Building control systems

CIBSE Guide H

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Foreword

The CIBSE Applications Manual *Automatic Controls and their implication for systems design* was published in 1985 with the stated aim 'to provide building services engineers generally with the detailed guidance required to ensure that automatic controls are considered as an integral part of the design philosophy'. The technology, both hardware and software, of automatic control systems has advanced greatly since then and the need for a new edition is clear. The Department of the Environment, Transport and the Regions granted an award for the production of a new edition of the manual under the Partners in Technology scheme. The DETR provided 50% of the funding for the project; the Partners provided the balance, with the initial publishing costs met by CIBSE. A contact for the preparation of the draft was placed with the Department of Building Engineering at UMIST, and the work has been supervised by a Task Group, drawn initially from the CIBSE IT and Controls special interest group.

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Preface

Controls are poorly understood in our industry. The subject is also disliked in university courses as it can become highly mathematical. It is probably partly due to this lack of appreciation of controls and their commissioning that I have yet to find a building that works properly and satisfies the occupants after it has been commissioned. This Guide is an attempt to redress some of these problems. It explains the topic of controls with the minimum of mathematics. It builds on and updates the earlier 1985 Applications Manual *Automatic Building Controls*.

Some points did come up a number of times in the Task Group discussions that could not be quantified in the body of the Guide but are worth mentioning here;

- Adequate time should be allowed for the commissioning process. It can take between 1 day and 6 months to commission a control system, depending on the size and complexity of the system. Another general and difficult-to-define quantity is the time to commission a BMS point, but figures between 8 minutes and 60 minutes are often mentioned.

- The form of contracts and subcontracts can have major implications for controls and especially the time for commissioning; slippages and cost cutting can end with the design and commissioning being done poorly. Partnering may help this.

- Part-load performance details of the HVAC system to be controlled will aid the design and commissioning of the control system. Rarely do systems operate at, or get commissioned at, the near-extreme conditions of design.

- The controls should be considered from the earliest stages of the design process.

- Occupant feedback, via a self-assessed questionnaire, can be a useful design and commissioning tool.

- In many new buildings occupants need to be involved in the control process and also informed of the control process.

I would like to give my sincere thanks to the Task Group, which has provided many useful comments and much guidance, to Donald McIntyre for helping to get them into a coherent, easy to read document, and to Ken Butcher for his help throughout the preparation process.

Geoff Levermore July 1999

Acknowledgements

Preparation of the manual would not have been possible without the generous help of the many people who provided information and literature, and gave their time to discuss the project and read the many drafts. While it is not possible to mention them all by name, their contributions were highly valued.

1 Introduction: the need for controls

This introductory section provides an overview of the Guide and will be of value when preparing the general case for a control system. It demonstrates the importance of controls in ensuring effective and efficient control of a building in order to:

— provide comfortable and productive working conditions
— provide the proper environment for industrial processes
— operate in an energy efficient manner
— be environment friendly.

1.1 Overview of the Guide

The first edition of this Guide was published in 1985 as an Applications Manual, under the title *Automatic Building Controls and Their Implications for Systems Design*. The many developments since then, particularly in the fields of microprocessor control and communications networks, have necessitated the production of an entirely new edition. The aim of the Guide has been restated since the first edition to reflect the growing importance of IT, and now reads: *to provide the building services engineer with a sufficient understanding of modern control systems and relevant information technology to ensure that the best form of control system for the building is specified and that proper provision is made for its installation, commissioning, operation and maintenance.*

The structure of the Guide is indicated in Table 1.1. This introductory section sets out the benefits to be gained from a modern building control system and will be of value in making the case that adequate provision be made at an early stage for a proper control system. The following section deals with the different types of control mode and their application in different situations; advice is given on the setting up and tuning of controllers to ensure stable operation.

Sections 3–6 deal with the practical design of control systems, starting with the hardware components, then their incorporation into control systems by linking them into networks, and then two sections on control strategies for HVAC systems and whole buildings. The Guide thus starts

Table 1.1 Organisation of the Guide

1 Introduction	The contribution that a modern building management system can make to the efficient and economical operation of a building
2 Control fundamentals	The basic types of control operation that are found in practice, ranging from the simple thermostat to microprocessor controlled self-learning algorithms. Guidance on the application of different control types and their tuning for optimum operation
3 Components and devices	The whole range of hardware components that constitute a control system, including sensors, valves, dampers, actuators, motors and basic controllers
4 Systems, networks and integration	The means by which components are brought together to form an operating control system. The various BMS architectures and the major standard protocols for bus systems. Characteristics of networks and the extension to full systems integration
5 Control strategies for subsystems	Control strategies for the fundamental parts of HVAC systems: safety interlocks, boilers, chillers, water and air systems, lighting
6 Control strategies for buildings	Control strategies for whole buildings. Avoiding conflict between subsystems. Illustrations of successful control installations
7 Information technology	The relation between BMS and IT. Energy monitoring and targeting, maintenance scheduling, facilities management
8 Management issues	The importance of the procurement method on the BMS design process. Commissioning, CDM requirements and cost issues

with the constituent components and moves up to complete systems. The user may prefer to consult the control strategies for systems of interest and then refer back in the Guide to obtain a fuller understanding of the component parts.

Section 7 deals with the relation between building management systems and information technology. The BMS and IT systems may share a communications network and the information gathered by the BMS can be used by the IT system for further purposes, enhancing the value of both systems. The final section shows the importance of the building procurement process in determining whether adequate resources are devoted to the design and installation of a suitable BMS and emphasises the necessity of taking control requirements into consideration at an early stage in the design process.

1.2 The modern control system

Good controls are essential for the safe and efficient operation of a modern building. The control system does more than keep the inside of a building comfortable for the occupants. It is required to keep the HVAC plant operating efficiently, to ensure that all plant operates safely in the event of any unforeseen circumstances, and it must be capable of two-way communication with the personnel charged with its operation. While it may be self-evident that modern highly serviced buildings require a sophisticated control system, it should be realised that simpler buildings relying on a boiler system and natural ventilation can still benefit from a modern BMS. The increasing emphasis on energy conservation and reduction of greenhouse gas emissions serves to increase the importance of efficient controls.

The late 1970s saw the introduction of digital data technology, in which information is transmitted not as an analogue electrical value, but as a number. Digital data transmission is less susceptible to error than analogue transmission and it is standard practice to construct the signal protocol in such a way that it is possible to detect whether an error has occurred during transmission. This was the beginning of direct digital control (DDC). It required the codification of rules by which values are converted to numerical messages for sending; such messages have to contain not only the value of the variable under consideration, but additional information such as the origin and destination of the message and error-checking information. Such conventions on the structure of the messages are the basis of data communication protocols. At the early stage of DDC, data handling was centralised and multiplexing circuits were used so that the central unit could contact each remote unit as required. As computing power rapidly increased, the functionality of the central control unit became more and more sophisticated, with the ability to handle increasing amounts of data and to perform additional functions such as the monitoring of energy consumption and the printing or reports.

The advent of the microprocessor allowed considerable computing power to be incorporated in a small device and meant that it was now no longer necessary for all control and monitoring functions to be carried out by a large centralised computer. Intelligent outstations placed round the building became capable of carrying out local control functions, while communicating with a central supervisor which could oversee their actions, receive any alarm signals and alter set points or operating times as required. There has been enormous progress in the field of data communication and the application of local area networks (LANs), which allow microprocessors and computers to communicate with each other over standardised networks. Communication may be extended to link together the operation of several buildings, which may be located miles apart, or even in different countries.

All these have contributed to the modern building management system. In this Guide the term 'control system' or 'building control system' is used to cover all control elements, including hardware, controllers, any linking network and central controllers. The term BMS refers to a system where components may communicate with each other and generally implies some form of central supervisor, which permits monitoring and control of the building from a single point. The period that saw the development of the BMS has also seen the rise in information technology (IT). A modern operation, whether it is office or factory, is likely to distribute and process large amounts of information dealing with the operation of the business. There may be advantages in linking IT and BMS, either for the economy of using shared networks or for the more efficient integration of management control over the many activities taking place in a building.

1.3 The global environment

The building industry is implicated in two major concerns about the possibility of global environmental change: global warming and damage to the ozone layer. Buildings are a major source of carbon dioxide emissions, whether directly by the consumption of fuel for space and water heating, or indirectly by the consumption of electricity for lighting, air conditioning and other uses. It is estimated that energy use in buildings in the UK accounts for about half of the total carbon dioxide emissions.

The destruction of the ozone layer is a distinct problem from climate warming, but the causes are linked. Chlorinated fluorocarbons (CFCs) are stable compounds which for years have been the most commonly used refrigerant in air conditioning applications. If released, CFCs interact with ozone in the upper atmosphere leading to a thinning of the ozone layer, which normally provides an effective barrier to excessive ultraviolet radiation from the sun. An international agreement has been reached to restrict the use of CFCs. The Montreal protocol allows the use of alternative refrigerants (HCFCs) with a much lower ozone depletion capacity than CFCs for an interim period, after which they would be banned as well[1]. Proposed EU legislation will further restrict the use of refrigerants. In summary:

— Any use of CFCs for new or existing systems is to be prohibited from 2001, including recovered and stockpiled CFCs.

— The use of HCFCs in new air conditioning plant will be phased out between 2001 and 2004, depending on the type of plant.

— The use of new HCFCs for maintaining existing systems is to be banned after 2010, though it will be possible to use recovered and recycled refrigerant.

— Recovery of CFCs and HCFCs on plant servicing or decommissioning will become mandatory and annual leak checks for larger systems will be compulsory.

There is therefore strong pressure to reduce energy consumption in buildings and to avoid the use of air conditioning wherever possible. This pressure may take several forms: further legislation can be expected, the price of fuel may be increased and responsible clients will incorporate environmental goals in the design brief. The *CIBSE Code of Professional Conduct* places a general duty on members to 'have due regard to environmental issues'[2] and the *CIBSE Policy Statement on Global Warming* recommends that members take positive steps to reduce global warming[3].

Any major reduction in energy use by buildings requires commitment by the client expressed in the design brief, followed by action at the design stage, where fundamental decisions on the form of the building and the use of air conditioning are made. Correct design and operation of building controls is essential to avoid waste of energy. Reduction in the use of air conditioning and the application of natural ventilation bring new challenges for effective building control and the maintenance of satisfactory internal conditions coupled with low energy use. The *CIBSE Guide to Energy Efficiency in Buildings*[4] has the objective of showing how to improve the energy performance of buildings. While primarily targeted at building services engineers, it is of use to all members of the building team.

1.4 The indoor environment

The function of the building services and their associated control system is to provide an environment within the building appropriate to the activities taking place therein. Several factors contribute to feelings of thermal comfort and their incorporation into the predicted mean vote (PMV) index is set out in European Standard *BS EN 7730*[5]. Recent research[6] strongly suggests that people adapt to their environment, allowing temperature settings to fall in winter and rise in summer. This has important implications for the design of naturally ventilated buildings. Guidance on the required conditions for a range of occupations and activities is given in CIBSE Guide A1[7]. Decisions on allowable excursions of the conditions outside the recommended comfort bands, e.g. during a summer heatwave, will have important repercussions on plant sizing. The specified control tolerances will affect the design and cost of the control system. The indoor environment affects not only comfort, but also productivity and health. Relevant legislation is referred to as appropriate in the text. *The Control of Fuel and Electricity*, Statutory Instrument[8], specifies a maximum heating level of 19°C in non-domestic buildings. The law has not been rigorously enforced. While it is difficult to substantiate precise claims of productivity gains, there is little doubt that comfortable conditions will have a beneficial effect. Surveys have consistently shown that the speed with which management attends to complaints is very important. Those companies where management attends promptly to problems are highly rated by the occupants[9]. The client's point of view for the specification of offices is represented in *Best Practice in the Specification for Offices*[10].

While the primary function of a building control system has been the control of temperature and humidity, the increased awareness of sick building syndrome (SBS) and other building related illnesses has emphasised the requirement to ensure good indoor air quality. The demands of energy conservation and healthy ventilation are sometimes in conflict, necessitating better attention to the control of ventilation to ensure a satisfactory compromise. More attention is being given to the quality as well as quantity of ventilation.

There are many buildings which house processes and operations which have their own special requirements for environmental control. Examples are low temperature for food preparation, high and controlled humidity for paper fabrication, clean rooms for electronic assembly. The pharmaceutical industry has its own special regulations for control of the environment, both for drug production and for animal housing. Companies producing goods for export may need to meet the requirements set down by the customer's country. It is outside the scope of this Guide to give the many regulations; it is the responsibility of the client or his representative to ensure that they are taken into account at an early stage in the design.

1.5 Energy conservation

Building controls have a vital role to play in preventing waste of energy. The amount of energy required to run a building is determined by:

- thermal efficiency of the building envelope
  - thermal insulation
  - airtightness
  - provision for passive solar gains
- requirements of the indoor environment
  - temperature schedule
  - ventilation needs
  - humidity control
  - indoor air quality
  - lighting requirement
  - hot water requirements
  - lifts and mechanical services
- processes within the building
  - IT equipment
  - industrial processes.

The above requirements taken together demand a level of base energy, which is the energy required to meet the business needs of the building operation. This provides a minimum level of energy expenditure. Any reduction in base energy requirement implies a change in building construction or use. The difference between actual energy expenditure and the base requirement represents avoidable waste. Examination of data from a number of UK buildings shows avoidable waste levels in the range 25 to 50%; in a well-managed building, avoidable waste levels of below 15% are achieved[11].

Avoidable waste has many causes, including:

- poor time and temperature control of the building interior
- ineffective utilisation of internal heat gains
- plant oversizing
- excessive ventilation
- low operating efficiency of the HVAC system
- poor system design and installation
- standing losses
- unnecessary use of artificial lighting and air conditioning.

The control system affects most of the above. Detailed applications will be found in the body of the Guide. Major contributions of the control system in reducing waste are:

- the limitation of heating and cooling to the minimum period necessary; this usually includes the use of optimum start controllers and some form of occupancy detection to avoid excessive out-of-hours use
- prevention of unnecessary plant operation and boiler idling
- monitoring to give early warning of malfunction or inefficient operation.

The establishment of a figure for base energy provides a clear figure to aim at and allows the performance of the building to be clearly and unambiguously stated in terms of avoidable waste. The base energy requirement must be estimated by a sound method, which is understood and respected by all parties involved. As far as possible, it should be broken down into components, to allow identification of areas which require action.

Fuel Efficiency Booklet 10[12] gives clear advice on the selection of an appropriate control system for energy saving purposes. It categorises control systems into four bands of ascending cost and complexity, shown in Table 1.2. The highest band gives the greatest potential energy savings, but may not be appropriate for all buildings or operating staff.

Band 0 is the minimum level of control required under the 1995 *Building Regulations*. Achieving this level of control in a building that has poor or non-existent controls will make considerable savings, and further savings of up to 20% may be made by the use of more sophisticated systems. Table 1.3, taken from the fuel efficiency booklet, gives rule-of-thumb assessments of cost savings that may be achieved. This table represents only a crude starting point. The decision on the type of control system to be installed in a building depends on more factors than simple energy payback savings and must be made on a deeper analysis of the costs and benefits to be expected.

1.6 Information technology and systems integration

A modern building contains several technical services in addition to heating and ventilation, such as lighting, lift control, security and access control, closed circuit television

Table 1.2 Banding classification of heating control systems, after Energy Efficiency Office[12]

Band	Time	Boiler	Distribution	Space heating	Hot water system
Output greater than 100 kW					
2	Optimiser plus time control of zones. Time control of HW storage	Boiler loading control. Off-line boilers isolated. Interaction with space control	Compensated with space temperature reset and separate zone circuits. Interaction with space control	All emitters with individual control, modulating where appropriate	Local gas fired water heaters or point of use electric units
1	Optimiser plus time control of zones. Time control of HW storage	Effective boiler sequencing and control strategies. High efficiency boilers	Compensated with space temperature reset and separate zone circuits	TRVs and room thermostats except in room with space reset sensor	Segregated HWS system, or top located or dual thermostats on calorifiers
0	Optimiser plus time control of HW storage	Effective boiler sequence control	Compensated with space temperature reset	None, or on emitters designed for separate control	Effective thermostats on calorifiers
–1	Timeswitch	None	No compensator	None or TRVs	Basic thermostat
Output less than 100 kW					
1	Optimiser plus time control of zones where appropriate. Time control of HW storage	Effective boiler sequencing and control strategies. High efficiency boilers	Compensated with space temperature reset and separate zone circuits	TRVs and room thermostats except in room with space reset sensor	Segregated HWS system, or top located or dual thermostats on calorifiers
0	Effective time control plus time control of HW storage	Effective boiler thermostat	Compensated with space temperature reset	None or on emitters designed for separate control	Effective thermostats on calorifiers
–1	Timeswitch	Boiler thermostat	Not compensated	None or TRVs	Thermostat

Table 1.3 Rule-of-thumb costs and benefits of control bands[12]

Control band	Capital cost increase over Band 0 (%)	Energy usage, compared with Band 0 (%)	Payback, over Band 0 base (years)	Comments
2	100–200	–20	2–4	Highly recommended for minimum energy usage
1	50–100	–10	1–2	Recommended for cost effective energy savings
0	0	0	N/A	Minimum
–1	N/A	≤ +50	N/A	Does not meet Building Regulations since 1985

(CCTV) systems, as well as the information technology network necessary for the user's business operation. All these services communicate within their own system using some form of network. There are major potential benefits if the various systems can communicate with each other, using the same communications network or a limited number of compatible networks:

— the reduction in cabling and infrastructure cost
— the ability of the systems to share information with each other.

This process is known as systems integration. At its most basic level, it means that devices from different manufacturers may use the same communications network, communicating with their peers and not interfering with other equipment. At the most advanced level, all systems within a building use the same communications network, exchange information with each other and are controlled from a single supervisor. For instance, the presence detectors of a lighting control system may feed information on out-of-hours occupancy to the security and access control systems. Full integration is also known as the intelligent building concept.

HVAC control systems operate in real time, ensuring proper operation of the environmental control system. The information generated may be fed into the information technology system where it can be used for the production of reports, energy monitoring and targeting and the preparation of maintenance schedules.

1.7 Building operation

A well-planned control system offers improved management of building services and can form the core of an integrated facilities management system, covering other building-related services such as access control, security, energy monitoring and targeting, information technology and maintenance. The amount of direct involvement by staff in the day-to-day running of an HVAC system has steadily reduced over recent years. However, it would be a mistake to assume that the control system can be left to take care of itself from the moment of handover. The client must choose from a range of options, from running the building services in-house with the client organisation's own staff, to outsourcing to a service bureau who may supervise efficient operation, deal with occupant requests and organise maintenance, all from a remote supervisor. Whichever form of organisation is chosen, there should be clear ownership of the control system with unambiguous responsibility for its successful operation. This requires a commitment by the client to ensure adequate resources for the operation and maintenance of the building control system; part of this commitment is the provision of proper training for staff. The organisation should ensure prompt and effective response to requests or complaints from the building occupants; several studies have confirmed the importance of rapid response in ensuring occupant satisfaction with their place of work.

The software which has been developed for BMS supervisors has greatly simplified the day-to-day management of even large BMSs and will show savings in operating staff costs compared with a simpler system which requires frequent attention. With the development of wide area networks, it is possible to have remote supervision. This enables skilled personnel to be located at a single site and able to monitor the performance of several BMSs in scattered buildings, leaving less qualified staff to carry out the daily operation on site. There will also be a saving in maintenance costs as the BMS is able to keep run-time records of all equipment, allowing maintenance to be planned effectively. Early warning of failure is available from monitoring. Plant life is extended by the reduction in hours of use that is obtained by scheduling, by reducing unnecessary device operation or unstable hunting and by reducing fan and pump speeds.

1.8 The benefits of a BMS

When deciding on the appropriate type of control system to specify for a building, it is necessary to remember that the

Table 1.4 Benefits of a BMS

Building owner	Higher rental value Flexibility on change of building use Individual tenant billing for services
Building tenant	Reduced energy consumption Effective monitoring and targeting of energy consumption Good control of internal comfort conditions Increased staff productivity Improved plant reliability and life
Occupants	Better comfort and lighting Possibility of individual room control Effective response to HVAC-related complaints
Facilities manager	Control from central supervisor Remote monitoring possible Rapid alarm indication and fault diagnosis Computerised maintenance scheduling Good plant schematics and documentation
Controls contractor	Bus systems simplify installation Supervisor aids setting up and commissioning Interoperability enlarges supplier choice

benefits of a modern control system are enjoyed variously by the different groups of users involved with the building. Table 1.4 lists some of the benefits to be achieved with an effective modern BMS. It goes without saying that these benefits will only be obtained if the system is properly specified, installed, commissioned, operated and maintained. It is the function of this guide to assist in achieving that goal.

1.9 Summary

Effective control of the heating, ventilating and air conditioning systems in a building is essential to provide a productive, healthy and safe working environment for the occupants. Without a properly functioning BMS the activities carried out in the building will be disadvantaged. Along with good building design and efficient HVAC plant, the BMS plays a vital role in the prevention of energy waste and reducing the environmental impact of the building.

Modern BMSs are based on intelligent controllers which may be programmed to carry out a wide range of control functions. Typically, a number of controllers are employed, each controlling an item of plant or an HVAC subsystem. The controllers communicate with each other and with a central supervisor over a local area network (LAN). The system manager is able to monitor and control the entire BMS from one point.

The scale and complexity of the control system should be appropriate to the building and its operation; highly effective and reliable control may be achieved with relatively simple control systems. However, when considering the cost effectiveness of a BMS, all the operational benefits that flow from a well-managed facility should be taken into account: not only energy saving but also the reductions in staffing cost, improved maintenance scheduling and the benefits of system integration with other building facilities. Such facilities as access control, security and lighting may be integrated with the BMS, giving total building management from one point. There is steady progress towards compatibility between products, so that devices from different manufacturers may share the same LAN and event interact directly with each other. The goal of freely interchangeable devices is termed interoperability.

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2 Control fundamentals

This section introduces the concept of feedback and the control loop. It describes the basic control modes used in HVAC controls, including:

- simple on/off control
- proportional, integral and derivative control
- optimisers and compensators
- intelligent controls.

Issues of stability are dealt with and methods of tuning control loops for the best combination of response speed and stability are given. The section goes on to discuss advances in adaptive controls, which learn by experience how to optimise operation of a controller.

2.0 General

A control system consists of three basic elements: a sensor, a controller and a controlled device (see Figure 2.1). The sensor measures some variable such as temperature and transmits its value to the controller. The controller uses this value to compute an output signal, which is transmitted to the controlled device, which then acts to change the output of the load, which acts on the controlled system. In the majority of cases relevant to this Guide we are dealing with closed loop systems, where the controller is attempting to control the variable whose value is being measured by the sensor. The results of its actions are fed back to the controller input and the system is said to have feedback. In the example shown in Figure 2.1, the controller is attempting to maintain room temperature at a set point. A low room temperature results in increased output from the heater, which then raises the room temperature. This increase is detected by the sensor and transmitted to the controller, which alters its output accordingly to reduce the difference between set point and the measured value of the controlled variable. In the discussion of control modes that follows, it is implicitly assumed that the system is inherently controllable. Poor design may result in a system that is practically impossible to control; this will be discussed further below.

Open loop or feedforward systems operate without feedback. As before, the operation of the controlled device is a function of the value measured by the sensor, but this does not result in a change to the measured variable. A weather compensator is an example of open loop control, where an external air temperature sensor is used to control the flow temperature in a heating circuit used to heat a building. The control system has no way of knowing if the desired internal temperature has been achieved.

In practice, a control loop may have more than one input signal and more than one output signal. Groups of control loops can be chained together to create control sequences. The simple description above implies that the input and output of the controller are continuous variables and this is so for such variables as temperature. An important part of practical control systems is a set of complex interlocks, where the operation of one part of the system is contingent on the operating state of several other variables and systems. Many inputs and outputs are thus binary (on/off) in nature. When preparing a points list, it is conventional to refer to them as digital inputs and digital outputs (DI and DO); this does not imply DDC.

2.1 Control modes

Consider again the simple closed loop system of Figure 2.1. The way in which the control system responds to a change in the controlled variable is described by the control mode. Several control modes are in use and it is important to select the appropriate mode for the job in hand.

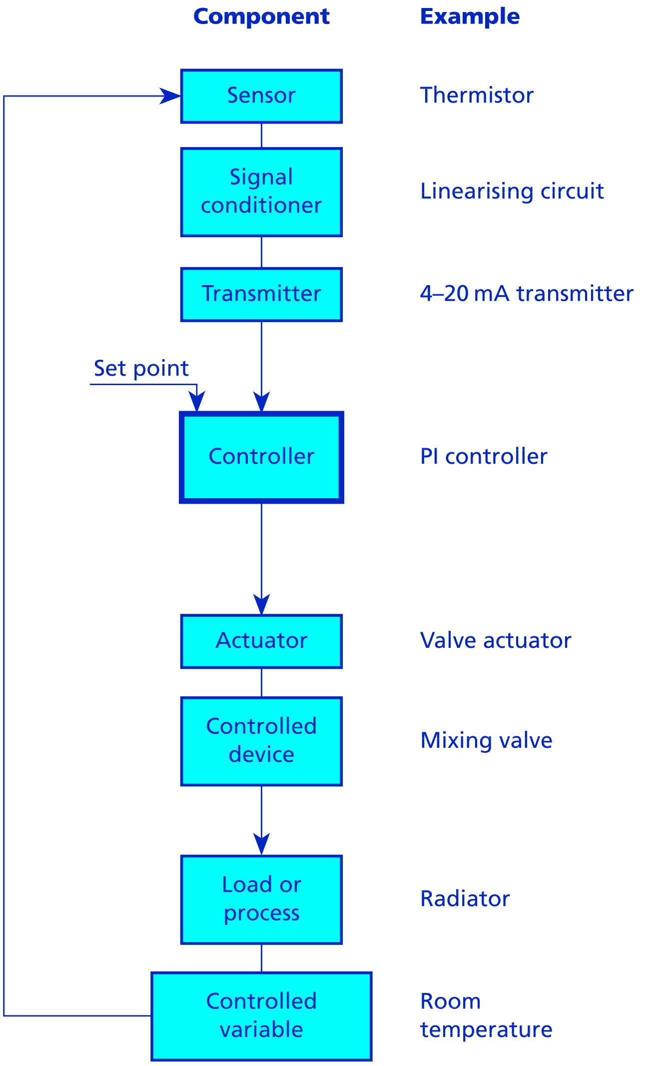

Figure 2.1 The components of a control system. In practice, some components may be combined

2.1.1 Two-position (on/off) control

In this mode, the controlled device gives either maximum or minimum output, typically on and off. Figure 2.2 illustrates two-position control for a simple heating system. It is desired to control temperature at the set point. For reasons that will become clear, it is necessary for there to be a temperature differential between switching on and switching off of the controlled device. With the heating on, the space temperature rises until the sensor output exceeds the set point. The heating then switches off and stays off until the temperature falls through the differential and reaches the lower limit, whereupon it comes back on and the cycle repeats. The temperature interval between the upper and lower limits is termed the differential gap or differential band; in American usage it may be referred to as the deadband. Within the differential gap the output may be either on or off, depending on the last switching operation. In accordance with present convention, the set point is taken to be the upper point of the differential gap; earlier conventions take it to be the centre point. The room temperature continues to increase for a time after the heating system has been switched off; this is caused by, for example, hot water present in the radiators. Two-position control results in a swing of temperature about the set point and a mean temperature that normally lies below the set point; some systems when operating under light loads may give a mean temperature above the set point. The swing may be reduced by reducing the differential, but at the cost of increased frequency of switching, with attendant wear on the system. The peak-to-peak variation in space temperature is termed the swing or operating differential and the differential of the controller itself, i.e. the differential that becomes apparent by turning the dial of the thermostat, is known as the mechanical or manual differential.

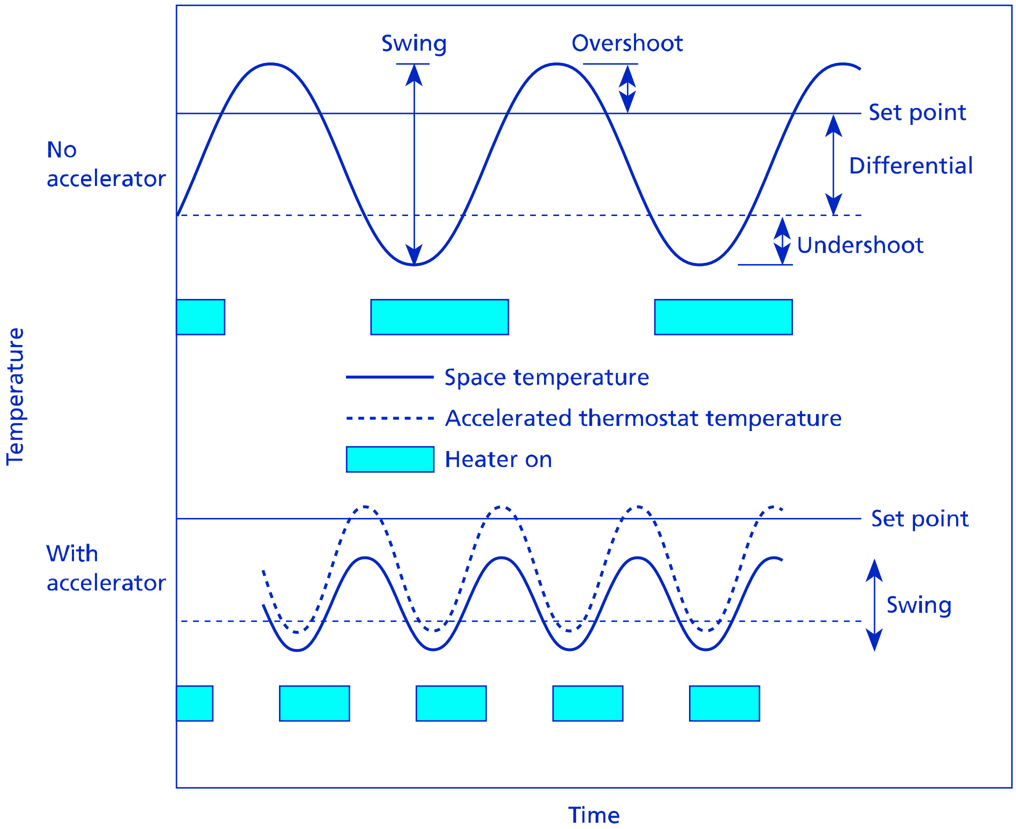

Figure 2.2 Two-position (on/off) control

The common domestic room thermostat is an example of a two-position controller. The inherent differential of the thermostat is of the order of 3 K, for mechanical reasons necessary to provide a snap action operation of the contacts to avoid arcing. The operating differential may be reduced by incorporating an accelerator heater in the thermostat. A low-powered heater within the body of the thermostat is wired in parallel with the load and comes on with the heating system. This has the result of increasing the temperature seen by the thermostat, resulting in earlier closure. The frequency of switching therefore increases, giving a lower operating differential and reduced temperature swings in the room. The effect of the accelerator is to reduce the mean room temperature achieved in practice below the set temperature and this control offset increases with load. This is equivalent to the load error found with proportional control and the action of the accelerated thermostat may be described as pseudo-proportional.

Floating control is a form of two-position control which requires that the controlled device can have its output increased or decreased by a slow-moving actuator. It is also known as three-position or tristate control. A typical example would be a motorised valve controlling flow of hot water. The valve moves slowly towards open or closed position during the application of a signal from the controller; with no signal, the valve stays where it is and holds its position. The output of the controller is now three rather than two position: increasing, decreasing and off (i.e. no change). Figure 2.3 illustrates this mode of control. When the room temperature exceeds the upper temperature limit, the controller signals the valve to start closing. The valve slowly moves towards the closed position, reducing the heat supply to the room. When the room temperature falls to the upper limit, the controller switches off and the valve stays where it is. The room temperature now floats within the neutral zone, until it crosses either the upper or lower temperature limit, whereupon the valve is driven in the appropriate direction. Such a system is designed to have a long operating time between fully open and closed positions of the controlled device; with a short operating time the action behaves like simple on/off control. Floating control is used for systems where the sensor is immediately downstream from the coil, damper or other device that it controls. It is not suitable for systems with a long dead time. A variant is proportional-speed floating control, where the further the value of the controlled variable moves outside the neutral zone, the faster the actuator moves to correct the disturbance. This is in fact very similar to integral action.

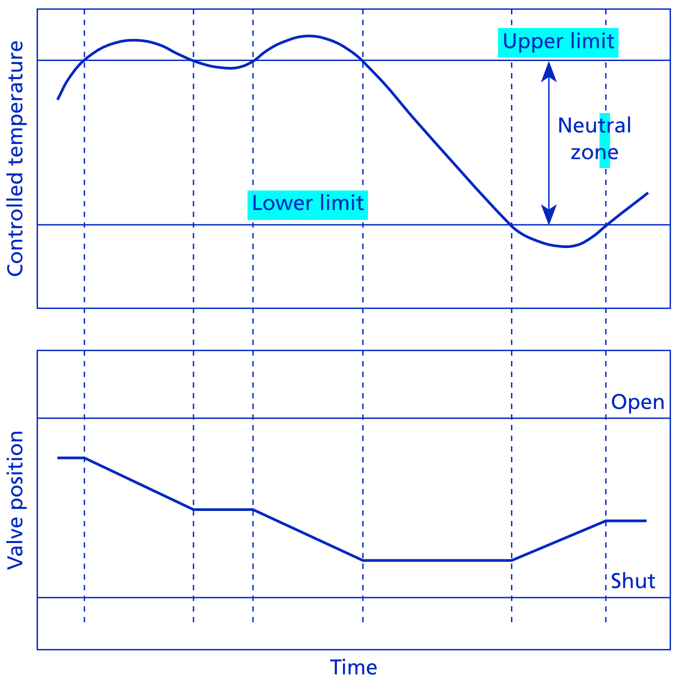

Figure 2.3 Floating control

2.1.2 Proportional control

Proportional control requires a continuously variable output of the controlled device. The control system produces an output which is proportional to the error signal, i.e. the difference between the value of the controlled variable and the set point. For the controller to produce an output to match the load on the system, it is necessary that there be an offset between the controlled variable and the set point. In steady-state conditions, a proportional controller produces an offset or load error, which increases with the load on the system. Figure 2.4 shows the operation of a proportional controller for a heating system. The control output increases from 0 to 100% as the input falls from the set point through the proportional band, also known as the throttling range. It can be seen that in steady-state conditions the equilibrium value of the control point will be below the set point and that this offset will increase with load, e.g. in colder weather when the heating load is greater. For cooling systems, the equilibrium value will be above the set point.

The proportional band may be expressed in units of the physical quantity being controlled, e.g. °C, %RH, pascal, or as a percentage of the controller scale range. If, for instance, the controller has a scale range of 0–80°C and a proportional band of width 20 K, the proportional band is 25%. The gain of a proportional controller is the reciprocal of the proportional band, expressed either in physical units, e.g. K^{-1} or non-dimensionally, e.g. a proportional band of 50% is equivalent to a gain of 2.

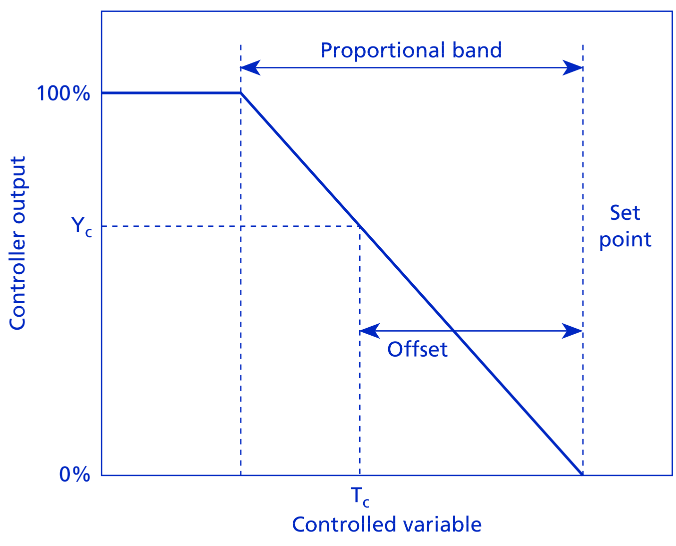

Figure 2.4 Proportional control. Diagram shows steady-state conditions with the controlled variable at T_c with a controller output Y_c. T_c is at an offset or load error below set point. (Sometimes the set point is in the middle of the proportional band)

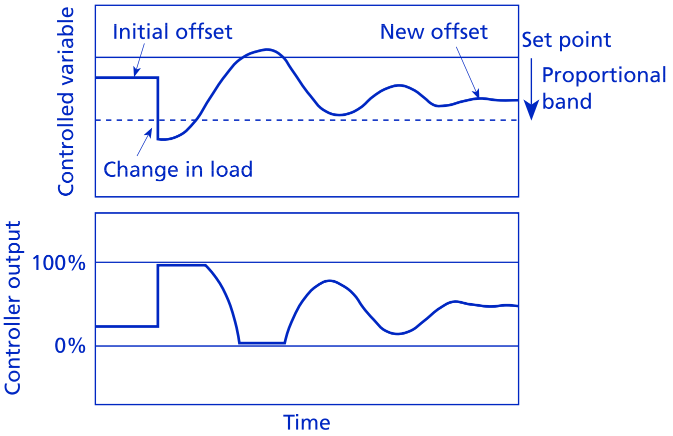

Figure 2.5 Response of a proportional controller to a sudden change in load

Figure 2.5 shows the response of a proportional control system to a change in demand. The value of the controlled variable follows a damped oscillation before settling down to the steady offset temperature. The amount of offset may be reduced by narrowing the proportional band, but at the risk of introducing instability; as the proportional band is reduced, the control action approaches on/off.

A form of proportional control known as time proportioning may be achieved even if the output device is only capable of a two-position output, e.g. high/low or on/off. The output from the controller varies the ratio of on/off times within a constant cycle period, e.g. if the cycle time is 10 minutes and the controller calls for 40% output, the output device will be switched on for 4 minutes and off for 6 minutes. The cycle time may be set independently; it should be sufficiently long to avoid any problems of wear caused by too frequent switching of the controlled device, but shorter than the response time of the overall system. The method is suitable for systems with long response times, where it will give much lower temperature swings than simple on/off control. The control behaviour is similar to a proportional system and will show a load error. Time proportioning control may be used for the control of electric resistive heaters where the switching frequency is limited by the requirement to avoid electrical disturbances on the supply(1).

2.1.3 Integral control

Integral control is not often found on its own, but is normally combined with proportional control in a PI controller. In its pure form it produces a rate of change of the output of the controller proportional to the deviation from the set point, or in other words, the output is a function of the integral over time of the deviation from the set point. When the controlled variable is at the set point, the rate of change of output is zero. The system should therefore settle to a steady-state condition, with steady output and zero offset. The control mode is similar to floating control, but with a zero width neutral zone and variable rate of change of output: compare with proportional-speed floating control. It is illustrated in Figure 2.6.

When integral control is used by itself, it must be used in systems with short time constants and fast reaction rates. It is not suitable for a system with slow responses or long time lags, where it will over-correct. A typical controlled device is a valve driven by a variable-speed actuator, which gives the required variable rate of change of control response. A constant-speed actuator may be used where the controller provides a variable duration pulsed current to give effective variable speed. The speed of closure of the valve must be slow compared to the speed of response of the controlled system. The more common combination of proportional and integral control is discussed below.

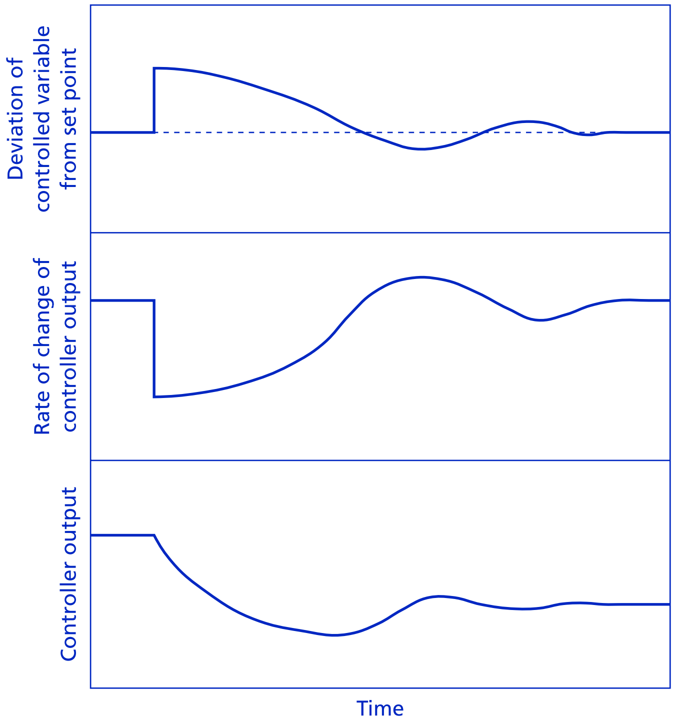

Figure 2.6 Pure integral control action. System is initially in steady state. Figure shows response to a step decrease in set point

2.1.4 PI — Proportional plus integral control

Adding integral control to a proportional controller compensates for the load error. This is probably the most widely used mode in HVAC control and when correctly set up is capable of providing stable control with zero offset. The controller integrates the deviation from set point over time and uses this value to adjust the control output to bring the controlled value back towards the set point. The proportional band may therefore be increased to give stable control; the load offset that would otherwise be introduced is eliminated over time by the integral action. The integral setting is characterised by the integral action time, which is the time it takes for the integral term of the control output equation to match the output change due to the proportional term on a step change in error. Alternatively, the integral setting may be characterised as the reset rate, which is the inverse of the integral time, and measured in resets per minute. Most PI controllers are interactive, where the integral gain is multiplied internally by the gain setting of the proportional action (see Appendix A2). The practical implication is that the proportional band may be adjusted without affecting the integral time. A non-interactive controller has independently adjustable gains for the proportional and integral actions, and so adjusting the proportional gain will alter the integral action time as defined above. A long integral time will increase the steady-state load error; in the limit of infinite integral action time the PI controller becomes a simple proportional controller. However, if the integral time is reduced to a value comparable to or less than the time constant of the controlled system, instability will result.

The output of the integral term depends on the past history of the controlled variable, and problems may result on start-up where the controller treats the preceding off period as a long-term error. This is known as wind-up. Wind-up will also occur if the controller output is 100% and the error remains positive; in this situation the integral action will continue to increase to a huge positive value. When the system becomes controllable again, a long period of negative error will be required to unwind the integral term and return to normal operation. Controllers incorporate anti-wind-up features to prevent this, either by locking the integrator at the pre-existing value whenever the controller output is at either extreme, or by limiting the integrator to some maximum value, typically 50% of full output. Similar problems can occur on starting up a system and some systems disable the integral action on start-up until the system is controlling within the proportional band.

2.1.5 PID — Proportional plus integral plus derivative

Derivative action provides a control signal proportional to the rate of change of the controlled variable. This has the effect of reducing control action if the controlled variable is rapidly approaching the set point, anticipating that the variable is about to reach the desired value and so reducing overshoot. It is therefore of value in systems with high inertia. Derivative action can cause problems in practice. If the measured variable is subject to rapidly varying random changes, the derivative action of the controller will produce an erratic output, even if the amplitude of the changes is small. See the note on derivative kick in Appendix A2. Derivative action is never used on its own, but is combined with proportional and integral action to produce PID control, also known as three-term control. A three-term controller is capable of maintaining a zero offset under steady conditions, while being able to respond to sudden load changes.

The gain setting of the derivative action is defined as the derivative action time, which is the time, usually measured in minutes, taken for the proportional term to match the derivative term when the error changes linearly with time. Derivative action is not normally required in HVAC applications and setting the derivative time of a PID controller to zero results in PI action. Three-term PID action is used mainly in process control applications.

Figure 2.7 shows the ideal characteristics of PID control on the behaviour of the controlled variable on start-up. With proportional control only, the output is a function of the deviation of the controlled variable from the set point. As the controlled variable stabilises, a residual load error results. With the addition of integral control, the controlled variable eventually returns to the set point, but there is still some overshoot before stable operation is achieved. Adding derivative control reduces the overshoot and the final set point is achieved in a shorter time.

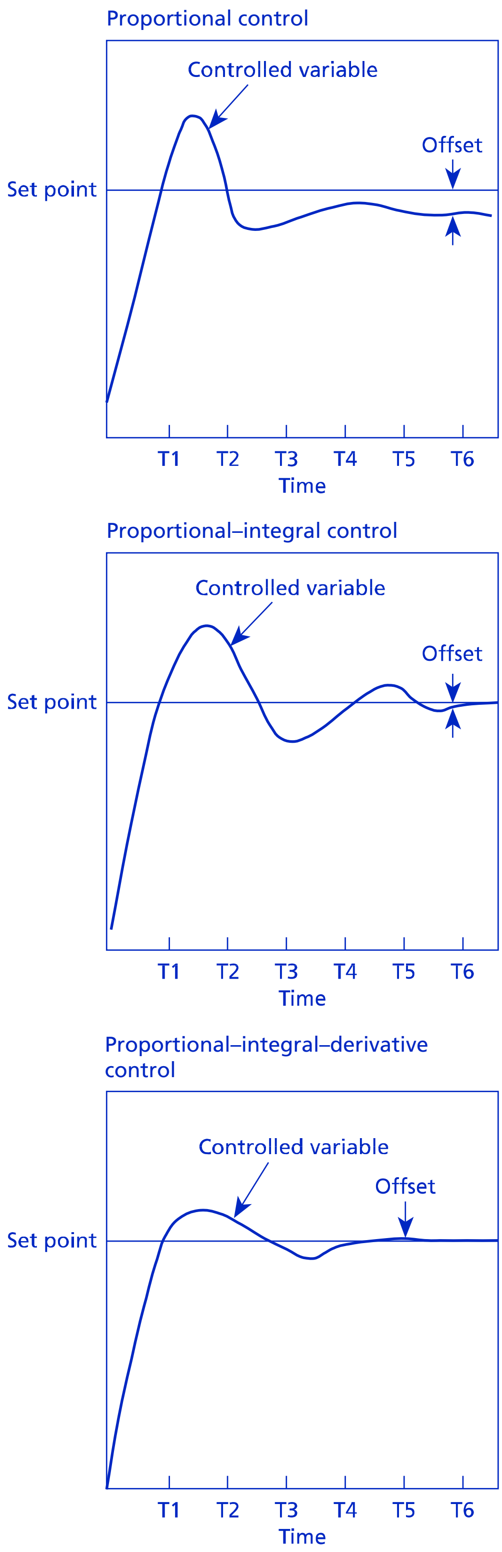

Figure 2.7 Illustration of PID control modes

2.1.6 Digital control

Microprocessor controllers operate by sampling values of the controlled variable at discrete intervals of time. The microprocessor then calculates the required controller output. For the most part, the processor mimics the analogue control modes described above. The controller is able to store past values of the controlled variable, which are needed to calculate derivative and integral terms. Programmable controllers are described in more detail in 3.8. One important difference between analogue and digital controllers is the effect of sampling rate. The frequency of sampling is limited by the speed of the processor and any multiplexing of the controller input, plus the ability of the network to transmit frequent messages. If the sampling rate is too low, instability may result if the controller is delayed in taking appropriate control action. Where there is a sufficiently fast sampling time, some controllers update the control output at intervals which are longer than the sampling interval; the interval between changes in output is known as the loop reschedule interval. Some controllers allow the loop reschedule interval to be adjusted independently from the sampling interval of the controller.

The control equations described in Appendix A2 are transformed in a digital controller into discrete time algorithms. The standard PID equation is called the position algorithm, since the position of the control element is related to the output signal. An alternative is the velocity or incremental algorithm. At each time step, the controller makes an adjustment to the position of the controlled device which is proportional to the change in the deviation of the controlled variable from the set point since the last sample, plus a term proportional to the deviation. Incremental control usually employs a slow moving actuator. At each time step, the controller calculates the required change in actuator position and sends a timed pulse to the actuator to move it the required amount. This control mode is similar to the floating control mode described in 2.1.1. It is found to work well and has the advantage of avoiding integral wind-up. The disadvantage is that the controller has no information on the actual position of the controlled device. If knowledge of the position is required, the controller can integrate the controller output and calculate the position of the controlled device. This integration calculation requires to be re-zeroed at intervals. This may be done by driving the actuator to a limit stop to provide a fix of its position. This may be done automatically each day during out-of-hours operation. The mathematical treatment of incremental control is given in Appendix A2.

2.1.7 Cascade control

For some applications it is an advantage to divide the controller into two subsystems: a submaster controller which controls an intermediate part of the controlled system, and a master controller which adjusts the set point of the submaster loop. A typical application is for temperature control of a large space, where the master controller controls the supply air temperature set point as a function of space temperature, and a submaster controller controls the supply air temperature by modulating the heating coil valve (Figure 2.8).

In its standard form, the submaster controller provides control of the supply air temperature against variations in incoming air temperature or fluctuating heating coil water temperature. The master controller resets the supply air temperature set point as a function of the space temperature using PI control. Care may be necessary to avoid instability if both loops use integral action. Some confusion in terminology may be found. An unambiguous term for this system of control is cascade control, and is used in this Guide. Cascade control is also commonly known in the UK as reset control. In the USA simple integral control may be referred to as reset, and a cascade controller is commonly referred to as master–submaster. The terms master–slave

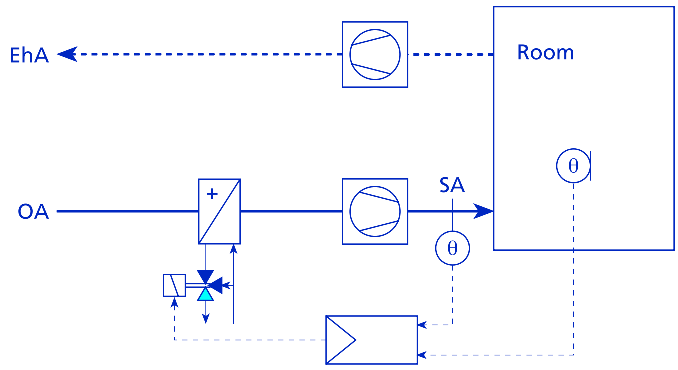

Figure 2.8 Cascade control. The room temperature is used to reset the set point of the controller controlling the supply air temperature

and primary–secondary are also used to refer to the two control loops. Cascade control is used when PI control alone is not suitable or will not provide stability, for instance where the space temperature responds slowly to variations in supply air temperature.

2.1.8 Time lags

In any feedback control loop, the response of the controlled system, as seen by a change in the sensor output, does not happen instantaneously upon a change in the controlled output. Two types of delay may be identified. A transport delay, also known as a distance–velocity lag, represents the time it takes for the heating or other medium to travel from its source to the point where its heat begins to be transferred to the controlled space. In large installations, distances can be very long and it can take some minutes for a change in water temperature at the boilerhouse to reach distant points in the building. The second type of delay, termed a transfer lag, depends on the time taken to increase the temperature of a component due to its thermal capacity. Consider the simple heating circuit of Figure 2.9. When the controller gives the signal to open the valve, hot water flows towards the heating coil, taking a time equal to the distance velocity lag to reach it. A series of first-order transfers then take place: primary water to heating coil, heating coil to calorifier water, water to cylinder material and finally cylinder metal to the sensor. The resultant response of the temperature sensor is shown. This is typical of a higher-order response, and may be approximated by a combination of dead time and first-order response as shown.

All lags contribute to poor control. Integral or floating control is unsuitable for systems with a significant dead time, since the controller will continue to change the output during the dead time, resulting in overshoot. PI control is then more suitable. The proportional control, with adequately wide proportional band, provides a stable control, and the integral action, with suitably long integral time, removes the load error.

2.1.9 Logic control

The use of microprocessor-based DDC controllers offers enormous freedom to the controls designer, since virtually any control strategy may be programmed into the controller software. In practice, digital controllers are based on the well-understood control modes described in this

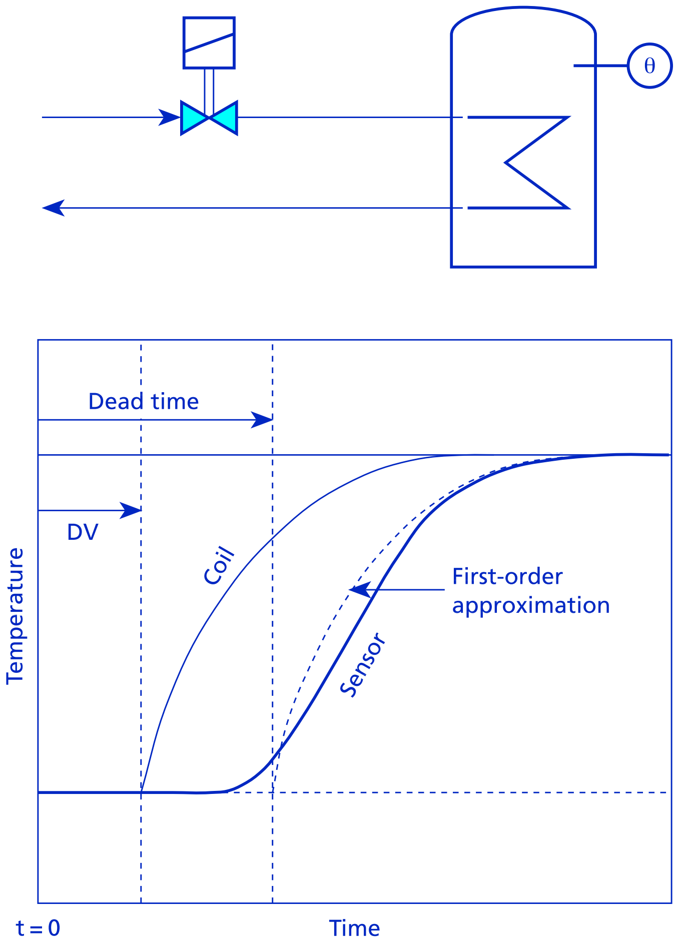

Figure 2.9 Response of system with dead time. On opening the valve at $t = 0$ there is a distance–velocity lag DV before the primary hot water reaches the heating coil. The coil then heats up with a first-order response. The sensor has a higher-order response, which may be approximated by a first-order response with dead time

section. The widely used universal controller, which incorporates pre-programmed control modules in its software is described in 3.8. The controller may be configured to meet the requirements of the actual control strategy to be implemented. Some examples of logic control are given in 5.8.2 and 5.14.3.2.

The controllers incorporate a number of logic control functions which may be used to improve control operation. Some examples are:

— *Hysteresis*. The hysteresis module only passes a change in input which is greater than a preset amount. It can be used to stop the control system responding to small fluctuations in the controlled variable, so reducing control action and wear.

— *Averaging*. The averaging module is used to produce a mean value of a number of inputs. For example, the system may be set up to control mean zone temperature, averaged over several temperature sensors. Sophisticated versions may be programmed to ignore extreme values.

— *Logic operators*. Logic modules provide the full range of Boolean AND, NOT, OR and XOR gates. They are used to provide software interlocks, e.g. preventing operation of a heating system when windows are open. Safety-critical interlocks should be hardwired.

— *Look-up tables*. Functional relationships can be provided in the form of look-up tables. Examples are the conversion of a thermistor resistance to a temperature or the software linearisation of a controlled element characteristic.

The full range of available modules is too great to list here. The range of modules is sufficient to cover most control requirements and the controller manufacturers provide examples of control strategies to assist in configuration. If required for special situations, it is possible to write control strategies using a high level programming language, such as BASIC or C.

2.1.10 Choice of control mode

When selecting the appropriate control mode, the following considerations should be taken into account:

— the degree of accuracy required and the amount of offset that is acceptable

— the type of load changes expected, including amplitude, frequency and duration

— the system characteristics, such as the number and duration of time lags and speed of response of subsystems

— the expected start-up situation.

In general, use the simplest mode that will meet the requirements. Using a complicated mode may result in difficulties in setting up and lead to poorer rather than better control. Derivative control is not normally required in HVAC systems. Its function is to avoid overshoot in a high inertia system by measuring the rate of approach to set point and reducing control action in advance. It is used in some boiler sequencers, where it will inhibit bringing an additional boiler on line if the rate of rise of water temperature shows that the operating boilers will achieve the required temperature on their own. Table 2.1 lists typical applications.

2.2 Optimum start

One of the most important functions of a building control system is time control, ensuring that plant is switched off when not needed. Substantial energy savings may be made by intermittent heating or cooling of a building compared with continuous operation. The savings achievable from

Table 2.1 Recommended control modes

Application	Recommended control mode
Space temperature	P
Mixed air temperature	PI
Coil discharge temperature	PI
Chiller discharge temperature	PI
Air flow	PI. Use wide proportional band and short integral time. PID may be required
Fan static pressure	PI. Some applications may require PID
Humidity	P, possibly PI for tight control
Dewpoint	P, possibly PI for tight control

intermittent heating compared with continuous heating depend on several factors. The savings will be greater in a lightweight building which cools and heats up quickly; any estimation of overall running costs must take into account all relevant factors. Heavyweight buildings are able to absorb peak gains and benefit from night cooling, which may outweigh any savings from intermittent heating. In general, intermittent heating and cooling will be more beneficial in the following situations:

— lightweight building (low thermal mass)
— short occupancy period
— generously sized plant.

Simple timeswitch control can be effective and is suitable for heating systems with a heat output of up to about 30 kW. Above this figure, an optimum start controller is recommended; above an output of 100 kW, optimum start control is required by the *Building Regulations*[(2)]. The time of switching on prior to occupancy is selected to ensure that the heating system has time to achieve a comfortable temperature at the start of the occupancy period. If this is correct in cold weather, the system will come on unnecessarily early in mild weather, giving higher energy consumption than necessary. Nor will a simple timeswitch be able to cope with the longer preheat period necessary after a weekend or holiday. An optimum start controller, or optimiser, is designed to calculate the latest switch on time under a range of operating conditions. Figure 2.10 illustrates the required control characteristic. During the unoccupied period, the plant normally operates to provide a minimum temperature to provide protection for the building fabric and contents. This is typically 10°C but may be lower. Separate frost protection must be provided for the heating system.

The primary function of the optimiser is to calculate the latest switch on time. Several algorithms have been proposed. The most widely used is BRESTART[(3)]. This calculates the switch-on time as a function of both internal space temperature and external air temperature. Most controllers incorporate a self-learning or adaptive feature. By following the building performance over a few weeks, the controller sets its internal parameters to match the characteristics of the actual combination of building and heating system. The optimiser also selects maximum heat output from the heating system during the warm-up period by disabling any weather compensator that may be fitted. The boost is terminated and compensation restored when the building reaches the desired temperature.

An optimum stop function may be fitted, whereby heating or cooling is switched off before the end of the occupancy period, at a switch-off time calculated to ensure that the space temperature does not drift outside predetermined comfort limits by the end of the occupancy period. With air-handling systems, the zone air temperature will approach the building fabric temperature within about 15 minutes after switch-off. This may not provide comfortable conditions and so limits the usefulness of optimum stop strategies. Optimum stop is used less often than optimum start and the potential savings are less.

2.3 Weather compensation

A building heating system is designed to provide full heating on a design day; in practice an additional margin is

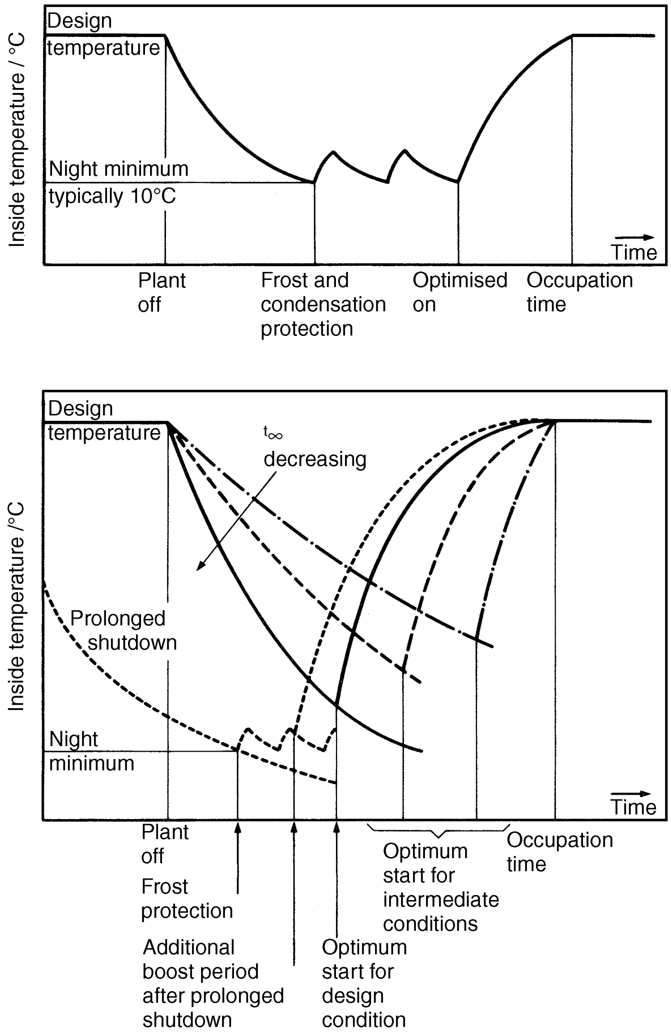

Figure 2.10 Optimum start control

allowed to provide extra power during the boost period of intermittent heating. The capacity of the heating system is therefore greater than required for operation in all but the coldest condition. For buildings heated by a conventional radiator system, operation during mild weather with the flow temperature at the full design value, typically 80°C, results in control problems, high temperature swings and consequent discomfort; it also results in wasteful heat loss from the hot water circuit. For buildings larger than domestic or the smallest commercial, it is required by the *Building Regulations* that weather compensation be provided to adjust the flow temperature in accordance with the outside temperature.

Compensation control allows the whole building to be controlled as one unit, or as a limited number of zones, thus eliminating the need to provide a large number of separate space temperature controls. It has the added advantage of limiting heat loss in the event of increased load, e.g. if windows are opened. If used as the only form of temperature control, it requires the radiator size to be carefully matched to the heat requirement of the building; since this is virtually impossible to do in advance, provision must be made for balancing the system and adjustment of the compensator control characteristic. A practical solution is to use weather compensation and trim local temperatures by the use of thermostatic radiator valves.

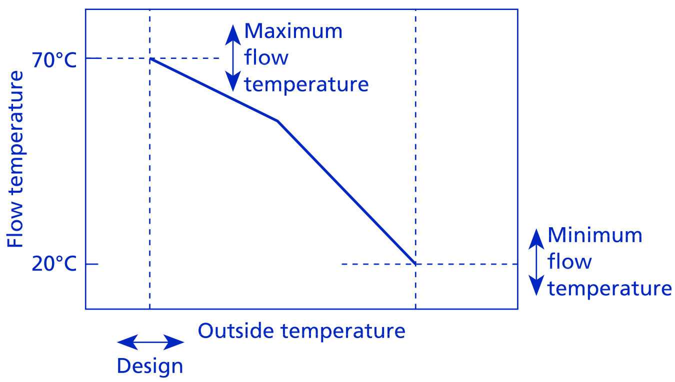

Figure 2.11 Weather compensation control characteristic with two adjustable slopes

The form of the weather compensator control characteristic is shown in Figure 2.11. The controller allows adjustment of the minimum and maximum flow temperatures and the slope of the characteristic curve. The heat output from a radiator is proportional to the 1.3 power of the difference between mean radiator temperature and room temperature and so the linear characteristic shown in the figure will tend to overheat in cold weather. Some controllers provide a two-slope or curved line to allow for this. This is discussed in detail in Levermore[4].

Figure 2.12 shows a common method used in smaller buildings of providing a compensated flow temperature. Water from the boiler is blended with cooler water from the secondary circuit return in a three-port mixing valve. The temperature sensor is downstream of the valve and responds quickly to temperature changes in the flow. For larger buildings or special circumstances, more complex control arrangements may be needed. Where different parts of the building respond differently to external climatic conditions, it will be necessary to subdivide operation into zones, and perhaps add additional external sensors, e.g. a solar detector to aid control of the southern side of the building.

The simple weather compensator described above is an example of open loop control; there is no feedback from zone temperature and the achievement of satisfactory temperature depends on the accuracy of setting up the characteristic relationship between outside temperature and flow temperature. The setting of the characteristic curve should be reviewed whenever there is a change in building use, which may affect the level of internal gains, or modification such as fitting insulation. Variations in solar gain with season or changes in shading due to foliage may also affect the settings. There are two modifications to the simple weather-compensated circuit which give improved control and are becoming more commonly used.

— *Zone trim*. The standard weather-compensated circuit is used, with a zone trim applied to the compensated water flow temperature. The trim modifies the set point by a margin proportional to the difference between the measured zone temperature and the desired set point.

— *Cascade control of zone temperature*. The outside temperature sensor is not used, but replaced by an internal zone sensor. This provides the input to a PI controller which resets the water flow temperature. This gives stable effective control of indoor temperature with no offset.

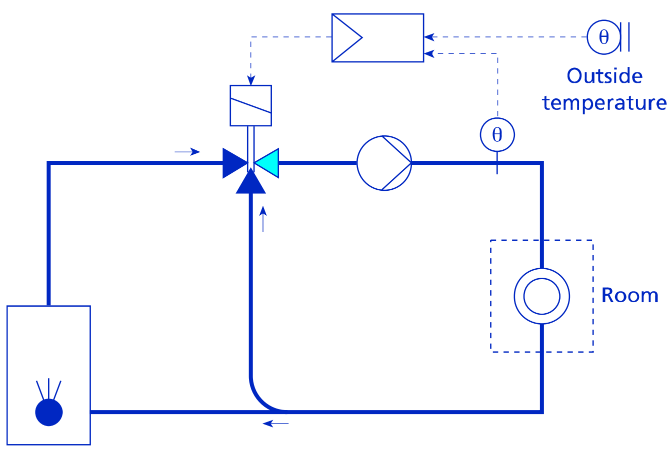

Figure 2.12 Weather compensator controlling flow temperature

2.4 Stability and tuning

The stability of a control system is concerned with its response to a disturbance. The disturbance may be a change in the external load, e.g. an increase in solar gain though the windows of a building. The HVAC system is required to react to bring the controlled variable (room temperature) back towards the desired value. For practical reasons, the stability of a system is usually considered in terms of its reaction to a sudden change in set point:

— *Stable*. After the change in set point, the controlled variable sooner or later settles down to a new steady value. On the way, there may be oscillations about the eventual steady-state value. All the systems shown in Figure 2.7 are characterised as stable; the presence of an offset from the set point (load error) is no disqualification.

— *Unstable*. The system does not achieve a steady state following a disturbance. There are two types of unstable response:

  — *Oscillatory*. The controlled variable continues to oscillate or hunt about the set point.

  — *Non-oscillatory*. The controlled variable continues to increase or decrease until it reaches a limiting value.

Non-oscillatory instability is unlikely to be produced in an HVAC system except by a design or installation error. For example, confusing the connection of room temperature sensors in different rooms will produce unstable control: an increase in heat load in Room A will reduce the heat input to Room B; the sensor in Room B will then demand more heat for Room A. Instability may be produced by the intervention of the occupants. If an occupant opens a window because the room is too warm and this results in cool outdoor air blowing over a poorly placed thermostat, heat input to the room may be increased.

On/off control inevitably produces an oscillating value of the controlled variable. If the proportional band of a proportional controller is reduced below a critical value, the control system goes into oscillation. When considering the sample content of CIBSE Guide H: Building Control Systems

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