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Introduction of Disturbance Observer

The **disturbance observer** is called as the pronoun of **motion control** and has been highly evaluated worldwide [1, 2]. Disturbances can be added to the input of the control plant, the output, or even any part of the **internal state**. There are two types of disturbance observers (DOBs): those that only estimate disturbances and those that also estimate state variables, such as position and velocity.[1] They are collectively called DOBs unless one wants to emphasize something in particular.

No matter how good the control or estimation method is, it is not a panacea. When a new control method is proposed, it is overhyped, leading to a boom. Examples include H_∞ control, sliding mode control, and model predictive control. However, as the boom continues for a while, their disadvantages become apparent, such as the need for the skill and technique in using them and their compatibility with the control plant. DOBs are no exception. It is essential to understand their pros and cons to use them well.

The intended readers are students and professionals learning the theories and techniques related to control engineering and motion control. They are assumed to have some knowledge of **classical control theory** and **modern control theory**. A minimal explanation is provided in the appendix for readers without sufficient knowledge.

1.1 Types of Disturbance Observers

1.1.1 Introduction

This book introduces eight types of DOBs for designing a DOB, as shown in Table 1.1. **Kalman filter** in the eighth line is not an observer but is included in

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[1] Examples have been proposed such as referring to it as disturbance and velocity estimation observer [3, 4] because it estimates velocity as well or reaction force estimation observer [5] because it estimates reaction force specifically.

Disturbance Observer for Advanced Motion Control with MATLAB/Simulink, First Edition. Akira Shimada.

Companion website: www.wiley.com/go/disturbanceobserver

Table 1.1 Types of disturbance observer design.

Systems	DOB design forms	Object to estimate
Continuous system	(1) Transfer function	Only disturbances
	(2) Identity observer	All state variables and disturbances
	(3) Minimal order observer	All state variables except outputs
	(4) Adaptive observer	Parameters, state variables and disturbances
Digital system	(5) Transfer function	Only disturbances
	(6) Identity observer	All state variables and disturbances
	(7) Minimal order observer	All state variables except outputs
	(8) Kalman filter	All state variables and disturbances

this table because it is designed for estimating disturbances. The Kalman filter and the adaptive observer can be designed as both continuous and digital systems, but they are limited to the above.

Many references use the **transfer function** of the continuous system to represent DOBs, specializing only in its estimation, which corresponds to the first line of Table 1.1. This may be because it is simple and easy for us to understand and implement. However, we can simultaneously estimate the control plant's original state variables, such as velocity and current other than disturbances, using the general observer theory. These correspond to lines 2–4 and 6–8 of the table.

Suppose that readers want to use various physical estimates effectively in designing the control system. In that case, they can design the DOB using the **identity observer** designing method. However, if they emphasize that they do not need to estimate the observed output, they can use the **minimal order observer** design method as an excellent choice.

Theoretically, DOBs expressed in transfer functions are equivalent to those derived from the design process for minimal order observers, as shown in rows 3 and 7. Many studies use the form of the transfer function from the beginning because only the disturbance estimation function is extracted and reexpressed in the form of a transfer function in the design process.

The difference between a continuous and a digital system is whether the design is based on continuous control theory or digital control theory.[2] If there is no need to consider the effect of the length or shortness of the control period, it is better to design a continuous system where the physical meaning is easy to grasp. However, it is more desirable to design it as a digital system if the control cycle and the

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[2] Note that this book does not distinguish between the words discrete systems and digital systems.

program to be implemented on a digital computer are considered. The best design method cannot be generally determined and is left to the designer's discretion.

1.1.2 Observer and Control System Design Concepts

The disturbance estimate $\hat{d}(t)$ in the DOB is often fed back with a sign for canceling disturbance.[3]

Figure 1.1 represents the structure of a basic control system that uses a DOB. In the figure, the "disturbance observer" outputs the disturbance estimate $\hat{d}$, and **positive feedback** is performed to cancel the disturbance d. Consequently, the control plant appears free of disturbances when viewed from outside the dotted section, and the apparent control input is $\bar{u}$. The control input is u, and $\bar{u}$ stands for the force f [N] for a linear mechatronics system, the torque τ [N m] for a rotating mechatronics system, and V [V] for the voltage input of an electric circuit. The output y is also chosen as the velocity v [m/s], ω [rad/s], position x [m], θ [rad], etc. In this book, we mainly use linear motion mechatronics systems as examples; thus, the explanation will be based on that assumption. For example, the equation of motion of a quality point in a vacuum is $f = ma$.

DOBs are often used to realize a control method called "**acceleration control**." The nominal value of the mass m_0 is connected in a series in front of the dotted line, and the apparent control input is the acceleration reference value a_{ref}.[4]

Suppose the actual acceleration can be made to match the acceleration reference value. In that case, the control plant can be regarded as a single-dotted line, and the position and velocity controllers or the force control controller can be

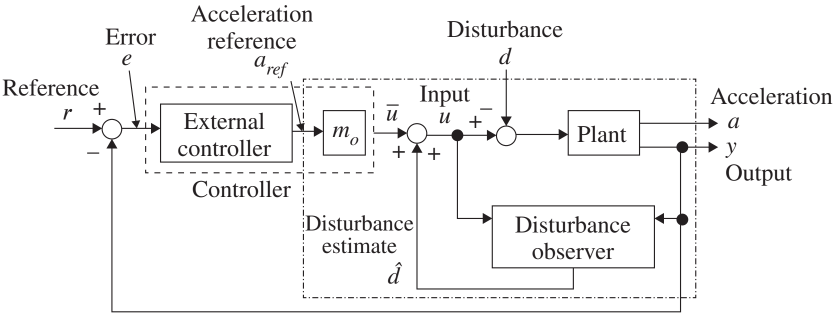

Figure 1.1 Basic structure of the control system based on acceleration control.

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[3] If the disturbance is input as a negative component, positive feedback is used to cancel it out (positive feedback), and negative feedback is used to define it with a positive sign (negative feedback). However, feedback is not always a must.

[4] In this book, m denotes the mass of the control plant generally. However, only when we want to emphasize that it is a nominal value this book uses m_0.

implemented outside. This means that this could enable the design of a simple control system. The acceleration controller is configured inside the control system based on the concept of "moving a mechatronics system by acceleration," and the controller for each application is configured on the outside.[5]

Suppose a control system is to be designed based on the basic principle of dynamics that "a mechatronics system is driven by force (or a rotating system is driven by torque)." It is natural to use u or $\bar{u}$ (=force f for a linear motion system or torque τ for a rotating system) as the control input instead of a_{ref} and design the control system according to the general dynamics model. Here, m_0 is unnecessary because the part in the broken line represents the outer controller.

An alternative is to work without the feedback from the disturbance estimate $\hat{d}$. For example, when designing the identity DOB based on the state-space model, the purpose is not to estimate the disturbance but to estimate the state variable $x(t)$ with high accuracy considering the effect of the disturbance.

This book introduces the disturbance estimation method and various control methods using various concepts, including the case when the control plant is a **multiple input, multiple output** (**MIMO**) system.

We consider various conditions and environments such as nonlinearity, instability, and the effect of noise. Flexible use of classical control, modern control, and other robust control theories can further extend the usefulness of DOBs.

1.2 Format of Example and Use of MATLAB

1.2.1 Format of the Example Problem

Most studies dealing with DOBs are examples of rotating systems based on motor control. However, to understand the essential theory, this book introduces single-input single-output (SISO) system examples with a cart as an instance of a linear mechatronics system because we believe that it is simple and easy to understand.[6] The reader who needs to design a rotating system could convert the linear model to a rotating model.

Consider a simple spring-mass damper system. Using the position x, velocity v, force f, external force f_{ex}, **coefficient of viscous friction** c [N/(m/s)], and **coefficient of elasticity** k [N/m], the following equations can be obtained:

$$m\dot{v}(t) + cv(t) + kx(t) = f(t) - f_{ex}(t) \tag{1.1}$$

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[5] The concept of acceleration control is to contain the problems of the dynamic system inside. After that, it is to consider the kinematic model as the control plant. However, this does not mean that friction and the like have disappeared. Therefore, care must be taken not to overlook the essential aspects of mechatronics system structure and dynamics.

[6] Some may argue that we are only dealing with low-dimensional objects, but we prioritize ease of understanding.

In contrast, assume that the rotation angle θ, rotation velocity ω, torque τ, disturbance torque τ_{ex}, moment of inertia of linear motion system J [kg m^2], coefficient of viscous friction c_θ [N m/(rad/s)], and the modulus of elasticity k_θ [N m/rad] satisfy:

$$J\dot{\omega}(t) + c_\theta\omega(t) + k_\theta\theta(t) = \tau(t) - \tau_{ex}(t) \tag{1.2}$$

Note that the disturbance estimation with the velocity information and that with the position information are often illustrated side by side.

1.2.2 Using MATLAB/Simulink

This book includes sample programs with "MathWorks" **MATLAB/Simulink®** to help the reader understand the specifics. Although the author is not an expert in MATLAB programming and does not have the latest knowledge, we have tried to make it accessible to a third party. However, the original m-file sample codes made by the author include long codes on how to draw figures as the simulation results, and the number of pages would be enormous. Hence, the sample m-files include up to the parts for calling and executing Simulink models but not the parts related to drawing figures. Readers would find the typical drawing program in the appendix helpful.

1.3 How This Book Is Organized

1.3.1 The Structure of This Document

The basics of DOBs are expressed in Chapter 2, mainly in the transfer function representation. Specifically, the concept of disturbances and the basic design methods are introduced, and disturbance rejection control and acceleration control methods are explained. An observer for estimating the reaction force is introduced, and then the **internal model principle** and **two-degrees-of-freedom** (**2-DOF**) **control system** are addressed. Finally, we describe the effect of modeling error.

In Chapter 3, we introduce the relationship between the stabilized control system using the coprime factorization and the control system with a DOB and show the design of the free parameter $Q(s)$ for the uncertainty of the control plant. This part is an encounter between the so-called "**robust control theory**" and the DOB.

Chapter 4 introduces DOBs and control system design methods for continuous systems based on modern control theory, especially **identity disturbance observer**, **minimal order disturbance observer**, **higher order disturbance observer**, and **periodic disturbance observer**. Additionally, observability, i.e. the possibility of observer design, is explained using a DC motor as a subject.

In Chapter 5, we present the design method for digital systems. As in Chapter 4, the same dimensions, minimum dimensions, and higher order disturbances are treated. We also explain the separation theorem, which allows us to design the control system's poles and the poles of the observer separately.

Chapter 6 deals with disturbance estimation for the **vibration system**. The disturbances in this chapter are neither input nor output disturbances but exactly disturbances to the internal state variables, i.e. **noninput/output disturbances**. However, they seem to be good examples of how they can be estimated if the observability is satisfied.

Chapter 7 introduces a technique to estimate the effect of **communication delays**, idle time disturbance, and stability maintenance.

Chapter 8 focuses on the **multirate control system**, which has recently attracted much attention and also introduces the impact of using a DOB in conjunction with it.

Chapter 9 introduces the **model predictive control** (MPC) combined with a DOB. Although the DOB in this chapter is not new and uses the observers in Chapter 5, we decided to introduce it because we believe the combination with MPC is meaningful.

In Chapter 10, we introduce a disturbance estimation method using the **Kalman filter**. The method is not a complete design method, and although the state variables can be estimated with high accuracy, the disturbance estimation is slow. To compensate for this shortcoming, the B and covariance matrices, subject to system noise, are set by trial and error. Other methods, such as assuming disturbances represented by higher order polynomials and modifying the error covariance matrix, are also reported, and future developments are expected.

In Chapter 11, we show that adaptive control theory can be used to design DOBs, such as the **adaptive disturbance observer**. An adaptive DOB is an observer that simultaneously estimates the parameters representing the control plant, the state variables, and the disturbances. This paper uses only classical design methods, and future developments are expected.

Chapter 12 is on velocity measurement and estimation, whose characteristics may feel different from all of the previous chapters. This chapter was added because there have been many reports on the use of velocity information in implementing DOBs. It is necessary to pay attention to the velocity measurement and estimation methods to ensure the accuracy of the estimation.

This book does not cover further developments in DOBs, such as **haptics** [6], or even applications to artificial intelligence. Nevertheless, we believe that this book will be found helpful and widely deployed.

1.3.2 How to Read This Book

While many technical books allow the reader to understand the book's core step by step as one reads from Chapter 1 onward, this book does not necessarily do so.

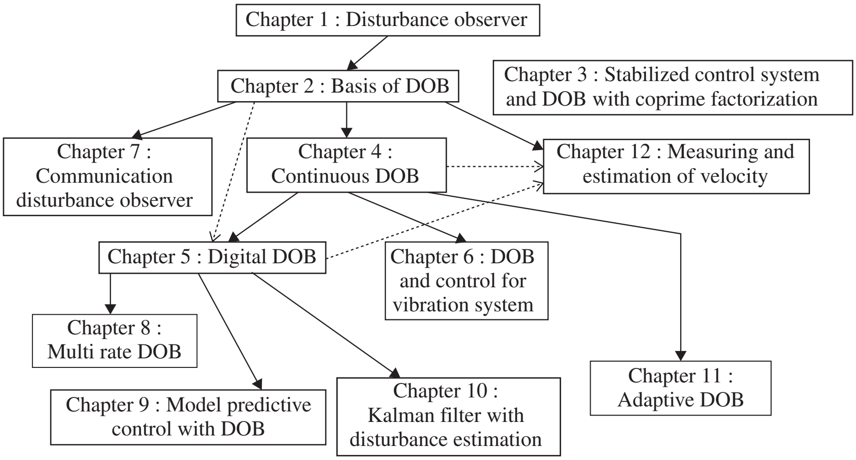

Figure 1.2 Structural diagram of this book.

Figure 1.2 shows the structure of the book. Here, the solid arrows indicate connection guides, and the dashed arrows are the candidates for connections. For instance, a reader who wants to learn about communication DOBs for systems with time delays can read Chapters 1, 2 and 7, skipping Chapters 3–6 even if the person does not know DOBs.

Chapters 8–10 are explained in digital systems and are recommended to be read after Chapter 5, but they are independent and do not need to be read in order. Furthermore, since many items are touched upon in Chapters 2, 4, and 5, some readers may not need to read through all of them. We hope that you will be able to “pick up” the items that interest you positively.

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