21世纪普通高等教育电气信息类规划教材

自动化专业英语

第三版

王树青　主编

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·北京·

本书共分 6 章和 2 个附录。第 1 章是自动控制基础知识，介绍反馈控制原理、自动控制系统稳定性分析、设计及控制器参数整定；第 2 章是测量和执行器，包括压力、液面、流量、温度的测量和执行阀；第 3 章是先进控制系统，介绍前馈、比值、串级、自适应和模型预测控制；第 4 章是计算机控制系统，包括计算机控制基础、系统结构、PLC、DCS、现场总线以及计算机控制系统通信；第 5 章是自动控制系统，其中有物理系统建模，控制用的直流电动机，太阳能跟踪系统，电站控制以及工业机器人；第 6 章是人工智能技术及应用，包括神经元网络、模糊逻辑、专家系统以及应用。

本书可作为高等学校自动化及相关专业学生的教材，也可作为自动化科技人员的参考资料。

图书在版编目 (CIP) 数据

自动化专业英语/王树青主编. —3 版. —北京：
化学工业出版社，2010. 6
21 世纪普通高等教育电气信息类规划教材
ISBN 978-7-122-08217-6

Ⅰ. 自…　Ⅱ. 王…　Ⅲ. 自动化-英语-高等学校-
教材　Ⅳ. H31

中国版本图书馆 CIP 数据核字（2010）第 066480 号

责任编辑：郝英华　　装帧设计：张　辉
责任校对：陈　静

出版发行：化学工业出版社（北京市东城区青年湖南街 13 号　邮政编码 100011）
印　　装：三河市延风印装厂
787mm×1092mm　1/16　印张 18½　字数 455 千字　2010 年 7 月北京第 3 版第 1 次印刷

购书咨询：010-64518888（传真：010-64519686）　售后服务：010-64518899
网　　址：http://www.cip.com.cn
凡购买本书，如有缺损质量问题，本社销售中心负责调换。

定　　价：33.00 元

第三版前言

《自动化专业英语》（前两版名为《工业自动化专业英语》）自2001年修订后已有近10年的时间了。在这10年里，自动化技术随着微电子、计算机等新技术的迅速发展，又前进了一大步。许多新的英语词汇不断出现在科技论文、专著和教科书中。因此，及时更新教材，使学生能尽快掌握日新月异的知识变化，极力促动着教材的修订工作。

在这次修订中，主要修改了计算机控制系统和测量与执行器两章的内容。其余部分内容几乎没有变更。经过修订后，全书内容共分6章和2个附录。第1章是自动控制基础知识，内容包括反馈控制、控制系统稳定性分析、过程控制系统设计和控制器参数整定；第2章是测量和执行器，内容有压力测量及传感器，液面测量及传感器，流量测量及流量仪表，温度测量及测量装置，以及执行器与流量控制执行阀；第3章是先进控制系统，内容有前馈、比值、串级控制，时滞补偿控制，选择性控制，自适应控制，统计质量控制，模型预测和监督控制；第4章是计算机控制系统，内容有计算机控制基础，计算控制结构，计算机集成控制，可编程控制器（PLC）及应用，集散型控制系统（DCS），现场总线，计算机控制系统通信；第5章是自动控制系统，内容有物理系统建模，控制系统直流电动机，太阳能跟踪控制系统，现代电站控制系统，工业机器人等；第6章是人工智能技术及应用，包括神经网络、模糊逻辑、专家系统以及人工智能在过程控制中的应用。

本书的结构和编排同前两版一致。

编　者
2010年6月

修订版前言

《工业自动化专业英语》于2000年6月由化学工业出版社第一次印刷出版。由于该书填补了高等院校工业自动化专业高年级学生没有一本较完整专业英语教材的空缺，因此，受到各高等院校的欢迎，不到一年时间，此书就售空。同时，有许多教授和专家对此书提出了许多宝贵的建议，其中特别强调的一条是希望把教材内容进一步向机电工业自动化领域扩展。据此，本书的主编之一王树青教授在较短的时间内为本书增编了第七章自动控制系统的内容，其中包括5篇课文和5篇阅读材料，内容有实际系统（机电系统）数学模型，直流电动机控制系统，宇宙飞船太阳跟踪控制系统，现代电力系统和工业机器人导论等。希望读者批评指正。

编　者

2001年2月16日

第一版前言

出版系列的专业英语教材，是许多院校多年来共同的愿望。在高等教育面向21世纪的改革中，学生基本素质和实际工作能力的培养受到了空前重视。专业英语水平是当今大学毕业生能力的重要组成部分。在此背景下，教育部（原国家教委）几次组织会议研究加强外语教学问题，制订有关规范，使外语教学更加受到重视。教材是教学的基本要素之一，与基础英语相比，专业英语教学的教材问题此时显得尤为突出。

国家主管部门的重视和广大院校的呼吁引起了化学工业出版社的关注，他们及时地与原化工部教育主管部门和全国化工类专业教学指导委员会请示协商后，组织全国十余所院校成立了大学英语专业阅读教材编委会。在经过必要的调研后，根据学校需求，编委会优先从各校教学（交流）讲义中确定选题，同时组织力量开展编审工作。本套教材涉及的专业主要包括化学工程与工艺、石油化工、机械工程、信息工程、工业自动化、应用化学及精细化工、生化工程、环境工程、制药工程、材料科学与工程、化工商贸等。

根据“全国部分高校化工类及相关专业大学英语专业阅读教材编审委员会”的要求和安排编写的《工业自动化专业英语》教材，可供工业自动化及相关专业本科生使用，也可以作为同等程度（通过大学英语四级）的专业技术人员自学教材。

本教材分为六章（Chapter），每章含有5个单元（Unit），每单元由一篇课文和一篇阅读材料构成。阅读材料提供与课文相关的背景知识，以进一步拓宽课文内容，为学生自学（开拓视野和训练阅读技能）提供合适的材料。根据课文和阅读材料的内容，配有相应的练习题。各篇课文之间、课文与所配阅读材料之间，既有一定的内在联系，又独立成章，可根据不同教学时数灵活选用。课文及阅读材料共计五十五篇，均选自原版英文教科书、科技报告、专著及专业期刊，大部分为国外20世纪90年代以来的出版物。其中:

Chapter 1 为工业过程控制原理，包括过程控制入门、反馈控制原理、自动控制系统稳定性分析、工业生产过程自动控制系统设计和控制器参数整定等;

Chapter 2 为工业过程参数测量和执行器，主要介绍工业生产过程参数的测量，如液面、压力、流量和温度的测量以及各种执行机构等;

Chapter 3 为工业过程模型化和系统辨识，其中包括数学模型的建立、系统辨识、最小二乘原理与迭代计算以及系统辨识实践步骤等;

Chapter 4 为复杂工业过程的先进控制，包括前馈和比值控制、纯滞后补偿控制、自适应控制、推理控制和模型预测控制等;

Chapter 5 为计算机与自动化，其中包括集散控制系统与可编程控制器，A/D 和 D/A 转换、微型计算机、数字化和基于 PC 控制器等;

Chapter 6 为智能控制，包括智能控制技术、神经网络控制、模糊逻辑应用、专家系统

和人工智能在过程控制中应用等。

在专业英语阅读阶段，掌握一定数量的科技词汇（包括专业词汇）是教学的主要目的之一。本教材覆盖了控制、测量和计算机等的基本内容。整个教材注意前后呼应，词汇的复现率高，每个单元均有词汇练习，有利于学生比较牢固地掌握基本词汇。附录中列出总词汇表。

大纲中对专业英语阅读阶段的学习技能有明确的要求，有针对性的练习是训练阅读技能的有效手段。本教材在设计练习时，作了一些尝试，主要的练习形式如下。

① 课文前设问题或要求。根据课文内容设计的问题或要求，置于课文前面，以激发学生通过阅读获取信息的欲望，有利于学生调动背景知识，变被动阅读为主动阅读。

② 大部分课文配有摘要填空的练习形式，要求学生在规定时间内选用课文中的（一般不多于3个）词填空，培养学生通篇浏览（Surveying）、查找信息（Locating Information）及寻找关键词（Keywords）的能力，这是对阅读技能的一种强化训练，也是对学生语言能力和专业知识水平的一种有效考查方式。

③ 教材中没有指定英译中翻译练习，教师可从课文和阅读材料中选取。

书中第1、4、6章和附录由浙江大学王树青编写，第2、3和5章分别由北京化工大学韩建国、田水滢和李大字、王晶编写，全书的统稿工作由王树青和韩建国完成。

本教材从结构、内容到练习设计都是一种尝试，我们热诚希望使用本书的广大师生提出宝贵意见。

致谢　本教材在成书过程中得到了化学工业出版社大力支持，华东理工大学蒋慰孙教授审阅了全书，并提出了许多宝贵的意见，浙江大学陆建中老师对全书进行了认真的校核，来国妹女士出色完成了全书的录入和排版工作。对他们的热情帮助和指导谨在此一并表示衷心感谢。

编　者
1999年9月9日

目 录

CHAPTER 1　FUNDAMENTALS OF AUTOMATIC CONTROL

1.1　Introduction to Process Control

Before reading the text below, try to answer the following questions:

1. What is the process control in a process plant?
2. What is the typical process control strategies?
3. Could you please give an example of process control?

In recent years the performance requirements for process plants have become increasingly difficult to satisfy. Stronger competition, tougher environmental and safety regulations, and rapidly changing economic conditions have been key factors in the tightening of plant product quality specifications. A further complication is that modern processes have become more difficult to operate because of the trend toward larger, more highly integrated plants with smaller surge capacities between the various processing units. Such plants give the operators little opportunity to prevent upsets from propagating from one unit to other interconnected units. In view of the increased emphasis placed on safe, efficient plant operation, it is only natural that the subject of *process control* has become increasingly important in recent years. In fact, without process control it would not be possible to operate most modern processes safely and profitably, while satisfying plant quality standards.

1.1.1　Illustrative Example

As an introduction to process control, consider the continuous stirred-tank heater shown in Figure 1.1.1 The inlet liquid stream has a mass flow rate w and a temperature T_i. The tank contents are well agitated and heated by an electrical heater that provides Q watts. It is assumed that the inlet and outlet flow rates are identical and that the liquid density ρ remains constant, that is, the temperature variations are small enough that the temperature dependence of ρ can be neglected.Under these conditions the volume V of liquid in the tank remains constant.

The control objective for the stirred-tank heater is to keep the exit temperature T at a constant reference value T_R. The reference value is referred to as a *set point*

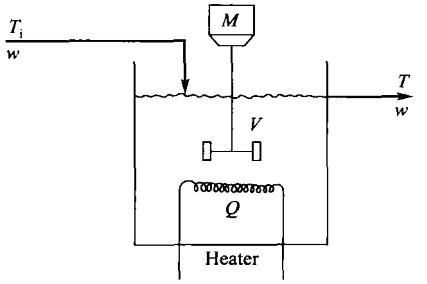

Figure 1.1.1　Continuous stirred-tank heater.

in control terminology. Next we consider two questions.

Question 1. *How much heat must be supplied to the stirred-tank-heater to heat the liquid from an inlet temperature* T_i *to an exit temperature* T_R*?*

To determine the required heat input for the design operating conditions, we need to write a steady-state energy balance for the liquid in the tank. In writing this balance, it is assumed that the tank is perfectly mixed and that heat losses are negligible. Under these conditions there are no temperature gradients within the tank contents and consequently, the exit temperature is equal to the temperature of the liquid in the tank. A steady-state energy balance for the tank indicates that the heat added is equal to the change in enthalpy between the inlet and exit streams:

$$\bar{Q} = \bar{w}C(\bar{T} - \bar{T}_i) \tag{1.1.1}$$

where $\bar{T}_i$, $\bar{T}$, $\bar{w}$, and $\bar{Q}$ denote the nominal steady-state design values of T_i, T, w, and Q, respectively, and C is the specific heat① of the liquid. We assume that C is constant. At the design conditions, $\bar{T} = T_R$ (the set point). Making this substitution in Eq. (1.1.1) gives an expression for the nominal heat input $\bar{Q}$:

$$\bar{Q} = \bar{w}C(T_R - \bar{T}_i) \tag{1.1.2}$$

Equation (1.1.2) is the design equation for the heater. If our assumptions are correct and if the inlet flow rate and inlet temperature are equal to their nominal values, then the heat input given by Eq. (1.1.2) will keep the exit temperature at the desired value, T_R. But what if conditions change? This brings us to the second question:

Question 2. *Suppose that inlet temperature* T_i *changes with time. How can we ensure that* T *remains at or near the set point* T_R*?*

As a specific example, assume that T_i increases to a new value greater than $\bar{T}_i$. If Q is held constant at the nominal value of $\bar{Q}$, we know that the exit temperature will increase so that $T > T_R$. (cf. Eq. (1.1.1)).

To deal with this situation, there are a number of possible strategies for controlling exit temperature T.

Method 1. Measure T and adjust Q. One way of controlling T despite disturbances in T_i is to adjust Q based on measurements of T. Intuitively, if T is too high, we should reduce Q; if T is too low, we should increase Q. This control strategy will tend to move T toward the set point T_R and could be implemented in a number of different ways. For example, a plant operator could observe the measured temperature and compare the measured value to T_R. The operator would then change Q in an appropriate manner. This would be an application of *manual control*. However, it would probably be more convenient and economical to have this simple control task performed automatically by an electronic device rather than a person, that is, to utilize *automatic control*.

Method 2. Measure T_i, adjust Q. As an alternative to Method 1, we could measure disturbance variable T_i and adjust Q accordingly. Thus, if T_i is greater than $\bar{T}_i$, we would decrease Q; for

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① specific heat 比热，根据国际 GB 3100～3102.1993 已改为 specific heat capacity 比热容.——编者注

$T_i < \bar{T}_i$ we would set $Q > \bar{Q}$.

Method 3. Measure T, adjust w. Instead of adjusting Q, we could choose to manipulate mass flow rate w. Thus, if T is too high we would increase w to reduce the energy input rate in the stirred tank relative to the mass flow rate and thereby reduce the exit temperature.

Method 4. Measure T_i, adjust w. In analogy with Method 3, if T_i is too high, w should be increased.

Method 5. Measure T_i and T, adjust Q. This approach is a combination of Methods 1 and 2.

Method 6. Measure T_i and T, adjust w. This approach is a combination of Methods 3 and 4.

Method 7. Place a heat exchanger on the inlet stream. The heat exchanger is intended to reduce the disturbances in T_i and consequently reduce the variations in T. This approach is sometimes called "hog-tieing" an input.

Method 8. Use a larger tank. If a larger tank is used, fluctuations in T_i will tend to be damped out due to the larger thermal capacitance of the tank contents. However, increased volume of tankage would be an expensive solution for an industrial plant due to the increased capital costs of the larger tank. Note that this approach is analogous to the use of water baths in chemistry laboratories where the large thermal capacitance of the bath serves as a heat sink and thus provides an isothermal environment for a small-scale research apparatus.

1.1.2 Classification of Control Strategies

Next, we will classify the eight control strategies of the previous section and discuss their relative advantages and disadvantages. Methods 1 and 3 are examples of *feedback control* strategies. In feedback control, the process variable to be controlled is measured and the measurement is used to adjust another process variable which can be manipulated. Thus, for Method 1, the measured variable is T and the manipulated variable is Q. For Method 3, the measured variable is still T but the manipulated variable is now w. Note that in feedback control the disturbance variable T_i is not measured.

It is important to make a distinction between *negative feedback and positive feedback.* Negative feedback refers to the desirable situation where the corrective action taken by the controller tends to move the controlled variable toward the set point. In contrast, when positive feedback exists, the controller tends to make things worse by forcing the controlled variable farther away from the set point. Thus, for the stirred-tank heater, if T is too high we would decrease Q (negative feedback) rather than increase Q (positive feedback).

Methods 2 and 4 are *feedforward control strategies*. Here, the disturbance variable T_i is measured and used to manipulate either Q (Method 2) or w (Method 4). Note that in feedforward control, the controlled variable T is *not* measured. Method 5 is a feedforward-feedback control strategy since it is a combination of Methods 1 and 2. Similarly, Method 6 is also a feedforward-feedback control strategy since it is a combination of Methods 3 and 4. Methods 7 and 8 consist of equipment design changes and thus are not really control strategies. Note that Method 7 is somewhat inappropriate since it involves adding a heat exchanger to the inlet line of the stirred-tank heater which in itself was designed to function as a heat exchanger! The control strategies for the stirred-tank heater are summarized in Table 1.1.1.

Table 1.1.1 Temperature Control Strategies for the Stirred-Tank Heater

Method	*Measured Variable*	*Manipulated Variable*	*Category*
1	T	Q	FB
2	T_i	Q	FF
3	T	w	FB
4	T_i	w	FF
5	T_i and T	Q	FF/FB
6	T_i and T	w	FF/FB
7	—	—	Design change
8	—	—	Design change

So far we have considered only one source of process disturbances, fluctuations in T_i. We should also consider the possibility of disturbances in other process variables such as the ambient temperature, which would affect heat losses from the tank. Recall that heat losses were assumed to be negligible earlier. Changes in process equipment are another possible source of disturbances. For example, the heater characteristics could change with time due to scaling by the liquid. It is informative to examine the effects of these various types of disturbances on the feedforward and feedback control strategies discussed above.

First, consider the feedforward control strategy of Method 2 where the disturbances in T_i are measured and the measurements are used to adjust the manipulated variable Q. From a theoretical point of view, this control scheme is capable of keeping the controlled variable T exactly at set point T_R despite disturbances in T_i. Ideally, if accurate measurements of T_i were available and if the adjustments in Q were made in an appropriate manner, then the corrective action taken by the heater would cancel out the effects of the disturbances before T is affected. Thus, in principle, feedforward control is capable of providing *perfect control* in the sense that the controlled variable would be maintained at the set point.

But how will this feedforward control strategy perform if disturbances occur in other process variables? In particular, suppose that the flow rate w cannot be held constant but, instead, varies over time. In this situation, w would be considered a disturbance variable. If w increases, then the exit temperature T will decrease unless the heater supplies more heat. However, in the control strategy of Method 2 the heat input Q is maintained constant as long as T_i is constant. Thus *no* corrective action would be taken for unmeasured flow disturbances. In principle, we could deal with this situation by measuring *both* T_i and w and then adjusting Q to compensate for both of these disturbances. However, as a practical matter it is generally uneconomical to attempt to measure all potential disturbances. It would be more practical to use a combined feedforward-feedback control system, since feedback control provides corrective action for unmeasured disturbances, as discussed below. Consequently, in industrial applications feedforward control is normally used in combination with feedback control.

Next, we will consider how the feedback control strategy of Method 1 would perform in the presence of disturbances in T_i or w. If Method 1 were used, no corrective action would occur until after the disturbance had upset the process, that is, until after T differed from T_R. Thus, by its inherent nature, feedback control is not capable of perfect control since the controlled variable must deviate from the set point before corrective action is taken. However, an extremely important advantage of feedback control is that corrective action is taken regardless of the *source* of the disturbance. Thus, in Method 1, corrective action would be taken (by adjusting Q) after a disturbance in T_i or w caused T to deviate from the set point. The ability to handle unmeasured disturbances of unknown origin is a major reason why feedback controllers have been so widely used for process control.

Selected from "*Process Dynamics and Control, D. Seborg & T. Edgar, John Wiley & Sons,* 1989"

Words and Expressions

1. plant [plɑːnt] *n.* 车间，工厂，系统
2. strategy ['strætidʒi] *n.* 策略
3. competition [kɔmpə'tiʃən] *n.* 竞赛，竞争
4. integrate ['intigreit] *v.* 使成整体；求……积分
5. surge capacity [səːdʒ kə'pæsiti] *n.* 谐振能力
6. upset ['ʌpset] *n.*; *v.* 混乱，扰乱
7. propagate ['prɔpəgeit] *v.* 传播，宣传
8. process control 过程控制
9. quality ['kwɔliti] *n.* 质量
10. standard ['stændəd] *n.* 标准
11. stirred-tank [stəːrid-tæŋk] *n.* 搅拌槽
12. heater ['hiːtə] *n.* 加热器
13. inlet ['inlet] *n.* 入口，进口
14. agitate ['ædʒiteit] *v.* 搅动
15. watt [wɔt] *n.* 瓦特
16. variation [vɛəri'eiʃən] *n.* 变化量
17. constant ['kɔnstənt] *n.* 常数，恒量
18. set point [set pɔint] *n.* 设定值，给定值
19. terminology [təːmi'nɔlədʒi] *n.* 术语
20. negligible ['neglidʒib(ə)l] *adj.* 可以忽略的，微不足道的
21. gradient ['greidiənt] *n.* 梯度
22. steady-state ['stedi-steit] *n.* 稳态
23. energy balance 能量平衡
24. enthalpy [en'θælpi] *n.* 焓，热函
25. intuitively [in'tjuːitivli] *adv.* 直觉地
26. implement ['impliment] *v.* 实现，执行
27. manual control 手动控制，人工控制
28. automatic control 自动控制
29. hog [hɔg] *v.* (使)拱(弯、扭)曲，变形
30. tie [tai] *v.* 结；约束
31. fluctuation [flʌktjueiʃən] *vi.* 波动

32. damp [dæmp] *v.* 阻尼；衰减
33. isothermal [aisəu'θəːməl] *n.* 等温线；*adj.* 同温的
34. heat sink [hiːt siŋk] *n.* 散热片，散热装置
35. feedback control 反馈控制
36. manipulate [mə'nipjuleit] *v.* 处理
37. negative feedback 负反馈
38. positive feedback 正反馈
39. feedforward control 前馈控制
40. heat exchanger 热交换器
41. ambient ['æmbiənt] *adj.* 周围的，外界的
42. heat loss 热损失
43. perfect control 完美控制
44. inherent [in'hiərənt] *adj.* 固有的，内在的，本征的

Exercises

1. *Complete the notes below with words taken from the text above.*

(1) A further complication ____________ modern processes ______________ more difficult to operate because of the trend toward larger, more highly integrated plants ________ smaller surge capacities between the various processing units.

(2) ______ determine the required heat input ______ the design operating conditions, we need ________ a steady-state energy balance ________ the liquid in the tank.

(3) Important to make a distinction ____________ and ____________ refers to the desirable situation where the ________ taken by the ________ tends to move the __________ toward the set point.

2. *Put the following into Chinese:*

performance
reference
automatic control
feedback control
process plant
operating conditions
manual control
set point
process control
disturbance
perfect control
controlled variable

3. *Put the following into English:*

带搅拌加热器
负反馈
密度
正反馈
比热容
前馈控制策略
热容
控制器
热损失

Reading Material:

Overview of Control Engineering

The goal of control engineering is to improve, or in some cases enable, the performance of a system by the addition of *sensors*, *control processors*, and *actuators*. The sensors measure or sense various signals in the system and operator commands; the control processors process the sensed signals and drive the actuators, which affect the behavior of the system. A schematic diagram of a general *control system* is shown in Figure 1.1.2.

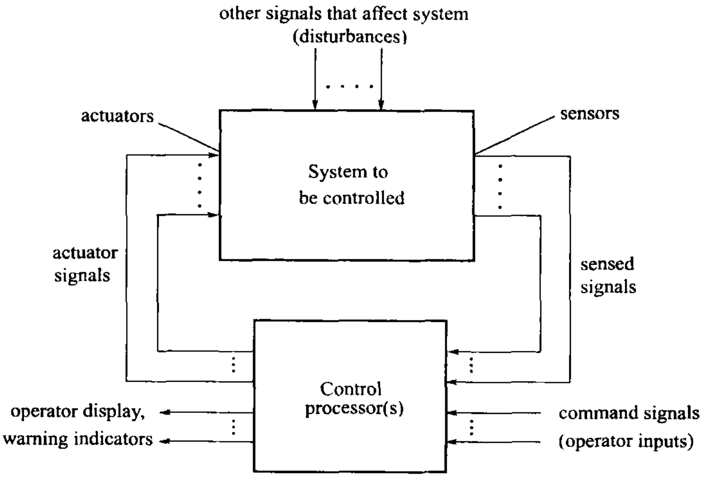

Figure 1.1.2 A schematic diagram of a general control system.

This general diagram can represent a wide variety of control systems. The system to be controlled might be an aircraft, a large electric power generation and distribution system, an industrial process, a head positioner for a computer disk drive, a data network, or an economic system. The signals might be transmitted via analog or digitally encoded electrical signals, mechanical linkages, or pneumatic or hydraulic lines. Similarly the control processor or processors could be mechanical, pneumatic, hydraulic, analog electrical, general-purpose or custom digital computers.

Because the sensor signals can affect the system to be controlled (via the control processor and the actuators), the control system shown in Figure 1.1.2 is called a *feedback* or *closed-loop* control system, which refers to the signal "loop" that circulates clockwise in this figure. In contrast, a control system that has no sensors, and therefore generates the actuator signals from the command signals alone, is sometimes called an *open-loop* control system①. Similarly, a control system that has no actuators, and produces only operator display signals by processing the sensor signals, is sometimes called a *monitoring system*.

In industrial settings, it is often the case that the sensor, actuator, and processor signals are *boolean, i.e.* assume only two values. Boolean sensors include mechanical and thermal limit switches, proximity switches, thermostats, and pushbutton switches for operator commands. Actuators that are often configured as Boolean devices include heaters, motors, pumps, valves, solenoids, alarms, and indicator lamps. Boolean control processors, referred to as *logic controllers*, include industrial relay systems, general-purpose microprocessors, and commercial *programmable logic controllers*.

In this book, we consider control systems in which the sensor, actuator, and processor signals assume real values, or at least digital representations of real values. Many control systems include both types of signals: the real-valued signals that we will consider, and Boolean signals, such as fault or limit alarms and manual override switches, that we will not consider.

1. System Design and Control Configuration

Control configuration is the selection and placement of the actuators and sensors on the system to be controlled, and is an aspect of system design that is very important to the control engineer. Ideally, a control engineer should be involved in the design of the system itself, even before the control configuration. Usually, however, this is not the case: the control engineer is provided with an already designed system and starts with the control configuration. Many aircraft, for example, are designed to operate without a control system; the control system is intended to improve the performance (indeed, such control systems are sometimes called *stability augumentation* systems, emphasizing the secondary role of the control system).

Actuator Selection and Placement

The control engineer must decide the type and placement of the actuators. In an industrial process system, for example, the engineer must decide where to put actuators such as pumps, heaters, and valves. The specific actuator hardware (or at least, its relevant characteristics) must also be chosen. Relevant characteristics include cost, power limit or authority, speed of response, and accuracy of response. One such choice might be between a crude, powerful pump that is slow to respond, and a more accurate but less powerful pump that is faster to respond.

Sensor Selection and Placement

The control engineer must also decide which signals in the system will be measured or sensed, and with what sensor hardware. In an industrial process, for example, the control engineer might decide which temperatures, flow rates, pressures, and concentrations to sense. For a mechanical system, it may be possible to choose *where* a sensor should be placed, *e.g*②., where an accelerometer is to be positioned on an aircraft, or where a strain gauge is placed along a beam. The control engineer may decide the particular type or relevant characteristics of the sensors to be used, including the type of transducer, and the signal conditioning and data acquisition hardware. For example, to measure the angle of a shaft, sensor choices include a potentiometer, a rotary variable differential transformer, or an 8-bit or 12-bit absolute or differential shaft encoder. In many cases, sensors are smaller than actuators, so a change of sensor hardware is a less dramatic revision of the system design than a change of actuator hardware.

There is not yet a well-developed theory of actuator and sensor selection and placement, possibly because it is difficult to precisely formulate the problems, and possibly because the problems are so dependent on available technology. Engineers use experience, simulation, and trial and error to guide actuator and sensor selection and placement.

2. Modeling

The engineer develops mathematical models of

- the system to be controlled,
- noises or disturbances that may act on the system,
- the commands the operator may issue,
- desirable or required qualities of the final system.