1
Introduction

1.1
The Idea of Control

Plant and animal life relies on numerous control mechanisms. Here one thinks of an ‘open-loop’ *causal* system in which cause (input) generates effect (output). Then the ‘control’ part operates around this in order to modify the effect (Figure 1.1).

All autonomous entities need ‘feedback’ paths like this. One might shut a door to reduce the noise level, eat to reduce hunger or turn the car steering wheel to keep in a lane. The control decision can be discrete, such as when the geyser thermostat switches on or the reserve bank adjusts the prime lending rate in order to control inflation, or it can be continuous, such as the variation of one’s iris with available light. The ‘system’ part can have various behaviours which make the decision difficult. Thus, when the shower it too hot, one cautiously increases the cold water, knowing that there is a (‘dead-time’) delay in the pipe. The doctor will adjust blood pressure medication in small steps as he/she waits to observe the body response. One also recognises that there are possibly multiple ‘causes’ at play. It may only be possible to observe a limited range of the effects, and usually one is only manipulating a small selection of the causes. Humans are not adept at coordinating multiple inputs.

What is common in these cases of feedback control is that one does not know where the inputs should be set exactly. The control problem amounts to ‘given desired levels of the outputs, at what levels should the inputs be set in order to best achieve this?’. So the ‘decision’ is a task of *inversion*, in just the same way as one might want to find an x such that a function $f(x) = 0$. A simple control law for this mathematical task was provided by Newton (Equation 1.1).

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{1.1}$$

This is closely related to the ‘dead-beat’ controller (Section 7.1.1), in which one attempts to hit the target on every time step.

It is intuitive that one can expect difficulty with automatic feedback adjustments. The decision to adjust the inputs will affect the outputs which in turn will affect the next decision. If one is over-reacting on each step, the output would be driven past its desired level by successively larger amounts. So adjusting the shower water in too big steps would successively cause scalding and freezing by greater amounts. The possibility of such endless growth makes considerations of *closed-loop stability* important in the study of process control.

Applied Process Control: Essential Methods, First Edition. Michael Mulholland.

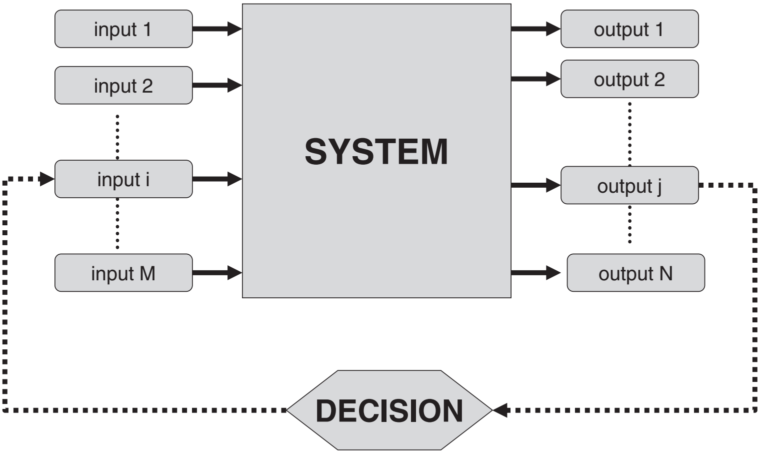

Figure 1.1 Feedback control mechanism.

A situation often arises where one tries to diminish the impact of disturbed inputs to a system by manipulating other inputs (Figure 1.2). This is 'feedforward' control. It is important to note that the outputs are not involved in this decision at all. Of course, one needs to be able to observe the relevant inputs first. Thus, the fuel to a boiler may be increasing in order to maintain pressure. Though the flue gas oxygen content may be unmeasured, a feedforward controller can increase the combustion air flow in proportion to the fuel flow in order to maintain a margin of oxygen excess. One realises that feedforward control will always require some kind of model, for example the air/fuel stoichiometric ratio. Models are never perfect, so it is likely that the relevant output may not be quite where it was planned. Often this error can be tolerated. In other cases, a feedback loop may be superimposed to provide the correction (Figure 1.3). There is nevertheless a benefit in using feedforward to eliminate most of the upset.

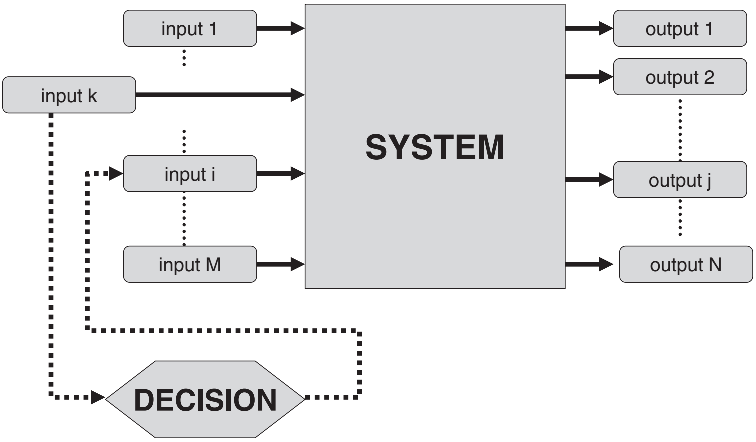

Figure 1.2 Feedforward control mechanism.

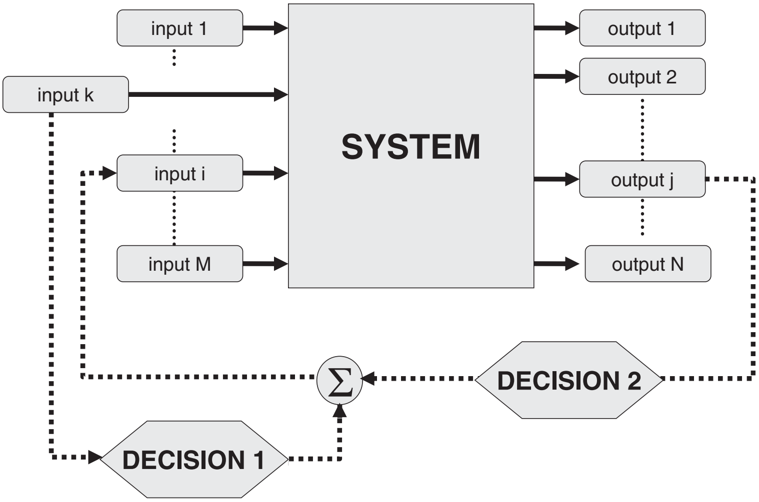

Figure 1.3 Combined feedforward and feedback.

The control engineer must learn to recognise 'information flows' in a system, that is from 'cause' to 'effect'. Sometimes these are not intuitive and have little to do with the physical arrangement. For example, the flow into a tank and the flow out of a tank could equally be used to affect the level in a tank.

1.2
Importance of Control in Chemical Processing

This book will focus on modelling, estimation, control and optimisation in the processing industries. There are unique challenges here to do with the inaccuracy of models and undefined disturbances. In addition, the widespread use of computers to handle process instrumentation in recent decades has spurred the concept of 'advanced process control' (APC), which has become a specialised process engineering domain. The objective is to take advantage of the plant-wide view of outputs, and access to inputs, of these computers, in order to enhance regulation and optimisation. In this way, industries have been able to work safely with narrower specifications and less loss (Figure 1.4). With the increasing globalisation of markets, industries which do not seek such efficiency improvements will soon find themselves uncompetitive and out of business.

In the processing industries, the automatic control aspects are viewed to constitute a pyramid of three main layers in which each layer achieves its objectives by supervising the layer below. Generally, this means that the control loop setpoints (SPs) are passed downwards (Figure 1.5).

Usually the base layer becomes the responsibility of instrumentation technicians, but more advanced inputs are required from control engineers in the upper layers. Of course, the overall control scheme, including the base layer, must be specified by engineers in the design phase. At that stage, additional specifications may be made, such as increased vessel hold-ups to facilitate 'advanced level control' (Section 4.11). Indeed, there is a growing trend to integrate the equipment design and control design at an early stage (Sakizlis, Perkins and Pistikopoulos, 2004). Increasing

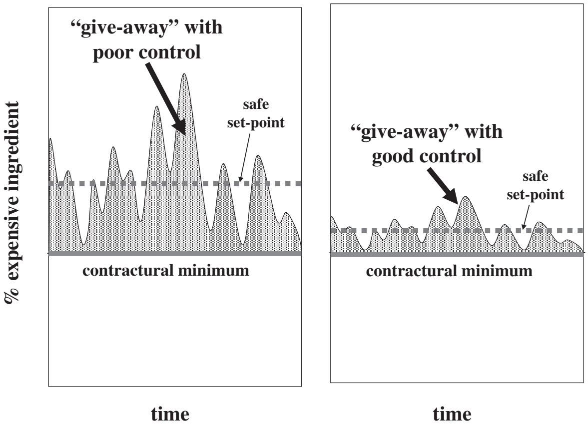

Figure 1.4 Reduction of an expensive ingredient through better control.

integration of processes through 'pinch' analysis often renders the internal regulation highly interactive, requiring special control approaches. Another lesson that has been learned is that the advanced control algorithms cannot simply be installed and left to operate without ongoing knowledgeable oversight.

The advanced algorithms focus on criteria such as throughput, product specifications and economics, not necessarily smooth process operation, and thus they can be unpopular with operating personnel. All too often such unwelcome behaviour can cause operators to switch off these algorithms. Thus, education is important, as well as investigation of downtime incidences and constant reviewing of performance. On one level, one aims to make a control scheme as simple and transparent as possible, to facilitate understanding. However, some algorithms are unavoidably complex,

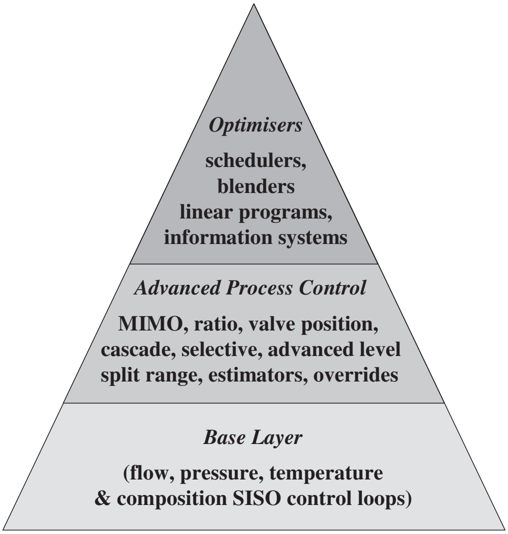

Figure 1.5 Main conceptual layers in a processing plant control scheme.

referring to a number of measurements as the basis of their output decisions. A specially trained control engineer is required to diagnose poor performance that might arise from a poorly calibrated measurement. Industries which recognise the need for ongoing care, and provide the necessary resources, have successfully increased the fractional online time of their optimisers and advanced controllers (Karodia, Naidoo and Appanah, 1999).

1.3
Organisation of This Book

With the increasing use of computers and digital communications in the processing industries, the employers' requirements of a process engineer are rapidly evolving. An engineer working day to day on troubleshooting and debottlenecking on a plant must already have a high proficiency in the use of computers for data extraction and analysis. He/she must comprehend a complex plant control scheme in order to identify the relationships between variables arising from such a scheme. Where a process engineer is specifically employed in the area of 'advanced process control', there will be even more of an expectation that good computer skills will be brought to bear on processing issues. The general brief given to such an engineer by the employer is likely to be: 'Do whatever you can with this computer know-how to safely maximise the profitability of this process!'. Well, that is a very open-ended request, extending far beyond the traditional 'process control' skills of drawing Nyquist plots to assure closed-loop stability.

At the outset, the strength of the process engineer in this environment is his/her understanding of the physics and chemistry at play, leading on to his/her ability to mathematically model the process. The model can be used effectively as the mathematical basis of the control scheme design, or simply to test proposed strategies developed in other ways. Regardless, it is the model that gives this engineer a clear insight into the process behaviour, and it provides an interpolative bridge between what is usually too few plant measurements.

Beyond the model, and now thinking of an alternative 'black box' approach, what will be important is to get an appreciation of a range of *ad hoc* methods of identification, control and optimisation which have proved useful industrially. Some of these defy mathematical treatment, and will not easily lead on to proofs of stability, which has been a major preoccupation of the field. Rather, the main purpose of mathematical treatments will be to promote understanding, and to allow one to move on quickly to useful algorithms for online implementation.

In order to establish the context of the considered algorithms, a view will initially be developed of the instrumentation and computer hardware required for their implementation. In connection with this, it will be important to understand conventions for representation of instrumentation and control on plant piping and instrumentation diagrams.

The present-day field of process control is built conceptually on remnants and artefacts of the past. For example, a computer representation of a loop controller has the equivalent switches and adjustments of the preceding panel-mounted analogue device. An engineer might claim that a control loop that oscillates a lot and won't settle down 'has a poorly damped closed-loop pole location'. One would be extremely hard put to find an application of such frequency response methods in the processing industries, yet this is the language that is naturally used. Why is this so? Well, the reason is that one's mind picture of the phenomena is built mostly on classical control theory. Though most of what is presently done in industry is based on the time domain, one ignores classical theory such as 'frequency response' at one's peril, because it is part of the language, and in many instances it is the route forward to deeper analysis and research. In some cases, for example the use of Laplace domain transfer functions, classical approaches give a much clearer view of relationships. The classical methods will thus also be used in parallel where appropriate.

Working on from simple controllers, more advanced algorithms for estimation and control will be considered, finally viewing the application of optimisation algorithms. Along the way, skills will be developed in the overall instrumentation and control of a process, effectively what is necessary to specify the key plant document, namely the piping and instrumentation diagram. Methods of quantifying and describing control performance and stability will be presented, largely connecting to the classical theory.

1.4
Semantics

Some concepts and related vocabulary in process control need to be clarified initially to avoid confusion:

System: all or part of a process which can be viewed in isolation (provides output values in response to input values).

Dynamic: the mathematical description involves a derivative with respect to time, or a time delay.

Static or *algebraic*: input values immediately determine output values.

Lumped: no spatial derivatives are involved in the mathematical description.

Distributed: variations also occur in space (e.g. position within a reactor bed), requiring spatial derivatives in the mathematical description.

Order: number of time derivatives of different variables involved in the mathematical description (each higher derivative also contributes 1 to the count).

States: a selection of variables describing a system such that if their initial values are known, and all future inputs are known, all future values of the states can be predicted. Effectively these are the variables in the set of first-order derivatives describing the system, so the *order* is equal to the number of *states*.

Open loop: information generated in the output does not influence the input.

Closed loop: information generated in the output is used to influence the input.

Stable: a system is stable if its outputs are bounded (non-infinite) for all bounded inputs.

Unstable: at least one bounded input excitation can cause an unbounded output – usually manifested as exponentially increasing oscillation or magnitude. Usually this type of behaviour is restricted to a *limit cycle* or final magnitude because of the physical limits of the equipment – unless failure occurs before this point.

Step response: output variation resulting from a step in one of the inputs.

Frequency response: output characteristics when the input is a steady oscillation (varies with frequency).

Tuning: choice of free parameters for controllers, estimators or optimisers, to obtain desired performance.

Controlled variable (CV): one of the outputs for which tracking of a *setpoint* is required.

Manipulated variable (MV): one of the inputs which is available to be varied by a controller.

Disturbance variable (DV): one of the inputs which is not available for manipulation.

Dead time: this is a time delay (usually caused by a plug flow transport lag).

Inverse response: the initial direction of the response (up/down) differs from the final position.

References

Karodia, M.E., Naidoo, S.G. and Appanah, R. (1999) Closed-loop optimization increases refinery margins in South Africa. *World Refining*, **9** (5), 62–64.

Sakizlis, V., Perkins, J.D. and Pistikopoulos, N. (2004) Recent advances in optimization-based simultaneous process and control design. *Computers & Chemical Engineering*, **28** (10), 2069–2086.