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Introduction

1.1 Introduction

The idea of feedback is deceptively simple and, yet, extremely powerful. Feedback can reduce the effects of disturbances, it can make a system insensitive to process variations and it can make a system follow commands faithfully. Feedback has also had a profound influence on technology. Application of the feedback principle has resulted in major breakthroughs in control, communication, and instrumentation. Many patents have been granted on the idea.

The PID controller is a simple implementation of feedback. It has the ability to eliminate steady-state offsets through integral action, and it can anticipate the future through derivative action. PID controllers, or even PI controllers, are sufficient for many control problems, particularly when process dynamics are benign and the performance requirements are modest. PID controllers are found in large numbers in all industries. The controllers come in many different forms. There are stand-alone systems in boxes for one or a few loops. The PID controller is a key part of systems for motor control. The PID controller is an important ingredient of distributed systems for process control. The controllers are also embedded in many special-purpose control systems. They are found in systems as diverse as CD and DVD players, cruise control for cars, and atomic force microscopes. In process control, more than 95 percent of the control loops are of PID type; most loops are actually PI control. Many useful features of PID control have not been widely disseminated because they have been considered trade secrets. Typical examples are techniques for mode switches and anti-windup.

PID control is often combined with logic, sequential functions, selectors, and simple function blocks to build the complicated automation systems used for energy production, transportation, and manufacturing. Many sophisticated control strategies, such as model predictive control, are also organized hierarchically. PID control is used at the lowest level; the multivariable controller gives the set points to the controllers at the lower level. The PID controller can thus be said to be the “bread and butter” of control engineering. It is an important component in every control engineer’s toolbox.

PID controllers have survived many changes in technology, ranging from

pneumatics to microprocessors via electronic tubes, transistors, and integrated circuits. The microprocessor has had a dramatic influence on the PID controller. Practically all PID controllers made today are based on microprocessors. This has created opportunities to provide additional features like automatic tuning, gain scheduling, continuous adaptation, and diagnostics. Most new PID controllers that are produced today have some capability for automatic tuning. Tuning and adaptation can be done in many different ways. The simple controller has in fact become a test bench for many new ideas in control. There has also been a renaissance of analog implementation in micro-mechanical systems because analog implementation requires less silicon surface than digital implementations. The PID controller is also implemented using field programmable gate arrays for applications where very fast control is required.

A large number of instrument and process engineers are familiar with PID control. There is a well-established practice of installing, tuning, and using the controllers. In spite of this there are substantial potentials for improving PID control. Evidence for this can be found in the control rooms of any industry. Many controllers are put in manual mode, and among those controllers that are in automatic mode, derivative action is frequently switched off for the simple reason that it is difficult to tune properly. The key reasons for poor performance are equipment problems in valves and sensors, process constraints and bad tuning practice. The valve problems include wrong sizing, hysteresis, and stiction. The measurement problems include poor or no anti-aliasing filters; excessive filtering in “smart” sensors, excessive noise, and improper calibration. Substantial improvements can be made. The incentive for improvement is emphasized by demands for improved quality, which is manifested by standards such as ISO 9000. Knowledge and understanding are the key elements for improving performance of the control loop. Specific process knowledge is required as well as knowledge about PID control.

Based on our experience, we believe that a new era of PID control is emerging. This book will take stock of the development, assess its potential, and try to speed up the development by sharing our experiences in this exciting and useful field of automatic control. The goal of the book is to provide the technical background for understanding PID control.

1.2 Feedback

A simple feedback system is illustrated by the block diagram in Figure 1.1. The system has two major components, the process and the controller, represented as boxes with arrows denoting the causal relation between inputs and outputs. The process has one input, the manipulated variable (MV), also called the control variable. It is denoted by u . The control variable influences the process via an actuator, which typically is a valve or a motor. The process output is called process variable (PV) and is denoted by y . This variable is measured by a sensor. In Figure 1.1 the actuator and the sensor are considered part of the block labeled “Process”. The desired value of the process variable is called the set point (SP) or the reference value. It is denoted by y_{sp} . The control error e is the difference between the set point and the process variable, i.e., $e = y_{sp} - y$.

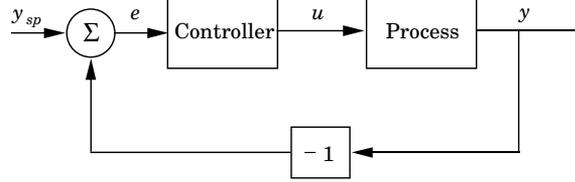


Figure 1.1 Block diagram of a process with a feedback controller.

Assume for simplicity that the process is such that the process variable increases when the manipulated variable is increased. The principle of feedback can then be expressed as follows:

Increase the manipulated variable when the error is positive, and decrease it when the error is negative.

This type of feedback is called *negative feedback* because the manipulated variable moves in opposite direction to the process variable since $e = y_{sp} - y$.

The PID controller is by far the most common form of feedback. This type of controller has been developed over a long period of time, and it has survived many changes in technology, from mechanical and pneumatic to electronic and computer based. Some insight into this is useful in order to understand its basic properties as is discussed in Section 1.4.

Some properties of feedback can be understood intuitively from Figure 1.1. If the feedback works well the error will be small, and ideally it will be zero. When the error is small the process variable is also close to the set point irrespective of the properties of the process. To realize feedback it is necessary to have appropriate sensors and actuators and a mechanism that performs the control actions.

Feedback has some interesting and useful properties.

- Feedback can reduce effects of disturbances
- Feedback can make a system insensitive to process variations
- Feedback can create well-defined relations between variables in a system

1.3 Simple Forms of Feedback

Many of the nice properties of feedback can be accomplished with simple controllers. In this section we will discuss some simple forms of feedback, namely, on-off control, proportional control, integral control, and PID control.

On-Off Control

The feedback can be arranged in many different ways. A simple feedback mechanism can be described as

$$u = \begin{cases} u_{\max}, & \text{if } e > 0 \\ u_{\min}, & \text{if } e < 0, \end{cases} \quad (1.1)$$

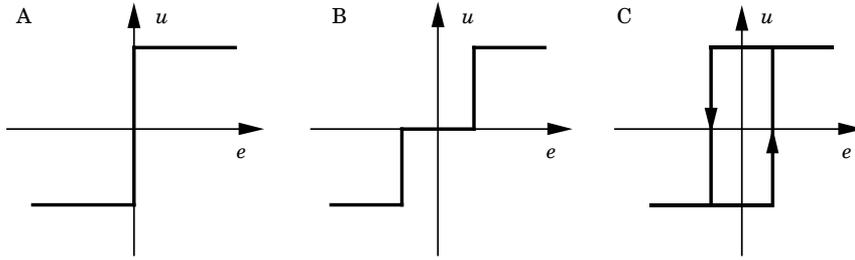


Figure 1.2 Controller characteristics for ideal on-off control (A), and modifications with dead zone (B) and hysteresis (C).

where $e = y_{sp} - y$ is the control error. This control law implies that maximum corrective action is always used. This type of feedback is called *on-off control*. It is simple and there are no parameters to choose. On-off control often succeeds in keeping the process variable close to the set point, but it will typically result in a system where the variables oscillate. Notice that in Equation 1.1 the control variable is not defined when the error is zero. It is common to have some modifications either by introducing hysteresis or a dead zone (see Figure 1.2).

Proportional Control

The reason why on-off control often gives rise to oscillations is that the system overreacts since a small change in the error will make the manipulated variable change over the full range. This effect is avoided in proportional control where the characteristic of the controller is proportional to the control error for small errors. This can be achieved by making the control signal proportional to the error

$$u = K(y_{sp} - y) = Ke, \quad (1.2)$$

where K is the controller gain.

Integral Control

Proportional control has the drawback that the process variable often deviates from the set point. This can be avoided by making the control action proportional to the integral of the error

$$u(t) = k_i \int_0^t e(\tau) d\tau, \quad (1.3)$$

where k_i is the integral gain. This strategy is called integral control. Integral control has an amazing property. Assume that there is a steady state with constant error e_0 and constant control signal u_0 . It follows from the above equation that

$$u_0 = k_i e_0 t.$$

Since u_0 is a constant it follows that e_0 must be zero. We thus find that if there is a steady state and a controller has integral action the steady-state error is

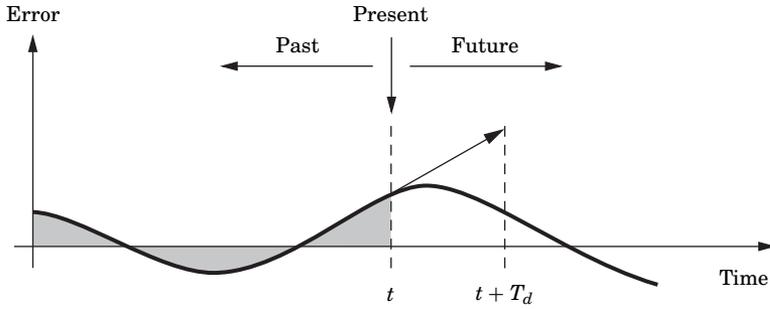


Figure 1.3 A PID controller takes control action based on past, present, and future control errors.

always zero. It follows that this is also true for the PI controller

$$u(t) = Ke(t) + k_i \int_0^t e(\tau) d\tau. \quad (1.4)$$

This is one of the reasons why PI controllers are so common.

PID Control

An additional refinement is to provide the controller with an anticipative ability by using a prediction of the output based on linear extrapolation. See Figure 1.3. This can be expressed mathematically as

$$u(t) = K \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right). \quad (1.5)$$

The control action is thus a sum of three terms representing the past by the integral of the error (the I-term), the present (the P-term) and the future by a linear extrapolation of the error (the D-term). The term $e + T_d \frac{de}{dt}$ is a linear prediction of the error T_d time units in the future. The parameters of the controller are called: proportional gain K , integral time T_i , and derivative time T_d .

It has been found empirically that the PID controller is capable of solving a wide range of control problems. There are more complicated controllers that differ from the PID controller by using more sophisticated methods for prediction.

1.4 How the PID Controller Developed

The PID controller has developed over a period of time that stretches over at least 250 years. It is useful to have some perspective of this development in order to understand many of the issues. The technology used to implement

the controllers has naturally changed significantly over the years. The first controllers were mechanical devices (centrifugal governors) used to control windmills and steam engines. Sensing of angular velocity was combined with actuation of valves. A great deal of cleverness was involved in devising integral action.

A significant change occurred in connection with the development of industrial process control. The functions of sensing, control, and actuation were then separated and special devices that performed the control actions represented by Equation 1.5 were built. An interesting feature was that signal transmission and computing were done pneumatically. A major advance occurred when the tubes used to transmit the pressure and the pressure levels were standardized to 3–15 PSI. This made it possible to combine sensors, controllers, and actuators from different suppliers. It also made it possible to concentrate controllers in separate control rooms that were located far away from sensors and actuators. Much cleverness was again used to obtain the controllers. The use of feedback in the controllers themselves was a major improvement. In this way it was possible to obtain linear action out of components that had strongly nonlinear characteristics.

Starting in 1950s, electronic versions of the PID controller became available. The control actions represented by Equation 1.5 were then obtained by a simple analog computer based on operational amplifiers. The signal transmission was also standardized as current signals in the range 4–20 mA. To represent zero by a nonzero current was useful for diagnostics.

Yet another advance occurred when digital computers were used to implement controllers. Strongly centralized systems were first used when computer control emerged, because digital computing was only cost effective in large systems. With the advent of microprocessors in the 1970s even simple controllers were implemented using computers. When a digital computer is used it is also possible to add many functions such as automatic tuning, adaptation, and diagnostics. This is an area of very active development.

Today we are experiencing other shifts in technology. Analog implementations are reappearing in micro-mechanical electrical systems (MEMS), and digital controllers are also implemented using field programmable gate arrays (FPGA), which admit very short sampling periods. The FPGAs differ significantly from digital computers because they are highly parallel.

Today we find PID controllers in many forms. There are dedicated controllers that can control one or a few loops. PID functions are found in Programmable Logic Controllers that were originally designed to replace relays. There are systems that contain many PID controllers implemented in computers ranging from small systems for a few dozen loops to large distributed systems for process control. PID controllers are commonly used in dedicated systems for motion control. There are also a whole range of special controllers such as autopilots and control systems for CD and DVD players and optical memories that are based on PID control.

1.5 Technology Changes and Knowledge Transfer

The PID controller is an interesting case study for management of technology, because it has a long history and it has experienced many technology changes. Since we have had personal experiences of several technology shifts, we will present some personal reflections where we discuss creation and destruction of knowledge and the role of key people and documentation.

Technology transfers are often abrupt and unplanned. The reason why a company decides to change technology may be drastic drops in hardware costs or pressure from competitors and customers. A switch in technology often means that R&D staff has to be replaced by new people that are familiar with the new technology, but often not with the old one. This means that there is a high risk that information is lost during the transition. Since the technology transfers often have to be done fast, there is also a high risk that the potential of the new technology is not utilized.

Early temperature controllers were of the on-off type. The on-off controllers are simple and cheap, but there are unavoidable oscillations. The amplitude of the oscillations can be kept at reasonable levels, since the dynamics of many thermal systems is lag dominated. When electronics became cost effective, there was a transition from on-off to continuous PID control. The development of the analog PID controller is well documented in publically available material from Eurotherm, which was started by faculty from the University of Manchester. The controllers were developed based on solid knowledge of modeling and control. Theory helps, because many applications of temperature admit high gains and derivative action can be very beneficial. Tuning rules were also provided and protection for windup was developed under the name of *integrator desaturation* and *crossed time-constants*. The result of the development was a drastic improvement of the performance of temperature controllers. It is interesting to observe that it took a long time before the interesting and important phenomena of integrator windup received any attention in academia.

When computer based process control emerged in the early 1960s, the focus was initially on higher-level control functions. Analog PID controllers were used at the base level and the computer supplied set point to the controllers. As the systems developed, the attention focused again on PID control where many PID loops were implemented in one computer, so called Direct Digital Control. The technical development focused on discretization of the PID algorithm, one reason being that computing resources was a bottleneck. Little attention was given to integrator windup, and some attention was given to filtering of sensor signals.

The emergence of the microprocessor made digital computing cheaply available in small quanta, a development which had a major impact on the PID controller. It resulted in small single loop controllers, controllers for a few loops, and large distributed systems. The development was slow for two reasons. Many new persons without previous experience of analog control entered the arena, and many old-timers were unwilling to learn the new technology. Important aspects such as integrator windup and filtering were not documented in a way that was easily accessible. Therefore, it took some time before the appropriate knowledge and experience was recaptured. There was also a tendency to

simply implement old ideas in new technology without considering the opportunities offered by the new technology. Gradually the potentials of the digital computer were exploited by incorporating features like, auto-tuning, adaptation, and diagnostics into the systems.

When distributed control system (DCS) systems replaced the analog systems, the distributed architecture was retained. Analog controllers and function modules were represented as blocks in the DCS programs. This was probably a good idea, but the opportunities given by the fact that all signals were available in one computer was not utilized. It took over a decade before DCS systems that handle anti-windup above the loop level were presented.

A couple of conclusions that can be drawn are that documentation, and open-minded persons who can bridge the gap between different technologies, are important. When new technologies are available it is also useful to stop and think to find out how the new technology can be exploited rather than to quickly implement old ideas in the new technology. It is also important to filter out the essence of the old systems so that good features are not lost. Finally, it is important to document ideas, write books, and ensure that information is not only transferred from human to human, but widespread.

1.6 Outline of the Contents of the Book

The reader is advised to look at the table of contents to see the overall structure of the book. Process dynamics is a key for understanding any control problem. Chapter 2 presents concepts that are useful for describing the behavior of processes. Static models are mentioned briefly, but the main focus of the chapter is on process dynamics. Representations in terms of time- and frequency responses are given. These dual views are very useful to gain a good understanding of dynamics. The notions of step responses and transfer functions are used throughout the book. A number of typical models that are used for PID control are discussed in detail. Models for disturbances are also treated as well as techniques for experimental determination of the models.

An in-depth presentation of the PID controller is given in Chapter 3. This includes principles as well as many implementation details, such filtering to provide high-frequency roll-off, anti-windup, improvement of set-point response, etc. The PID controller can be structured in different ways. Commonly used forms are the series and the parallel forms. The differences between these and the controller parameters used in the different structures are treated in detail. The limitations of PID control are also described. Typical cases where more complex controllers are worthwhile are systems that have long dead time and oscillatory systems. Extensions of PID control to deal with such systems are discussed briefly.

Chapter 4 treats controller design in general. There is a rich variety of control problems with very diverse goals. The chapter gives an overview of ideas and concepts that are relevant for PID control. It is attempted to bring design of PID controllers into the mainstream of control design. Topics such as fundamental limitations, stability, robustness, and specifications are treated.

Feedforward control, a simple and powerful technique that complements

feedback, is treated in Chapter 5. A systematic design of feedforward control to improve set-point responses is given as well as a discussion of design of model-following systems. The special case of set-point weighting is discussed in detail, and methods for determining the set-point weights are provided. The chapter also shows how feedforward can be used to reduce the effect of disturbances that can be measured.

Chapter 6 describes methods for the design of PID controllers. Many different methods for tuning PID controllers that have been developed over the years are presented. Their properties are discussed thoroughly. It has been attempted to strike a balance by providing both an historical perspective and to present powerful methods.

A reasonable design method should consider load disturbances, model uncertainty, measurement noise, and set-point response. A drawback of many of the traditional tuning rules for PID control is that such rules do not consider all these aspects in a balanced way. New tuning techniques that do consider all these criteria are presented in Chapter 7.

Chapter 8 treats model predictive controllers. The Smith predictor, which is a special case, is first presented and analysed, and modifications to treat integrating processes are provided. Then other types of model predictive controllers are presented, such as the MPC controller, the Dahlin-Higham controller, dynamic matrix control, and minimum variance control.

In Chapter 9 we discuss some techniques for adaptation and automatic tuning of PID controllers. This includes methods based on parametric models and non-parametric techniques. Supervision of adaptive controllers and iterative feedback tuning are also discussed. A number of commercial controllers are described to illustrate the different techniques.

Chapter 10 treats methods for commissioning, supervision and diagnosis of control loops. Loop assessment procedures are used to investigate properties of the control loop, e.g. signal levels, noise levels, nonlinearities, and equipment conditions. Performance assessment procedures are used to supervise the control loops during operation, and ensure that they meet the specifications.

The PID controller is typically used as a single-loop controller. In practice, there are often interactions between the loops. Some key issues about interacting loops that are of particular relevance for PID control are discussed in Chapter 11. In particular it is shown that controller parameters in one loop may have significant input on dynamics of other loops. Bristol's relative gain array, which is a simple way to characterize the interactions, is also introduced. The problem of pairing inputs and outputs is discussed, and a design method based on decoupling, which is a natural extension of the tuning methods for single input single output systems, is presented.

In Chapter 12 it is shown how complex control problems can be solved by combining simple controllers in different ways. The control paradigms of repetitive control, cascade control, mid-range and split-range control, ratio control, and control with selectors are discussed. Use of currently popular techniques such as neural networks and fuzzy control are also covered briefly.

Chapter 13 presents implementation issues related to PID control. A short overview of the early analog pneumatic and electronic implementations are first given. A detailed presentation of computer implementation aspects such

as sampling, pre-filtering, and discretization of the PID algorithm is then given. Operational aspects such as bumpless transfers are presented, and the chapter ends with a discussion about the different controller outputs that have to be used depending on which actuating device is used.

1.7 Summary

In this section we have given a brief description of the concept of feedback. The application of feedback has had very useful and sometimes revolutionary impact. Some of the useful properties of feedback, its ability to reduce disturbances, insensitivity to process variations, linearity between set point and process variable, have been discussed. We have also briefly described some simple forms of feedback such as on-off control and PID. The development of PID controllers has been discussed briefly, and the contents of the book have finally been outlined.

1.8 Notes and References

PID controllers were used extensively in the early development of control from the 1870s through 1920. The modern form of the PID controller emerged in the development of process control in the 1930s and 1940s, as discussed in [Bennett, 1979] and [Bennett, 1993]. The PID controller is still the standard tool for solving industrial control problems. In a detailed study of the state of the art in industrial process control by the Electric Measuring Instrument Manufacturer in Japan from 1989 it is found that more than 90 percent of the control loops were of the PID type; see [Yamamoto and Hashimoto, 1991]. The paper [Desborough and Miller, 2002] surveyed the U.S. industry. It is found that there are more than 8 million facilities in the petrochemical, pulp and paper, power, and metals industries. Each facility has between 500 and 5000 regulatory control loops, 97 percent of them are of the PID type. The PID controllers are manufactured in large quantities in other industries too. Optical memories for CD and DVD contain three PID loops for control of rotation speed, focus, and track following. About 140 million units were manufactured in 2002; see [Akkermans and Stan, 2002]. In addition, there is a large number of PID controllers for motor drives and positioning systems. It is therefore safe to say that the PID controller is one of the most common tools for control.

PID control is discussed in most textbooks on process control such as [Luyben, 1990; Shinskey, 1994; Marlin, 2000; Bequette, 2003; Seborg *et al.*, 2004], and there are also books that focus on PID control [McMillan, 1983; Corripio, 1990; Suda *et al.*, 1992; Wang and Cluett, 2000; Quevedo and Escobet, 2000; Wang *et al.*, 2000; O'Dwyer, 2003; Michael and Moradi, 2005].

The theory of PID controllers was for a long time based on special techniques. Lately there have been efforts to bring PID control into the mainstream of control theory. A notable effort was made in the year 2000 when the International Federation of Automatic Control (IFAC) arranged a workshop on

the past, present, and future of PID control; see [Quevedo and Escobet, 2000]. A collection of papers from this workshop was also published as a special issue of *Control Engineering Practice*. The papers [Bennett, 2000] and [Åström and Hägglund, 2001] give a perspective on the development of PID control.

Because of the large number of PID controllers and their widespread use there are still significant benefits in improving the practice of PID control. Such an improvement requires attention to the complete control loop and not just the controller itself as is demonstrated in the paper [Bialkowski, 1994] which describes audits of paper mills in Canada. A typical mill has more than 2000 control loops, 97 percent of the loops are based on PI control. It was found that only 20 percent of the control loops worked well and decreased process variability. The reasons why performance is poor are bad tuning (30 percent) and valve problems (30 percent). The remaining 20 percent of the controllers functioned poorly for a variety of reasons such as: sensor problems, bad choice of sampling rates, and poor or non-existing anti-aliasing filters. Similar observations are given in [Ender, 1993], where it is claimed that 30 percent of installed process controllers operate in manual mode, that 20 percent of the loops use default parameters set by the controller manufacturer (so-called “factory tuning”), and that 30 percent of the loops function poorly because of equipment problems in valves and sensors.