DIGITAL SIGNAL AND IMAGE PROCESSING SERIES

Signals and Control Systems

Application for Home Health Monitoring

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First published 2016 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

ISTE Ltd
27-37 St George's Road
London SW19 4EU
UK

www.iste.co.uk

John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

www.wiley.com

Library of Congress Control Number: 2016957652

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-78630-127-7

Contents

Preface

This preface gives an overview of signals and systems, generalities and notions of process control and regulation.

Introduction

The main objective of these two volumes is the analysis and the study of linear, time-invariant, causal signals and deterministic systems of finite dimensions. We will focus our efforts on defining a set of tools useful to automatic control and signal processing, after which we will discuss methods for the representation of linear dynamic systems for the analysis of their behavior. Finally, the identification and the synthesis of control laws will be addressed for the purpose of stabilization and regulation in systems control. Chapter 6 of the other volume [FEM 16] will be dedicated to the use of the Nao robot for a specific application; in this case, home care service.

Signals and systems: generalities

Whether in the analog or digital field the study of the characteristic properties of signals and systems, the knowledge of mathematical tools, processing and analysis methods are constantly evolving and of late are increasingly significant. The reason is that the current state of technology, in particular of electronics and computer science, makes possible the implementation of very advanced processing systems, which are effective and increasingly less expensive in spite of their complexity. Aims and requirements generally depend on applications. Figure 1 presents the connections between the various disciplines, the scientific and technological resources for their operation with the aim of processing signals or automatic control for the operation or the development of current applications[1].

In all areas of physics, for study, analysis and understanding of natural phenomena, a stage for modeling and for the study of the structure of the physical process is necessary. This has led to the development of techniques for modeling, representation and analysis of systems using a fairly general terminology. This terminology is difficult to introduce in a clear manner but the concepts which it relies upon will be defined in detail in the following chapters.

Signal processing concerns the various operations carried out on analog or digital physical quantities with the purpose of analyzing, interpreting and extracting information. These operations are illustrated in Figure 2.

The mastery and the implementation of signal processing techniques require the knowledge of a number of theoretical tools. The objective of this book is to establish the basic concepts of the theoretical study and clarify common processing methods.

A physical process is divided into several components or parts forming what is called a system. This is the case, for example, of an engine that consists of an amplifier, power supply, an electromagnetic part and a position and/or speed sensor. The input to the system is the voltage applied to the amplifier and the output is either the position or the speed of the rotation of the motor shaft.

Among the objectives of the control engineer is the modeling, behavior analysis and the regulation or control of a system, aiming for the dynamic optimization of its behavior. The operation of the system or control is designed to ensure that the variables or system outputs follow a desired trajectory (curve over time in general) or have dynamics defined by the specifications document. For temperature regulation of a speaker to a reference value, one of the following diagrams can be used. Details of vehicle operation is shown in Figure 3.

Notions of process and operation control

The objective of automatic control is to design control and operation systems that are able to assign to a dynamic process (physical, chemical physical, biological, economical, etc.) a behavior defined in advance by the operator based on the requirements specifications. For example, we can consider speed regulation of a car that gives the process (the car) a previously determined speed, regardless of the disturbances that may occur (variation of the slope, etc.). Other examples include a

1 The author advises to avoid the book Traitement du signal Asservissement linéaires by I. Jelinsky in the series Vuibert Technologie in order to avoid giving readers any incorrect interpretation and confusion with the concepts presented in this book.

radar antenna alignment system for the monitoring of the trajectory of an airplane or a satellite, and an air conditioner designed to stabilize the temperature at a constant value fixed in advance.

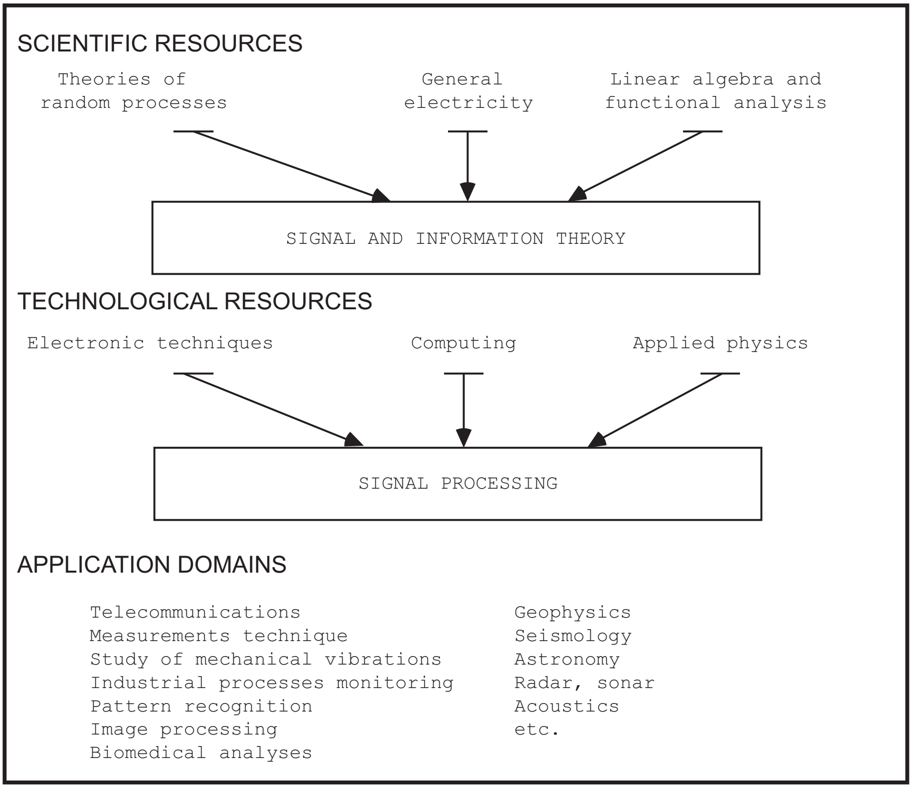

Figure 1. *Applied scientific and technological resources*

A process can be defined by establishing relationships between input and output quantities (this will be formally defined in different ways throughout this book. It is represented in Figure 4.

In the example of the car, the output is the speed and inputs may be the position of the accelerator pedal, the slope of the road and/or any other physical quantities that have an influence on the speed (the output of the system). Inputs consist of variables that can be manipulated (position of the pedal) and upon which no action is possible (the slope of the road). The latter are called disturbance inputs, they may be measurable or not accessible, random or deterministic. The variables that can be manipulated can be used as control inputs.

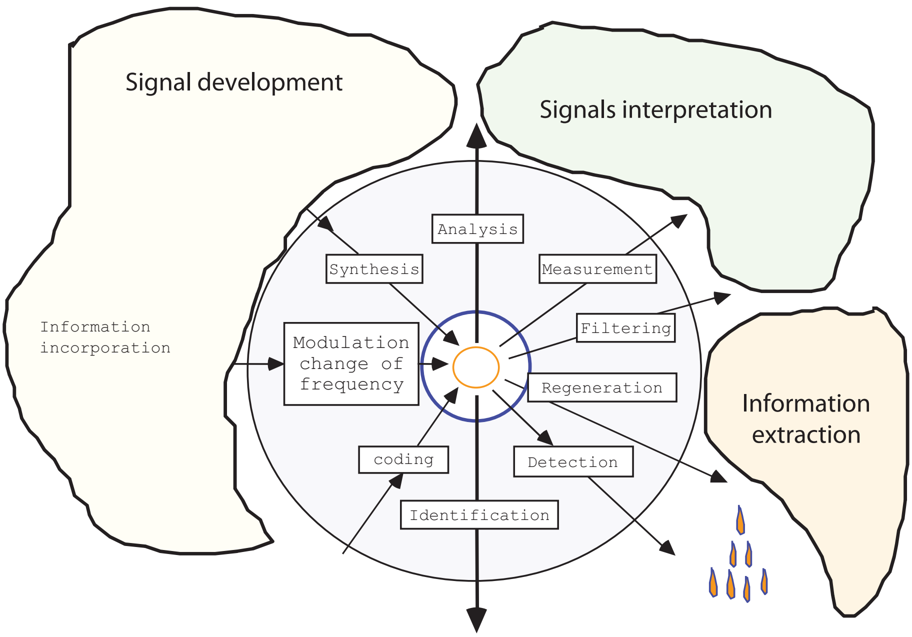

Figure 2. *Basic concepts of theoretical study and processing methods*

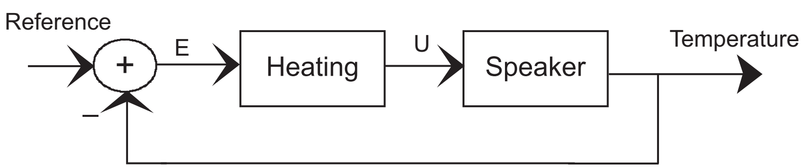

Figure 3. *Diagram of the model for vehicle operation*

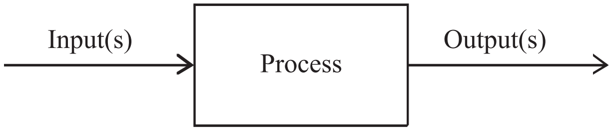

Figure 4. *Process with multiple input and output quantities*

In order to maintain the constant speed of a vehicle, a mathematical model of the process must be developed, in which the vehicle speed is linked to the position of the accelerator pedal, and then by inverting this model, the necessary input to obtain a specified speed can be derived. As a result, if the system output is not taken into consideration, an open-loop control is carried out (see Figure P.5).

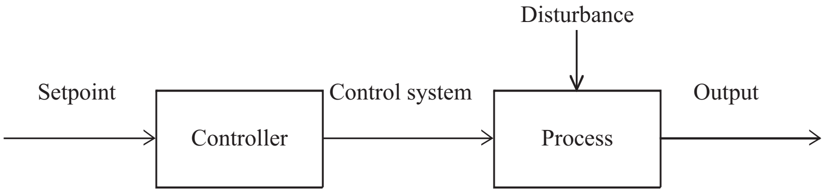

Figure 5. *Open-loop process*

This diagram shows that the control system does not account for disturbances; it cannot function properly. For example, if the vehicle is confronted with different slopes, the slope is considered a disturbance input for the process. It will be required that the model take the slope into account and thus a measurement system of the slope (which would result in a compensation of the measurable disturbances).

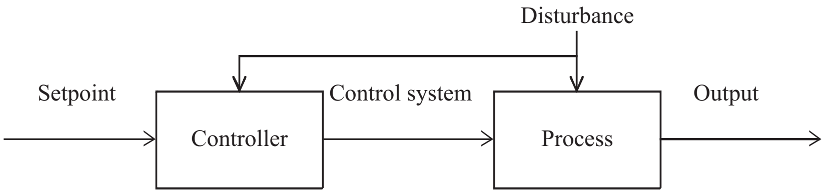

Figure 6. *Open-loop process with disturbances*

To improve the behavior, a control system can be defined that calculates, based on the desired speed obtained speed difference, the necessary action on the pedal to regulate (stabilize) the speed at a value specified by the operator. We will thus obtain an automatic control system of the speed of the vehicle. A sensor measuring the speed obtained is necessary. This system automatically performs what the driver does: it compares the target speed with the actual speed (displayed by the dashboard (sensor)) and acts upon the accelerator to reduce the speed difference to zero. The result will then be a *control system* or *loop system* or servo (servo system). The block diagram (functional) of the principle of a servo system is shown in Figure 7:

– y^d: setpoint is an electrical quantity that represents the desired value of the output of the system;

– ε: error signal between the setpoint and the actual output of the system;

– u: control signal generated by the control system;

– y: is a physical quantity that represents the system output.

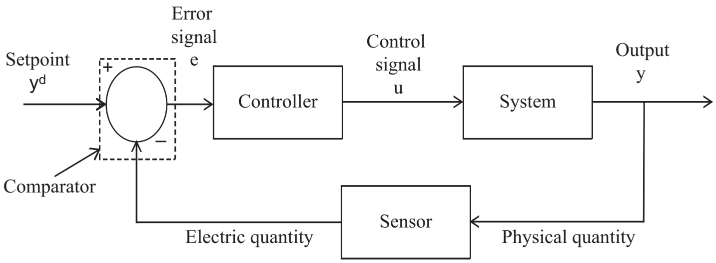

Figure 7. *Functional block diagram of a servo system*

The physical quantity y is measured with a sensor that translates it into an electrical quantity. This electric quantity is compared to the setpoint using a comparator.

One of the great advantages of a looped system compared to an open-loop system lies in the fact that the loop system automatically rejects disturbances. In control systems, when the setpoint (reference) is constant, it is referred to *control* (for example oven temperature control and speed control of a motor); in the case where the reference is not constant, this is referred to as *tracking* (for example target tracking by an antenna).

An additional input (measure of the slope), with respect to the equipment existing in the previous example, would complete this diagram with an *anticipation* about the effect of the disturbance (due to the slope variation).

A system is said to be controlled when there is a loop between the output and the input or when the variable to be adjusted is the setpoint input of the system. For example, for the heating system of a house or of an enclosure, the input is the temperature setpoint and the output is the temperature in the enclosure. An open-loop heating system is a system that does not show any loopback, taking into account the effective temperature of the enclosure. Thus, it is sensitive to external shocks, a rise in the external temperature would cause an excess of heating.

Examples:

The examples are as follows: temperature system control of an oven, fluid flow servo control, speed system control of the trajectory of a vehicle. When the desired path is reduced to a point, this is referred to as regulation and not as system control because the aim here is to stabilize the output of the system at a point. A control system can be qualified by its degree of stability, accuracy, response speed, sensitivity to disturbances acting on the system, robustness with respect to disturbances on measures and errors or variations of the characteristic parameters of the system. The accuracy of a control system can be characterized by the maximum amplitude of the position error.

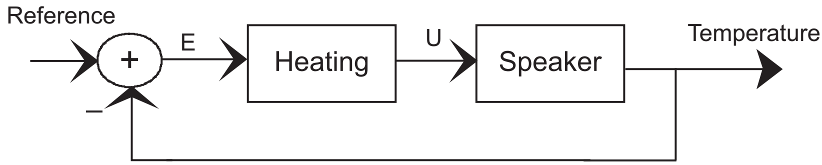

Figure 8. *Speed regulation of a motor*

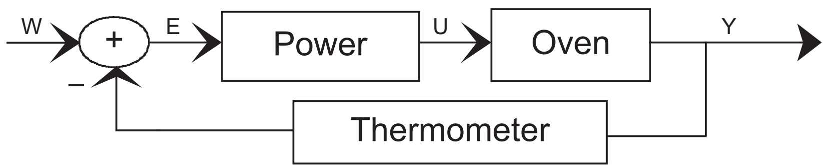

Figure 9. *Temperature regulation of an oven*

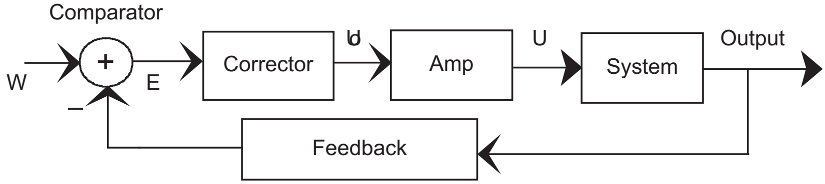

Figure 10. *Control system with correction*

In the definition of a control system, we will write transfer functions as follows: $H(p)$ transfer of the system to be controlled, p is the Laplace operator; $R(p)$ transfer of the sensor or measurement unit, $C(p)$ transfer of the corrector or controller. The setpoint is $\omega(t)$ and the output to be controlled $y(t)$. The direct chain consists of $C(p)$ and $H(p)$. Block $R(p)$ constitutes the feedback chain. $e(t)$ is the difference between output and setpoint also called control error or trajectory tracking error. In order to simplify study, we consider a unity feedback scheme in which $R(p) = 1$.

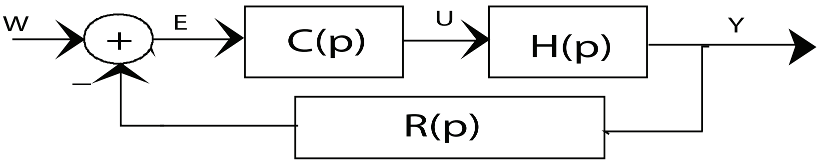

Figure 11. *Controlled transfer function with feedback*

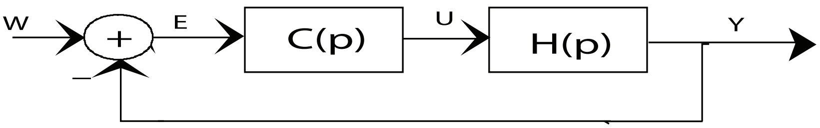

Figure 12. *Controlled transfer function without feedback*

In general, transfers $H(p)$ and $R(p)$ are known, estimated or can be obtained and the goal is the determination of a corrector $C(p)$ that can satisfy the required performances for the closed-loop system (transfer from w to y).

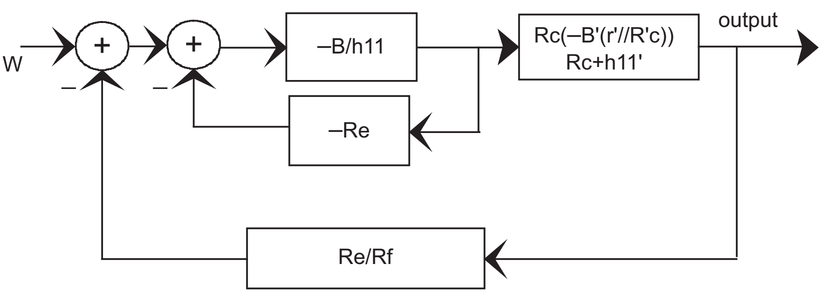

Figure 13. *Control system with closed-loop system controller*

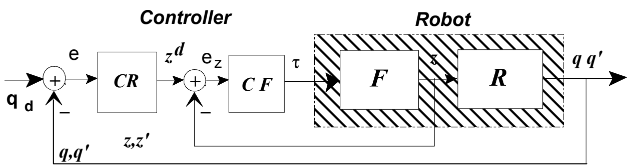

Figure 14. *System control with correction of a robotized system*

Several types of systems can be distinguished:

– continuous systems for which all measured quantities are continuous;

– discrete systems for which all measured quantities are only measured at very specific times (discontinuous or discrete); these are referred to as sampled data or digital systems;

– linear systems (they can be described by linear differential equations);

– nonlinear systems (described by nonlinear differential equation). It is possible, often in the first approximation, to linearize nonlinear systems based on an operation point (equilibrium), considering small variations around this point;

– time-invariant systems (described by differential equations with constant coefficients) and time-variable systems (described by differential equations with time-variable coefficients).

In this book, we consider time-invariant linear, continuous and sampled-data systems.

NOTATION 1.– *Consider a continuous r-input system denoted u and m outputs y,*

$$u \in U \subset R, y \in Y \subset R \quad \text{[P.1]}$$

$$u \in U \rightarrow . \rightarrow y \in Y \quad \text{[P.2]}$$

A minimal state representation of this system will be written as:

$$\dot{X} = A.X + Bu \quad \text{[P.3]}$$

$$y = C.X + D.u \quad \text{[P.4]}$$

Its transfer function

$$G(p) = C(pI - A)^{-1}B + D \quad \text{[P.5]}$$

is denoted as:

$$G(p) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = [A, B, C, D] \quad \text{[P.6]}$$

A is stable: the eigenvalues of A have a real part < 0.

$G(p)$ *is stable: the poles of* $G(p)$ *are in* $Re(p) < 0$.

$G(p)$ is instable: the poles of $G(p)$ are in $Re(p) > 0$.

$\tilde{G}(p) = G(-p)$

$G(p)$ is an eigen transfer function if $G(\infty)$ is finite.

$G(p)$ is a strictly eigen transfer function if $G(\infty) = 0$.

A^T is the transpose of matrix

$$A = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \quad [P.7]$$

$$A^T = \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \end{bmatrix} \quad [P.8]$$

A^{-T} is the inverse transpose matrix of A.

A^* is the conjugate transpose matrix of $A = [a_{ij}]$ (or Hermitian transpose matrix of A). $A^* = [a_{ij}^*]$

$\lambda_i(A)$ is the ith eigenvalue of A.

$\sigma_i(A)$ is the ith singular value of A.

$\underline{\sigma}(A)$ and $\bar{\sigma}(A)$ are the minimal and maximal singular values of A.

$Diag(a_i)$ is the diagonal matrix whose diagonal elements are the a_i.

C_- is the set of complex numbers with a negative real part.

C_+ is the set of complex numbers with a positive real part.

$\boldsymbol{C}^n$ is the set of complex vectors with elements in C.

$\boldsymbol{C}^{nxm}$ is the set of complex matrices of dimensions (nxm) with elements in C.

$< x, y >$ is the scalar product of x and y.

$h \circledast u$ is the convolution product of $h(t)$ and $u(t)$.

$\mathcal{F}$ is the Fourier transform operator.

θ_h convolution operator by $h(t)$, $H(p)$ should denote the Laplace transform of $h(t)$.

$\Lambda_{Hg} = H(p).g(p)$ *is the Laurent operator or multiplication in the frequency domain.*

$\oplus$ *Direct sum of two spaces.*

$H_2^{\perp}$ *Orthogonal space at* H_2*;*

with the set H_2=$\{H(p)$ analytic matrix function in $Re(p) > 0\}$

Π_1 is the orthogonal projection on H_2 and Π_2 is the orthogonal projection on $H_2^{\perp}$.

NOTATION 2.– $\mathcal{B}(x, r) \equiv$ *Globe of radius* r*, centered in* x *of the space; example* $\mathcal{B}(0, 1)L_2 = \mathcal{B}L_2$ *refers to the Globe of unit radius of the space* L_2*.* L_2 *is the set of square-integrable functions.*

In the literature, a real rational transfer function refers to a rational transfer function with real coefficients.

Nao robot: application for home care

In view of these considerations and following previous and present works, the purpose of this section is the perception for the joint understanding of space and surroundings of an autonomous, cognitive and sociable personal robot. This Nao robot will typically act according to a planned action scheme, ensuring their viability, the consistency of current models and the presence of entities opposed to its initial plan, while interacting with the physical world through perception. The selected approach, which is clearly aimed at integrating perceptual functions on robotic platforms, relies on probabilistic modeling to consider multiple and uncertain percepts. At the sensory level, these percepts will be mainly originating from the vision embedded in the robot. These perceptual functions are to be derived from autonomy, cognition and sociability capabilities outlined for our Nao robot.

An increasingly more worrying situation due to the aging of the population is the increase in the number of elderly people living alone, far away from their loved ones, sometimes physically or mentally vulnerable. Studies recommend that, at the social level as well as at the economic level, people stay at home, eventually resorting to help (cleaning, care, gardening, etc.), to preserve as much as possible the references and the social network of the person. However, with the cost of home care being relatively burdensome, assistance times are limited and are not always enough to fight solitude. In addition, when the elderly person presents risks of accidents (fall, stroke, etc.), or when undergoing medical treatment, monitoring solely based on domestic help has become risky, or even insufficient (admission to hospital then being preferable).

To fight more effectively against isolation and the dependence of elderly people, the presented system aims to implement a prototype for an automated and robotic system for home care. Without claiming that it is capable of recreating or replacing real human contact, the proposed system, based on the integration of several technologies, will create a permanent, friendly and reassuring, presence at home. Due to the use of modern means of audio/video communication (speech recognition, speech synthesis, etc.), by the mobile humanoid Nao robot from Aldebaran Robotics and that of fixed cameras allowing the environment to be perceived, the objective is to provide a set of services that makes it possible to assist senior citizens in their daily tasks (engaging with relatives, remote medical consultation, looking for objects, medication reminders, etc.), entertain them (games, physical exercises, friendly presence, etc.) and detect dangerous or abnormal situations (falls, prolonged inactivity, unusual behavior, etc.) to, in the end, alert the doctor and relatives.

1

Control, Servo-mechanisms and System Regulation

This chapter explores compensator servo-mechanisms and control, correction and proportional control.

1.1. Introduction

1.1.1. *Generalities and definitions*

In all areas of physics, for the research, analysis and understanding of natural phenomena, a stage for modeling and the study of the structure of the physical process is necessary. This has led to the development of modeling, representation and analysis techniques of systems using a fairly general terminology. This terminology is difficult to introduce in a clear manner but the concepts, which it relies upon, will be defined in detail in the following chapters.

A physical process is divided into several components or parts forming a system. For example, this is the case of an engine that consists of an amplifier, power supply, an electromagnetic part and a position and/or speed sensor. The system input is the voltage applied to the amplifier and the output is either the position or the speed of rotation of the motor shaft.

Among the objectives of the control engineer, we can identify modeling, behavior analysis and the regulation or control with the aim of dynamically optimizing the behavior of the system. It should be noted that one preliminary and very important step is the *configuration* of the system before its control. During this step, the automation expert must define sensible choices of sensors, actuators and their placement in the system to optimize the control (control means verification of the good functioning of all sensors, actuators, system and corrector or control law). It is only after this stage that control synthesis finds its place, which might simply be reflected by the use of

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a conventional controller (proportional, proportional, integral and derivative (PID), phase advance or phase delay or other).

Driving the system or control serves the purpose of ensuring that the variables to be adjusted or system outputs follow a desired trajectory (curve with respect to time in general) or have dynamics defined by the specification requirements, for example temperature control of an oven, fluid flow control or speed and trajectory control of a moving object. When the desired trajectory is reduced to a point, this is referred to as regulation and not as control because the main purpose here is to stabilize the output of the system in a point. The role of control is to allow or to improve the resulting performance of a system, using actuators and sensors available for information acquisition and enabling reaction based on behavior. In general, this can be done using a negative-feedback loop (return or feedback loop) and sometimes a compensation or anticipation chain of the dynamic effects of the system (feedforward or (pre or post) compensation). The operation of a vehicle is according to the block diagram shown in Figure 1.1.

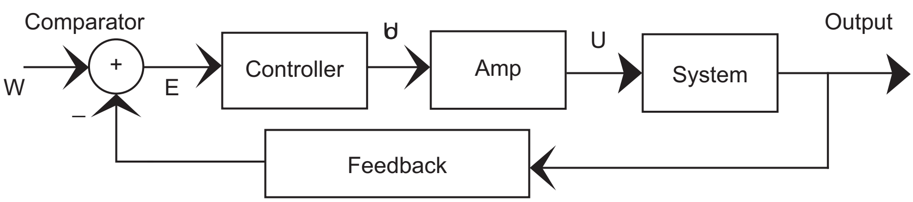

Figure 1.1. *Schematic diagram of a controlled system with compensation and feedback sequence*

In the definition of a control system, we will express transfer functions as follows:

– $H(p)$ transfer of the system to be controlled, p is the Laplace operator;

– $R(p)$ transfer of the sensor or measuring device;

– $C(p)$ transfer of the corrector or servo controller element.

The setpoint is $w(t)$ and the output to control is $y(t)$. The direct chain consists of $C(p)$ and $H(p)$ and $R(p)$ constitute the feedback chain. The difference between output and setpoint is $e(t)$ and is also called control error or trajectory tracking error. In order to simplify the study, we are considering a unity feedback scheme in which $R(p) = 1$.

In general, transfers $H(p)$ and $R(p)$ are known or can be obtained and the objective is to obtain a corrector $C(p)$ that is able to satisfy the performances required for the closed-loop system (transfer from w to y).

For the regulation of the temperature of a speaker to a reference value, it is possible to use one of the following block diagrams.

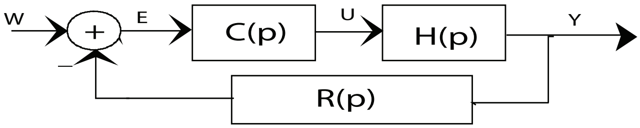

Figure 1.2. *Schematic diagram of a feedback system* $R(p) = 1$

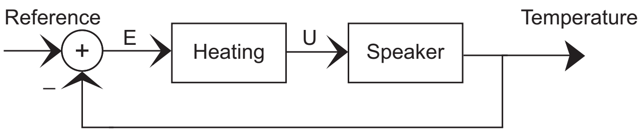

Figure 1.3. *Speed regulation of a motor*

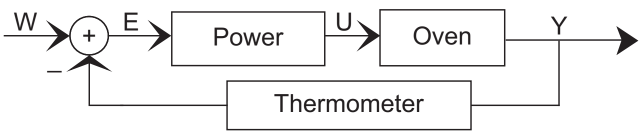

Figure 1.4. *Temperature regulation of an oven*

Vehicle operation follows the principle of the diagram shown in Figure 1.5.

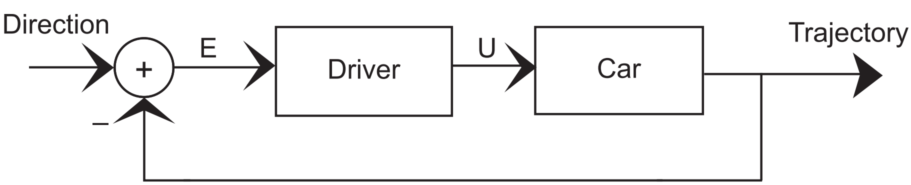

Figure 1.5. *Schematic diagram of the model for vehicle operation*

In this preface, we are going to cover some conventional methods for the design of a control system. This study will serve the purpose of finding a control structure allowing a servo system to be given dynamic characteristics or performances established *a priori* in the definition of the requirements, either in terms of temporal response or in terms of frequency response. In general, the latter is defined to ensure:

– the stability of the controlled system (loop system);

– the smallest possible permanent errors;

– a suitable dynamic behavior: a response quickly reaching its asymptote, the lowest overshoot possible, etc.

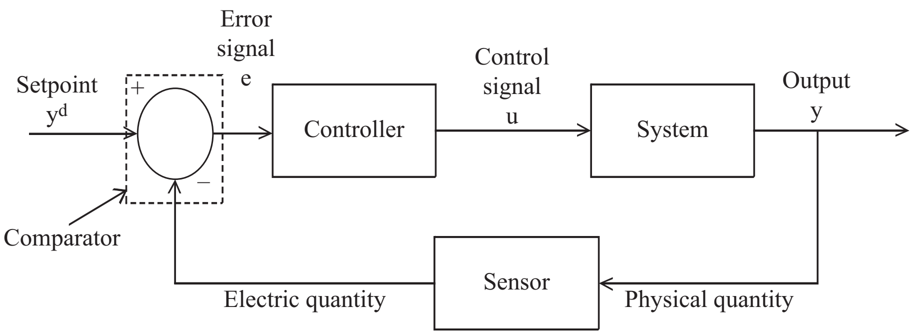

Figure 1.6. *Servo system*

The conventional operation of a servo system is shown in Figure 1.6:

– y^d: the setpoint is an electrical quantity that represents the desired output value of the system;

– ε: the error signal between the setpoint and the actual output of the system;

– u: the control signal generated by the controller;

– y: a physical quantity that represents the system output.

The physical quantity y is measured with a sensor that translates it into an electrical quantity. By means of the comparer, this electric quantity is compared to the setpoint, which is an electric quantity.

A model describing the dynamic behavior (physic) of the open-loop (OL) system is necessary for control synthesis. In general, the accuracy required for modeling is dependent of the finality of the control and the required performance. It should be noted that there are several types of models.

The *simulation model* is useful for the study of behavior and the response of the system to different excitations. It allows that the laws of control be tested and that performance be evaluated before application to the actual system. It has to be as accurate as possible (including disturbance, noises, nonlinearity and all the parts able to be modeled etc.).

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