Y. 1967.
20. KORN, G.A.
"Minicomputers for Engineers and Scientists",
McGraw-Hill, N.Y. 1973

21. LAB. 8/E USER'S HANDBOOK
Digital Equipment Corporation
Maynard, Mass. 1973.
22. LAWRENCE, D.I. AND FENWICK, P.M.
"Data Acquisition and Real-Time Systems".
University of Queensland Press, 1971.
23. LEE, T.H., ADAMS, G.E., AND GAINES, W.M.
"Computer Process Control, Modelling and Optimisation".
John Wiley and Sons Inc. N.Y. 1968.
24. MARTIN, J.T.
"Design of Real-Time Computer Systems".
Prentice-Hall Inc. N.J. 1967.
25. NEW ZEALAND COMPUTER SOCIETY INC.
Third National Conference. P.N. August 1972.
Proceedings, Vol. 1.
26. SAVAS, E.S.
"Computer Control of Industrial Processes"
McGraw-Hill, N.Y. 1965
27. SMITH, C.L.
"Digital Computer Process Control"
Intext Education Publishers, Scranton, 1972.

28. WOOD, G.G.

"Digital Control In Industry",

Automation and Control, NZ, July, 1974, pp 23-26.

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