CE103
Thermal Process Control

All due care has been taken to ensure that the contents of this manual are accurate and up to date. However, if any errors are discovered please inform TQ so the problem may be rectified.

A Packing Contents List is supplied with the equipment. Carefully check the contents of the package(s) against the list. If any items are missing or damaged, contact your local TQ agent or TQ immediately.

TQ Education and Training Ltd
Products Division

PW/PE/JSL/djb/0203

CONTENTS

CONTENTS

1.0 INTRODUCTION.

1.1 General

The **CE103 Thermal Process Control Apparatus**, shown in Figure 1.1, is one of a unique range of products designed specifically for the theoretical study and practical investigation of basic and advanced control engineering principles. This includes the analysis of static and dynamic systems using analogue and/or digital techniques.

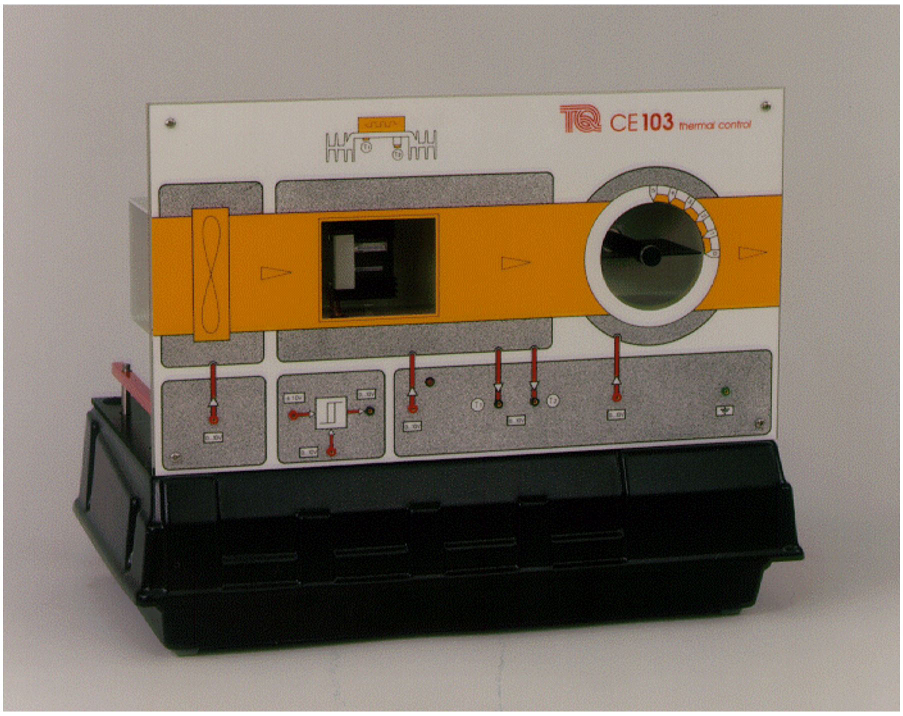


Figure 1.1

The CE103 relates specifically to heat and heat transfer control problems as they would typically occur in process control industries. It may also, however, be used as a practical introduction to the design, operation and application of control systems in general.

The CE103 has been designed to provide an intrinsically safe, adaptable and self-contained facility for students of control engineering so that they may practically investigate and compare a wide range of functional control system configurations.

In particular with the CE103, they are able to examine the control of temperature of a block with varying energy input and then changing the heat dissipation through a variable speed fan. The additional facility to introduce physical changes to the block using a rotating vane (or shutter) in the airstream is available to extend the scope of the investigations.

IMPORTANT

The CE103 is supplied for operation at the local mains supply voltage, either 110/120V or 220/240V, unless otherwise indicated at the time of ordering. The set voltage is shown on the Test Certificate supplied with the CE103 or on the Serial Number Plate to be found at the rear of the unit.

Section 2 of this manual gives a step by step development of the fundamental and advanced control theory required to support the educational use of the CE103. This enables the performance of a particular process/controller configuration to be either verified in the case of an existing system or predicted at the design stage.

An introduction into the important topic of digital control techniques is contained in Section 3, giving the basic requirements of a computer program algorithm for a three-term (PID) controller. To implement the routine requires it to be embedded into a larger program in which input/output routines enable it to access data and then provide an appropriate control signal.

The scope and content of the recommended experiments provided in Section 4 address a wide range of control engineering principles, starting with basic transducer calibration routines and system response observations and leading to advanced tuning techniques. This comprehensively supports the control theory given in Section 2.

The experiments are written on the assumption that the CE103 will be monitored and controlled by the analogue facilities contained within the **CE120 Controller**.

The experimental topics which can be investigated using the CE103 include,

1. Heat transfer.

2. ON/OFF or relay control. Experiment includes investigation of overshoot and undershoot, ON and OFF time ratio, variable rates of heating and cooling, together with off-set and hysteresis.

3. Proportional (P), Proportional + Integral (PI) and Proportional + Integral + Differential (PID) control. The experiments consider stability, frequency response, etc.

4. Use of Feedforward control.

5. Thermal inertia and variable time-constants.

6. Multi-function control - up to three variables to be monitored and individually controlled.

The flexible design of the equipment enables many other analysis and control exercises to be developed by the user to suit his local requirements. This includes extended or advanced control experiments. The equipment is also ideal for student project work.

Further, because of the fully open design and structure of the CE103, it is possible to extend the range of experiments to cover other aspects of control engineering as required. The circuit outline diagram blank contained in Appendix 2 is intended to assist in the production of new experimental procedures.

The performance analysis of thermal process/heat transfer systems is widely used in control engineering texts as a typical process control system. Texts that deal specifically with the system in some detail are listed in the Citation Index contained in Appendix 1.

A Glossary of Terms is given in Appendix 3 to assist in the understanding of the explanations given in this manual.

The CE103 is designed to operate with external analogue, digital or other standard industrial control elements. The **CE120 Controller** and the **CE122 Digital Interface** are provided within the TQ Control Engineering Range to satisfy this requirement while also being fully compatible with the input/output signal requirements of the CE103.

To ensure that this document is a totally self-contained technical and operating manual for the CE103, Section 1.3 contains sufficient information on the CE120 (CE122) to achieve satisfactory operation. It is, however, recommended that the CE120 (CE122) Operating Manual be read so that this instrument's full capabilities are understood and, therefore, may be fully utilised.

The CE120 and CE122 are supplied with general-purpose applications software packages for IBM PCs, or 100% compatibles. These allow the units to perform open and closed-loop control investigations on any other item of laboratory equipment with compatible analogue inputs and outputs. Additional software packages, again written for the IBM PC, are available for specifically controlling the CE103 via the CE120 or the CE122. All packages are menu driven program suites that allow the user to interactively investigate various aspects of digital control leading up to three-term (PID) controllers and beyond. Each package is accompanied by detailed operating instructions that describe the software functionality and also provide experimental procedures where appropriate.

As an alternative, the CE103 may be controlled by any other compatible analogue or digital controller. However, it will be necessary to make the relevant amendments to the operating procedures and connection diagrams given in the manuals.

1.2 CE103 Thermal Process Control Apparatus

The **CE103 Thermal Process Control Apparatus** models the industrial situation commonly found in such equipment as air conditioning plant where temperature control is achieved through a combination of either,

a) Varying the heat energy input to the system.

b) Varying the speed of a circulating fan.

c) Restricting the actual flow channel itself using a remotely controlled vane mounted in the flow path.

d) Any combination of a, b or c.

The process contained within the CE103 comprises an air duct through which air may be circulated using an electrically driven variable speed fan. An electrically heated process block is mounted in the air flow path such that it attains equilibrium temperature by balancing the heat gained through the energy supplied to it via the heater coil and the heat lost through convection/conduction.

Two platinum resistance thermometers monitor the actual temperature of the block, one in direct thermal contact with the block and the other mounted with an insulating spacer to introduce thermal inertia and variable time constant effects into the control loop.

Additional CE103 units may be connected in cascade, using the adapter, supplied with the apparatus. The adapter fits at the ends of the air ducts.

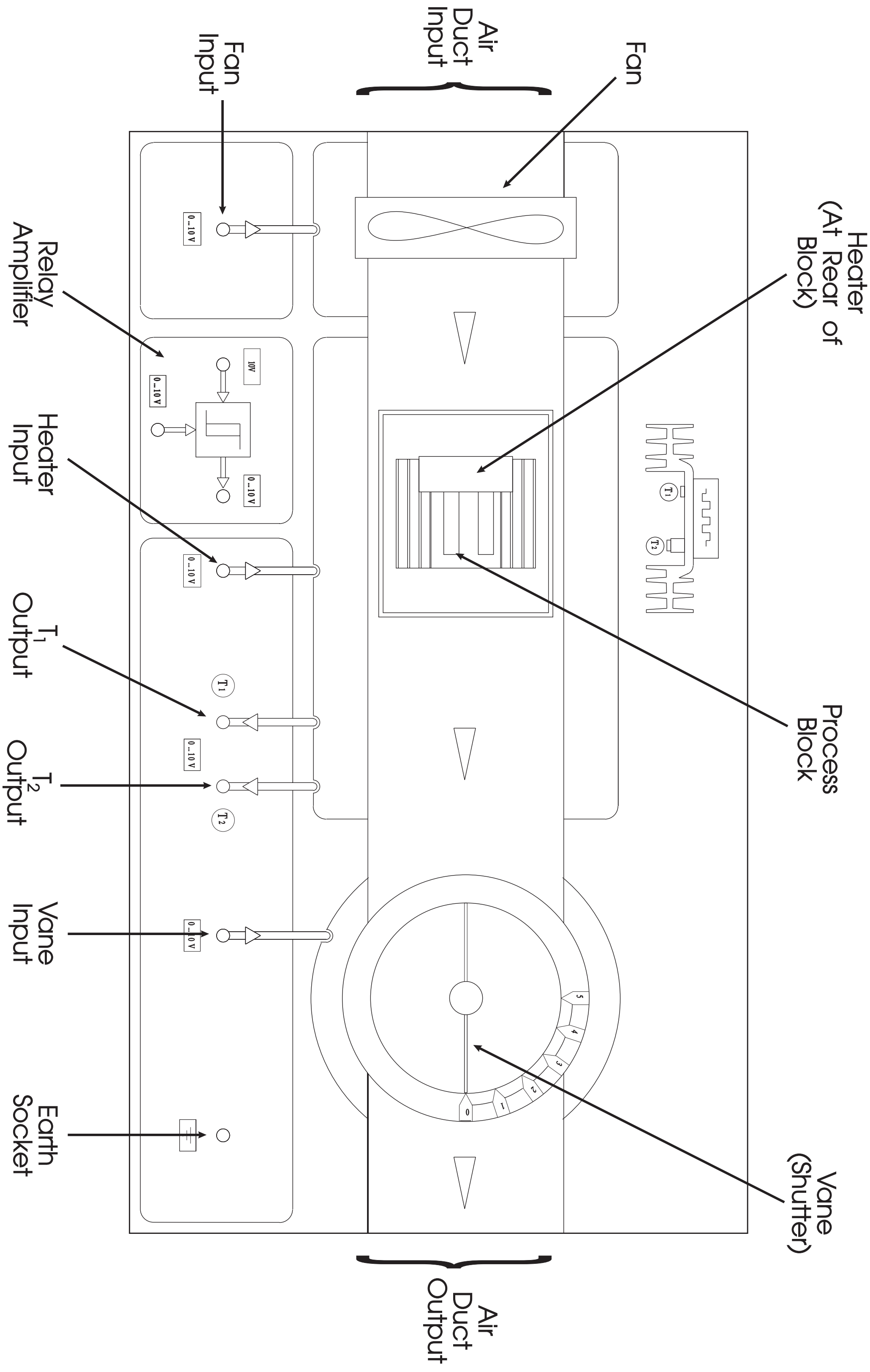

Fan
Air Duct Input
Fan Input
Heater (At Rear of Block)
Relay Amplifier
Heater Input
T_1 Output
T_2 Output
Process Block
Vane Input
Earth Socket
Vane (Shutter)
Air Duct Output

Figure 1.2

A servo driven vane, mounted after the fan and the process block, can be used to create further variations in the control system, which may be investigated.

The unit contains the power supplies to energise the heater and fan circuits as well as the signal conditioning circuits for the thermometers to provide outputs of 100 mV/°C.

The control problem to be investigated is that of maintaining the process temperature within acceptable limits while operating under various heat input/output conditions. This is achieved through a combination of regulating the electrical energy to the heater coil, varying the air flowrate and/or by rotating the vane to restrict the passage of air and, therefore, the heat transfer rate.

The CE103 contains the power supplies for the fan, vane servo and heater circuits as well as to the signal conditioning circuits for the sensors. The platinum resistance thermometer outputs are calibrated to produce 100mV/°C.

The front panel of the CE103, shown in Figure 1.2, provides a schematic functional detail of the unit as well as providing quick and easy access, via 2mm terminals, to both the individual transducers and also to the heater control circuits.

The Fan Input Socket inputs a signal in the range 0 to +10V to provide variable speed and, therefore, variable airflow through the duct. It must be noted that a minimum, threshold, voltage must be applied to this terminal before the motor will start. There is no feedback on the fan so any change in load, as caused by the vane closing for instance, will cause the fan speed to change. Negative voltages will be ignored.

The process block, shown in Figure 1.3, is mounted in the duct and can be viewed through the clear window in the front panel.

The heater is mounted at the rear of the block and the two platinum resistance thermometers are clearly visible on the front surface. The adjacent schematic diagram shows the relative positioning of the heater and the thermometers.

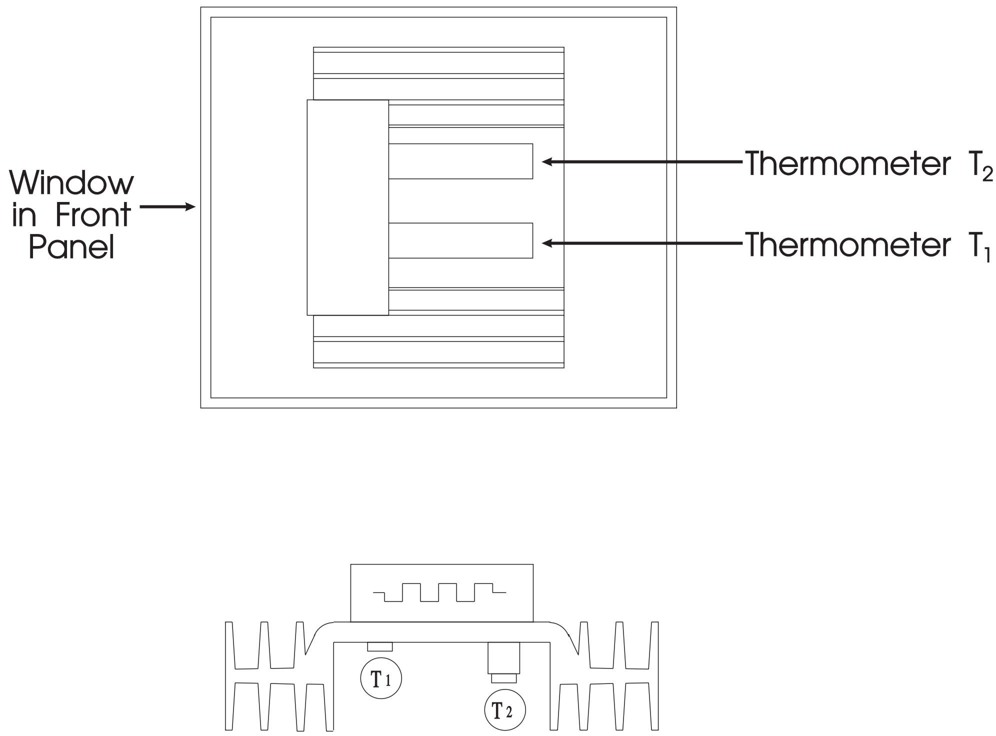


Figure 1.3

The Heater Input Socket, when supplied with a signal in the range 0 to 10V, controls the power to the heater by regulating the duty cycle of a pulse width modulated heater amplifier. The period is approximately 1 second. The adjacent LED indicates when the heater is ON. If the temperature of the process block exceeds 100°C, the heater circuit is disabled until the temperature falls below 100°C. Negative voltages will be ignored.

The socket labelled $\mathbf{T_1}$ is the output from the platinum resistance thermometer that is in direct contact with the process block. The output signal is calibrated to provide a signal of 0.1V/°C up to a maximum of 100°C. That is, 0V at 0°C and 10V at 100°C.

The socket labelled $\mathbf{T_2}$ is as for the $\mathbf{T_1}$ socket except that it connects to the platinum resistance thermometer mounted on the spacing block.

The drive motor for the Vane is servo controlled for position. A signal in the range 0 to 10V to the Vane Input Socket will cause the Vane to rotate from the fully open position (horizontal) to the closed position (vertical). With no input signal the Vane will be fully open. For a step input of 10V, the Vane will close in approximately 5 seconds. Sufficient gap has been allowed to ensure that, even when the Vane is closed, the fan will not stall or overheat.

The Earth socket is the common for all inputs and outputs to the CE103. It is internally connected to mains earth.

The Relay Amplifier Section, shown separately in Figure 1.4, provides the variable hysteresis required by some experiments for ON/OFF control investigations.

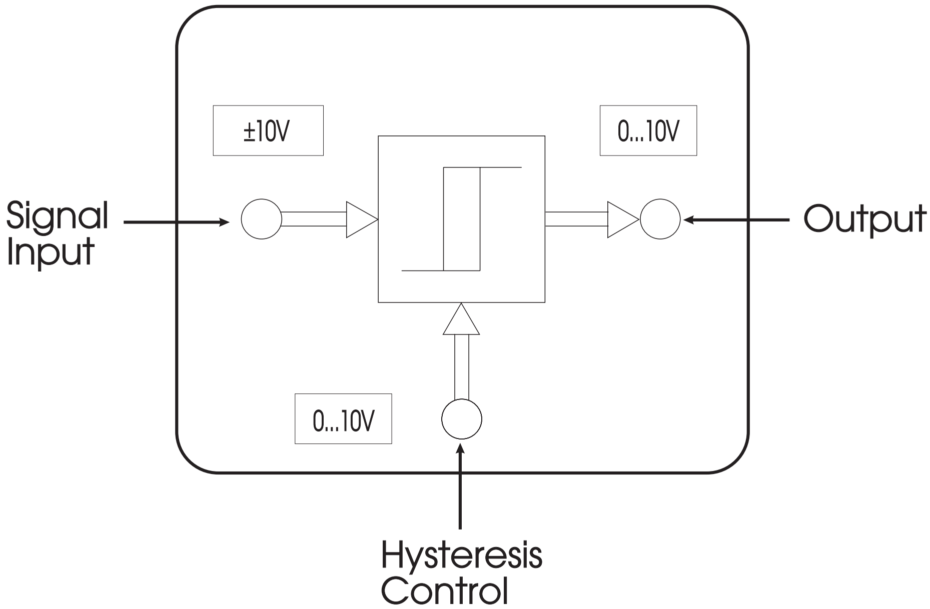


Figure 1.4

The Input Socket accepts an analogue signal in the range -10 to +10V. This signal is proportional the energy required by the heater, though in an unsuitable format to achieve ON/OFF control.

A control signal, in the range 0 to +10V, to the Hysteresis Control Socket, varies the amount of hysteresis in the amplifier. For example, with a 3V signal on this socket, the output will rise to 10V when the input rises through 1.5V and will remain at that level until the input falls below -1.5V.

The signal at the Output Socket will be 10V when High and 0V when Low, as controlled by the separate inputs to the signal and hysteresis sockets. The output signal is intended to drive the Heater Input for ON/OFF control of temperature.

IMPORTANT

As previously stated in Section 1.1, every effort has been made to ensure that the CE103 has been configured for the local mains supply voltage, either 110/120V or 220/240V. The Test Certificate supplied with the CE103 or the Serial Number Plate at the rear of the unit indicates the actual voltage setting.

Connection between external power supplies, control modules/measuring instruments and the heater/transducer circuits of the CE103 are made via 2mm terminals mounted on the front panel. The connecting leads supplied with the CE103 enable the user to make circuit/unit interconnections and so assemble a wide range of functional control systems as required.

To readily facilitate the connection of the CE103 to most standard laboratory equipment, such as instrumentation, adapters are supplied to convert the 2mm format of the CE Range to either a 4mm and/or to a BNC format.

1.3 CE120 Controller

The **CE120 Controller**, shown in Figure 1.5, is one of a range of modular units designed to practically investigate the basic and advanced principles of control engineering. It is primarily intended as the combined analogue/digital control element for use with the **TQ Control Engineering Range, CE103-CE110**. It may also be used as a stand-alone and general-purpose laboratory analogue and/or digital controller with any other electrically compatible control equipment.

The front panel layout of the CE120, shown in Figure 1.6, has been designed to provide a logical and, hence, easy to use item of laboratory equipment.

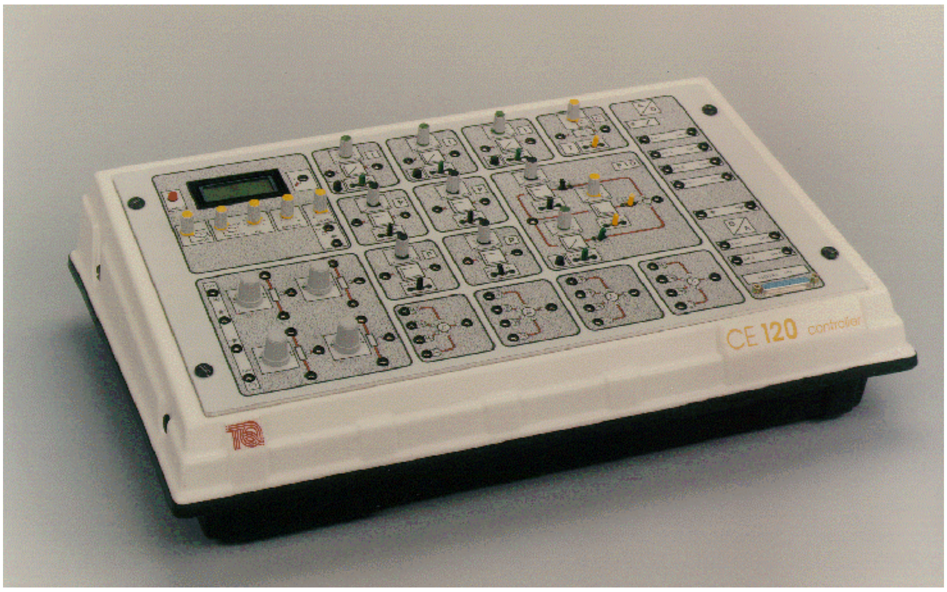


Figure 1.5

Each of the individual control circuits and ancillary modules are represented and accessed on the front panel in appropriately labelled functional blocks. The legend clearly details the purpose of each of these circuits. The symbols used conform to international standards and also correspond to those used in this manual.

Input and output signal access is achieved using the 2mm terminals mounted on the front panel of the CE120. All circuits are internally protected against short-circuit and over-load.

The front panel is functionally divided into three distinct operational areas;

AREA A. SIGNAL MONITORING AND WAVEFORM GENERATOR.

Function Generator - for variable frequency and amplitude sinewave, squarewave or sawtooth output signals with a frequency range of 0.01 Hz to 100 Hz. Output via 2mm terminal.

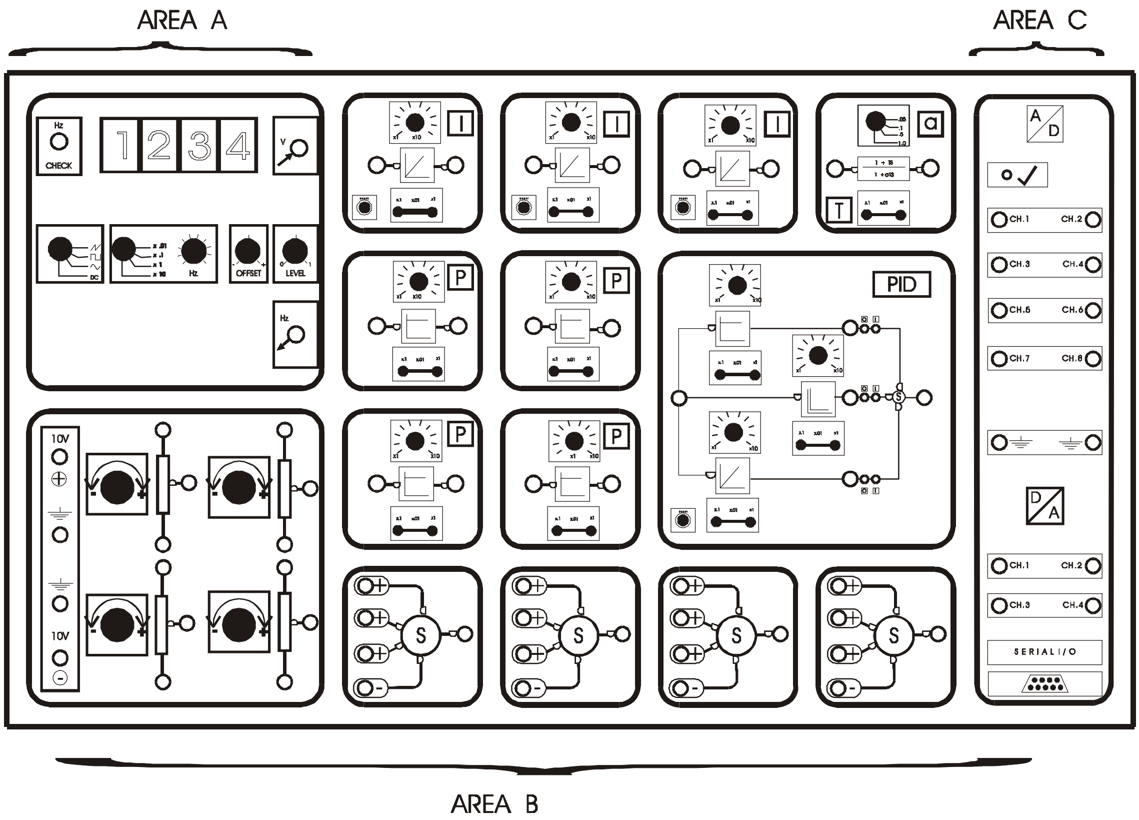


Figure 1.6

Signal levels are variable from 0 to ±10V with the facility for a 0 to ±10V offset. These levels would be accurately and conveniently set by connecting the output to the adjacent digital voltmeter located on the front panel.
The meter also includes an internal facility to monitor the frequency of the output signal (See next paragraph).

Digital Voltmeter - $3^1/_2$ digit, 7 segment. Range ±19.99V. Input via 2mm terminal mounted to the right of the meter. The 'Push Button' located to the left of the meter enables temporary display of the frequency of the output signal from the internal Function Generator when depressed.

AREA B. ANALOGUE SECTION.

D.C. Supply - Two separate constant voltage outputs of +10V and -10V respectively. These, when used in conjunction with the four adjacent potentiometers, provide all circuit voltage levels required by a typical system in the range of ±10V.

Potentiometers - Four multi-turn linear potentiometers. For general-purpose applications such as adjusting the 'Set-Points', attenuating signals, etc.

Summing Amplifiers - Four off, each with 3 '+ve' inputs and 1 '-ve' input. Unity gain.

Proportional Amplifiers - Four off, each with calibrated Proportional Gain ($\mathbf{k_p}$) in the range 0.01 to 10 via range switches and continuously variable potentiometers.

Integrating Amplifiers - Three off, each with calibrated variable gain to provide Integrating Factors ($\mathbf{k_i}$) of 0.01 to 10 obtainable through range switches and continuously variable potentiometers.

Three-Term (PID) Controller - includes fully variable proportional, integral and differential gain amplifiers with a unity gain summing amplifier to produce a single output of all three.
Toggle switches in the output of each of the three terms, before their summation, provide the means of selectively removing them from the PID output. 2mm terminals provide access to individually monitor the P, I and D output signals.
The P and I ranges are as previously described for the individual circuits. The Derivative amplifier range is continuously variable to provide a Differential Factor ($\mathbf{k_d}$) between 0.01 and 10.

Phase Lead Network - An amplifier with a variable transfer function, ratio of the output to the input, with a characteristic which follows the expression,

$$\frac{1+\tau s}{1+\alpha\tau s}$$

The time constant, $\boldsymbol{\tau}$ **(Tau)**, sets the frequency, $\boldsymbol{\omega_1}$, at which phase advance begins. The phase advance is removed at frequencies above $\boldsymbol{\omega_2}$ where,

$$\omega_1 = \frac{1}{\tau} \quad \text{Radians/s}$$

and,

$$\omega_2 = \frac{1}{\alpha\tau} \quad \text{Radians/s}$$

So the phase advance coefficient α (**Alpha**) sets the width of the frequency band ($\omega_2 - \omega_1$) over which phase advance is applied.

Comprises a three-position toggle switch that enables τ to be set to 1, 2 or 4, and a rotary switch providing selection for α (**Alpha**) of 0.05, 0.1, 0.5 or 1.0. Both τ and α may be individually set to produce the transfer function required.

AREA C. DIGITAL SECTION.

Analogue input/output terminals, 2mm format, provide the facility to enable a computer to both input data as well as generate output signals under the control of software. A panel-mounted socket provides the actual link between the CE120 and the host computer.

The facilities available within this area are,

8 A-D Inputs -	12 bit, each ±10V.
4 D-A Outputs -	12 bit, each ±10V.
Serial I/O -	9 pin "D" Type connector mounted on front panel with pin configuration conforming to the RS232 standard. Provides the digital input/output link between the CE120 and the host computer via the ribbon cable provided.

Full technical details of this port and its functionality are provided in the CE120 Manual.

The **CE120 Controller** is supplied with comprehensive operating instructions. These include specific information about using the CE120 with other equipment in the TQ Control Engineering Range or with any compatible equipment when being used as a general-purpose laboratory analogue and/or digital controller.

The **CE122 Digital Interface** is a digital-only alternative to the CE120, containing all of the facilities previously described for the Digital Section of the CE120. The only difference being the enclosure in which the unit is contained.

Operational software is supplied with both the CE120 and also the CE122 for general-purpose data acquisition and control. The menu driven format allows the user to configure each of the A-D and D-A inputs/outputs as required and to display the data on the computer monitor. Additional software packages are available which are dedicated to each of the Control Engineering Range, CE103-CE110.

Note

The sensors in this product are calibrated before leaving the factory and will not normally need recalibration. Occasionally, however, environmental differences may cause the sensors to become out of calibration.
If recalibration of this product seems necessary, please contact your local TQ agent or TQ directly for information.

2.0 CONTROL THEORY.

2.1 Fundamentals of Control Theory

2.1.1 Introduction

The object of this Section is to provide an introduction to control engineering principles by firstly considering the operating characteristics of the individual elements used in typical control engineering systems. It then further considers the performance of these elements when combined to form a complete control engineering system.

The text includes the development of control theory relating to heat transfer systems. This is considered essential in ensuring that the student both understands and is able to explain the results obtained from the practical investigations contained in Section 4 of this manual. This also allows the initial controller settings for the individual systems to be set or established as directed. It then helps in the analysis of how the systems actually respond to various steady state and transient operating criteria.

The primary object of the **CE103 Thermal Process Control Apparatus**, of which this manual forms an important part, is to provide a practical environment in which to study and understand the control of a heat transfer system. These systems occur widely throughout the process industries to such an extent that a grounding in temperature control forms a basic component of a control engineer's training. A simple but widespread industrial application of temperature control is the regulation at a constant temperature of an industrial heat transfer process. In addition, climate control (air conditioning/room heating) are important examples of a thermal control system.

The following theory and examples are based upon the need to maintain a selected value of temperature in a metal block under varying operating conditions. The definitions of the terms used are given in Appendix 3 of this manual.

2.1.2 Control Principles

Consider a simple system where a heater is used to heat an industrial process, represented by a finned block, at a constant rate, as shown in Figure 2.1.

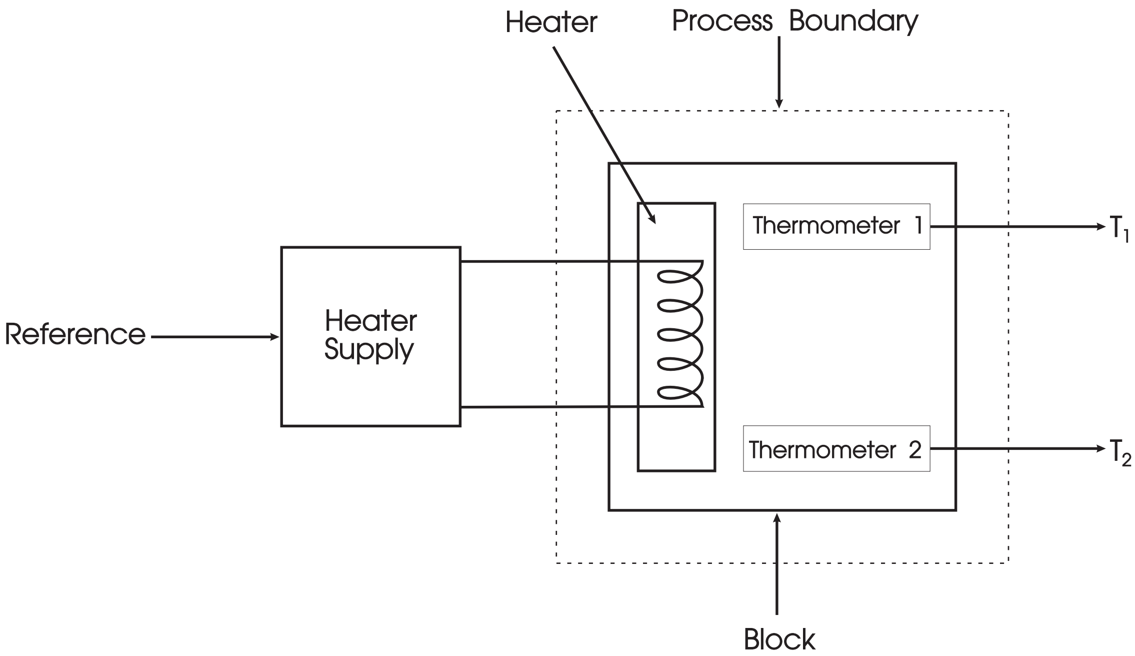


Figure 2.1

A cooling fan, operating at an adjustable speed, removes heat from the process such that, after a period of time, the temperature of the block will achieve a constant level.

Under these conditions,

HEAT SUPPLIED BY HEATER = HEAT REMOVED BY COOLING EFFECTS

or,

ENERGY IN = ENERGY OUT

When this condition is reached, the system is said to be in **Equilibrium** since the temperature will be maintained at this level for as long as both the heater and fan settings remain unchanged.
If the heater and/or the fan settings were to be altered, the temperature would automatically adjust to a new equilibrium.

When operated in this way the system is an example of an **Open-Loop Control System** because no information concerning the changes in process temperature are fed back to the heater circuit to compensate for the changes.

The same configuration as described above exists in many industrial applications or as part of a much larger and sophisticated plant. As such the cooling rate may be varied by external effects and considerations which are not directly controlled by the heater/fan arrangement. In such a system an operator may be tasked to observe any changes in the block temperature and make manual adjustments to the heater when the temperature is changed. In this example the operator provides;

a) The measurement of temperature by using a suitable measurement device and then observing the actual value against a calibrated scale.

b) The computation of what remedial action is required, by using his knowledge and experience, to increase or decrease the energy to the heater the required amount.

c) The manual effort to accomplish the heater controller adjustment required to achieve the desired changes in the system performance, or by adjusting the supply to the heater.

Again, reliance is made on his experience and concentration to achieve the necessary adjustment with minimum delay and disturbance to the system.

This manual process is both time consuming and expensive, since an operator is required whenever the system is operating. Throughout a plant, even of small size, many such operators would be required giving rise to poor efficiency and high running costs. This may cause the process to be an uneconomic proposition, if it can be made to work at all!

There are additional practical considerations associated with this type of manual control of a system in that an operator cannot maintain concentration for long periods of time and also that he may not be able to respond quickly enough to maintain the required system parameters.

A more acceptable solution is to use a transducer to produce an electrical signal which is proportional to the temperature. Electronic circuits would then generate an **Error Signal** that is equal to the difference between the measured signal and the **Reference Signal**. The Reference signal is chosen to achieve the temperature required. It is also termed the **Set-Point** (or **Set Temperature** in the case of the thermal control system).

The Error Signal is then used, with suitable power amplification, to drive the heater and so automatically adjust the actual performance of the system. The use of a signal measured at the output of a system to control the input condition is termed **Feedback**.

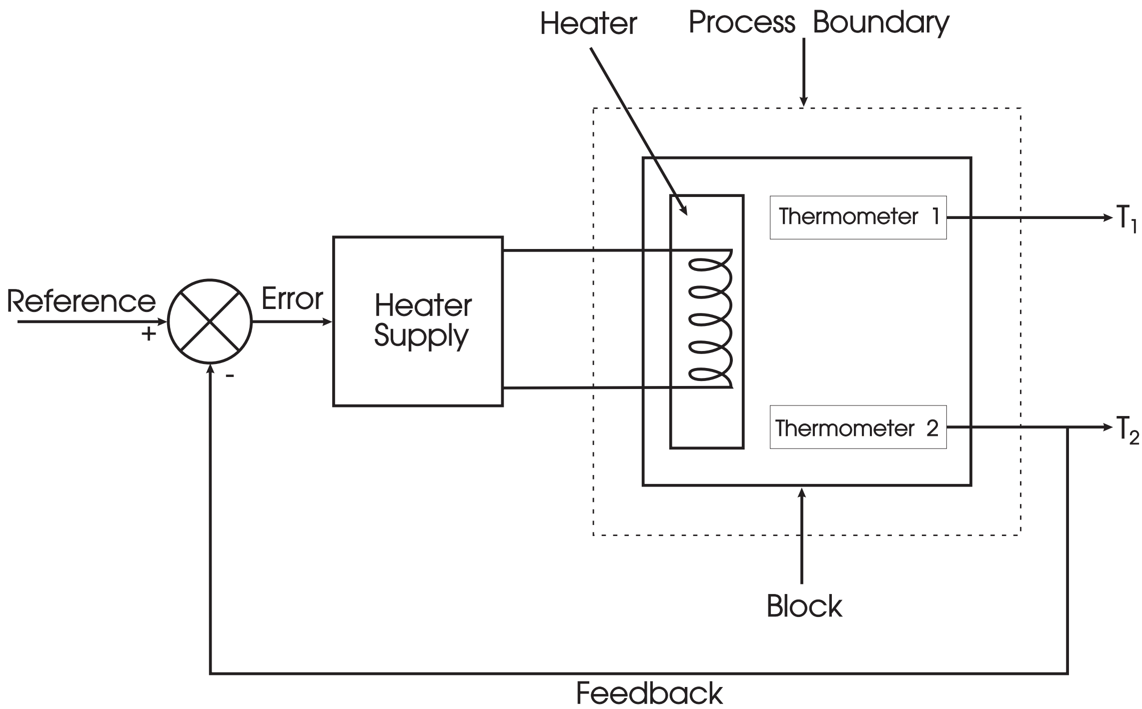


Figure 2.2

In this way the information contained in the electrical signal concerning the level, whether it be constant or varying, is used to control the heater output to maintain the temperature as constant as possible under varying discharge conditions. This is then termed a **Closed-Loop Control System** because the output state is used to control the input condition.

Figure 2.2 shows a typical arrangement for a closed-loop control system that includes a feedback loop applied to a thermal control process. The schematic diagram shown in Figure 2.3 represents the general form of the closed-loop control system described previously.

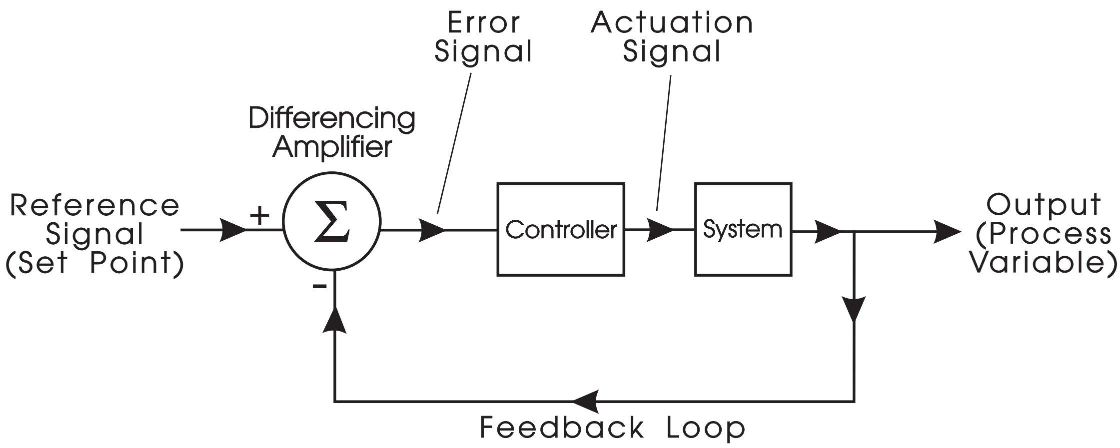


Figure 2.3

Next, consider the situation when the system is initially in equilibrium and then the temperature is caused to fall by increased fan speed. With no immediate change in the heat input rate to the process, the temperature will fall and the Error signal increase. This will in turn increase the energy supplied to the block via the heater and the temperature will increase automatically.

As the temperature is being returned to the original **Set-Point** value, the Error signal reduces causing the energy supplied to the heater to also reduce. Eventually the supply to the heater would reduce until a new equilibrium was produced where the heat input rate equalled the cooling rate and the Error achieves a new constant value.

This constant difference between the **Actual Temperature** and the **Set Temperature** is termed the **Steady State Error** of the system.

If the **Gain** of the amplifier was increased, the Steady State Error would be reduced but not totally removed, for exactly the same reasons as given previously. If the Gain were to be increased too much the possibility of **Instability** may be introduced into the system. This would become evident by the actual temperature becoming oscillatory.

The system described above is said to have **Proportional Feedback** since the **Gain** of the amplifier is constant. This means that the ratio of the output to the input is constant once selected. Figure 2.4 shows the characteristic of a typical Proportional Control Amplifier with the **Gain** set at different levels, increasing from **G1** to **G5**.

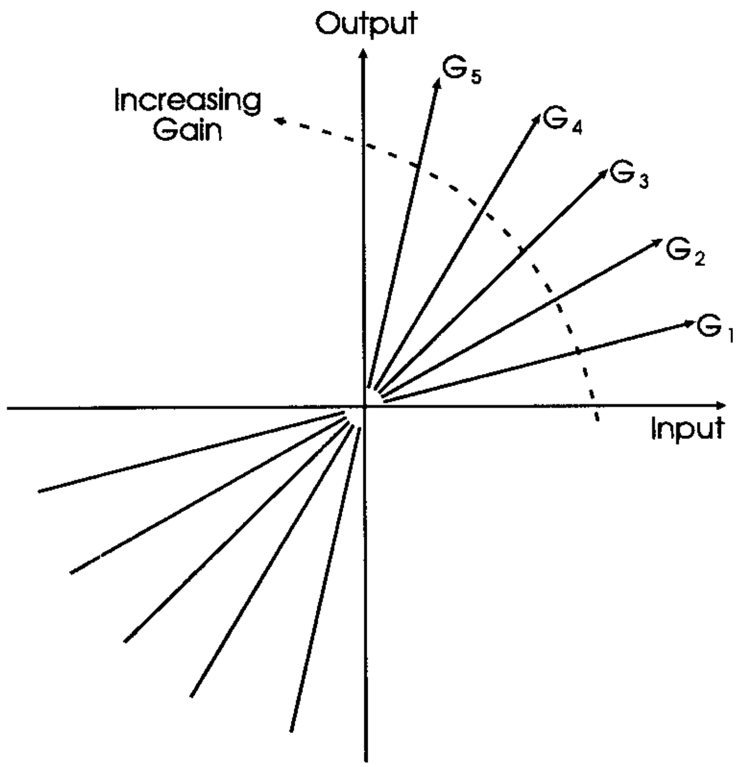


Figure 2.4

In order to maintain a non-zero input to the heater, there must always be a non-zero error signal at the input to the proportional amplifier.

Hence, on its own Proportional Control cannot maintain the temperature of the process block at the desired value, with zero Error, other than by manual adjustment of the Reference signal. Moreover, proportional gain alone would not be able to compensate fully for any changes made to the operating conditions.

Operating with zero Error may, however, be achieved by using a controller that is capable of **Proportional and Integral Control - (PI)**.

Figure 2.5 shows a typical schematic diagram of a PI Controller.

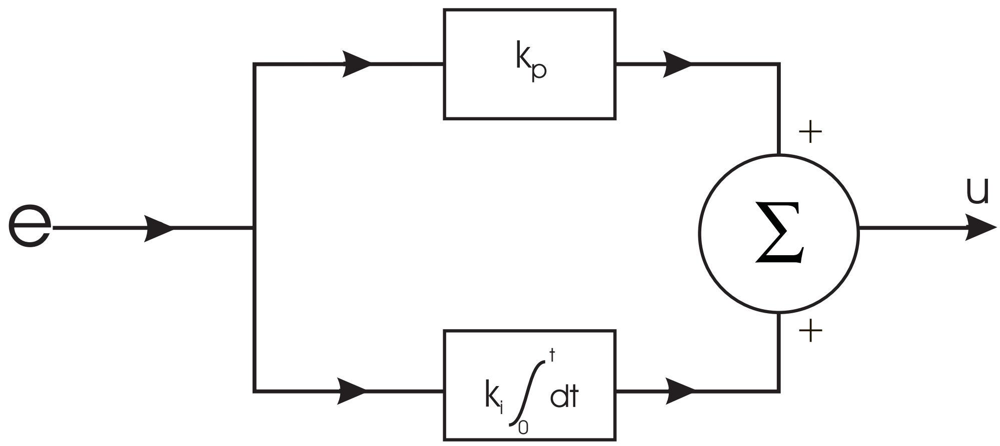


Figure 2.5

The Proportional Amplifier in this circuit has the same response as that shown previously in Figure 2.4 (**G_1** to **G_5**).

An Integrating Amplifier is designed such that its output is proportional to the integral of the input. Figure 2.6 shows the typical response of an Integrating Amplifier supplied with a varying input signal.

From this figure it can be seen that:

a) When the input is zero the output remains constant.

b) When the input is positive the output ramps upwards at a rate controlled by the actual magnitude of the input and also the gain of the integrator.

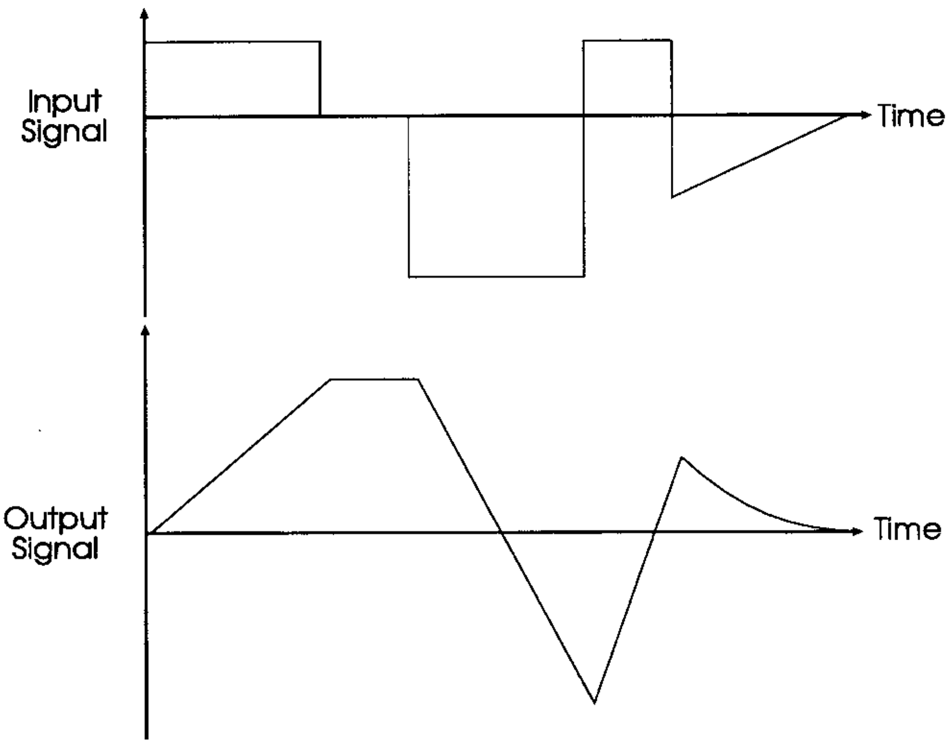


Figure 2.6

c) When the input is negative the output ramps downwards at a rate controlled by the actual magnitude of the input and also the gain of the integrator.

d) If the input itself is ramping or changing in any way then the output will follow an integral characteristic, again following the criteria given in **(a)** and **(b)** above.

e) When a change in input polarity occurs, the output responds in the manner described above, starting at the instantaneous output value at which the change occurred.

f) The magnitudes achieved at the output are dependent on the magnitude of the input signal and also the time allowed for the ramping to occur. In a practical integrator, the output signal is also limited by the voltage of the power supply to the integrator itself.

Effectively, when a constant d.c. signal is supplied to the input of an Integrating Amplifier its output will 'ramp' at a constant rate. Whether it ramps up or down is determined by whether the input polarity is either positive or negative. By arranging the polarity of the Error signal in a control system correctly, the output from the integrator can be configured to always drive the system in the correct direction so as to minimise (zero) the Error.

In practice, an integrator would be used, as shown in Figure 2.5, with proportional amplification to give an overall system response of the required characteristic. The overall response of the PI Controller to a step change in Set-Point (or changes to the block temperature due to the cooling rate) is the combined effects of its two circuits, as shown in Figure 2.7.

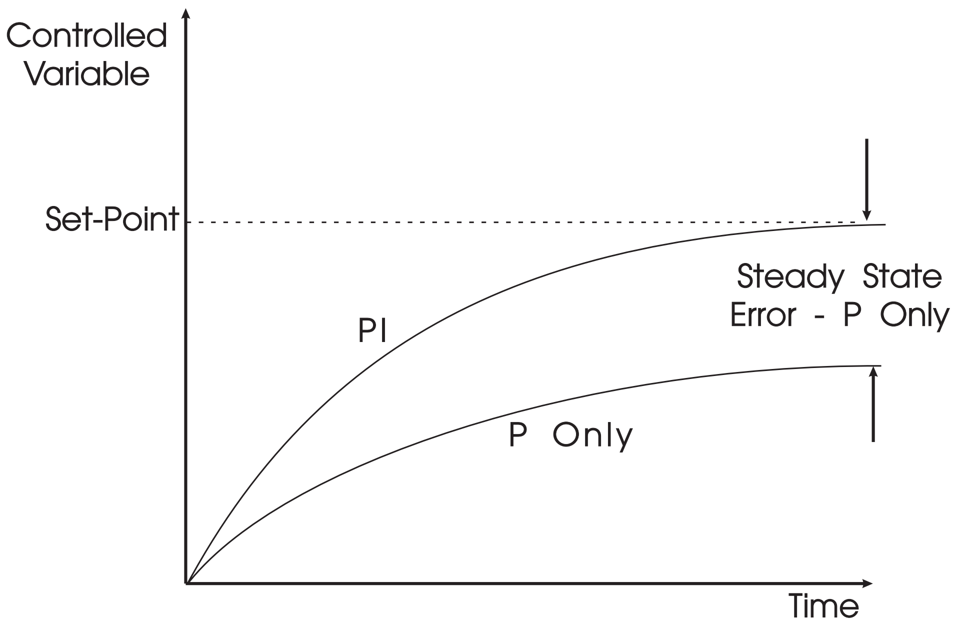


Figure 2.7

Consider the system described previously in Figure 2.2, where the cooling rate is increased by increasing the speed of the fan, but now with a PI Controller in the Feedback loop.

As before, the Proportional Amplifier on its own will leave an Error at the instance of the change in temperature. However, with the Integrator output signal increasing, ramping up in response to this error, the energy supplied to the heater increases, which causes the block temperature to increase also. The temperature will rise until the Set Temperature is achieved and the Error is zero. At this condition the heating and cooling rates are equal and the system is in equilibrium.

This new operating condition will be maintained until another disturbance causes the level to change once again, whether upwards or downwards, and the controller automatically adjusts its output to compensate. In practice the PI Controller constantly monitors the system performance and makes the necessary adjustments to keep it within specified operating limits.

The amount of Integral Action will affect the response capability of the system to compensate for a change. Figure 2.8 shows the typical response of a system with constant Proportional and varying levels of Integral Action.

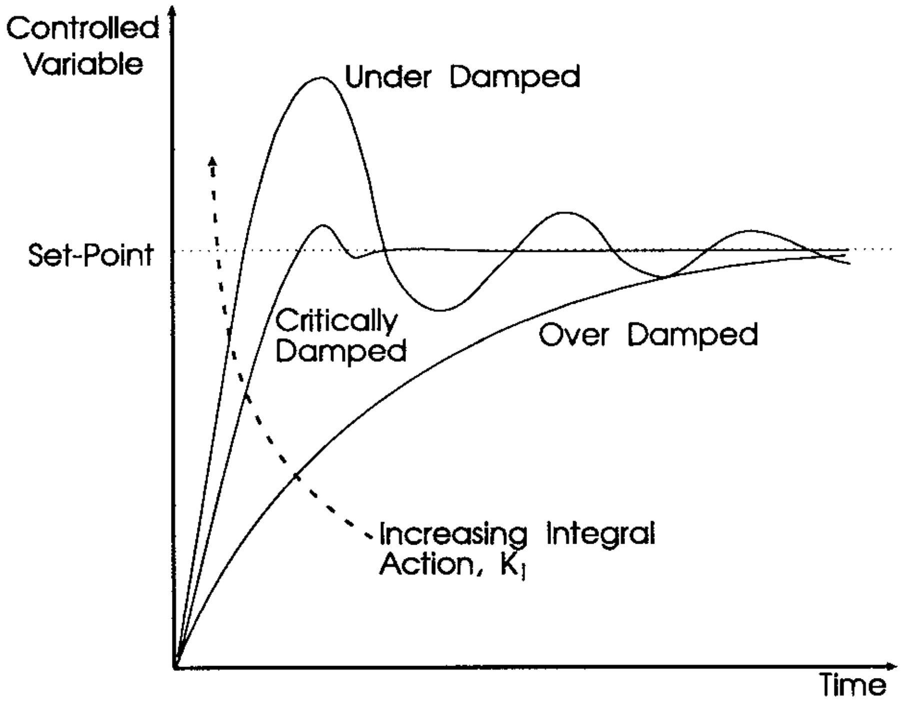


Figure 2.8

With an intermediate level of Integral Action the system moves quickly, with minimum overshoot, to the Set-Point value. In the example shown, the value of Integral Action chosen is said to achieve **Critical Damping**.

With a low level of Integral Control there is a very slow response, giving rise to a distinct time delay between when a change occurs and when the control circuit re-establishes the Set-Point once again. This type of system is said to be **Over Damped**.

With a high level of Integral Control, the response of the system may be so fast that it overshoots the required value and then oscillates about that point under Integral Action until it finally settles down to the steady state condition, if at all. Note that, in the example given, the time for the system to settle down is greater than when the Integral Control value was small. This type of system is said to be **Under Damped**. For large levels of Integral Control, the system oscillations of the under damped system might grow and become unstable.

In general:

a) Any increase in the amount of integral action would cause the system to accelerate more quickly in the direction required to reduce the Error and have a tendency to increase instability.

b) Decreasing the integral action would cause the system to respond more slowly to disturbances and so take longer to achieve equilibrium.

Where fast response is required with minimum overshoot a Three-Term Controller is used. This consists of the previous PI Controller with a **Differential Amplifier** included to give a **PID** (or **Three-Term**) **Controller**.

The performance of a Differential Amplifier is that the output is the differential of the input. Figure 2.9 shows the characteristic of a Differentiater supplied with a squarewave input.

Each time the input level is reversed the output responds by generating a large peak that then decays to zero until the next change occurs. In a practical Differentiater the maximum peak value would be achieved at the power supply rail voltage levels to the Differentiater itself.

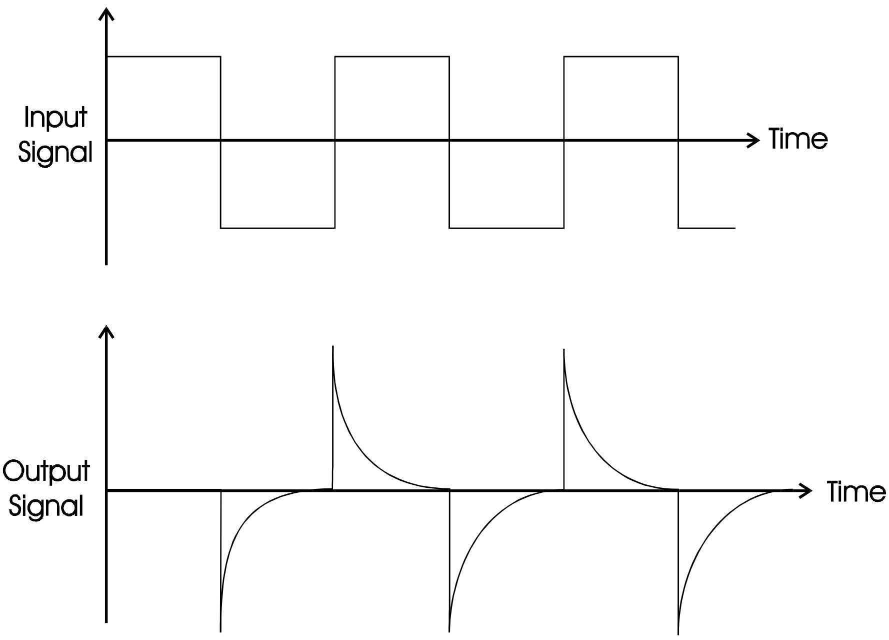


Figure 2.9

In a PID Controller the polarity of the output would be configured to actually oppose any change and thereby dampen the response of the system. The gain of the Differentiater would control the amount of damping provided, both in amplitude and duration.

The damping required for the situation described in Figure 2.8 could also, therefore, be achieved by including a Differentiater in the control loop to suppress the high acceleration caused by the Integrator without affecting its ability to remove the Error. It is the balance between the Integral and Differential Action which now controls the overall system response to a step change in Set-Point.

The speed and manner with which a system can overcome disturbances is termed the **Transient Response**. By careful selection of the parameters of the proportional, integral and differential amplifiers it is possible to produce a system Transient Response to suit the specific application.

This Section so far has only dealt with control engineering principles in a very basic way so that the **CE103 Thermal Process Control Apparatus** can be used by students and engineers new to control engineering without them having to be familiar with the mathematics. It is possible to verify these principles by setting up suitable test circuits with the CE103 and the CE120 and then confirming the various system responses.

The next Section builds upon these fundamental principles and introduces the advanced topics of mathematical modelling, system tuning and predicting system performance. This includes the more complex control of temperature with thermal lags and external disturbances.

2.2 Advanced Principles of Control

2.2.1 Introduction

In this Section we build on the introductory material of Section 2.1 and describe more advanced methods for the analysis and control of the Heat Transfer system.

The ability to analyse a system, real or otherwise, is especially important in establishing the relevant design parameters for new plant or in predicting the performance of existing equipment that is to operate under new conditions. Being able to predict the performance of any complex engineering system in advance of its construction and operation will both reduce costs and also minimise project development time.

The ability to represent a control situation using mathematical equations also allows computers to be used as an invaluable development tool for the engineer. The computer, once programmed to respond in exactly the same way as the chosen system, can thoroughly 'test' or simulate that system under all possible operating conditions, both quickly and cheaply.

For some equipment it may only be possible to simulate certain operating conditions. Since in real life the actual condition cannot be safely or economically reproduced, e.g. the landing on the moon could only be achieved **after** the equipment had been designed and built. Yet the engineers had the confidence to commit vast resources to the development and construction project, as well as gaining experience in advance through the use of simulators. Most importantly, they were able to commit the safety of humans to man the vehicles.

2.2.2. Thermal System: Modelling

The first step in controlling an industrial process is to fully understand how the system dynamics behave. This process is termed **System Modelling**.

Initially, consider the heat transfer process as a simple block (which we will take to represent an industrial process whose temperature must be controlled), as shown in Figure 2.10.

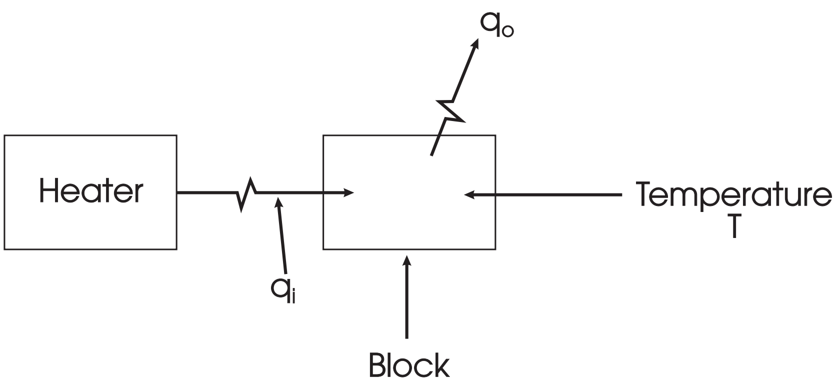


Figure 2.10

The heater supplies heat energy at a rate $\mathbf{q_i}$ and the block cools due to radiation and convection at a rate $\mathbf{q_o}$.

The system model is determined by relating the heat flow into the block, $\mathbf{q_i}$, to that leaving, $\mathbf{q_b}$. Hence we have,

$$
\begin{aligned}
q_i - q_o &= \text{Rate of Change of Heat in the Block} \\
&= m.c_e \frac{dT}{dt}
\end{aligned}
$$

(2.1)

where **m** is the Mass of the Block
$\mathbf{c_e}$ is the Specific Heat of the Block
T is the Temperature of the Block

We will use,

$$c = m.c_e$$

where **c** is the Thermal Capacity of the Block.

If the block is assumed to lose heat according to radiation and convection then the heat output $\mathbf{q_o}$ is a complex, non-linear function of the Temperature (**T**) of the Block, the Ambient Temperature ($\mathbf{T_{am}}$), the Surface Area of the Block and other parameters. However, for the small temperature differences encountered in the **CE103 Thermal Process Control Apparatus** we can assume a linear relation.

$$q_o = h.A(T - T_{am})$$

(2.2)

where
h is the Heat Transfer Coefficient
A is the Available (Exposed) Surface Area of the Block for heat transfer

If we consider small changes in temperature (**ΔT**) around the ambient temperature ($\mathbf{T_{am}}$), the system model can be written as the linear first order differential equation,

$$c.\frac{d\Delta T}{dt} + h.A.\Delta T = q_i$$

(2.3)

Taking Laplace transforms gives the transfer function,

$$\Delta T(s) = \frac{k}{\tau.s + 1}.q_i(s)$$

(2.4)

where **τ** is the system Time Constant, given by;

$$\tau = \frac{c}{h.A}$$

(2.5)

and the Gain **k** is given by,

$$k = \frac{1}{h.A}$$

(2.6)

Influence of Fan Speed:

The above model assumes that a constant cooling rate is applied. In practice, however, the cooling rate will vary according to the speed of the cooling fan. This can be incorporated into the model as a change in **h**, the Heat Transfer Coefficient, from the block. If the fan speed is controlled by an input voltage $\mathbf{v_f}$ then, the approximate relationship applies,

$$h = h_o + k_f . v_f$$

(2.7)

where $\mathbf{h_o}$ The basic Heat Transfer Coefficient for still air

$\mathbf{k_f}$ A constant relating the cooling effect of the fan with the heat transfer properties of the block

Notice that for the linearised model used here, the effect of increasing the fan speed is to decrease the system Time Constant **τ**, and the Gain **k**.

2.2.3 Heater and Temperature Sensor Characteristics

When the heat transfer system is used as a control system, the heat flowrate, $\mathbf{q_i}$, is controlled by a voltage applied to an electrical heater. Likewise, the temperature may be sensed by one of two electrical sensors. One is in direct contact with the block (Temperature Output (**T1**)) and the second sensor is partly insulated from the block (Temperature Output (**T2**)).
The overall system may be represented schematically as shown in Figure 2.11.

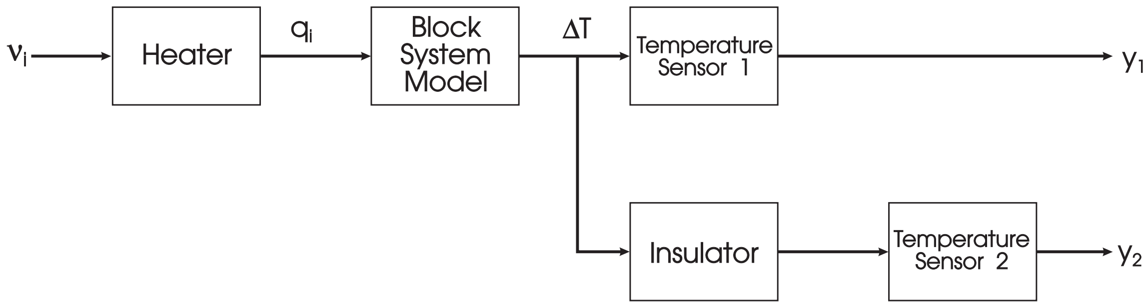


Figure 2.11

The heater input voltage, vi, and the heat flowrate, $\mathbf{q_i}$, have been arranged to be linearly related. The same is true of the temperature sensor characteristic for Sensor 1.

If $\mathbf{k_i}$ and $\mathbf{k_{si}}$ are the heater and Sensor 1 gains,

$$q_i = k_i . v_i$$
$$T_1 = k_{si} . \Delta T$$

(2.8)

Combining these with the transfer function, Equation 2.4, gives the standard first order system,

$$T_1(s) = \frac{G}{(\tau . s + 1)} . v_i(s)$$

(2.9)

The second sensor suffers a thermal lag through the insulator such that an additional sensor time constant (**τ'**) is introduced. The temperature **ΔT** and the Sensor 2 output are related by,

$$T_2(s) = \frac{k'_{s2}}{(\tau' . s + 1)} . \Delta T$$

(2.10)

Therefore, when sensing the block temperature through Sensor 2, the standard second order system transfer functions occurs,

$$T_2(s) = \frac{G'}{(\tau.s+1)(\tau'.s+1)}.v_1(s)$$

(2.11)

Notice that the insulator time constant can be obtained because (from Equations 2.8 and 2.10) the sensor outputs are related by,

$$T_2(s) = \frac{g}{(\tau'.s+1)}.T_1(s)$$

(2.12)

where $g = \frac{G'}{G}$

represents the difference in gain between the two temperature sensors. It may be used as a measure of the heat lost in the insulating block associated with Sensor 2.

2.2.4 Measurement of System Characteristics

The characteristics of a thermal process like the **CE103 Thermal Process Control Apparatus** are best measured experimentally from step response techniques.
Consider first the time constant of the block.

Step Response Measurement: The Block

For a first order system, like the heated block, the Gain **G** and the Time Constant $\boldsymbol{\tau}$ can be obtained from the step response as follows.

With reference to Figure 2.13, the **Gain, G**, is determined by applying a step change, with amplitude **U**, to the input of a system. The final, or Steady State, change in output will be the product **U×G**, from which the system gain **G** can be readily determined.

The time constant $\boldsymbol{\tau}$ is defined as the time required for the step response of the system to reach 0.632 of its final value.

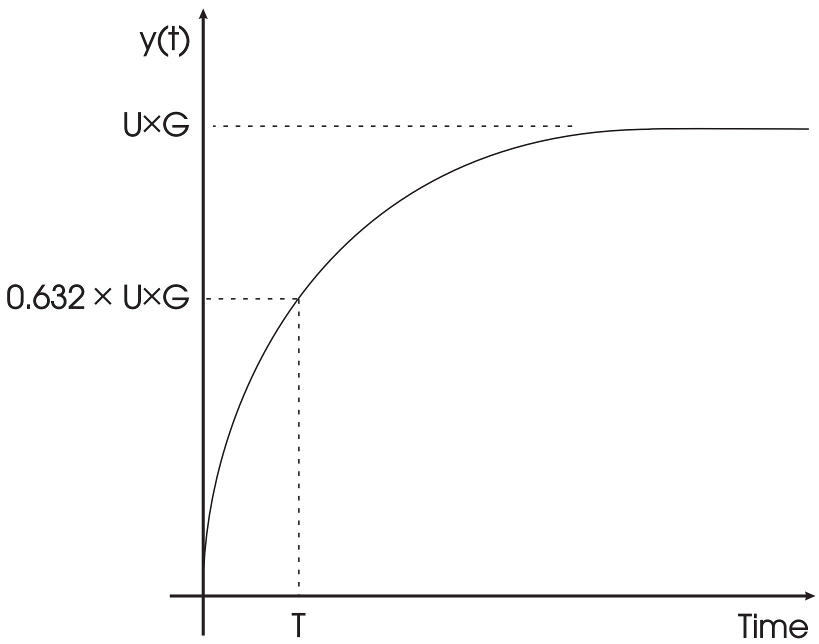


Figure 2.13

The above measurement method is generally easy to use, and gives reasonably accurate results, provided the system characteristic is known to be first order. The modelling exercise of Section 2.2.1 establishes this for the heated block system.

2.2.5 Controller Design: ON-OFF Control

In this section we consider some of the basic principles of control applied in temperature control.

Figure 2.14 shows a typical feedback control system applied to the heat transfer apparatus.

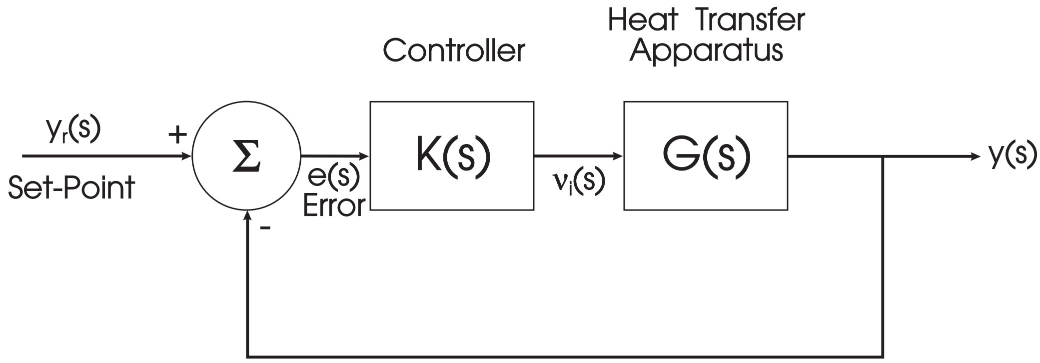


Figure 2.14

The controller **K(s)** produces an actuation signal **v_i(s)** that forms the input to the heater. In order to reduce cost in temperature control systems, the controller **K(s)** is often a relay which gives full heater power for positive error **e(s)** and zero heater power for negative error.

Figure 2.15 shows a simple relay characteristic in which full power is for the heat transfer system 10V and zero power is 0V.

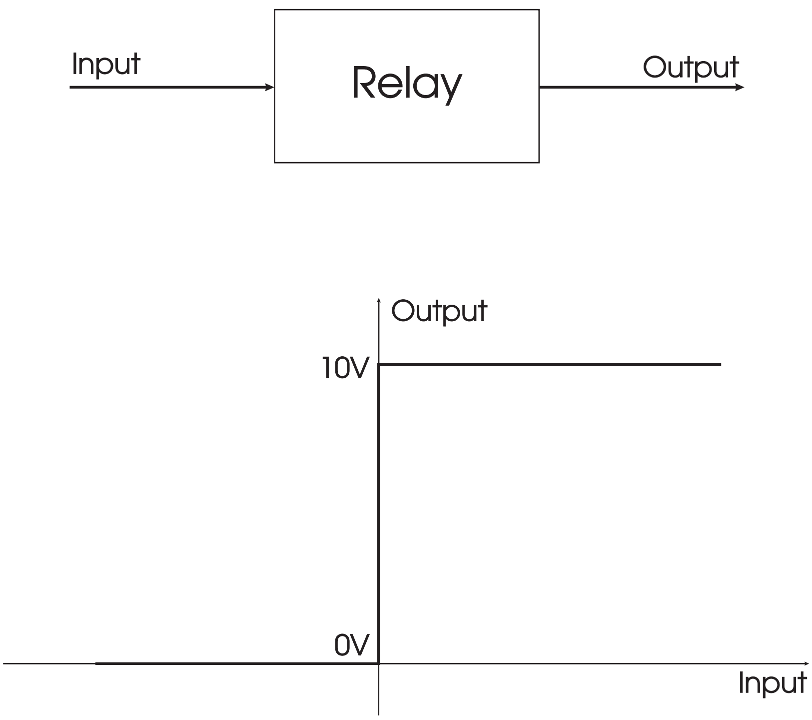


Figure 2.15

A relay is a cost effective and compact replacement for an industrial electronic controller and is commonly used in domestic and some office heating systems (the thermostat used to control room or hot water boiler temperature is a relay controller).

Unfortunately, despite the low cost of relay control, there are some disadvantages. First, and from a practical viewpoint, most relays suffer from hysteresis. This is the phenomenon whereby in decreasing the input signal applied to a relay the '**Switch-Off**' point occurs at a lower voltage than the '**Switch-On**' point when the input signal is increased.

Figure 2.16 illustrates a relay amplifier with hysteresis.

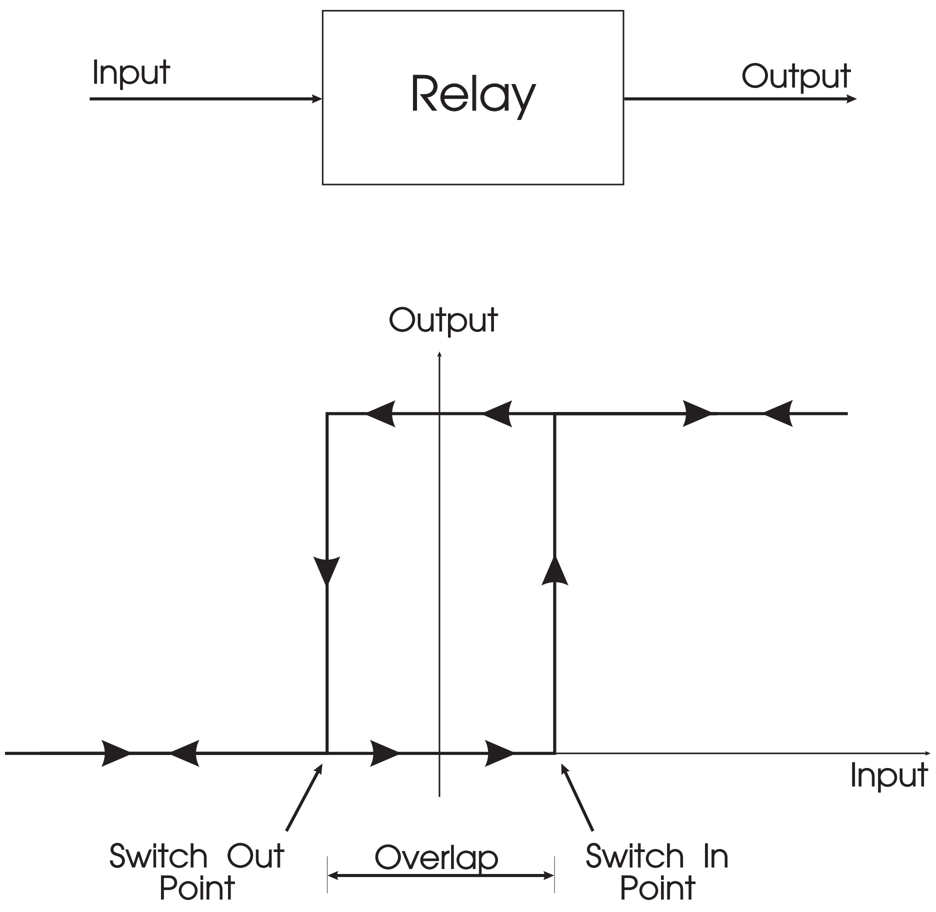


Figure 2.16

The difference between the '**Switch-On**' point and '**Switch-Off**' point is called the '**Hysteresis Width**' or the '**Relay Overlap**'.

Second, and from an accuracy viewpoint, relay amplifiers provide less exact control than a conventional PID controller. Specifically, a relay control system output will always be cycling (or '**Hunting**') around the desired Set-Point (see Figure 2.17).

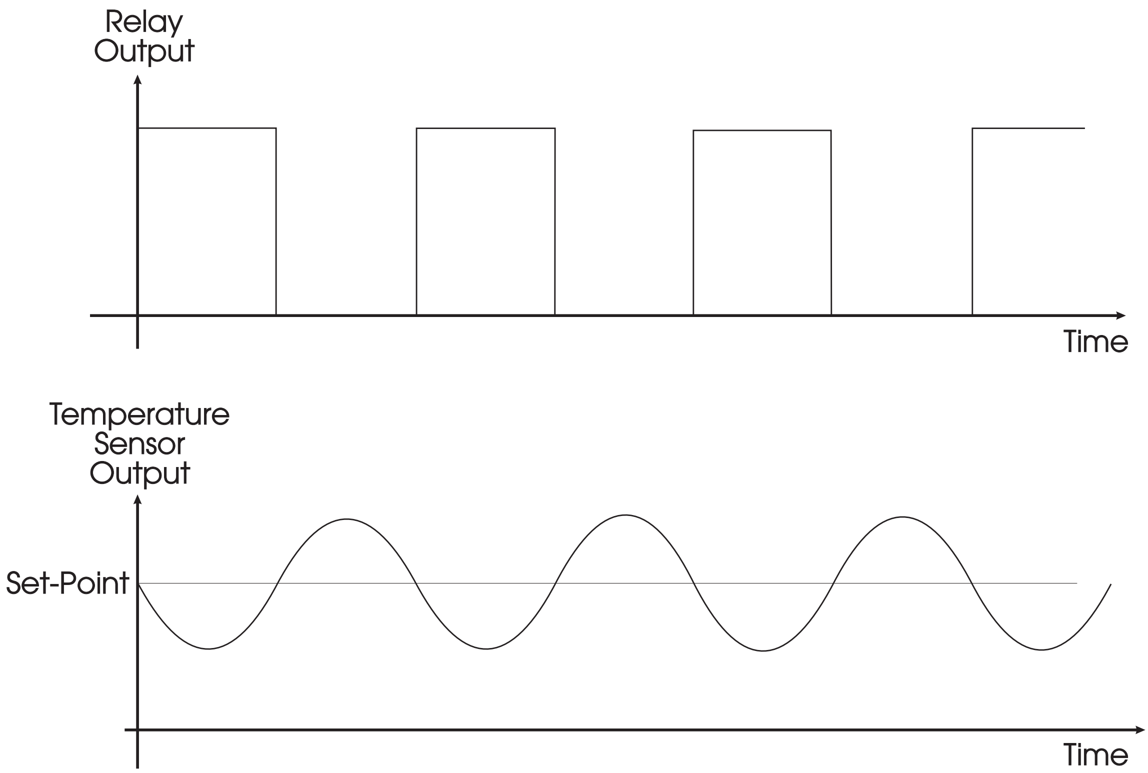


Figure 2.17

For large relay overlaps this cycling can turn into an unstable oscillation. This feature will be explored in the experimental section.

2.2.6 Controller Design: Three-Term Control

Improved control can be obtained (at additional hardware cost) by the use of a three-term temperature control system. In this section we consider general properties of these continuous controllers as compared to the '**ON-OFF**' relay controller considered in the previous section.

Steady State Errors

A main reason for applying feedback control to a system is to bring the system output into correspondence with some desired reference value. The theory developed in Section 2.1.2 'Control Principles' has already explained that there is often some difference between the reference and the actual output. In this Section we see how these errors are quantified when the steady state has been reached.

The steady state error, $\mathbf{e_{ss}}$, is a measure of how well a controller performs in this respect. The steady state error is defined as,

$$e_{ss} = \lim_{t \to \infty} [e(t)]$$

(2.13)

Where the error, **e(t)**, is the difference between the **Set-Point** value and the actual output, as shown in Figure 2.18.

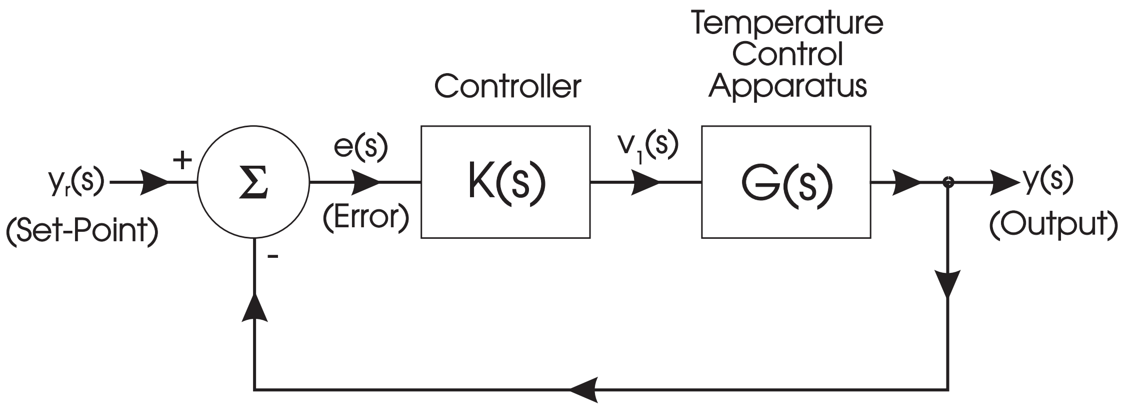


Figure 2.18

Equation 2.13 can be re-written in the frequency domain as,

$$e_{ss} = \lim_{s \to 0} [s.e(s)]$$

(2.14)

For a constant set-point or reference input, $\mathbf{y_r}$, the steady state error (from Figure 2.18) is,

$$e_{ss} = \lim_{s \to 0}\left[\frac{y_r}{1 + K(s).G(s)}\right]$$

(2.15)

Where **K(s)** is the controller transfer function and **G(s)** is the system transfer function.

If proportional control is used then,

$$K(s) = k_p$$

and,

$$e_{ss} = \lim_{s \to 0}\left[\frac{y_r}{1 + k_p.G(s)}\right]$$

(2.16)

Thus proportional control for the thermal control system will involve a steady error which is inversely proportional to the Gain, $\mathbf{k_p}$.

Proportional Plus Integral Control: Definition

A proportional plus integral (or PI) controller can be written as,

$$K(s) = \left(k_p + \frac{k_i}{s}\right)$$

(2.17)

or equivalently,

$$K(s) = k_p\left(1 + \frac{1}{s.\tau_i}\right)$$

(2.18)

If proportional plus integral (PI) control is used,

$$K(s) = k_p + \frac{k_i}{s}$$

and,

$$e_{ss} = \lim_{s \to 0} \left[\frac{s.y_r}{s + (k_p.s + k_i).G(s)} \right] = 0$$

(2.19)

Thus, with proportional plus integral (PI) control, for the thermal process system the Steady State Error is zero.

Proportional Plus Derivative Control: Definition

A proportional plus derivative controller (PD) can be written as,

$$K(s) = \left[k_p + s.k_d \right]$$

(2.20)

or equivalently,

$$K(s) = k_p \left[1 + s.\tau_d \right]$$

(2.21)

The derivative action adds a controller term that is proportional to the rate of change of the error. Thus, if the error is decreasing rapidly, the derivative term is negative and acts to remove excessive control action. If the error is increasing rapidly, the derivative action increases the control action accordingly.

Proportional, Integral and Derivative Control: Definition

A three-term or PID (**P**roportional, **I**ntegral and **D**erivative) controller can be written,

$$K(s) = \left[k_p + \frac{k_i}{s} + s.k_d\right]$$

(2.22)

or equivalently,

$$K(s) = k_p\left(1 + \frac{1}{s.\tau_i} + s.\tau_d\right)$$

(2.23)

The use of the integral term removes steady state offset and the derivative term increases transient speed.

2.2.7 Transient Response of Proportional Controllers

Consider the proportional controller with a first order system as shown in Figure 2.19.

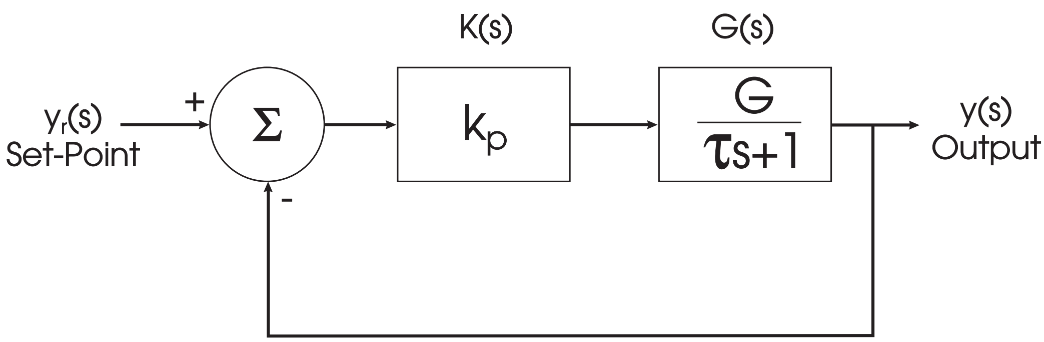


Figure 2.19

The closed-loop transfer function is,

$$\frac{y(s)}{y_r(s)} = \frac{K(s).G(s)}{1 + K(s).G(s)}$$

(2.24)

$$= \frac{k_p.G}{1 + k_p.G + s.\tau}$$

$$= \frac{\left(\dfrac{k_p.G}{1 + k_p.G}\right)}{1 + s\left(\dfrac{\tau}{1 + k_p.G}\right)}$$

The closed-loop time constant is,

$$\tau_{cl} = \frac{\tau}{1 + k_p.G}$$

(2.25)

Thus it is possible to increase the speed of response of a system by increasing the proportional gain, $\mathbf{k_p}$. This reduces the closed-loop time constant, $\boldsymbol{\tau_{cl}}$.

2.2.8 Feedforward Control

It often occurs that an external disturbance will influence the quality of control. (For example, closing the vane (shutter) in the **CE103 Thermal Process Control Apparatus** will cause the temperatures T_1 and T_2 to rise).

A good feedback controller with integral action can compensate for external disturbances. However, if the disturbance can be measured then better control can be achieved by using the measured disturbance in the control system. This is called **Feedforward Control** and is illustrated in Figure 2.20.

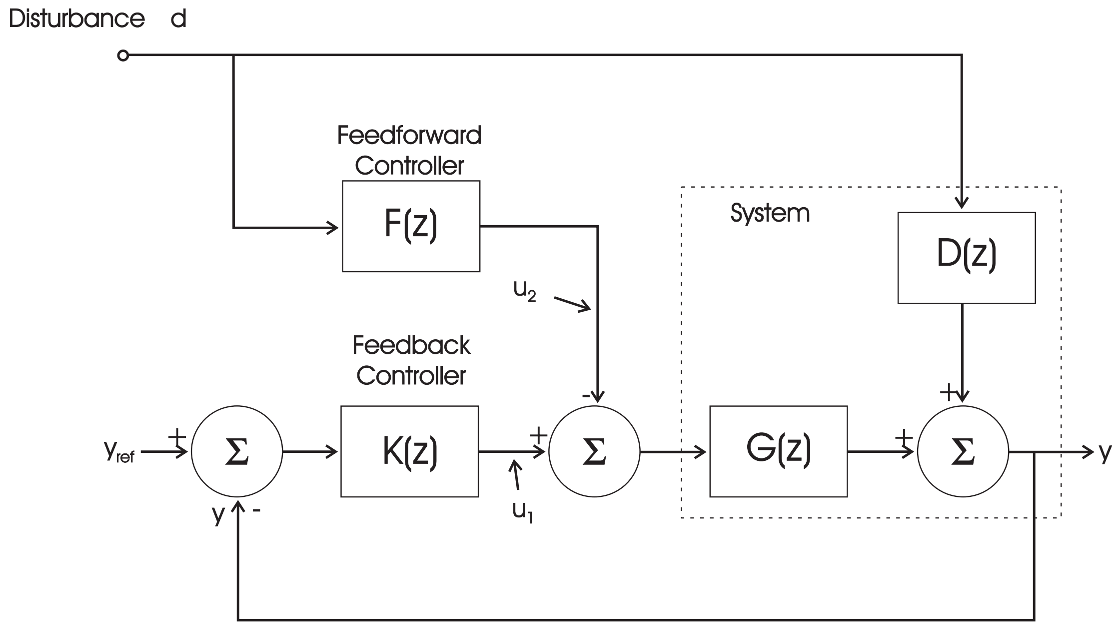


Figure 2.20

In the figure, the disturbance signal, **d**, is fed through a feedforward controller and subtracted from the output of the feedback controller. By correct choice of **F(s)** (see Figure 2.20) the amount subtracted from the output of **K(s)** will exactly compensate for the influence of the disturbance.

An easy way to design **F(s)** is to measure how much the feedback controller output, $\mathbf{u_1}$, (see Figure 2.20) decreases when the disturbance **d** increases from zero to **D**. If the decrease in $\mathbf{u_1}$ is $\mathbf{\Delta u_1}$, then in order to leave the feedback controller unaffected by the disturbance, the feedforward controller must subtract exactly $\mathbf{\Delta u_1}$ when the disturbance changes by an amount **D**.

Selecting **F(s)**, the feedforward controller, to be a gain $\mathbf{k_f}$ means that the correct choice of $\mathbf{k_f}$ for exact disturbance cancellation is,

$$k_f = \frac{\Delta u_1}{D}$$

This ensures that the feedforward controller output, $\mathbf{u_2}$ is equal to $\mathbf{\Delta u_1}$ when the disturbance **d** is equal to **D**.

3.0 DIGITAL CONTROL TECHNIQUES.

3.1 Fundamental Digital Control Principles

Microprocessors and computers have become increasingly important tools for the engineer in recent years for design, data analysis and other routine purposes. However, it is in the field of system control that these devices have had the most significant impact on most branches of science and engineering. The speed and flexibility of operation enables them to be programmed for a much wider range of eventualities than their equivalent analogue circuits.

Software may be written to generate control functions based on the error between actual and demanded values of the variables such that the optimum transient response and steady state condition is attained.

As with any system that requires accurate control, whether digital or analogue, the system must include some method of measuring the relevant physical parameters and then be able to respond to any changes so detected. In a computer-controlled system, the transduced signals are converted into the required digital format and then fed to the input port of the computer. Under software control the computer then interprets and compares this data with a programmed demand value held in memory and uses the result to affect it's response, as shown in Figure 3.1.

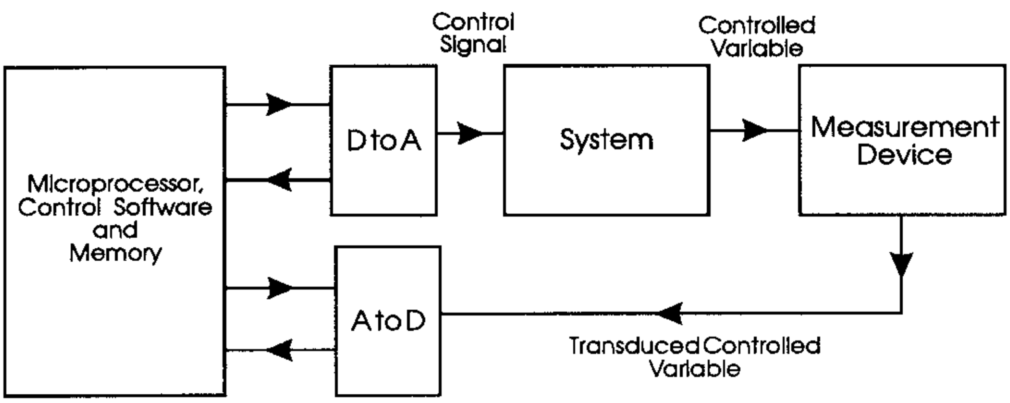


Figure 3.1

There are, however, disadvantages in using digital techniques in control applications. These mainly arise because of the periodic sampling of the data and also the subsequent update of the output signal.

3.2 Software Implementation

Mathematically, the output of the three-term controller may be written as,

$$e_{out} = e.k_p + k_i \int e.dt + k_d.\frac{de}{dt}$$

(Note. This is equivalent to the PID transfer function given in Equation 2.22).

where, $\mathbf{k_p}$, $\mathbf{k_i}$ and $\mathbf{k_d}$ are the coefficients of the proportional, integral and differential terms respectively.

Varying each of these terms will directly affect the response of the controller and so careful selection is important. If any of these coefficients were to be set to zero, then the whole of the respective term will be removed from the overall control function.

From the previous section it is clear that there are three possible control strategies that may require programming on the microcomputer.

a) Proportional only

b) Proportional and Integral

c) Proportional, Integral and Derivative.

Each one shall now be considered in turn, and developed into a flow chart as the first step in writing a program.

In the following sections, each physical parameter is represented in the way it may be written into a computer program. This is not intended to be an alternative to the symbols used in Section 2, but instead a practical application of them.

The symbols used are,

E	**-**	Error Signal
EP	**-**	Proportional Term
EI	**-**	Integral Term
ED	**-**	Differential Term
KP	**-**	Proportional Constant
KI	**-**	Integral Constant
KD	**-**	Differential Constant
OUTP	**-**	Combined Three-Term Controller Output

3.2.1 Proportional Control

This is the simplest form of control and requires the computer to multiply the error signal by a constant value, **KP**.

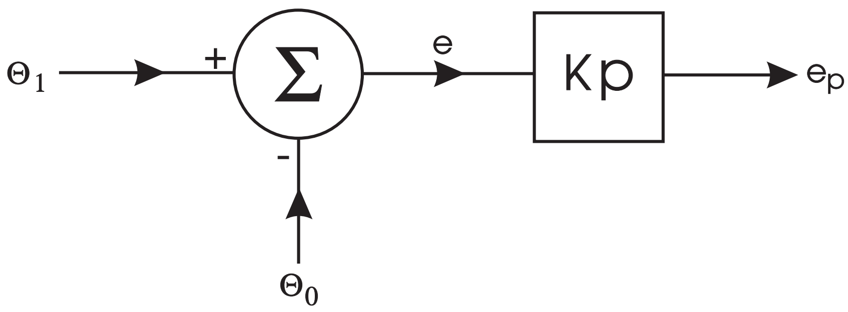


Figure 3.2

From Figure 3.2, the control equation for the computer program can be used to express the Proportional constant as,

$$EP = E \times KP$$

where,

$$E = y_r - y$$

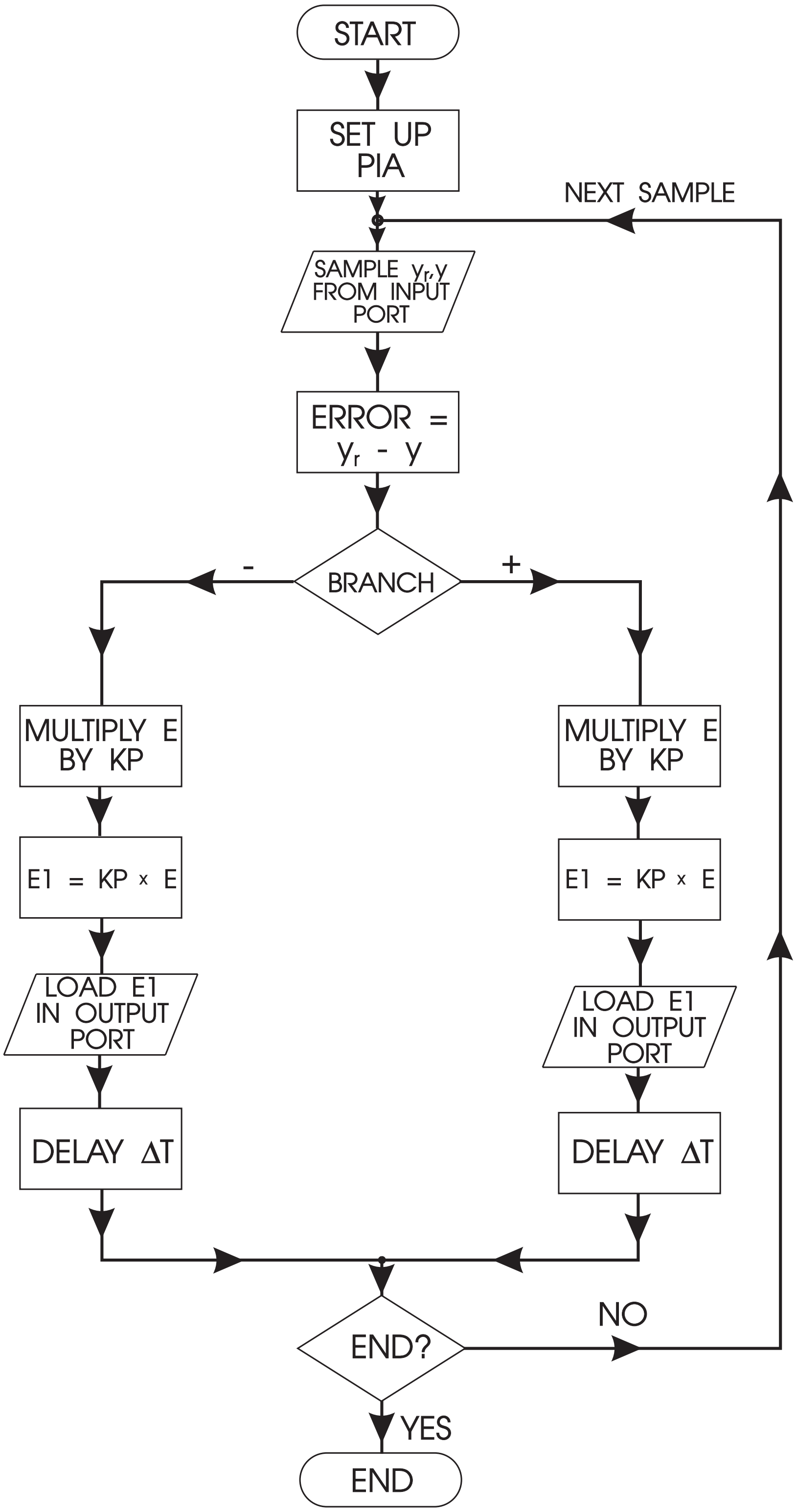

START
SET UP PIA
NEXT SAMPLE
SAMPLE y_r, y FROM INPUT PORT
ERROR = y_r - y
BRANCH
-
+
MULTIPLY E BY KP
E1 = KP x E
LOAD E1 IN OUTPUT PORT
DELAY ΔT
MULTIPLY E BY KP
E1 = KP x E
LOAD E1 IN OUTPUT PORT
DELAY ΔT
END?
NO
YES
END

Figure 3.3

Since this is a digital computer, and samples are taken at regular intervals in time, a continuous update must be performed to ensure that the error signal, **E**, is correct.

The flowchart shown in Figure 3.3 shows how such a procedure would be implemented on a microcomputer.

3.2.2 Proportional and Integral Control

The additional control function is the integration term. If the process of integration and its meaning is examined in discrete time format, then,

$$dt \rightarrow \Delta T$$

This may be graphically represented as shown in Figure 3.4.

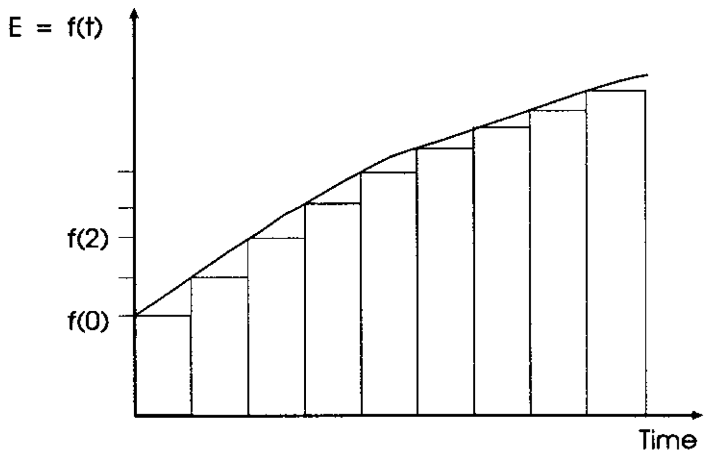


Figure 3.4

In the form of a mathematical series this becomes,

$$f(t)dt = f(0)\Delta T + f(1)\Delta T + \ldots\ldots etc$$

or,

$$f(t)dt = F(t)\Delta T$$

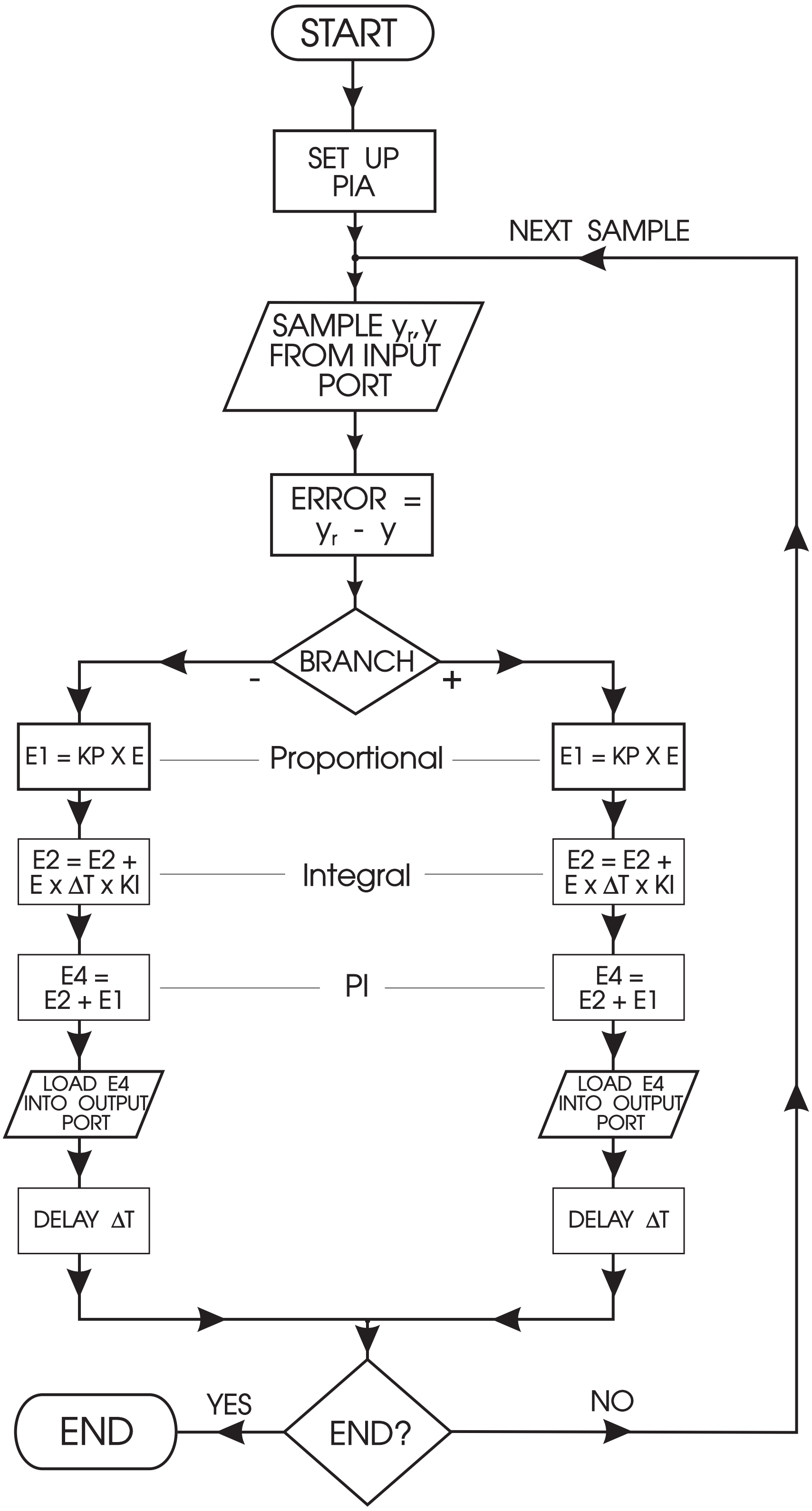

START
SET UP PIA
NEXT SAMPLE
SAMPLE y_r, y FROM INPUT PORT
ERROR = y_r - y
BRANCH
-
+
E1 = KP X E
Proportional
E1 = KP X E
E2 = E2 + E x ΔT x KI
Integral
E2 = E2 + E x ΔT x KI
E4 = E2 + E1
PI
E4 = E2 + E1
LOAD E4 INTO OUTPUT PORT
LOAD E4 INTO OUTPUT PORT
DELAY ΔT
DELAY ΔT
END
YES
END?
NO

Figure 3.5

In the computer program, change in the value of the Integral term may be calculated as,

$$EI = E \times T \times KI$$

This value is used to constantly update the previous Integral term and so this becomes,

$$EI = EI + (E \times T \times KI)$$

The summation of the previous value of the Integral term to the present value provides the ability to increase or decrease the combined output so that the system will always be driven to the zero error condition.

A flowchart to implement a PI routine is shown in Figure 3.5.

3.2.3 Proportional, Integral and Differential Control.

The additional function for this mode of control is the differential of the error signal,

$$ED = KD.\frac{de}{dt}$$

Again, in discrete time intervals the equation becomes,

$$ED = KD.\frac{\Delta E}{\Delta T}$$

This is shown graphically in Figure 3.6. **T** is constant, because the sampling periods are equal, and so it can be included in the value of **KD**. This eliminates the need for division in a machine code program.

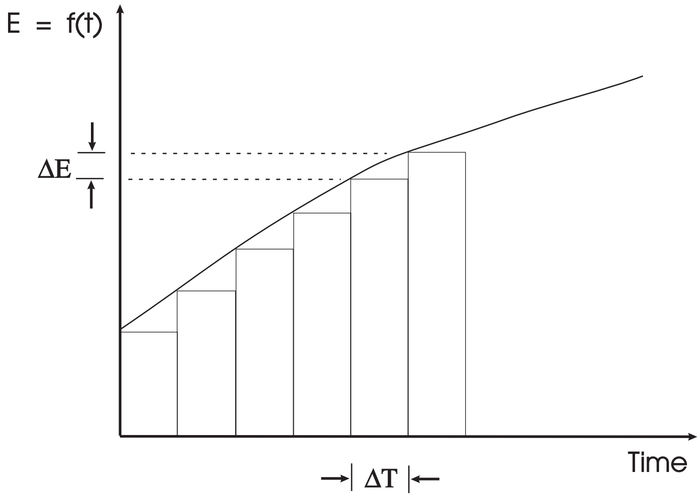


Figure 3.6

A measure of the rate of change (or derivative) is, therefore, the difference between the present value of error **E** and the previous value of error. This is reset to **E0**.

The control function for differential control may be expressed as,

$$ED = KD \times (E - E0)$$

The total PID output expression becomes,

OUTP =OUTP +(EP +EI +ED)

A flowchart to implement the PID algorithm is given in Figure 3.7.

3.3 Implementation of Closed-Loop Control

The following procedure, written in the BASIC programming language, may be used in a practical system to achieve closed-loop control.

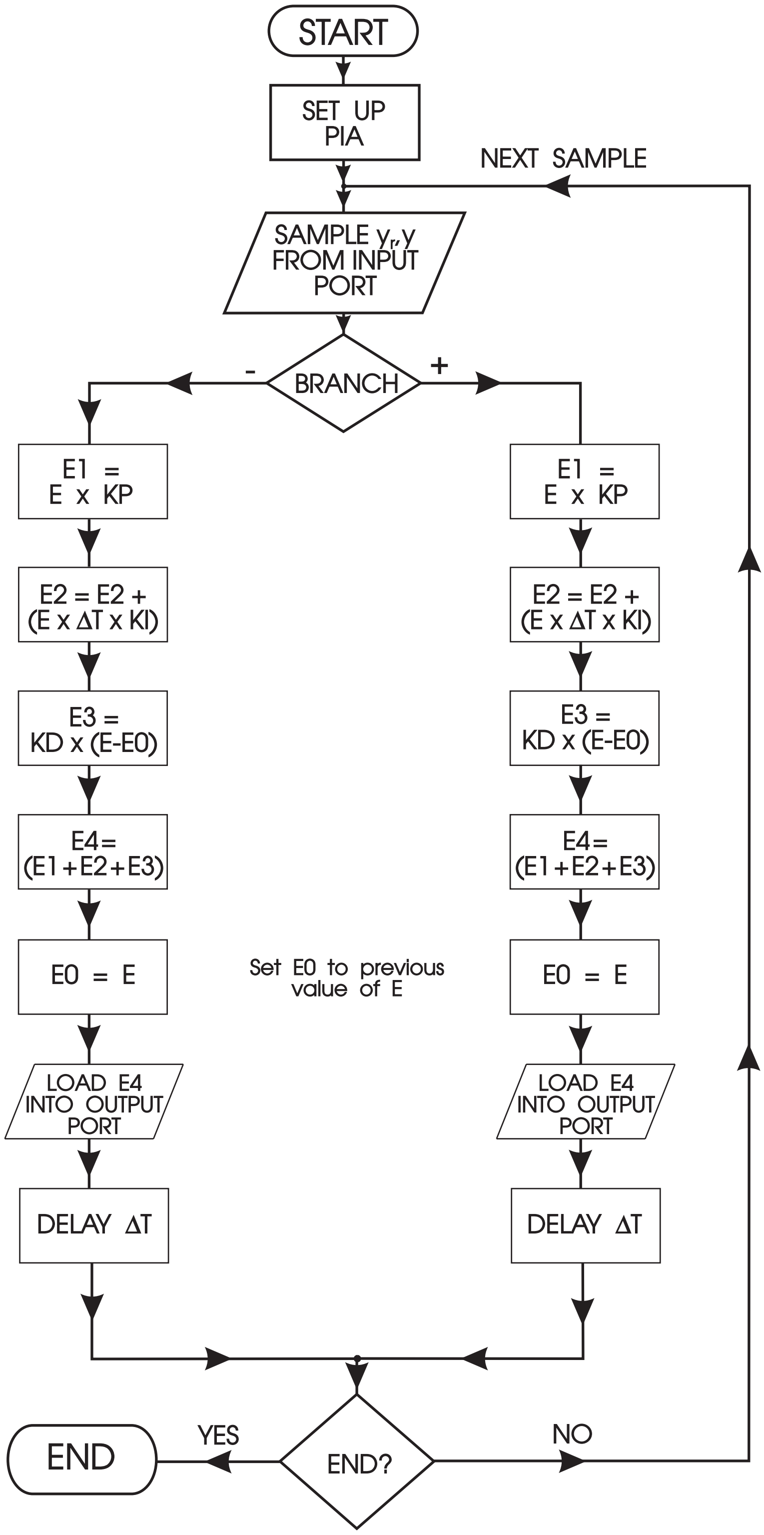

START
SET UP PIA
NEXT SAMPLE
SAMPLE y_r, y FROM INPUT PORT
-
BRANCH
+
E1 = E x KP
E2 = E2 + (E x ΔT x KI)
E3 = KD x (E-E0)
E4= (E1+E2+E3)
E0 = E
Set E0 to previous value of E
LOAD E4 INTO OUTPUT PORT
DELAY ΔT
E1 = E x KP
E2 = E2 + (E x ΔT x KI)
E3 = KD x (E-E0)
E4= (E1+E2+E3)
E0 = E
LOAD E4 INTO OUTPUT PORT
DELAY ΔT
END
YES
END?
NO

Figure 3.7

```
1000 DEFPROCFEED
1010 EP=(KP×E)                      :REM Proportional Term
1020 EI=EI+(E×T×KI)                 :REM Integral Term
1030 ED=KD×(E-E0)                   :REM Differential Term
1040 OUTP=OUTP+(ED+EI+ED)           :REM PID Output
1050 E0=E                           :REM E0 is re-set
1060 ENDPROC
```

The constants **E0**, **T**, **E**, **KI**, **KD**, **KP** and **EI** must be initialised before calling this procedure.

A similar routine, suitably adapted, may be written in another computer language to achieve much the same result. For languages such as 'C' and Pascal the benefit to the control process is increased speed and also better control over the actual computer functions.

In a practical software package, the above procedure would need to be embedded within a much larger program so that essential facilities such as displaying the current input/output/scaling parameters, allowing them to be amended as required, data logging, etc., are included.

4.0 EXPERIMENTATION.

4.1 Introduction

The experiments described in this Section provide full practical support to the theory given in Sections 2 and 3 of this manual. These experiments, when used in conjunction with the theory, are a self-contained course in practical control principles and applications.

Additionally, once the basic principles have been investigated and understood, the equipment may be easily configured to illustrate a wider range of control topics. This may be necessary to comply with the experimental requirements of a particular syllabus.

In each experiment it is assumed that the **CE103 Thermal Process Control Apparatus** is used in conjunction with the **CE120 Controller**.

TQ recommend that each student is supplied at the beginning of the experimental session with a photocopy, or similar, of the relevant experiment. Accordingly, TQ Education & Training Ltd give their permission for any part of this manual to be copied provided that it is for internal college use only.

On completion, the results, graphs and conclusions can then be compared and commented upon against the typical results provided in Section 5.

The experimental connection diagrams are given for each experiment to both reduce setting up time as well as simplifying the presentation. This will not only increase the proportion of each laboratory period spent performing the experiments but will also provide a better understanding of what is being achieved by each configuration. It is, however, important that care is taken to identify the correct terminals before a connection is made to achieve the required circuit and performance.

It is recommended that the experiments are completed in the order given since the performances of the later assignments are to be compared with the earlier, more basic ones.

The blank experimentation circuit diagram provided in Appendix 3 is to allow users to develop their own test circuits. May we suggest that you photocopy the original outline drawings of the CE103/CE120 and then add the required connection leads. In this way the original may be used to produce an indefinite number of copies.

The CE103 Thermal Process Control Apparatus/CE120 Controller combination has been designed to provide a totally self-contained control system, with all devices and facilities required to assemble and investigate a wide range of control situations. However, the experiments provided may be additionally enhanced by the use of commonly available laboratory equipment, such as oscilloscopes and XY/Yt recorders. In the experiments provided, where a transient response is required to be analysed, the use of an optional Yt Chart Recorder has been recommended.

Any additional instruments should be suitably connected to the experimental circuits provided - adapters are provided to change from the 2mm connection format used throughout the CE Range to either a 4mm or BNC format.

In many cases it may be found convenient to use the Digital Section of the **CE120 Controller** (and the software supplied) to monitor system performance. By connecting the A-D inputs (up to eight are available) to the relevant points in the analogue control systems, facilities are readily available via a computer to not only acquire and display data but also to 'save' it for later consideration. Throughout the experiments the user will also be able to produce graphical hard copy of each experiment via a printer.

IMPORTANT

The performance of this equipment, as with any other scientific instrument, is dependent upon it being connected to a reliable and stable voltage mains supply. The Serial Number Plate, mounted at the rear of the unit, defines the correct power supply requirements. Should the power supply vary during usage, for whatever reason, it must be anticipated that the performance of the equipment will be affected and the quality of the results impaired. In extreme cases it may be necessary to consider the use of a voltage stabilising device.

TQ Education & Training Ltd can accept no responsibility for damage caused to equipment which is connected to an unsuitable supply voltage.

4.2 Experiment 1 : Basic Tests and Familiarisation

Object: The object of this experiment is to familiarise the user with the various controllers and outputs on the Thermal Process Control Apparatus.

Apparatus:

CE103 Thermal Process Control Apparatus
CE120 Controller

Procedure

Part 1: Heater Characteristics

Connect the equipment as shown in the Figure E1.1.

Initial Control Settings:

CE120 Potentiometer fully anti-clockwise.

Turn up the potentiometer slowly, noting that the light which indicates the power applied to the heater blinks approximately every second.

As the voltage applied to the heater is increased the light stays on for a greater percentage of the blink period. Thus, for 0V input the light does not come on at all, for a 5V input the light comes on for 50% of the blink period; for a 10V input the light comes on for 100% of the time.

Observe this phenomena and see that it is a form of signal known as a pulse width modulated input.

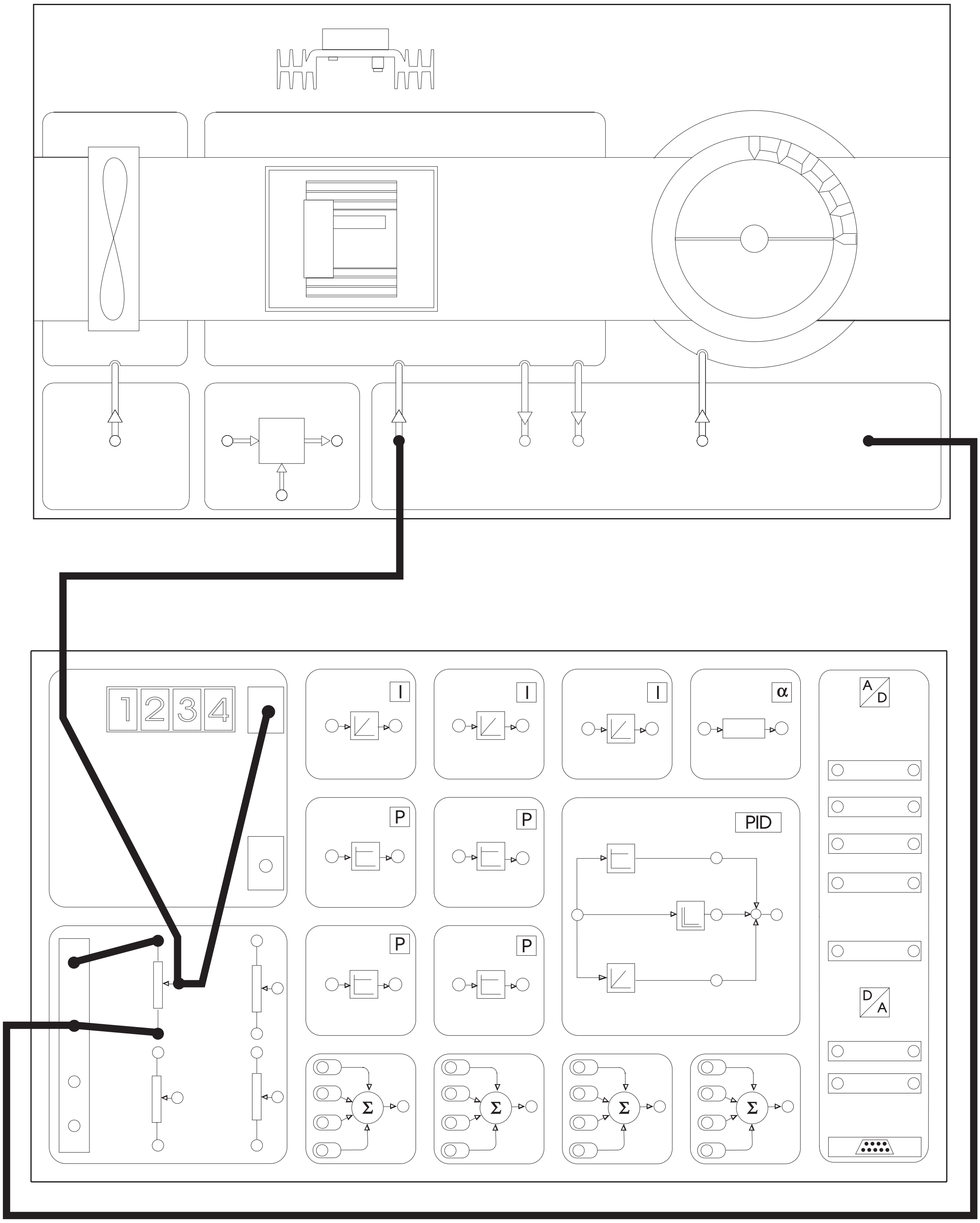


Figure E1.1

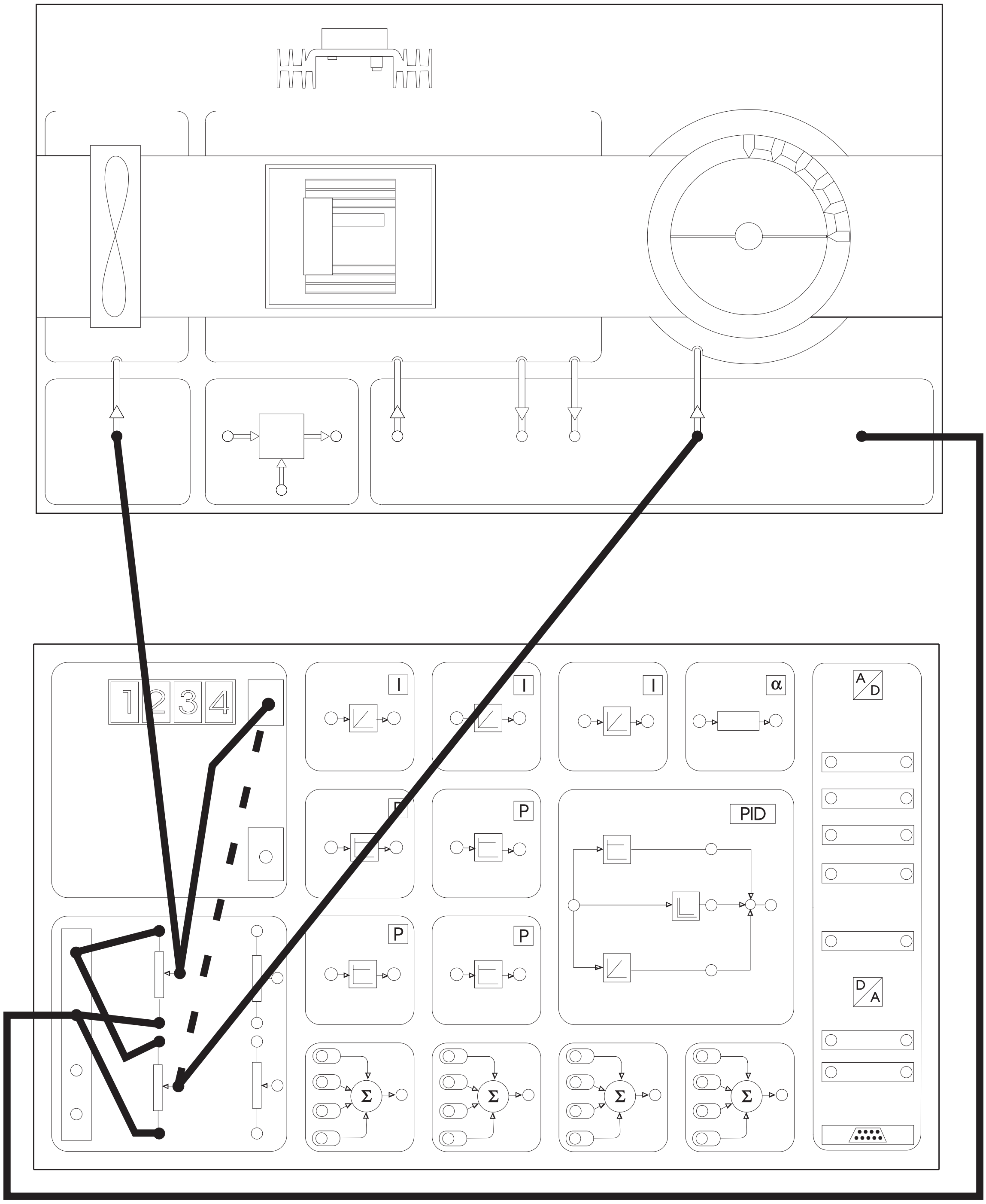


Figure E1.2

Comment on how the blink rate (or, more correctly, the pulse rate) may be selected to ensure that the heater performs in the same way as a normal linear amplifier.

Part 2 : Fan and Shutter Characteristics

Connect the equipment as shown in Figure E1.2 (omit the dotted connection).

Initial Control Settings

CE120 Both potentiometers fully anti-clockwise.

Turn the upper potentiometer slowly clockwise noting that the fan speed increases approximately in proportion to the voltage. No readout of fan speed is provided, use the fan noise in order to judge the fan speed in a qualitative manner.

Turn the upper potentiometer to fully anti-clockwise.

Disconnect the voltmeter from the upper potentiometer and connect it to the lower potentiometer as indicated by the dotted connection in Figure E1.2.

Turn the lower potentiometer slowly clockwise, noting that the shutter position changes in a linear manner with the applied voltage. Increase the shutter to position one and note the input voltage, repeat for positions two, three, four and five.

Complete Table T1 and plot a graph of Shutter Position against Applied Voltage to verify that the relationship is approximately linear.

Shutter Position	Applied Voltage (V)
0 (Fully Open)	
1	
2	
3	
4	
5 (Fully Closed)	

Table T1. Shutter Calibration

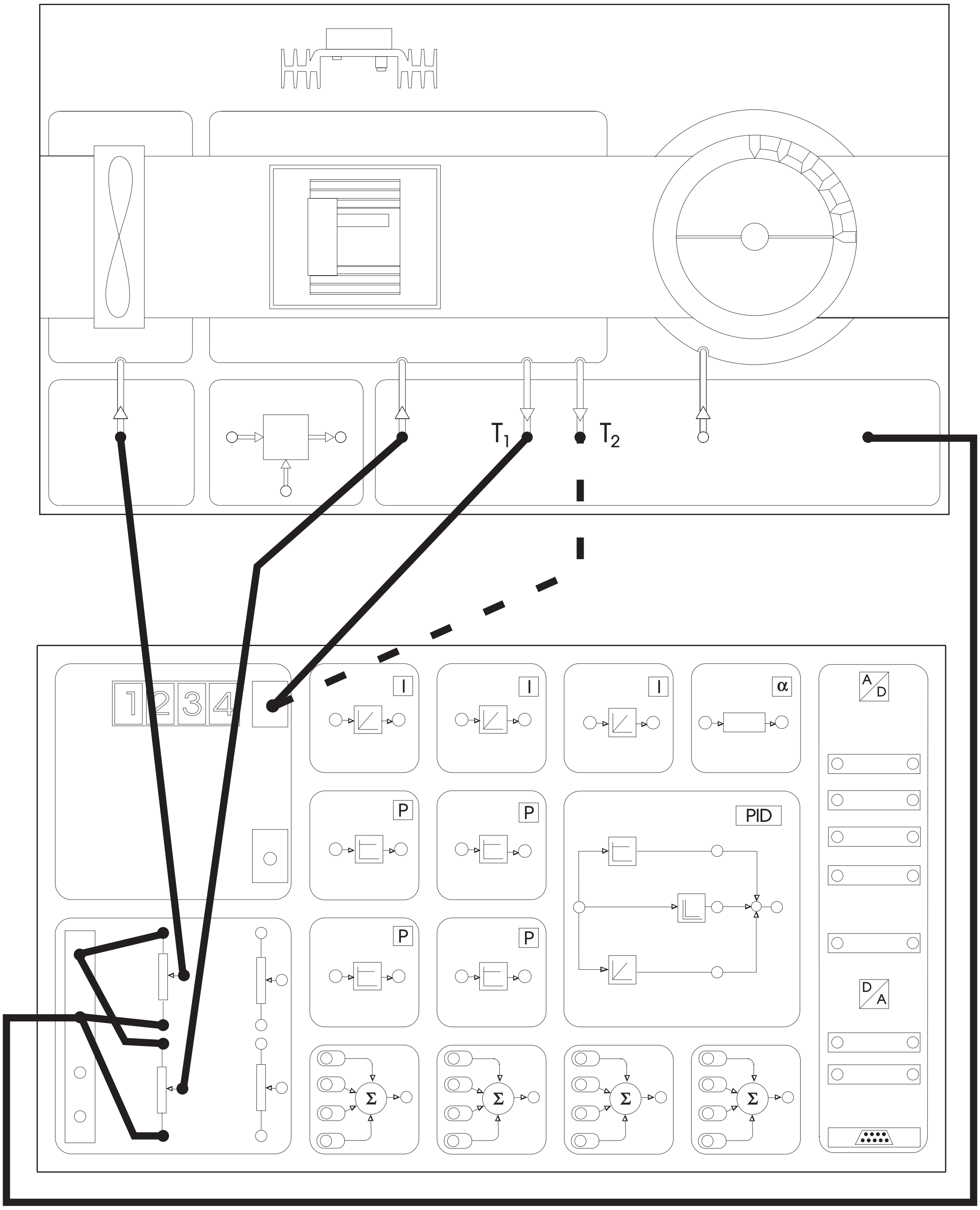


Figure E1.3

Note that the fan and shutter interact by setting a fan input of about 5V and gradually closing the shutter. Note also, that the fan slows as the shutter opening is reduced. Comment on why this should happen and the possible effect on a control system.

Part 3 : Temperature Sensor Characteristics

Connect the equipment as shown in the Figure E1.3 (omit the dotted connection).

Initial Control Settings:

CE120: Both potentiometers turned fully anti-clockwise.

The temperature sensors are calibrated to read 100 mV/°C.

Verify this (approximately) by noting that the $\mathbf{T_1}$ output (which is connected to the voltmeter) reads (approximately) the room temperature divided by ten (i.e. 25°C room temperature will be read as 2.5 V). Switch the voltmeter connection to output $\mathbf{T_2}$ (this is the dotted connection in Figure E1.3) and confirm that it reads a similar voltage.

Reconnect the voltmeter to the $\mathbf{T_1}$ output and turn the lower potentiometer clockwise until a steady heater blink rate is obtained (about 3 turns).

Note that the temperature $\mathbf{T_1}$ begins to increase. Measure the temperature $\mathbf{T_2}$ and note that it lags $\mathbf{T_1}$. This is due to the insulating effect of the material between Temperature Sensor 2 and the block.

Allow the temperature $\mathbf{T_1}$ to rise for about 5 minutes.

Turn the upper potentiometer fully clockwise, this sets the fan to full speed. Note that the temperature increase of $\mathbf{T_1}$ will slow and then start to decrease.

You have now verified the actions of the two principle controls in the temperature of the block,

1. Fan Speed,
2. Heater Voltage.

After this experiment you will have an appreciation of the functions of the thermal control apparatus, and will have checked the functioning of the system components.

4.3 Experiment 2: ON-OFF Control

Object: The object of this experiment is to investigate the performance of 'ON-OFF' control using the relay amplifier on the front panel.

Apparatus:

CE103 Thermal Process Control Apparatus
CE120 Controller
Chart Recorder - recommended (e.g. E17C)
Stop watch - recommended (e.g. HAC10D)

Procedure

Connect the circuit as shown in Figure E2 (omit the dotted connection).

Initial CE120 Controller Settings:

Upper potentiometer turned to 2V.
Lower potentiometer turned to 5V.

Part 1: Sensor T_1

Allow the system to settle down and observe the temperature $\mathbf{T_1}$ as it cycles up and down under ON-OFF control.

Plot the temperature sensor $\mathbf{T_1}$ output against time (suggested timebase 0.5 mm/sec), noting the time during each cycle that the heater is OFF and the time during each cycle that the heater is ON.

Note also the maximum and minimum temperature achieved by the block and enter these figures, together with the cycle times, in Table T2.1.

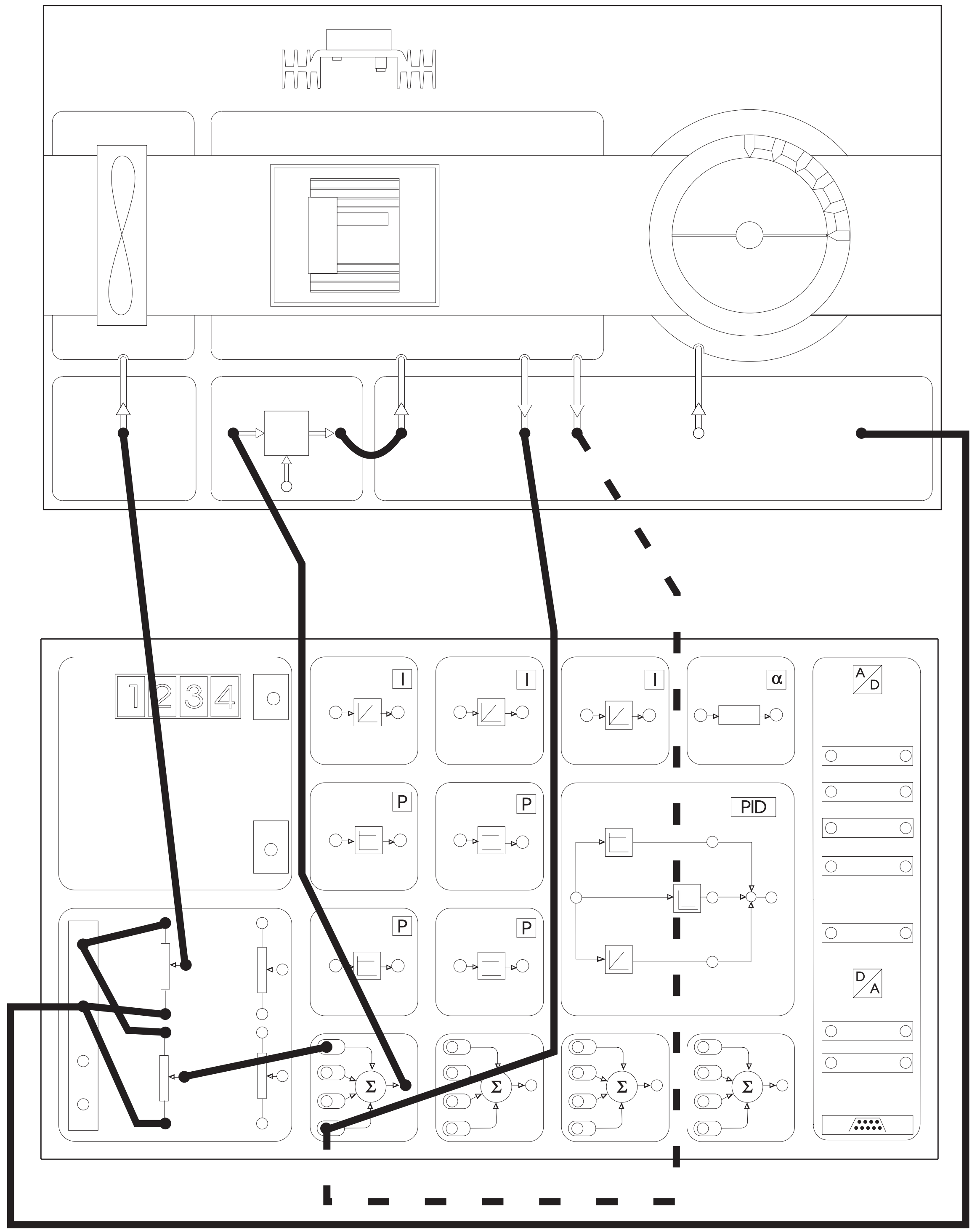


Figure E2

Set-Point (V)	**Fan Input (V)**	**Heater Cycle Time**		**Extreme Temperature**	
		ON	**OFF**	**MIN**	**MAX**
5	**2**				
5	**10**				

Table T2.1 'ON-OFF' Temperature Control Results (Sensor T_1)

Repeat the procedure with the fan input voltage set to 10V. Complete the appropriate columns of Table T2.1.

Part 2: Sensor T_2

Change the sensed temperature to sensor $\mathbf{T_2}$ by disconnecting the connection to $\mathbf{T_1}$ and making the dotted connection in Figure E2.

Set the fan input voltage to 2V and allow the system to settle down and achieve equilibrium.

Plot the variations (suggested timebase 10 mm/min) in the sensor $\mathbf{T_2}$ temperature against time and complete the appropriate columns of Table T2.2.

Set-Point (V)	**Fan Speed (V)**	**Heater Cycle Time**		**Extreme Temperature**	
		ON	**OFF**	**MIN**	**MAX**
5	**2**				
5	**10**				

Table T2.2 'ON-OFF' Control of T_2

Repeat the above procedure with the fan voltage set to 10V.

Conclusions

Comment on:

a. The difference in temperature control between the lower fan speed and high fan speed

b. The difference in control accuracy between control of temperature $\mathbf{T_1}$ and control of temperature $\mathbf{T_2}$.

4.4 Experiment 3 : ON-OFF Control with Hysteresis

Object: The object of this experiment is to investigate the performance of 'ON-OFF' control with hysteresis, using the relay amplifier provided.

Apparatus:

CE103 Thermal Process Control Apparatus
CE120 Controller
Chart Recorder - Recommended (e.g. E17C)

Procedure:

Connect the circuit as shown in Figure E3.

Initial CE120 Controller settings:

Upper potentiometer turned to 1V
Lower potentiometer turned to 6V
Signal generator set to d.c., Offset zero, Level 4V

Part 1: Control of T_1

Attach the $\mathbf{T_1}$ output to the Y input of the Yt recorder and select a suitable timebase (10 mm/min recommended).

Allow sufficient time for the system to settle down and achieve equilibrium, and note that with the recommended settings the set-point temperature is 60°C with an overlap in the hysteresis amplifier of ±0.5V (i.e. the overlap is one half of the one volt input to the amplifier hysteresis input).

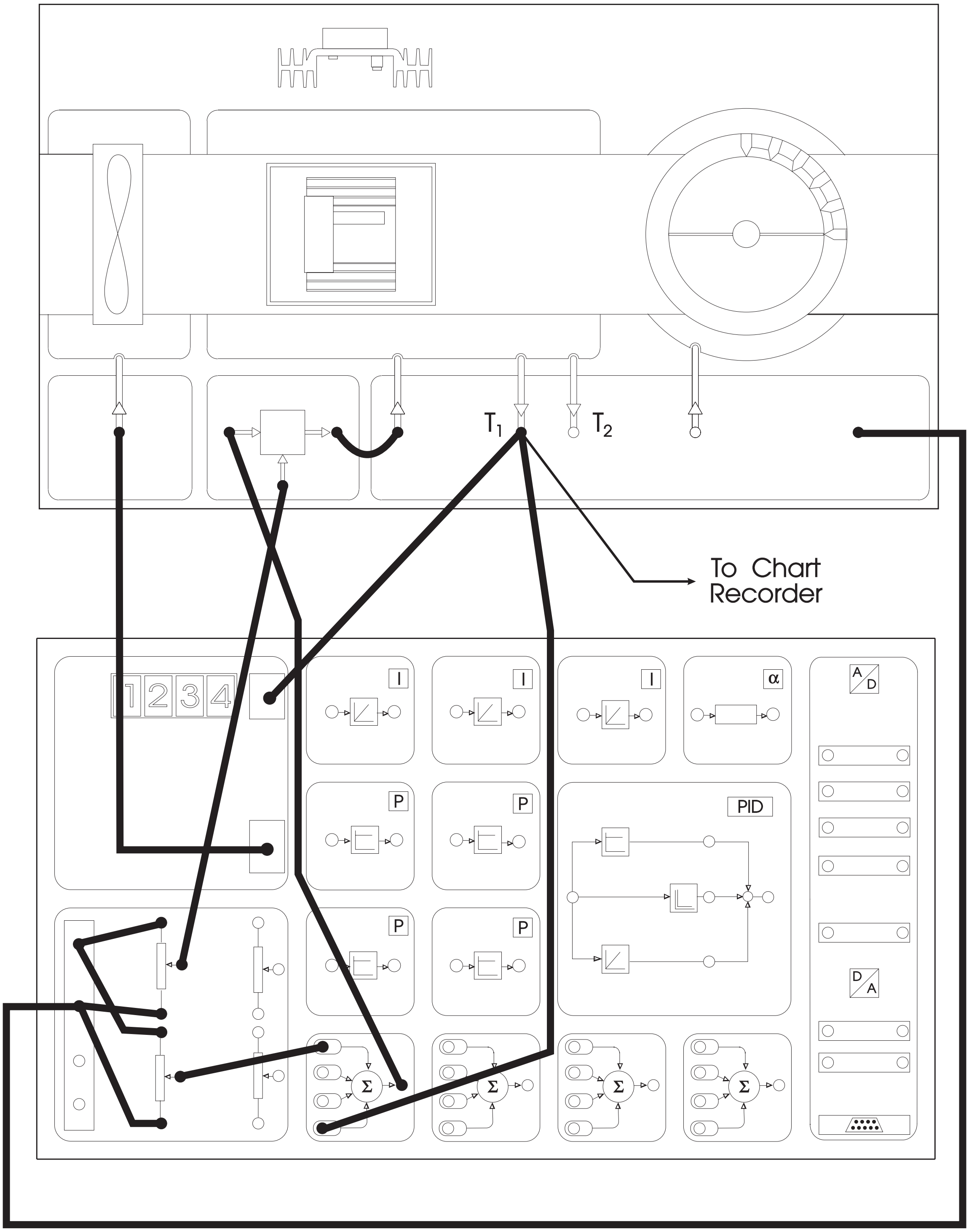


Figure E3

With these settings, observe that the temperature $\mathbf{T_1}$ should cycle between approximately 65°C and 55°C and that the cycle period should be increased from Experiment 2 where no overlap was used).

Verify this by measuring the period of the heating cycle for which the heater is ON and the period for which it is OFF and enter your results in Table T3 below.

Sensor	**Heater Cycle Time (s)**		**Extreme Temperature (°C)**	
	ON	**OFF**	**MIN**	**MAX**
T_1				
T_2				

Table T3

Part 2 : Control of T_2

Repeat the above procedure for sensor $\mathbf{T_2}$ by taking the group of connections attached to sensor $\mathbf{T_1}$ output and connecting them to sensor $\mathbf{T_2}$ output.

If time permits, repeat the exercise for a relay amplifier overlap of ±0.25V and ±2V. Note the differences in the extremes of temperature and the heater cycle times.

Conclusions:

Comment on:

a. The influence of the overlap on the accuracy of control.

b. Can you think of a thermal control system in which overlap is desirable?

c. Mention examples where overlap is undesirable.

4.5 Experiment 4 : Proportional Control

Object: To practically investigate the thermal control system under proportional control.

Apparatus:

CE103 Thermal Process Control Apparatus
CE120 Controller
Yt Chart Recorder - Recommended (e.g. E17C)

Procedure:
Connect the equipment as shown in Figure E4.

Initial CE120 settings:

Upper and lower potentiometers to 5V.
Signal generator to d.c., Offset 0V and Level 0V.
Proportional controller gain $\mathbf{k_p}$ to 10.

Part 1 : Steady State Errors

Allow the system to stabilise for about 5 minutes. Note the error between the requested (set-point) temperature and the actual temperature $\mathbf{T_1}$. This is the steady state error. Use the voltmeter to measure the error, (as indicated in Figure E4). Enter the value in Table E4.1.

Reduce the controller gain to 1 and repeat the exercise.

Next, increase the controller gain to an intermediate value (say 5) and repeat the exercise. (Note: allow about 5 minutes for the temperature $\mathbf{T_1}$ to stabilise in each case).

Controller Gain (k_p)	Set-Point (°C)	Measured T_1	Steady State Error (Set-Point - T_1)
10	50		
5	50		
1	50		

Table E4.1

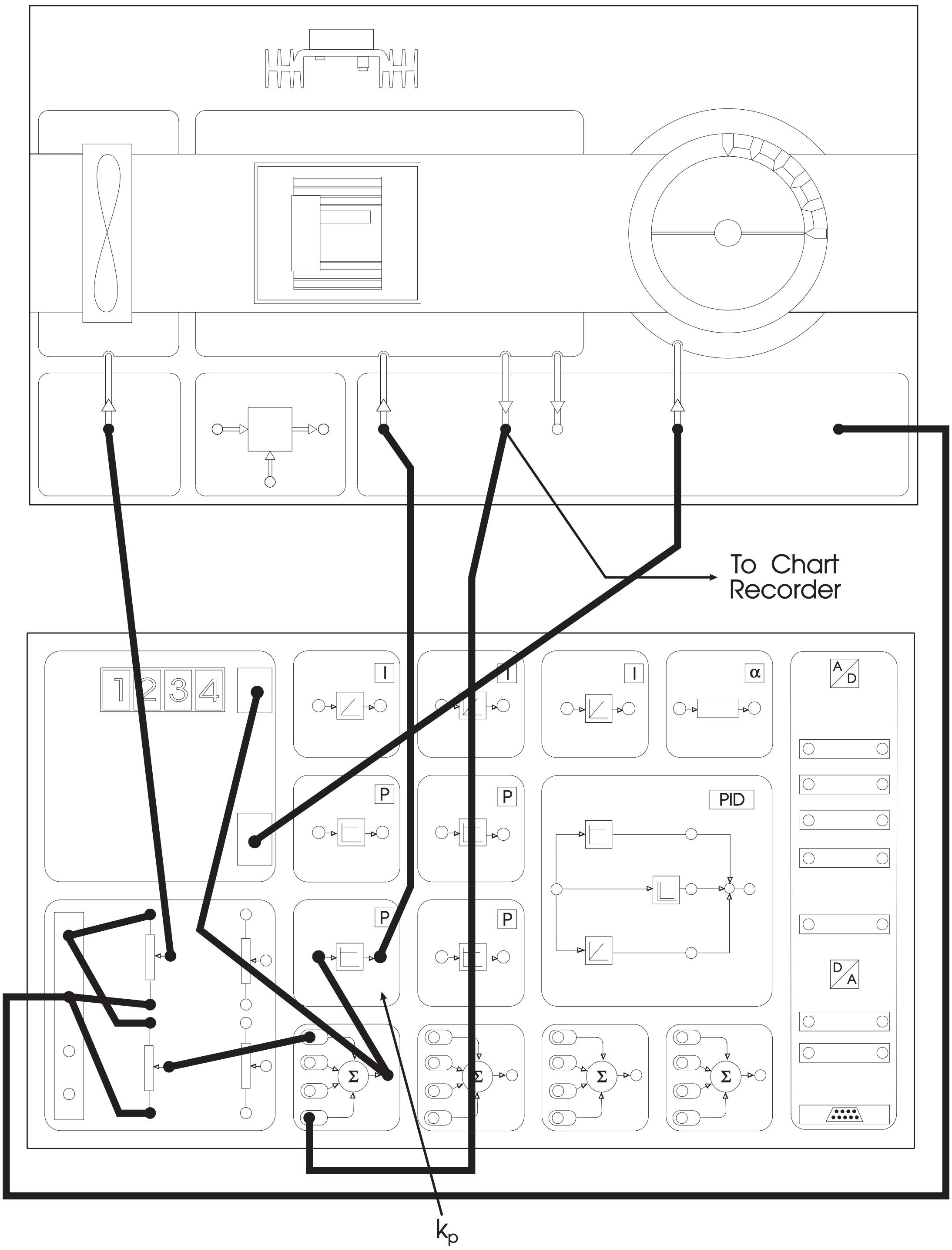


Figure E4

Part 2 : Step Response

With the initial CE120 settings specified in the first section of the procedure, allow the system to stabilise.

Connect the $\mathbf{T_1}$ output to the 'Y' channel of a chart recorder, with a suitable timebase setting (suggested setting 10 mm/min). Quickly increase the voltage by 1 V to introduce a step change in the set-point (the lower potentiometer). (It will be sufficient to do this by hand).

Repeat the exercise for the controller gains 1 and 5. Compare the step responses for the different gains.

Part 3 : Effect of Disturbances

This experiment shows the effect that external disturbances have on a proportional controller's accuracy. The external disturbance is provided by varying the opening of the shutter.

With the initial CE120 settings specified in the first section of the procedure, allow a few minutes for the system to stabilise.
Note the value of $\mathbf{T_1}$ in Table E4.2.
Turn the generator level to maximum, this will close the shutter (i.e. move it to position 5).

Allow two or three minutes for the temperature to stabilise and note the temperature $\mathbf{T_1}$.
Repeat the procedure with a controller gain of 1 and 5. Record the results in Table E4.2.

Comment on your results.

Controller Gain	**Set-Point (°C)**	**Measured T_1**	
		Shutter Open	**Shutter Closed**
10	**50**		
1	**50**		
5	**50**		

Table E4.2

4.6 Experiment 5 : Proportional plus Integral Control

Object: The object of this experiment is to practically investigate the addition of integral action to the thermal controller.

Apparatus:

CE103 Thermal Process Control Apparatus
CE120 Controller
Yt Chart Recorder - Recommended (e.g. E17C)

Procedure:

Connect the equipment as shown in Figure E5.

Initial CE120 Controller settings:

Upper potentiometer to 10V
Lower potentiometer to 5V
Signal generator to d.c., Offset 0V, Level 0V.
PID controller, P action switched in, integral and derivative action switched out.

Part 1: Integral Action - Steady State Errors

Select a proportional gain of 2, allow the system to settle and observe the error on the voltmeter.

Now select an integral gain of 0.05, press the reset button and switch the integral block on the PID controller into circuit.

Observe the error reduce to (approximately) zero as the integral term takes effect (this may take a minute or two).

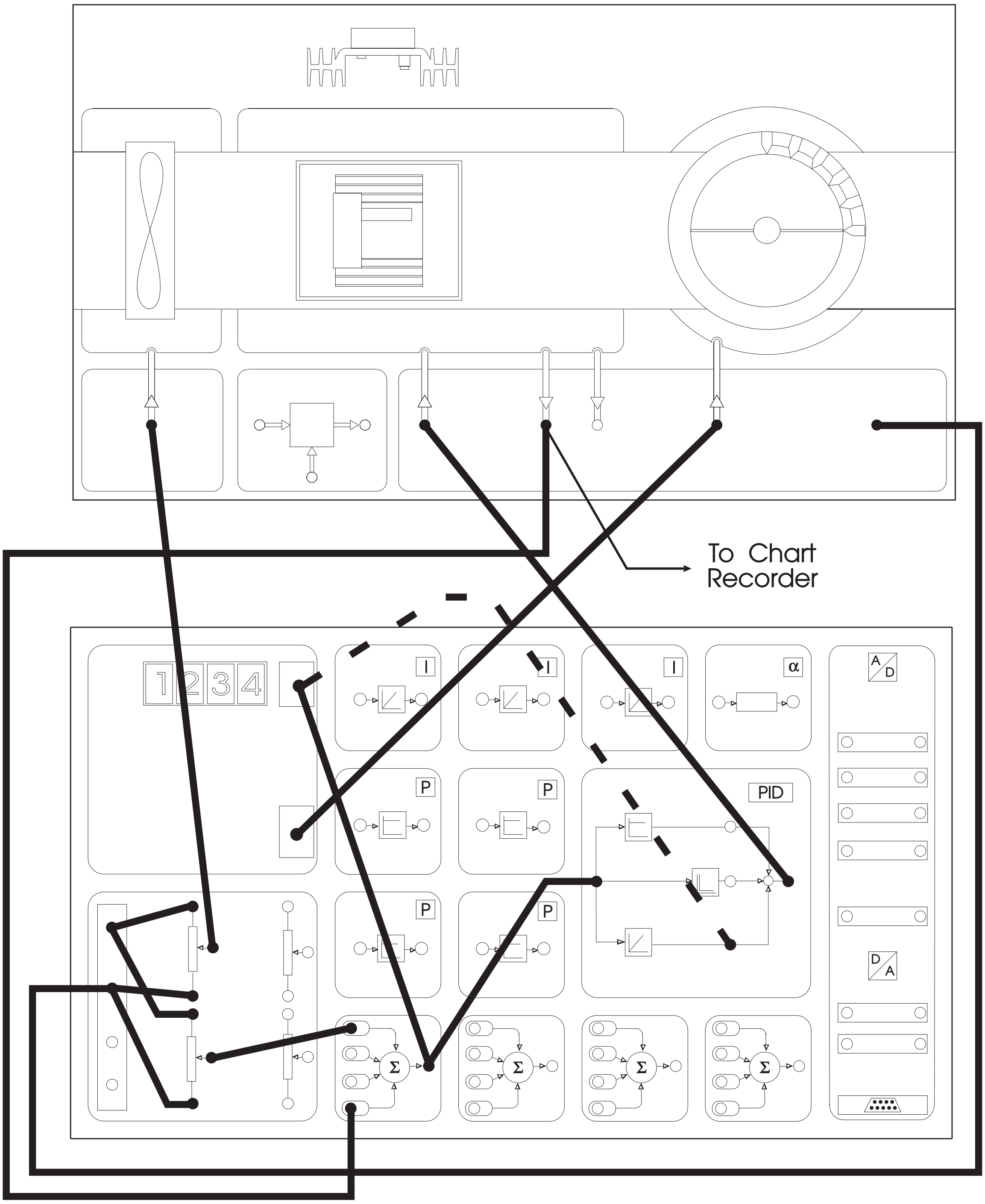


Figure E5

Now disconnect the voltmeter from the error signal and connect it to the output of the integral block (this is the dotted connection shown in Figure E5).

Note the reading (in Table T5) and then press the reset button. The integrator output will drop to zero and then start to rise to the previous level. The integrator will continue to increase until the error is zero. Thus it provides the component of output (additional to the proportional block) which is required to make the output equal the set-point.

Next turn the signal generator level fully clockwise, thus closing the shutter. Notice that the integrator output reduces gradually to a new level which will give zero error. Thus the integrator removes the influence of the disturbance introduced by the closing of the shutter.

Record the value in Table T5 and verify the error is approximately zero.

Set-Point (°C)	**Shutter Position**	**Integrator Block Output**
50	**Fully Open (0)**	
50	**Fully Closed (5)**	

Table T5

Part 2 : Integral Action - Transient Response

Select the initial controller settings laid out at the beginning of this experiment.

Select a proportional gain of 3, an integral gain of 0.005 and allow the system to settle.

Make a step change in the set-point (lower potentiometer) of 10°C and plot the result using the chart recorder (suggested timebase setting 10 mm/min).

Plot the result for 5 minutes.
Reset the set-point to 50°C and let the system settle. Increase the integral gain to 0.5 and repeat the procedure, noting the oscillating nature of the response.

Monitor the integral block output during the step response.
Now increase the proportional gain to 10 and repeat the exercise.

Comment on the results.

4.7 Experiment 6 : Feedforward Control

Object: The object of this experiment is to practically investigate the addition of feedforward control action to compensate for disturbances introduced by varying the shutter opening.

Apparatus:

CE 103 Thermal Process Control Apparatus
CE120 Controller
Yt Chart Recorder - Recommended (e.g. E17C)

Procedure:

Connect the equipment as shown in Figure E6.1 (omitting the dotted connection).

Initial CE120 Controller setting:

Upper potentiometer to 10V
Lower potentiometer to 5V
Signal generator to d.c., Offset 0V, Level 0V.
PID controller, proportional action switched in, integral action switched in.

Select a proportional gain of 3 and an integral gain of 0.05 and allow the system to settle.

Connect the sensor $\mathbf{T_1}$ output to the chart recorder (suggested timebase setting 10 mm/min).

Now increase the signal generator level to 10V (thus fully closing the shutter).

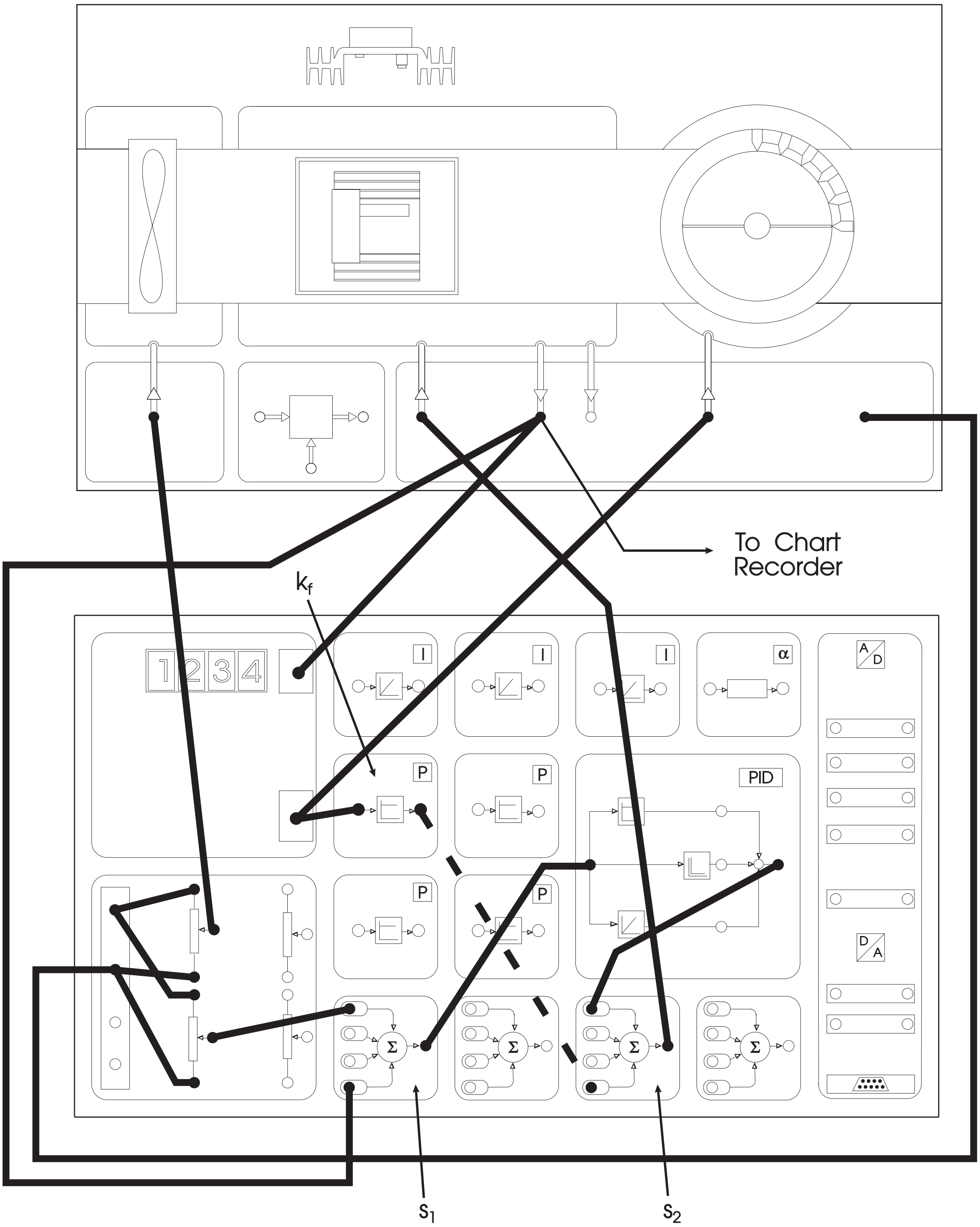


Figure E6.1

Plot the resulting disturbances in the output temperature $\mathbf{T_1}$ and note the maximum deviation from set-point and the steady state output from the PID controller with the shutter closed and then open.

Enter the results in Table T6.

Turn the level control fully anti-clockwise, thus fully opening the shutter.

Next, connect the dotted connection shown in Figure E6.1, thus adding a feed-forward control signal from the shutter input which, with an appropriate setting of feedforward gain $\mathbf{k_f}$, will cancel the influence of the shutter on the heater. The corresponding block diagram is shown in Figure E6.2.

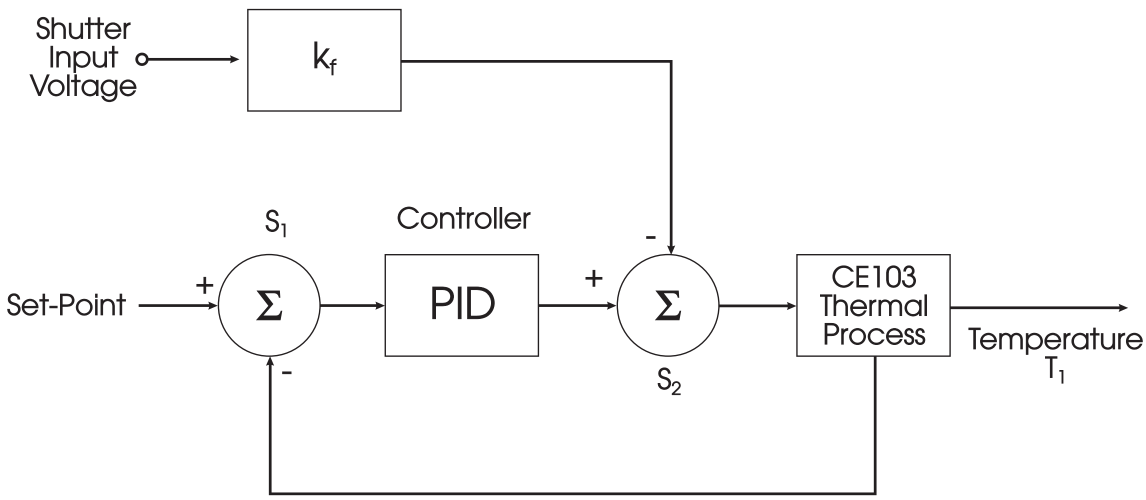


Figure E6.2

Wait for the system to stabilise at the 50°C set-point and then set a gain $\mathbf{k_f}$ of 0.1 and repeat the procedure of closing the shutter, plotting the variation in $\mathbf{T_1}$.

Observe and record the peak variation $\mathbf{T_1}$ and the PID controller output in Table T6.

Repeat the entire procedure for $\mathbf{k_f}$ **= 0.15** and $\mathbf{k_f}$ **= 0.4**.

Comment on the results.

Set-Point (°C)	**Peak Variation in T_1**	**PID Controller Output**		**Feedforward Gain (k_f)**
		Shutter Open	**Shutter Closed**	
50				Disconnected
50				0.1
50				0.15
50				0.4

Table T6

4.8 Further Experiments

The experiments contained within this manual have focused upon control of the temperature output, $\mathbf{T_1}$.

Further experimentation is possible by repeating the experimental procedures described for sensor $\mathbf{T_1}$ but substituting sensor $\mathbf{T_2}$.

Comparison between the two sets of results should be made to appreciate the effect of delay in the control circuit.

5.0 RESULTS AND COMMENTS.

The results and comments contained in this Section are for the experiments contained in Section 4.

This information is provided as a guide to lecturers and laboratory supervisors so that they have a readily available reference and source of specimen results for these experiments. They are **NOT** intended to be taken as being absolute and so some variations are to be expected.

Because of the operating variations between different units and their component parts as well as the nature of the control valves on the front panel of the CE103, the results are only intended to be representative of the values and characteristics for each of the configurations tested.

5.1 Experiment 1: Results and Conclusions

Your results should comprise a table of shutter position against shutter supply voltage.

5.1.1 Part 1: Heater Characteristics

The pulse (or blink) rate in a pulse width modulated amplifier is selected such that, after the smoothing effect of the thermal time constant of the block, the system performs with the same characteristics as if a linear amplifier was used. If the block time constant was (for example τ seconds) then a pulsed heater supply of pulse period less than $\mathbf{0.05\times\tau}$ would be sufficient). The selected period of 1 second satisfies this criteria.

5.1.2 Part 2: Fan and Shutter Characteristics

The fan audibly speeds up in a proportional manner as the supply voltage is increased. The shutter opening is linear with the supply voltage as is verified from the Table T1 and graph shown in Figure 5.1.

Shutter Position	**Applied Voltage (V)**
0 (Fully Open)	0.00
1	2.16
2	4.07
3	6.06
4	7.95
5 (Fully Closed)	10.05

Table T1

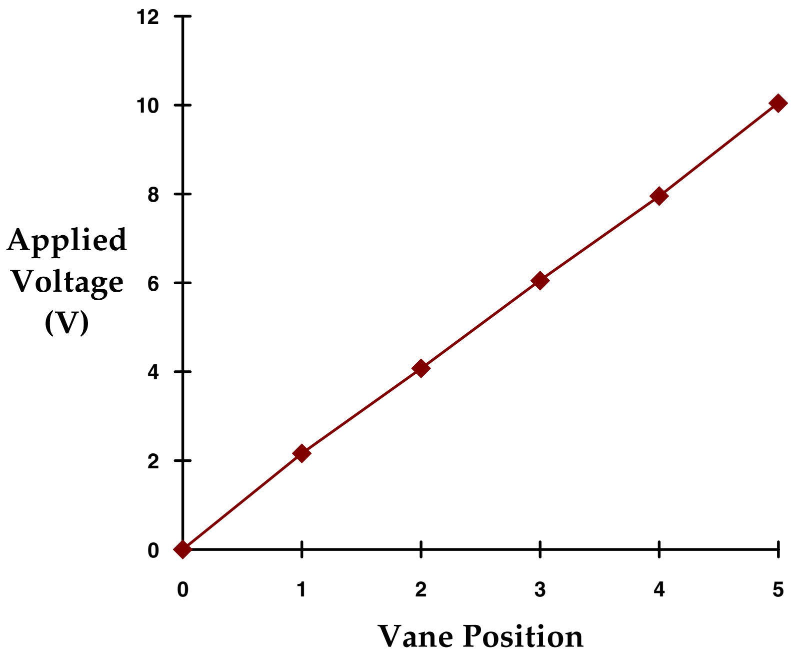


Figure 5.1 Vane Calibration Graph

The fan audibly slows as the shutter is closed. This interaction would adversely affect a temperature control system with both fan and shutter under proportional control. In particular, the interaction, if not accounted for, could introduce a destabilising element into the closed-loop controller.

5.2 Experiment 2: Results and Conclusions

Your results should comprise completed Tables T2.1 and T2.2. Typical entries for these tables are given below. In addition, you should have plots of the temperatures **T_1**, **T_2** under **ON-OFF** control.

Set-Point (V)	Fan Input (V)	Heater Cycle Time (s)		Extreme Temperatures	
		ON	OFF	MIN	MAX
5	**2**	4	14	49.98	51.50
5	**10**	5	6	49.95	50.07

Table T2.1 (Sensor T_1)

Set-Point (V)	Fan Speed (V)	Heater Cycle Time (s)		Extreme Temperatures (°C)	
		ON	OFF	MIN	MAX
5	2	25	67	49	54.7
5	10	39	36	48	52.5

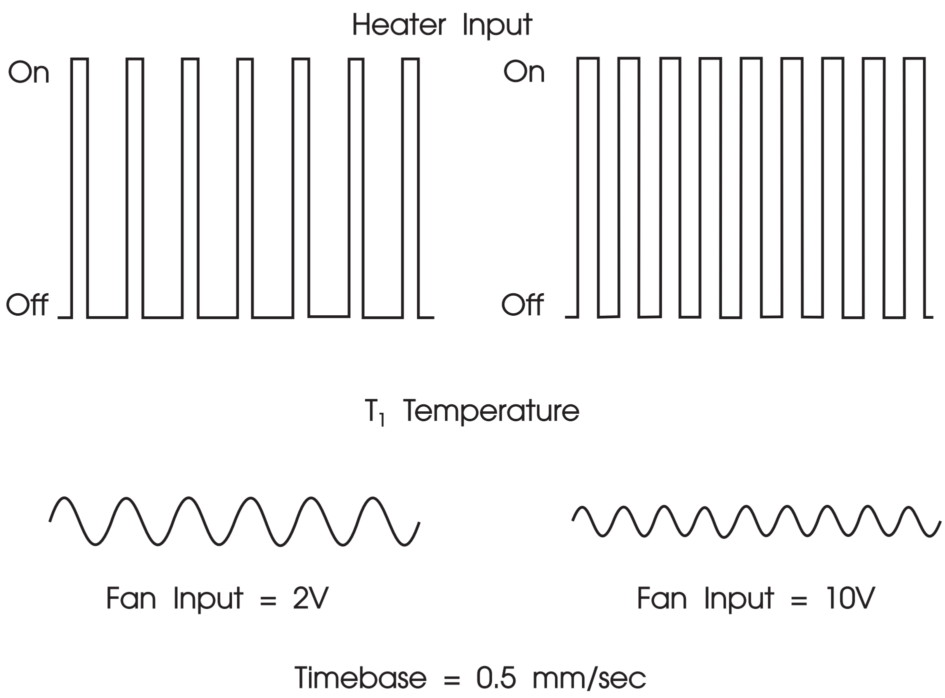
Table T2.2 (Sensor T_2)

Part 1 : Control of Sensor T_1

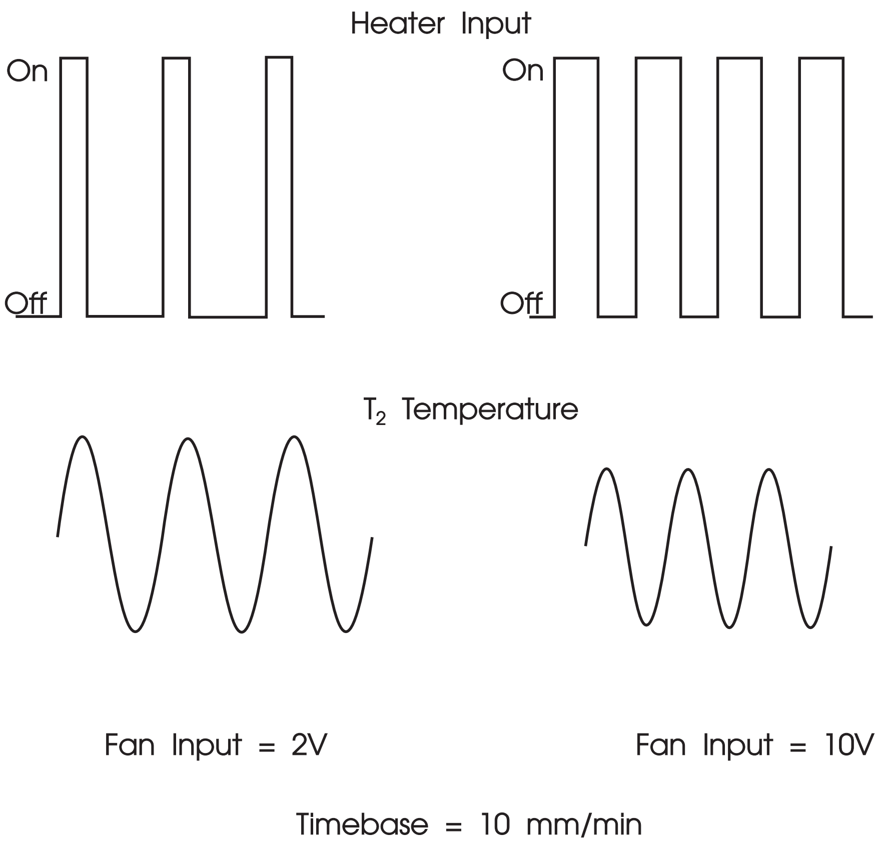
With sensor **T_1** that is in close contact with the control block, control is quite accurate with only a small spread between the maximum and minimum temperatures.

With a low fan speed, the time with the heater off and the maximum temperature are increased because we have only limiting cooling.

Plot P2.1 shows a typical output temperature trace for **T_1** and heater input for the two fan settings.



Plot P2.1



Plot P2.2

Part 2: Control of Sensor T_2

With the added insulation associated with $\mathbf{T_2}$, the spread in maximum and minimum temperatures is increased (compared with $\mathbf{T_1}$) due to the additional thermal delays. In addition the heater cycle time is increased because of the thermal delay introduced by the extra insulation.

Plot P2.2 shows a typical output temperature trace for $\mathbf{T_2}$.

5.3 Experiment 3 : Results and Conclusions

Your results should comprise a completed Table T3. Typical values are shown below. In addition, you should have plots of the temperature $\mathbf{T_1}$ and $\mathbf{T_2}$ against time (Plots P3.1 and P3.2 respectively).

Part 1 : Control of Sensor T_1

The introduction of overlap into the relay will cause the control to deteriorate with an increased spread in the output temperatures to be at least the width of the overlap (55°C to 65°C in the experiment). Also the cycle period will be increased because of the extra time taken to heat/cool across the overlap temperature band. Plot P3.1 shows a typical response.

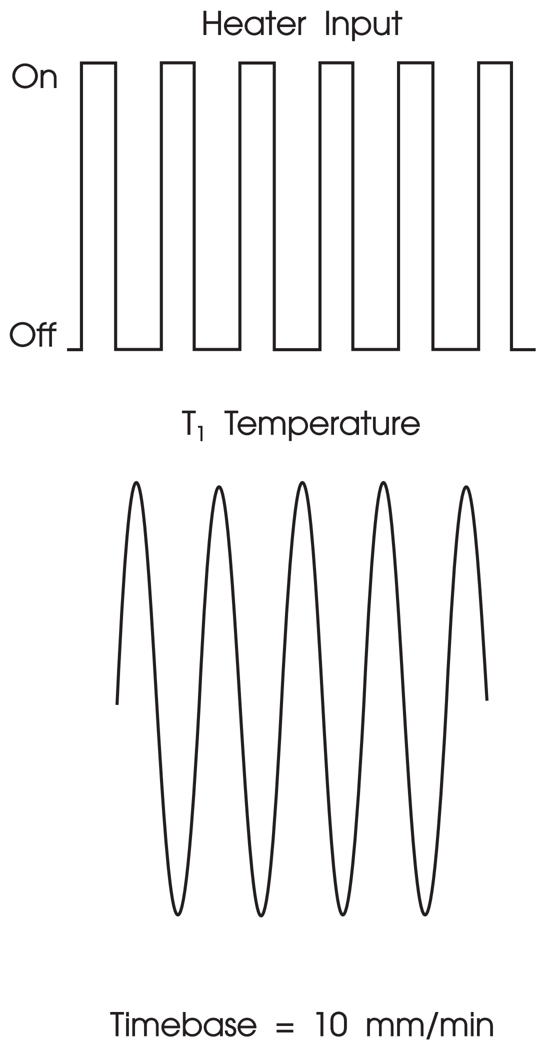
In some thermal systems overlap is desirable to prevent physical damage due to rapid cycling of the heater. A gas-fired boiler is an example of such a system.

Part 2 : Control of Sensor T_2

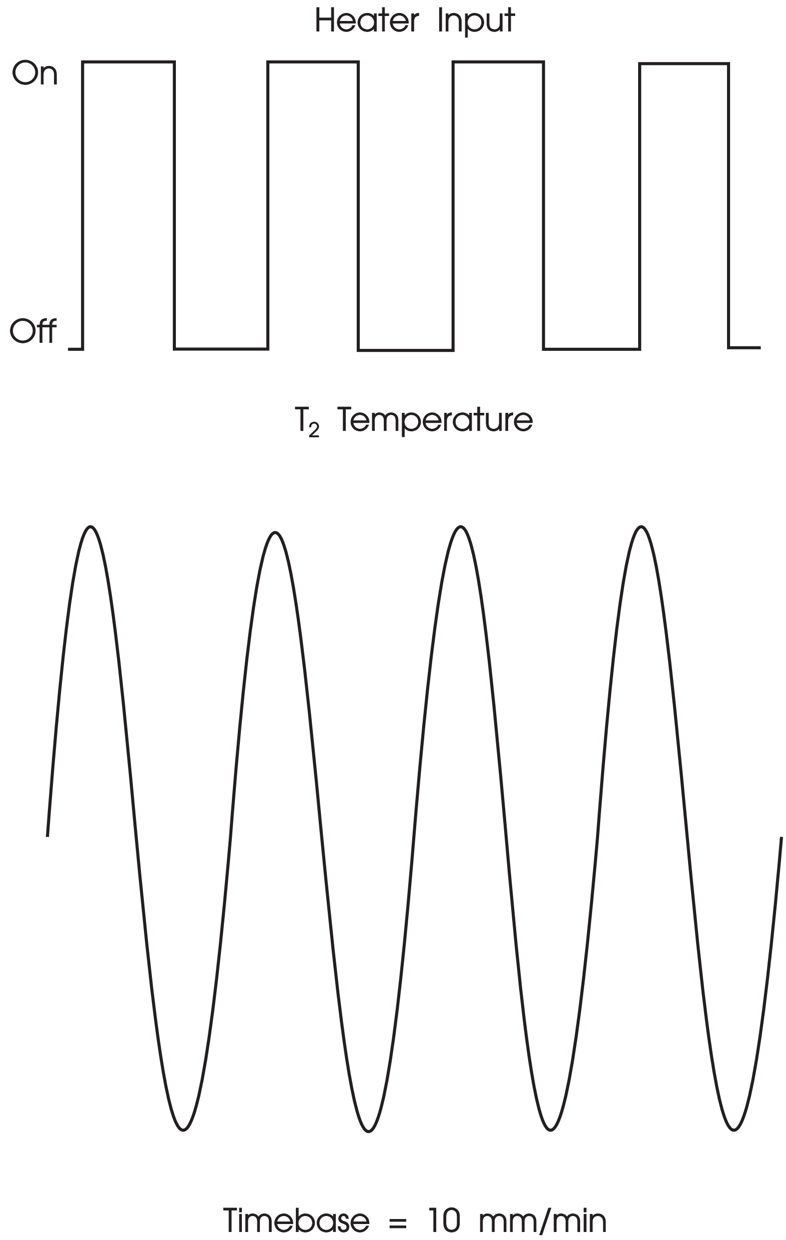
The increased time lag associated with sensor $\mathbf{T_2}$ results in the spread between the maximum and minimum temperatures being larger than that for $\mathbf{T_1}$. Also the heater cycle times are very much increased (Plot P3.2 shows a typical response). It is in situations such as this, where large thermal delays occur, that relay overlap is undesirable.

Sensor	Heater Cycle Time (V)		Extreme Temperatures (°C)	
	ON	**OFF**	**MIN**	**MAX**
T_1	24	37	54.7	66.0
T_2	65	75	52.5	68.5

Table T3



Plot P3.1



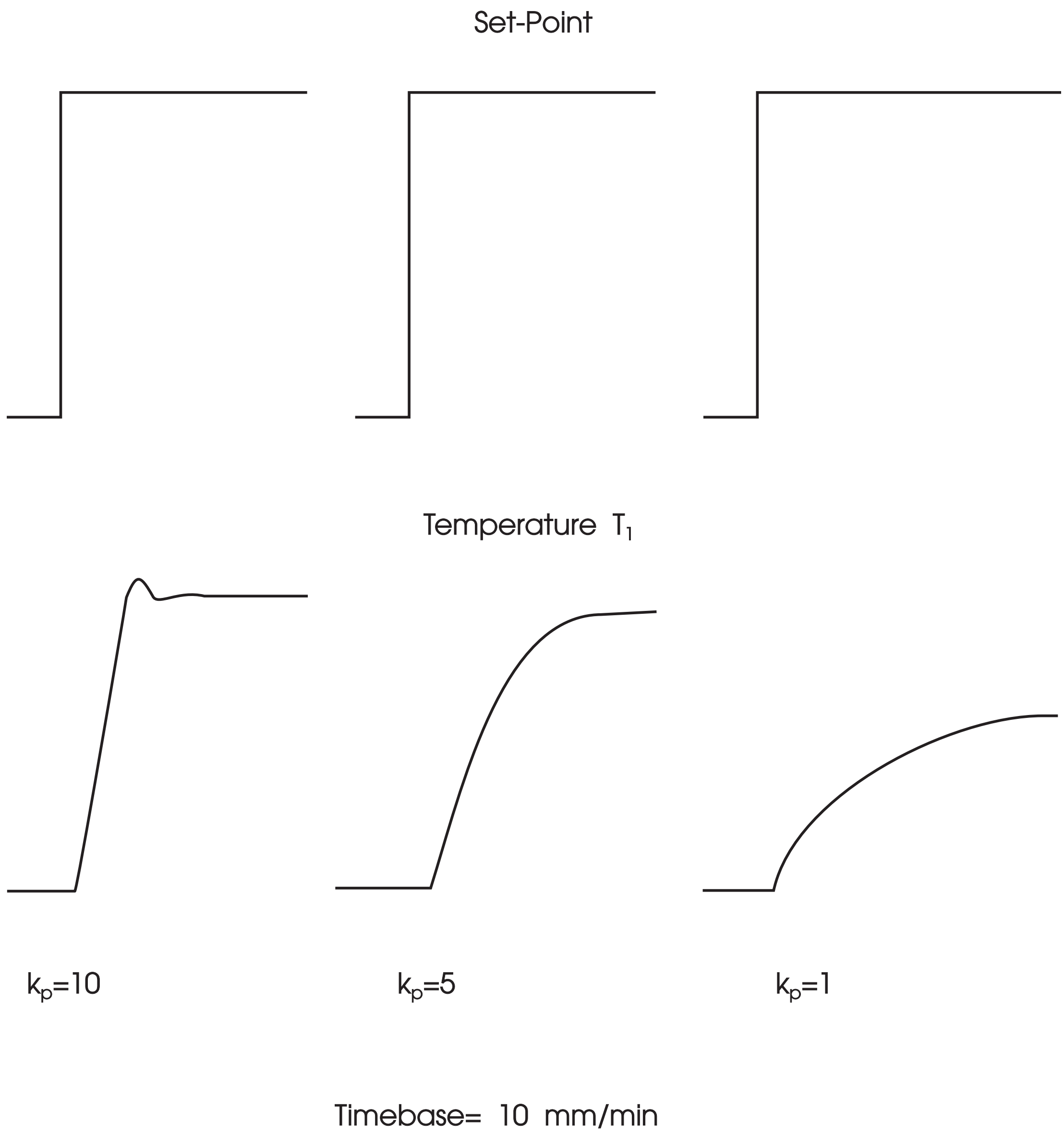
Plot P3.2

5.4 Experiment 4 : Results and Conclusions

Your results should comprise a completed Table T4.1, a set of three step responses with different controller gains (Plot P4) and Table T4.2.

Part 1

This should show that the steady state error is inversely proportional to the controller gain as indicated in the theory section.



Plot P4

Part 2

This should show that the closed-loop step response speed increases as the controller gain is increased. This corresponds to a time constant reduction as predicted by Equation 2.25 in Section 2. Plot P4 shows a typical set of plots of step responses and set-point steps for $\mathbf{k_p}$ **= 10, 5** and **1**.

Part 3

The external disturbance affects the accuracy of the control system by changing the steady state error. The higher the controller gain, the less the system is affected by the disturbances.

Controller Gain	Set-Point (°C)	Measured T_1 (°C)	Steady State Error (°C)
10	**50**	47.0	3.0
1	**50**	34.0	16.0
5	**50**	44.5	5.5

Table T4.1

Controller Gain	Set-Point (°C)	Measured T_1 (°C)	
		Shutter Open	**Shutter Closed**
10	**50**	47	48
1	**50**	34	37
5	**50**	45	47

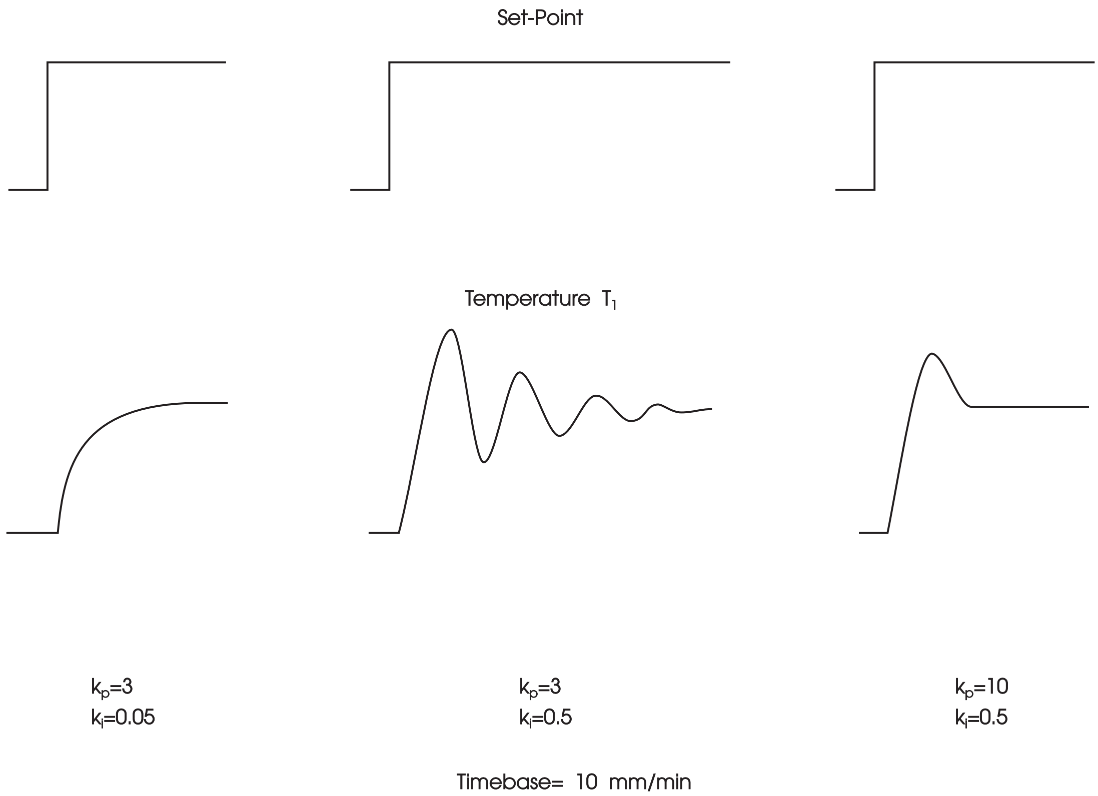
Table T4.2

5.5 Experiment 5 : Results and Conclusions

Your results should comprise a completed Table T5 and step responses under various proportional and integral controller settings (Plot P5).

Part 1

This should show that the addition of integral action makes the steady state error go to zero and also remove the influence of disturbances upon the controller.



Plot P5

Part 2

This will demonstrate (see typical Plot P5) that for small integral gain the step response to a change in set-point is well balanced and stable. Increasing the integral gain causes the step response to become oscillatory. This can be reduced by introducing a commensurate increase in the proportional gain. However, too much integral action will cause unstable oscillations in the output.

Check this by setting the integral gain to 10 and observe the growing oscillations in system $\mathbf{T_1}$ output.

The integral action will change so as to remove the error associated with varying the shutter position. Table T5 shows typical results.

Set-Point (°C)	Shutter Position	Integrator Block Output (V)
50	**Fully Open (0)**	3.20
50	**Fully Closed (5)**	2.36

Table T5

5.6 Experiment 6 : Results and Conclusions

Your results should comprise a completed Table T6 and plots (see Plot P6) of disturbance rejection responses of a PI controller with various levels of feed-forward controllers gain.

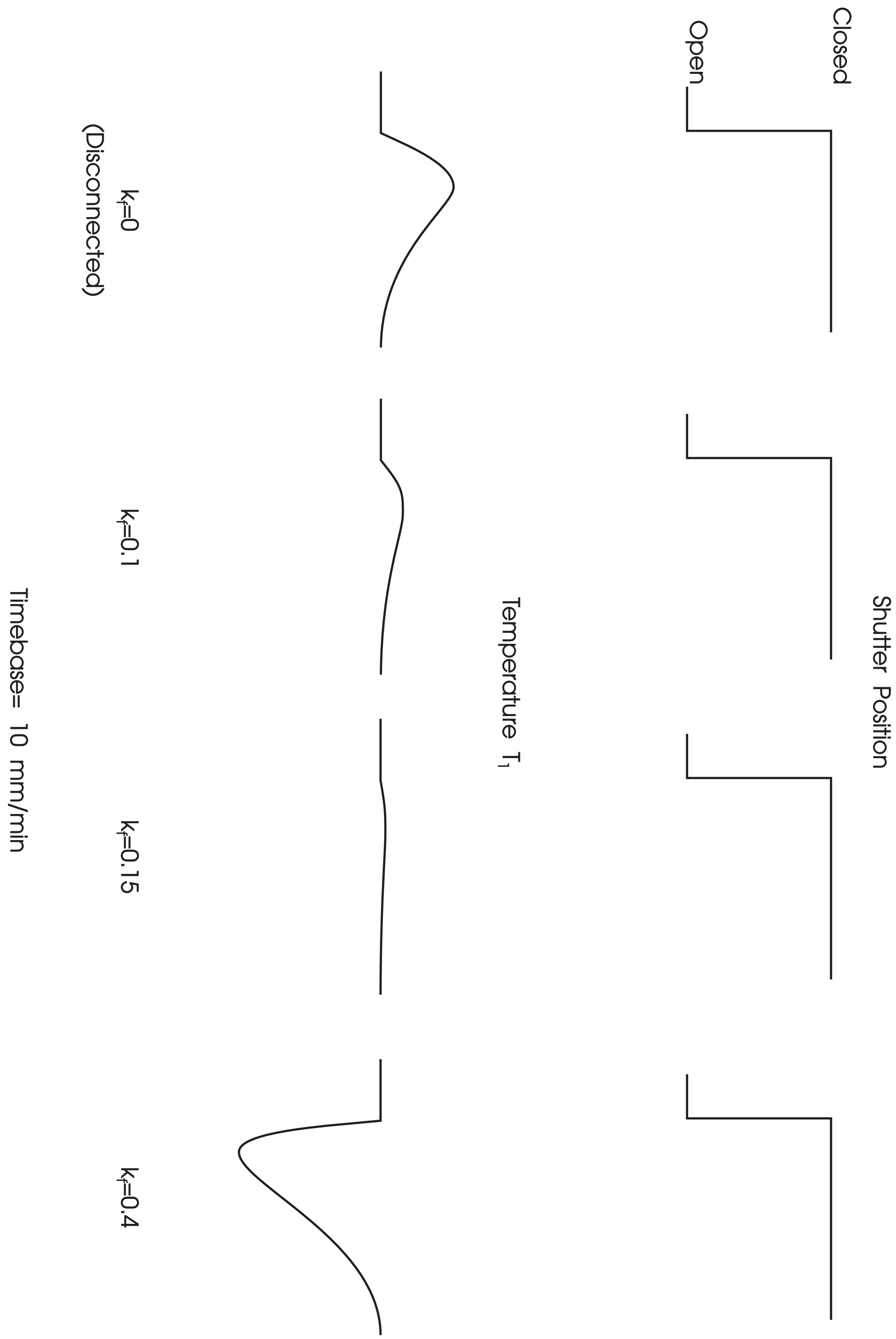
The results should show that the PI controller without feedforward will eventually remove the disturbance caused by closing the shutter. However, to do this the PI controller block output must change by (see Table T6) 1.5V from 4.6V to 3.1V.

The addition of $\mathbf{k_f=0.1}$ partially compensates for the disturbance (see Plot P6). However, when $\mathbf{k_f=0.15}$, the feedforward block removes 1.5V from the signal fed to the heater, such that the PI need not vary at all. This provides exact feedforward compensation for the disturbance (see row three of Table T6).

Increasing $\mathbf{k_f}$ beyond 0.15 causes over compensation and the temperature decreases until the PI controller compensates for the decrease (which is due to the feedforward controller).

Set-Point (°C)	Peak Variation in T_1 (°C)	PID Controller Output (V)		Feed-Forward Gain (k_f)
		Shutter Open	Shutter Closed	
50	**54.0**	4.6	3.1	Disconnected
50	**51.0**	4.6	4.2	0.10
50	**50.2**	4.6	4.6	0.15
50	**45.0**	4.6	7.0	0.40

Table T6


Closed
Open
Shutter Position
Temperature T_1
k_f=0
(Disconnected)
k_f=0.1
k_f=0.15
k_f=0.4
Timebase= 10 mm/min

Plot P6

APPENDIX 1. CITATION INDEX.

The following listing of papers and reference books relate to the **TQ Control Engineering Range**, both in general terms and also for specific control applications.

GENERAL APPARATUS

" Teaching Control with Laboratory Scale Models",
P. Wellstead, IEEE Trans. on Education (special issue on Control Engineering Education), Vol 33, 3, 1990 (pp 285-290).

"Personal Computers in Laboratory Teaching of Control",
P. Wellstead, Proc. IFAC Symposium on Identification and System Parameter Estimation, York (U.K.), 1985 (pp 575-579).

"Scale Models in Control System Engineering",
P. Wellstead, Trans. Inst. M.C. Vol 2, 3, July 1980 (pp 137- 155).

"The Ball and Hoop System",
P. Wellstead, Automatica, Vol 19, 4, 1983 (pp 401-406).

"Personal Computers in the Laboratory Teaching of Identification and Control".
D. Jordon and P. Wellstead, Proc. Workshop on Computer Based Teaching, Cambridge, 1985.

"Ball and Beam Control Experiment",
P. Wellstead, V. Chrimes, P.R. Fletcher, R. Moody and A.J. Robins.
Int Jour: Elect. Eng. Ed., Vol 15, 1989 (pp 21-39).

"A Real-Time Software Package for Teaching Digital Control".
M. Marcos, P.E. Wellstead and J.M. Sandoval.
Int Jour: Elec. Eng. Ed., Vol 28, 1991 (pp 5-20).

COUPLED TANKS APPARATUS

Described in detail and used as a main example in;

"Engineering Applications of Microcomputers Instrumentation and Control",
R. Ball and R. Pratt, Prentice Hall, 1986 (pp 126-146).

Used as a student assignment in;

"Linear Control Systems Analysis and Design: Conventional and Modern",
J.J. d'Azzo and C.H. Houpis, McGraw-Hill, 1988 (pp 60-62).

"Feedback Control of Dynamic Systems",
G.F. Franklin, D.J. Powell and A. Emami-Naeini, Addison Wesley, 1986.

"Digital Control and Estimation",
R. Middleton and G.G. Goodwin, Prentice Hall, 1990.

The Coupled Tanks is useful because it illustrates the control problems associated with, e.g. liquid storage systems. See, for example,

"Process Dynamics and Control",
D.E. Seborg, T.F. Edgar and D.A Mellichamp, Wiley, 1989 (pp 25-26).

"Automatic Control Engineering",
F.H. Raven, McGraw-Hill, 1968 (pp 28-32).

In addition to fulfilling a basic teaching function, the Coupled Tanks has also proven popular as a demonstration tool for new control ideas. See for example;

"Adaptive Control of a Coupled Tanks Apparatus",
J.M. Fernandes, C.E. DeSouza and G.C. Goodwin. Int. Jour. of Adaptive Control and Signal Processing. Vol 3, 4, 1989 (pp 319-332).

BALL AND BEAM APPARATUS

"A Real-Time Software Package for Teaching Digital Control".
M. Marcos, P.E. Wellstead and J.M. Sandoval.
Int. Jour: Elec. Eng. Ed., Vol 28, 1991 (pp 5-20).

Used as a student assignment in,

"Feedback Control of Dynamic Systems",
G.F. Franklin, D.J. Powell and A. Emami-Naeini, Addison Wesley, 1986.

"Modern Control Systems",
R.C. Dorf, Addison Wesley, 1986 (p. 85).

Used as a standard process throughout the book,

"Computer Controller Systems",
K.J. Astrom and B. Wittenmark, Prentice Hall, 1984 (e.g. see p.400).

The Ball and Beam, like the Coupled Tanks, has been used as a demonstrator of new theoretical results. For example;-

"Non-Linear Control via Approximate Input-Output Linearisation: The Ball and Beam Example",
J. Hanser, S. Sastry and P. Kukotoric.
IEEE Trans. Automatic Control, 37, 3, 1992 (pp 392-398)

The double integrator dynamics of the Ball and Beam are useful because they are the same as some problems encountered in aerospace.

For example, satellite yaw-axis control, see,

"Digital Control Systems Analysis and Design",
C.L. Phillips and H.T Nagel, Prentice Hall, 1984 (pp 7-8).

"Digital Control and Dynamics Systems",
C.L. Franklin and J.D. Powell, Addison Wesley, 1980 (pp 291-292).

COUPLED DRIVES APPARATUS

Used as a case study (in the form of a tape drive) in,

"Feedback Control of Dynamic Systems",
G.F. Franklin, D.J. Powell and A. Emami-Naeini, Addison Wesley, 1986.

Used to illustrate tension control in paper machines (page 117) and as a magnetic tape drive for military applications (page 235) in,

"Modern Control Systems",
R.C. Dorf, Addison Wesley, 1986.

Occurs as an extended case study in,

"Control Systems: Engineering and Design",
S. Thompson, Longman Scientific, 1989 (pp 261-266).

BALL AND HOOP APPARATUS

Used as a case study in,

"Engineering Applications of Microcomputers Instrumentation and Control",
R. Ball and R. Pratt, Prentice Hall, 1986 (pp 147-161).

Used as a student assignment in,

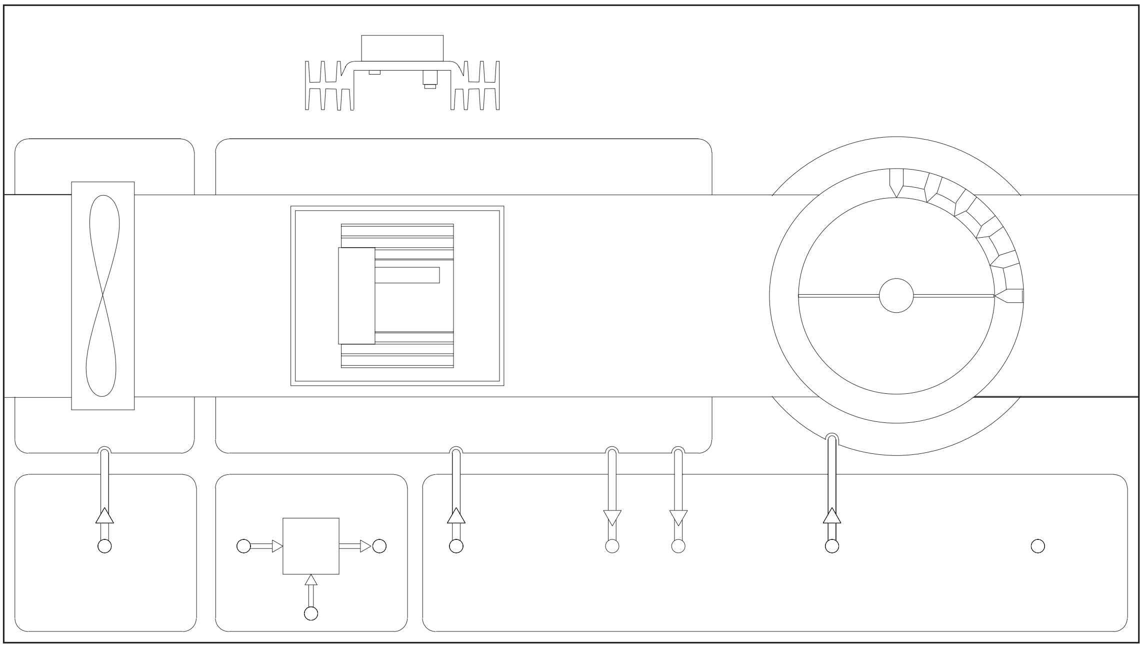
"Modern Control Systems",
R.C. Dorf, Addison Wesley, 1986.

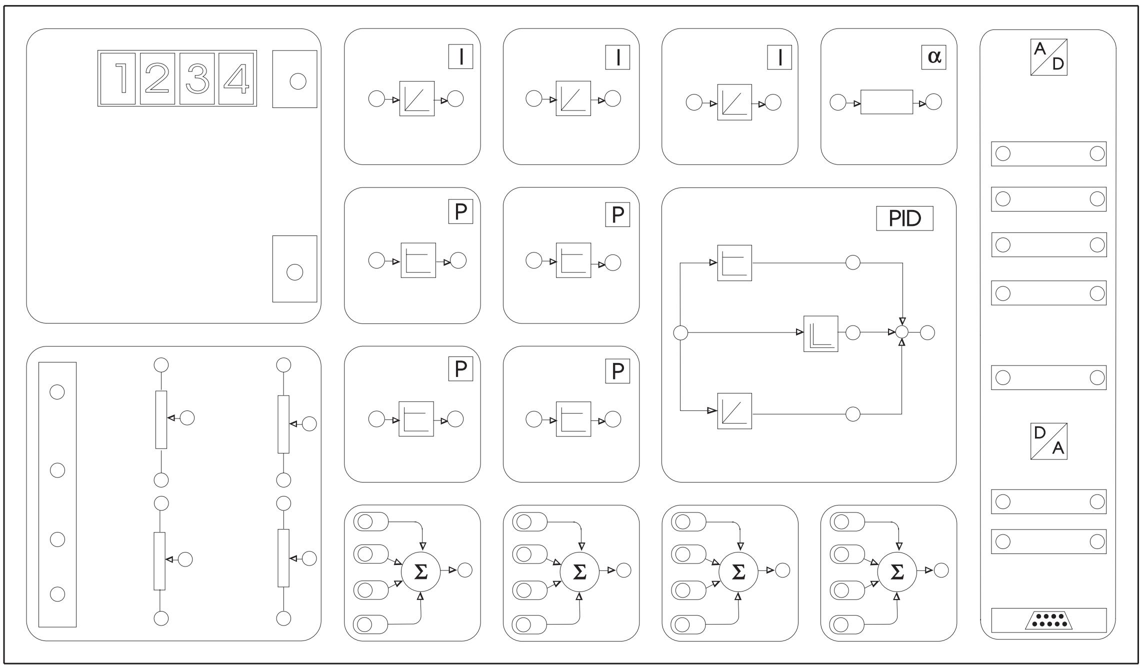
APPENDIX 2. BLANK EXPERIMENTATION CIRCUIT DIAGRAM.

The following diagrams provide outlines of both the **CE103 Thermal Process Control Apparatus** and the **CE120 Controller**.

These may be used as required to enable the production of experiments additional to those provided in Section 4 of this manual. All that is required is for the actual circuit connections to be added. If any other controller is to be used it will be necessary for the user to produce a suitable diagram to be combined with the CE103 diagram.

It is recommended that a photocopy, or similar, is made of this diagram so that it may be used as many times as required.




1234
I
I
I
α
A/D
P
P
PID
P
P
D/A
Σ
Σ
Σ
Σ

APPENDIX 3. GLOSSARY OF TERMS.

Any study of control engineering, especially for those unfamiliar with the specialist terms used, requires an understanding of the terminology used. The following definitions are given to assist in following the explanations given in earlier Sections of this manual;

Analogue - Where the circuit elements are designed and assembled to operate with input and output signal(s) which vary in smooth continuous manner. For example, an oscilloscope could be used on an analogue circuit to trace a signal from the input to the output and this would be seen on the screen as a continuous waveform of the required shape, frequency and amplitude at each stage.

Closed-Loop Control System - Where the state of the output is measured and then used to affect the input condition so as to change the output performance as required.

Damping - The opposition to change which, to varying degrees, may be used to prevent a system overshooting and oscillating.

Differential Action - Where the output signal is the differential of the input. In practice, this essentially means that the output signal is proportional to the rate of change of the error signal at the input.

Changes in both the waveform shape and amplitude are probable between the input and the output.

Differential Action is used in a control system to oppose the change in error and, hence, dampen the transient response so as to minimise the overshoot and also the tendency of the system to oscillate.

Digital Circuits - Where the input and output signal(s) take the form of patterns (codes) of voltages obtained by switching between high and low voltage levels. These would be processed mathematically to achieve the required objectives.

Modern computers incorporate digital circuits to process and store information as it is passed around the system in packages of data. Because of its need for information in a digital format the interface with the outside world includes the ability to convert analogue data into digital and then back again when outputting.

Drift - The changes in a signal level not attributable to any system change. This would normally be occurring over a period of time.
A common cause of Drift in a system are the variations in ambient temperature, outside the actual control system, which produce performance changes in such components as resistors, transistors, etc. If necessary, circuits have to be designed to either tolerate Drift, from whatever cause, or to compensate for it.

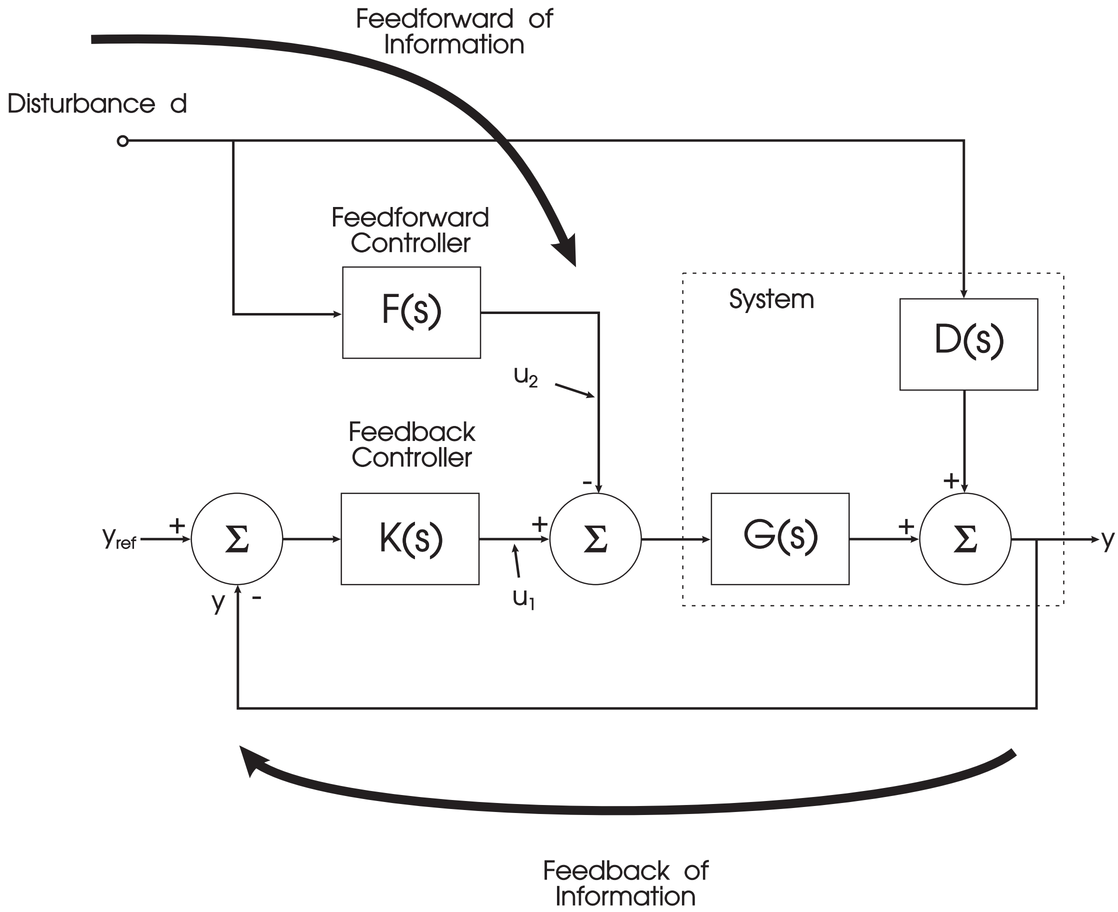
Equilibrium - The balance achieved in a system when operating conditions become constant.

Feedback - Where information gained about the output is used to affect the input such that the required operating conditions are achieved. A system that employs Feedback is termed a **Closed-Loop Control System**.
Feedback may be 'positive' or 'negative' depending upon the actual configuration of the Feedback signal polarity. The choice for the type of Feedback, positive or negative, is dependent upon the operating requirements of the system.

Feedback System - The particular circuit within an overall system that processes the feedback signal into the required form. This may be tailored to optimise the system steady state conditions as well as the transient response.

Feedforward - Where information gained from an external disturbance can be incorporated into the control system so as to reduce the effect of the disturbance upon the output or process variable.

Feedforward System - A Feedforward system is illustrated below. This particular circuit operates in conjunction with a feedback system by adding a signal (which is proportional to the measured disturbance) to the output of the feedback controller, the object being to minimise the effect of the disturbance.



Gain - The ratio of the output to input signal magnitudes.

Hybrid Circuits - In many applications it is necessary to combine digital and analogue circuits to produce a hybrid system. At the interfaces between each type of circuit (analogue and digital) it is necessary to convert the format of the information from analogue into digital (A to D) or digital into analogue (D to A).

Instability - A system is said to be unstable if, after a disturbance, it is unable to return to an equilibrium position. Instability, in the form of system oscillations, is a major design and operating consideration in high gain systems.
In some systems no stable state exists naturally and so external controllers are essential to achieve any level of useful performance at all.

Integral Action - Where the signal at the output of a circuit or system is the integral of the signal at the input. Changes in the waveform shape and amplitude are likely.

In practice, the function of Integral Action in a control circuit is to continually operate to remove the system error and also to affect the transient response (acceleration).

Measured Variable (Process Variable) - The physical parameter(s) measured by transducers to produce the feedback signal in the control system.
The Measured Variable in the CE103 is the temperature of the process block.

Modelling - This is the process of using mathematical expressions to represent a system so that predictions can be made of its response to different operating conditions.
This is particularly beneficial to designers who need to be confident their proposals are feasible. Computers are a common tool for control engineers to model systems, especially complex ones with multiple inputs and outputs, once the mathematical model has been developed.

Natural Frequency (Resonant Frequency) - This is the specific frequency at which a system will oscillate if allowed. Normally, this frequency is given particular attention to prevent the system experiencing undesirable oscillations that may affect its performance.

Open-Loop Control System - Where the state of the output has no effect on the input condition.

Output (or Process Variable) - This is the actual state of the system being controlled, e.g. the level in the tank, the speed of a rotating shaft, the temperature of a body, etc.

PID (Three-Term) Action - Where the output is the sum of proportional, integral and differential action. The relative values for each of these terms would be set to achieve optimum system performance.

Process Variable - See Measured Variable.

Proportional Action - Where the output signal from a circuit/system is proportional to the input, usually the Error. Although the relative signal magnitudes may be different, the actual waveforms will have exactly the same shape and will also be in phase.

Set-Point (or Reference) - A signal selected, often by manual adjustment, to establish a required level of performance.
In the example of liquid level control, the Set-Point (Reference) input would be selected and adjusted to achieve the required height of a column of liquid in the range 0 to +10V to achieve an actual level of between 0 and 250mm.

Stability - A system is said to be stable if, after a disturbance, it returns to an equilibrium position. The CE103 is essentially a stable system.

Steady State - The condition a system stabilises to when all operating parameters remain constant.

System - Any combination of components, circuits and devices that interconnect to form a single working entity. A system may be in many forms, e.g. electrical, mechanical, biological, physical, organisational, etc.

For the theory and practical exercises described in this manual it is assumed that the System comprises an air duct in and around which are mounted;
A metal process block,
An electrical heater,
Two platinum resistance thermometers for temperature monitoring and control,
A variable speed fan,
A variable angle vane,
Various electronic control and signal conditioning circuits.
Computer/Interface/Software/Instruments (optional).

System Error (or Error) - The difference between where the system is required to operate and where it actually exists. This may also be the difference between the feedback signal and the reference, as produced by a summing amplifier.
The Error signal may be either positive or negative, depending upon the actual state of the system, as measured by the transducer, compared with the Set-Point.

System Input (or Manipulated Variable) - This is the actual input to the system which is used to manipulate or actuate the system, e.g. pump motor drive signal, power supplied to a heater, drive signal to a flow control valve, etc.

Transducers (Sensors) - These are devices that are designed, constructed and mounted in, on or around a system such that they are only affected by changes in a particular selected physical parameter. They then produce electrical signals that are proportional to the absolute value or to the magnitude of any changes in that parameter.

It is the output from transducers that produce the feedback signals in a closed-loop control system.

In the CE103, the process temperature is sensed by platinum resistance thermometers. Electronic signal conditioning circuits are calibrated to provide an output of 100mV/°C.

A rotary potentiometer connected to the vane enables it to be positioned under the control of a d.c. signal at the input to its control circuit.

Transfer Function - Essentially the ratio of amplitudes of the output signal to the input signal with additional information concerning any phase shift occurring. It is used to predict how a system will perform under different operating conditions.

Transient Response - The particular characteristic of a system responding to a disturbance or a change in the set-point (reference) input.

For a fuller description and explanation for each of these terms it will be necessary to refer to another source of information.