FUNDAMENTALS OF CONTROL THEORY

Andreas Bunzemeier
ABB Utility Automation GmbH, Minden, Germany

Lothar Litz
Institute for Process Automation, University of Kaiserslautern, Germany

Keywords : Adaptive control, Actuator element, Artificial Neural Network, Binary control, Boolean function, Control error, Linearity, Petri net

Contents

Summary

The theory of open and closed loop control is an essential constituent of the field of process instrumentation, control and automation and is the subject of Chapter Introduction to Process Control. It may be seen as a fundamental basis for a

deeper insight into the proceedings taking place within technical processes and - resulting from this – a sounded design of modern control concepts. Against this background in the course of the previous section an overview has been given about the fundamentals of control theory.

After a consideration of different kinds of control being relevant in practice, basic requirements are formulated usually to be met by a control concept. In that context, commonly used terms are introduced to describe the control characteristic as well as the control quality. An important prerequisite for a theoretical treatment of process control problems is the knowledge of a mathematical formulation of the respective process characteristic. This aspect of process modeling is subject matter of the following section where it was shown that the needed information may be achieved either as the result of a theoretical process analysis or alternatively in an experimental way.

Following that, an overview has been given about the relevant controller concepts being state of the art beginning with the so-called standard controllers of the proportional-integrative-derivative (PID) type up to higher sophisticated concepts used in special kinds of application. Finally, a consideration of the fundamental problem of stability led over to the wide area of controller design. For the class of continuous control, parameter optimization methods as well as easy-to-handle setting rules have been discussed in more detail. Regarding the class of binary control concepts it was necessary to distinguish between "logical control" and "sequential control". For both of them appropriate design concepts were outlined, too.

1. Introduction - Kinds of Control

The notion of control covers a variety of special aspects such as open loop control, feedback (or closed loop) control, continuous control, discrete control, sequential control, binary control, supervisory control and so on. All these terms are important when realizing a complex control task on a decentralized control system (DCS) and most of these occur in special control theory. Therefore here the kinds of control are summarized from a theoretical point of view. Later, two of these that are most important in the industrial context, will be discussed in greater detail.

Controlling industrial processes always implies information processing and information flow between the three units shown in Figure 1. The controller acts on the plant via the actuators and gives information to the human operators. The information inputs of the controller are gained from the plant by the sensor signals and are due to the orders given by the operators.

Figure 1. Information flow in process control.

This structure holds in any case of control, especially in continuous feedback control and in binary sequential control, the two most important ones in industrial application. But, in theory, some special fields have been established, mainly depending on the kind of signals between the middle and the right block in Figure 1. These signals can be continuous in amplitude and in time. Then they represent physical variables like temperature and pressure coming from the sensors, or valve position and motor voltage influencing the actuators. The two right blocks in the general structure of Figure 1 can then be detailed according to Figure 2.

This is the common structure of continuous feedback control. Two tasks have always to be done. The controller should match the setpoint with the actual process value forcing the control error to zero, even if disturbances are present. Feeding back the process value causes a closed loop with any variable in the loop - e.g. the process value - acting always on itself. A large part of control theory deals with this matter. See further explanations in the following sections on continuous control.

Certain kinds of continuous control follow from special kinds of signals in the control loop. Digital (e.g. field bus) instead of analog signals (e.g. the well-known 4 … 20 mA) between the controller and the plant block imply amplitude and time discretization. Because of a normally high resolution (e.g. 2^{12}=4096 steps) there is only a weak influence of amplitude discretization. This usually holds for discrete time instead of continuous time signals, too. So discrete time control must only be considered if the control loop includes a sample and hold unit with a sample time which is large in comparison with the overall system dynamics. The sample times of today's decentralized control systems (DCS) being 1 second or less are no restrictions in this sense when controlling temperatures, levels, flows, pressures and so on in large chemical plants. Therefore the theory of continuous feedback control can be applied in such cases.

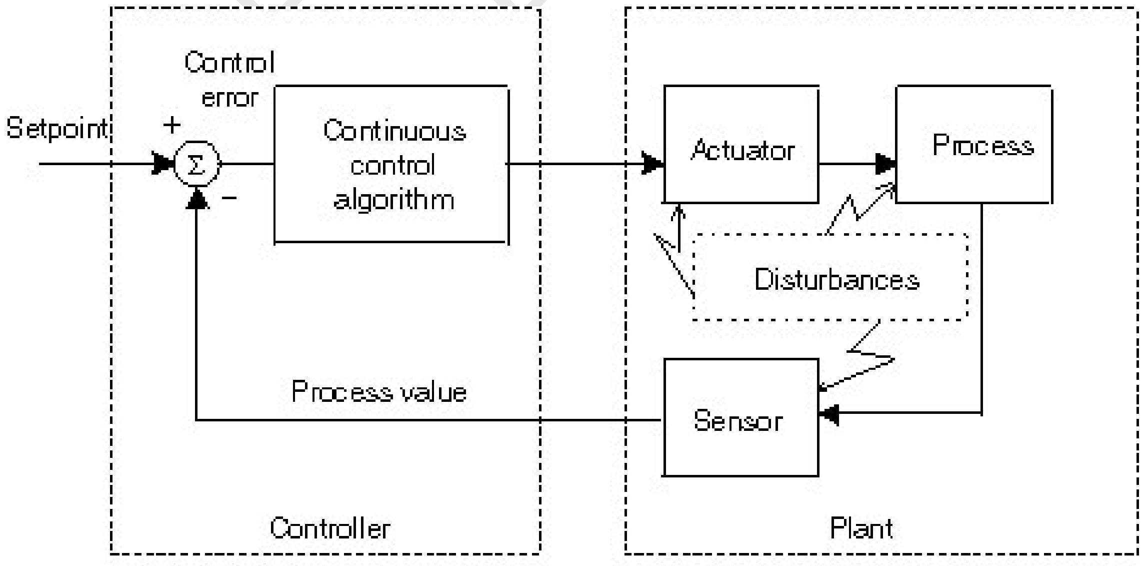

Figure 2. Structure of continuous feedback control.

Continuous open loop control can be considered as a simple special case and can be treated by the same continuous control theory. "Open loop" implies the closed loop to be cut and kept open without feedback. This situation is possible due to several reasons: missing sensors or sensors in maintenance, or a controller switched from automatic to manual mode of operation. In the latter mode the controller output does not depend on the process value. This mode is usual in the start-up phase. Note that open loop has only to be interpreted in a structural sense (see Figure 3). It does not involve any feedback loop. The kind of signal transfer or signal processing does not matter: it can be continuous (continuous open loop control) or binary (binary open loop) control).

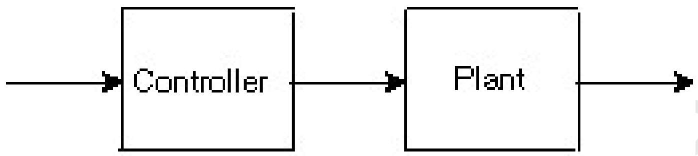

Figure 3. Structure of open loop control.

Completely different types of (feedback) control result if the information contents of the signals in Figure 1 are not continuous but binary. This is the domain of logic and sequential control, see Figure 4.

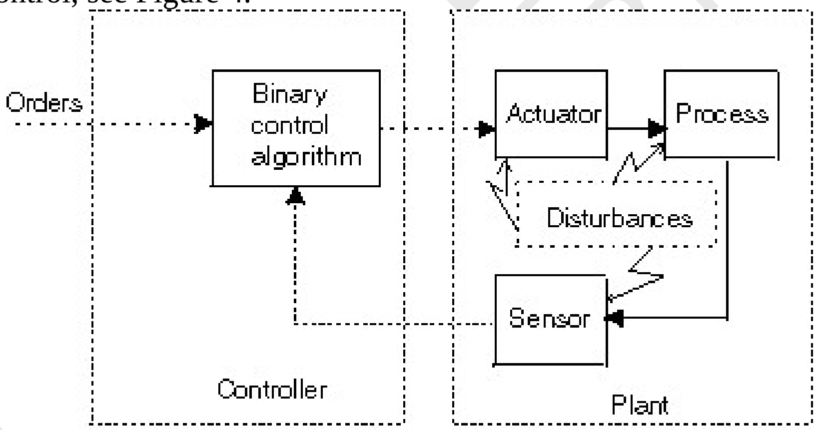

Figure 4. Structure of binary control.

Despite the similarity of Figures 2 and 4 in some senses, there is a major difference in principle. Following the binary character of the signals round the controller (see broken lines denoting connections in Figure 4) there is no longer a matching of set points and process values. Instead, the binary control algorithm processes orders and binary sensor information into binary controller outputs. These act on the plant to move the valves, motors and heaters on and off, respectively. So the binary control algorithms fulfill various tasks on the plant, which can never be as easily characterized as in continuous feedback control. Also, in Figure 4 there is no closed loop in the sense of Figure 2, because any variable in Figure 4 need not act on itself.

Two main groups of binary control, both having the structure of Figure 4, can be distinguished: logical control and sequential control. In the case of logical control the orders and sensor signals as inputs of the binary control algorithm are mapped into its output signals. It employs Boolean, memory and time functions, but it does not involve any sequences, which may have to be executed step by step. On the other hand, sequential control involves the execution of a sequence of steps and actions. The transition from one step to another possible step, which may be stated in the program, depends on the transition conditions.

The purpose as well as the theory of binary control differs significantly from those of continuous control. The rest of this chapter will focus on both continuous and binary control, the two most important domains of control in the industrial context.

2. Basic Requirements on Control Quality

The first step in designing a control system is to find out what the user would like to obtain from the plant in terms of quality of product or performance, cost of operation, capital costs, reliability and maintainability, etc.

2.1. Specifications of Continuous Control Systems

We generally require a continuous control system to fulfill certain expectations in its behavior or response. These expectations or specifications are often stated in the time domain, or the frequency domain, or both. In theory, a frequency domain response can be uniquely transformed into the time domain, and so specifications stated in the time or frequency domain tell us the same thing. As a result, specifications can be defined by parameters such as the steady-state accuracy, gain margin, phase margin, bandwidth, etc.

The fact that the system should be stable is a fundamental requirement, as only stable systems can fulfill their task. The purpose of controller design is, therefore, to maintain stability (which is related to the gain margin and phase margin), to achieve zero steady-state error. In certain cases, fast response (which is related to the bandwidth) and robustness (Ackermann 1993) are required.

Of great importance in control system specification is steady-state accuracy. Clearly for a given system, the steady-state error depends on the type of input. It is standard procedure to compute the steady-state error of the system when driven by constant, ramp or parabolic inputs as a measure of its performance.

Sensitivity of the system to changes in the system parameters and degree to which the system is affected by disturbance inputs are other important measures of system performance.

In an important class of control systems, it is desired that a plant output "track" or "follow" a controller input, where the speed of response to commands is an important factor. This can be expressed in terms of the transient response to a step, ramp, or impulse input. The step response may take the form as shown in Figure 5, see Levine (1996) and Franklin et al. (1994). The transient response can be characterized by the parameters indicated in Figure 5.

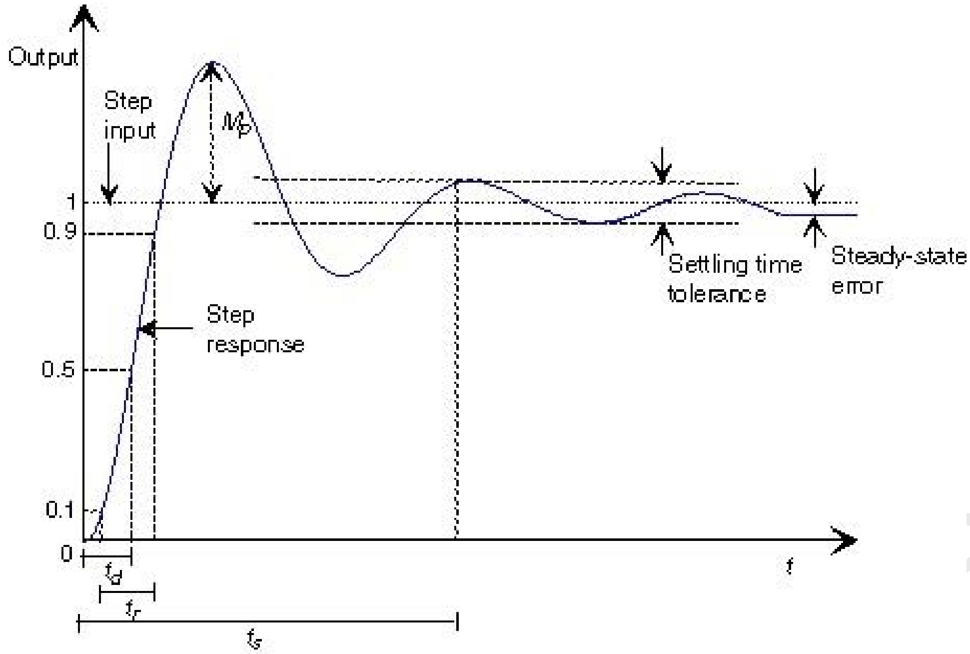

Figure 5. The step response of a system.

Rise time (t_r) is indicative of the speed of response and is defined as the time it takes for the response to rise from 10 to 90 per cent of its final value.

Delay time (t_d) shows the time it takes for the system response to reach some measurable level, usually taken as 50 per cent of the final value, following the point of excitation.

Settling time (t_s) indicates the time at which the response begins to stay within a specified tolerance.

Overshoot (M_p) is the maximum amount the system overshoots its final value divided by its final value (and often expressed as a percentage).

Parameters like overshoot and rise time are empirical in nature and therefore lack mathematical exactitude. Another approach is to use a single index of performance as a measure of acceptable operation of a system. A performance index is usually chosen to be mathematically tractable and, of course, sensible. Some of the commonly used indices to be optimized are

(a) The integral of the square-error criterion (ISE) is characterized by the following performance index:

$$J_{\mathrm{ISE}} = \int_0^\infty e^2(t)\,\mathrm{d}t. \tag{1}$$

Often the upper limit of the integration is taken to be some large but finite number:

$$J_{\mathrm{ISE}} = \int_0^T e^2(t)\,\mathrm{d}t \tag{2}$$

T large.
This form is useful if $e(\infty) \neq 0$.

(b) Integral of time-multiplied square-error criterion (ITSE):

$$J_{\mathrm{ITSE}} = \int_0^\infty t\, e^2(t)\,\mathrm{d}t. \tag{3}$$

(c) Integral of absolute error criterion (IAE):

$$J_{\mathrm{IAE}} = \int_0^\infty |e(t)|\,\mathrm{d}t \tag{4}$$

(d) Integral of time-multiplied absolute error criterion (ITAE):

$$J_{\mathrm{ITAE}} = \int_0^\infty t\, |e(t)|\,\mathrm{d}t \tag{5}$$

2.2. Specifications of Binary Control Systems

Specifications can always be classified into two groups: general ones not depending on the considered problem just to be solved, and special ones relating only to that problem. In continuous control, stability and steady-state accuracy are general specifications while the special ones refer to settling time, maximal overshoot and so on. In binary control, the special specifications follow from the special control task, descried either in verbal form or by an appropriate formalism (see also Section 7). But what are the general specifications in binary control, applicable to any control task? The most important one should be the transparency demand. A transparent control shows clearly

- What it is doing at the moment,
- What it is wanted to do at the moment
- What it should do in the near future

Note that this information is very important at different stages in the life cycle of binary control, in the start-up phase, for function tests and to detect and to overcome malfunctions. Transparency is not a property that is commonly attributed to any binary control; it has to be constructed consciously while planning the control. This is in contrast to continuous feedback control, where the general task is always to match the control error to zero, and observing the set point, process value and control error is the common key for transparency. In binary control the control error does not exist.

Binary control algorithms can be highly complex to execute complex control tasks. As a rule, complex control tasks are not defined once to work all the time in the same manner. They are rather redefined from time to time to fulfill new tasks more or less similar to the previous ones. Redefining can be done the more easily the more flexible the control algorithm that has been constructed. So flexibility is a further general demand. The degree of flexibility has to be stated at the earliest stage of control design. It influences the structure of the binary control algorithm. The most flexible structure, the so-called recipe control, based on modular control elements, arranged in a hierarchical manner. So the whole recipe procedure consists of unit procedures containing operations as elements. The operations are built up by phases on the lowest hierarchical level (see ISA/SP88 Report 1995). Redefining a control task then means rearranging well-tested control elements in a new manner and supplying them with new parameters to reach the new functionality.

In some circumstances further specifications exist. If the purpose of binary control is safety control the time performance of the algorithm may be of interest. The time from the occurrence of an event until the activation of some actuators can be limited for reasons of protecting men or machines. Then consequences result for soft- and hardware to realize a binary control algorithm working within the given time constraints.

3. Process Modeling

A model of a process is a useful and compact way to summarize the knowledge about the process. Model building is the only key for making use of control theory. Development of mathematical models is necessary to understand the dynamic behavior of processes, and modeling enables a mathematical treatment of systems leading to a mathematical description of the controller (see Cellier 1991, Ljung and Glad 1994, Rao et al. 1994, and Luyben 1990). Without an adequate model of the plant to be controlled, the synthesis of a control algorithm is only possible by trial and error.

In addition, models make it possible to explore situations that would be hazardous, difficult or expensive to set up in the actual system. Simulation models are hence valuable for "what if?" analyses of complex engineering processes. Chemical plant, aircraft and space-vehicle simulators are well-known examples.

-
-
-

Bibliography and Suggestions for further study

Ackermann J (1993) Robust Control: Systems with Uncertain Physical Parameters. New York: Springer.

Bittanti S, Laub A J and Willems J C (1991) The Riccati Equation. New York: Springer.

Cellier F E (1991) Continuous System Modeling. New York: Springer publishing house.

Chen T and Francis B A (1995) Optimal Sampled-Data Control Systems. New York: Springer.

Cox E (1994) The Fuzzy Systems Handbook. Boston: AP Professional.

Driankov D, Hellendoorn H and Reinfrank M (1993) An Introduction to Fuzzy Control. New York: Springer.

Driels M (1996) Linear Control Systems Engineering. New York: McGraw-Hill.

Eykhoff P (1974) System Identification: Parameter and State Estimation. New York: John Wiley.

Franklin G F, Powell J D and Emami-Naeini A (1994) Feedback Control of Dynamic Systems, 3rd ed. MA: Addison-Wesley.

Gabasov R, Kirillova F M and Prischepova S V (1995) Optimal Feedback Control. New York: Springer.

Gibson J E (1963) Nonlinear Automatic Control. New York: McGraw-Hill.

Gupta M M and Sinha N K (1996) Intelligent Control Systems. IEEE Press.

Haykin S (1994) Neural Networks: A Comprehensive Foundation. New York: Macmillan.

Helmke U and Moore J B (1995) Optimization and Dynamical Systems. New York: Springer.

IEC 1131-3 (1995) Programmable Logic Controllers - Programming languages.

ISA/SP88 (1995) Batch Control Draft 12.

Kaufman H, Bar-Kana I and Sobel K (1994) Direct Adaptive Control Algorithms: Theory and Applications. New York: Springer.

Kuhn U (1995) A practice oriented setting rule for PID-controllers: The T-sum-rule. Automatisierungstechnische Praxis 37(5), 10-16. Munich: Oldenbourg publishing house [in German].

Lancaster P and Rodman L (1995) Algebraic Riccati Equations. Oxford: Clarendon Press.

Levine W S (1996) The Control Handbook. CRC Press.

Ljung L (1987) System Identification: Theory for the User. Englewood Cliffs: Prentice Hall.

Ljung L and Glad T (1994) Modeling of Dynamic Systems. Englewood Cliffs: Prentice Hall.

Luyben W L (1990) Process Modeling, Simulation and Control for Chemical Engineers. New York: McGraw-Hill.

Maren A, Harston C and Pap R (1990) Handbook of Neural Computing Applications. San Diego: Academic Press.

MATLAB (1992) Users Guide. The Mathworks Inc. Natick, MA.

Miller W T, Sutton R S and Werbos P J (1990) Neural Networks for Control. Cambridge: The MIT Press.

Norton J P (1986) An Introduction to Identification. London: Academic Press Inc.

Peterson J L (1981) Petri Net Theory and the Modeling of Systems. Englewood Cliffs: Prentice Hall.

Pham D T and Xing L (1995) Neural Networks for Identification, Prediction and Control. London: Springer.

Pintelon, R.; Schoukens, J. 2000. *System Identification*. New York, IEEE Press. 605 pp. [In this book frequency-domain representation of data is used for system identification.]

Popov E P (1958) Dynamic Automatic Control Systems. Sec. 60. Berlin: Akadamie publishing house.

Rao M, Xia Q and Ying Y (1994) Modeling and Advanced Control for Process Industries: Applications to Paper Making Processes. New York: Springer.

Samad, T. (ed.) 2001 *Perspectives in Control Engineering*. New York, Institute of Electrical and Electronic Engineers. 503pp. [This book provides a broad review of the state-of-art in control science and engineering, with particular emphasis on new research and application directions.]

Slotine J-J E and Li W (1991) Applied Nonlinear Control. Englewood Cliffs: Prentice Hall.

Søderstrøm T and Stoica P (1989) System Identification. Englewood Cliffs: Prentice Hall.

Unbehauen H and Rao G P (1987) Identification of Continuous-Time Systems. Dordrecht: North Holland.

Vaccaro R J (1995) Digital Control: A State-Space Approach. New York: McGraw-Hill.

van der Schaft, A. J.; Schumacher, J. M. 2000. *An Introduction to Hybrid Dynamical Systems*. London, Springer-Verlag. 174 pp. [This book gives a deep introduction into the field of hybrid dynamical systems.]

Wolovic, W. A. 1994. *Automatic Control Systems*. Fort Worth, Saunders College Publishing. 450 pp. [This introductory text focusses on the classical and modern design of linear controllers for single-input/single-output systems.]

Zhou, K.; Doyle, J. C.; Glover, K. 1996. *Robust and Optimal Control*. Upper Saddle River, N. J., Prentice Hall. 596 pp. [This book gives a fairly comprehensive and step-by-step treatment of the state-space control theory.]