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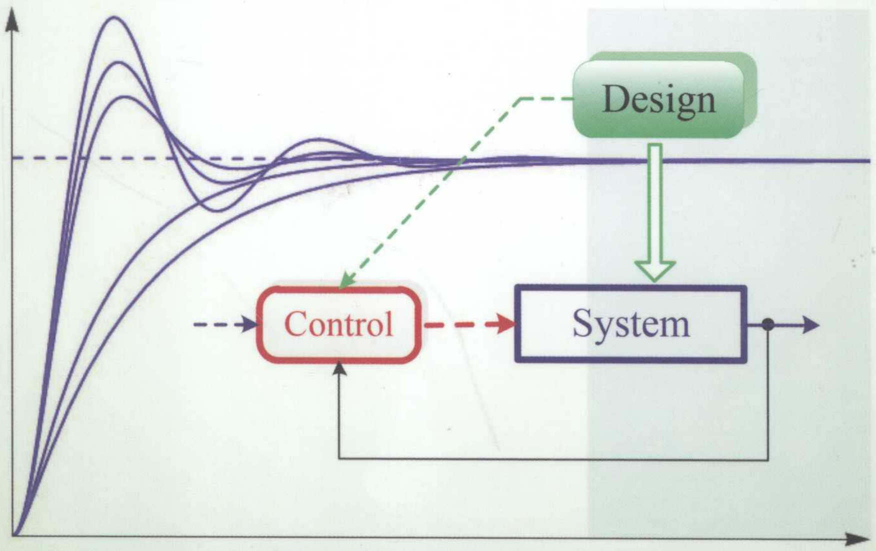
System Design AND Control Integration FOR Advanced Manufacturing



Han-Xiong Li • XinJiang Lu

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SYSTEM DESIGN AND CONTROL INTEGRATION FOR ADVANCED MANUFACTURING

HAN-XIONG LI
XINJIANG LU

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PREFACE

The manufacturing industry has changed drastically from the traditional industry, like steel and auto factory, to the semiconductor or IC industry of the 1980s, and to the internet-based global manufacturing nowadays. Advanced manufacturing involves the use of technology to improve products and/or processes, with the relevant technology being described as "advanced," "innovative," or "cutting edge." The distinctions between traditional manufacturing and advanced manufacturing are in terms of volume and scale economies, labor and skill content, and the depth and diversity of the network surrounding the industry, and intelligence added in the system. No matter how complex or advanced the manufacturing operation is, it always consists of basic actions offered by basic systems that can be categorized as static systems, dynamic systems, and their combination. Performance of each basic system will be crucial to the overall performance of the manufacturing.

In order to design and manufacture these high quality products at lower costs, accurate mechanical systems are crucial in the manufacturing industry. One problem is inconsistent performance caused by uncontrollable variations in manufacturing operations, material properties, and complex operating environments. This inconsistent performance often results in a failure in operation. Thus, robust performance, insensitive to all possible changes in demand, model uncertainties, and external disturbance, is one of the most important concerns in the design and control of these systems.

Robust design and its integration with control are the most important methods commonly used to achieve robust performance of the system. The studies of robust design and its integration with control are becoming increasingly important. In the last few decades, there have been many studies on robust design and its integration with control. There are still many unsolved problems. The purpose of this book is to provide a brief view of the previous work on robust design and its integration with control, and develop new design and integration methods to tackle some of these unsolved problems.

In this book, a systematic overview and classification is first presented on robust analysis/design for static and dynamic systems, and the integration of design and control. Limitations and advantages of various approaches are also discussed. Next, three novel robust design approaches are proposed for design of the static system: the variable sensitivity based robust design approach for small-scale parameter variation, the multi-domain modeling-based robust design for large-scale parameter variation, and the hybrid model/data-based robust design for both parameter variation and model uncertainty. Then, the robust eigenvalue design methods are developed to maintain both stability and robustness of the dynamic system under parameter variation and model uncertainty. Finally, two novel methods are proposed for integrating design and control for the hybrid system under parameter uncertainty. One method is for the dynamic system with hybrid discrete/continuous variables. An easily controlled dynamic behavior will first be obtained through the process design, and then integrated with control under the robust pole assignment. Another method is for the hybrid system working in a large region with an unmeasured overall performance. A low level process control will be integrated with high level system design with the help of fuzzy modeling method, and optimized with the particle swarm optimization (PSO) method. All the methods presented in this book have been successfully applied to the design of some mechanical equipment and the curing process in IC packaging, and are applicable to a wide range of systems in the manufacturing industry.

The book will be of great benefit to undergraduate and postgraduate students in many disciplines, including manufacturing engineering, mechanical engineering, electrical engineering, and control engineering. The book is also intended for researchers, research students and application engineers interested in robust design and its integration with control.

HAN-XIONG LI

City University of Hong Kong
Central South University

XINJIANG LU

Central South University

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PART I

BACKGROUND AND FUNDAMENTALS

CHAPTER 1

INTRODUCTION

This chapter is an introduction of the book. It briefly introduces background, motivation, and objectives of the research, followed by the contribution and organization of the book.

1.1 BACKGROUND AND MOTIVATION

Since we moved into the Industrial Age, most of the products used have been manufactured by machines and production lines. The manufacturing industry has changed much from the traditional sector, like steel and auto factory, to the semiconductor or IC industry in 1980s, and to the internet-based global manufacturing nowadays. Advanced manufacturing uses the so-called "advanced," "innovative," or "cutting-edge" technology to improve products and/or processes. The distinctions between traditional sectors of manufacturing and advanced manufacturing are in terms of volume and scale economies, labor and skill content, and intelligence added in the system.

In modern IC industry, the higher speed, the higher precision, and the higher intelligence have become common requirements to many of the processes involved, for example, epoxy/silicone dispensing (Li et al., 2007), curing process (Li, Deng, and Zhong, 2004; Deng, Li, and Chen, 2005), bonding/wiring process (Li and Zuo, 1999), and so on. Even in a traditional industry, like the forging press machine (Lu, Li, and Chen, 2012), the machine will seek help from an intelligence unit for meeting quality

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and economic constraints. Modern information technology can make a traditional system more advanced.

No matter how complex or advanced the manufacturing operation is, it always consists of basic actions offered by basic systems. These basic systems could be classified into the following three different categories.

- ***The static system.*** The performance is invariant over time, so it is discrete.
- ***The dynamic system.*** The performance is varying over time, so it is continuous.
- ***The hybrid system.*** It is a combination of the above two, which forms a hybrid system with discrete/continuous parameters, or a hybrid discrete/continuous system.

Design for advanced manufacturing is actually centered on the design and control of these basic systems, as the performance of every basic system is crucial to the overall performance of the manufacturing.

Since advanced manufacturing usually involves more complex system configuration and more advanced technologies, it will require a higher quality design of each basic system involved in the operation. However, unavoidable external variations in manufacturing operations, material properties, and a complex operating environment will result in an inconsistent performance of the system, which will be a big challenge to design for manufacturing. If these variations are not properly considered in product design, the degraded performance may result in a failure in operation (Caro, Bennis, and Wenger, 2005). Thus, robust performance, insensitive to all possible changes in demand, model uncertainties, and external disturbance, is one of the most important concerns in the design of any system.

In system design, robust design is the most important method commonly used to achieve robust performance. Its fundamental principle is minimizing the sensitivity of the performance to uncontrollable variations. Most of these approaches are for static systems, a few for dynamic systems. Furthermore, design and control are always separated in both academic research and industrial applications, which leads to few effective methods for the hybrid system.

The principal goal in this book is to develop effective design methods for fundamental systems existing in advanced manufacturing, including

1. novel robust design methods for both static and dynamic systems; and
2. robust design and control integration methods for the hybrid discrete/continuous system.

Though these methods are studied for basic systems in this book, they should be easily applied to any advanced manufacturing or production.

There are three different sets of variables that will appear in robust design.

- ***Design variable (or control variable).*** This is the controllable variable with its nominal value to be designed ideally between the upper and lower bounds. The variations around its nominal value are usually caused by poor manufacturing.

- ***Uncertainty.*** This usually includes parameter variation, noise, and model uncertainty. It cannot be adjusted by the designer, and thus is uncontrollable.
- ***Performance.*** This is the objective of the design and depends on the system model, design variable, and uncertainty.

Based on the above definition, we will introduce and discuss robust design and control integration in the rest of the chapter.

1.1.1 Robust Design for Static Systems

Robust design for the static system minimizes the influence of uncertainty on steady-state performance. Two typical robust design examples of the static system are introduced in Examples 1.1 and 1.2.

Example 1.1: Nonlinear system The damper structure widely exists in manufacturing industry and can be simplified as in Figure 1.1 (Caro, Bennis, and Wenger, 2005), where M and C_d are mass of the moving part and damping coefficient in the chamber, respectively. The excitation force $F(t)$ is assumed to be $F\cos(\omega \cdot t)$. The displacement will be $X(t) = X\cos(\omega \cdot t + \phi)$, where ϕ is the phase.

The performances X and ϕ can be expressed as follows:

$$X = \frac{F}{\omega\sqrt{C_d^2 + \omega^2 M^2}}, \quad \phi = \tan^{-1}\left(\frac{\omega M}{C_d}\right) \tag{1.1}$$

The objective is to keep the displacement and the phase at desirable values under the given excitation force. Due to manufacturing error, variations coming from fluid properties and the operating environment, there are large uncontrollable variations from the design variable M as well as the model parameter C_d in this system. Thus, this nonlinear system should be designed to be robust to these uncontrollable variations. ■

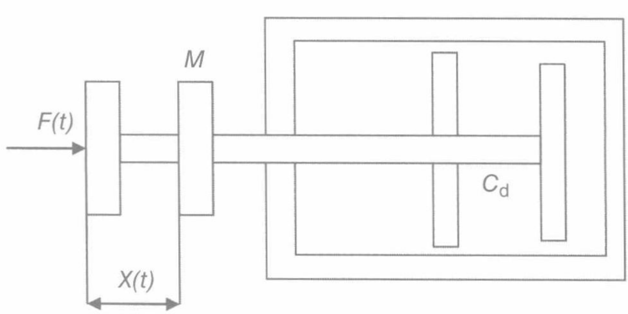

FIGURE 1.1 Damper

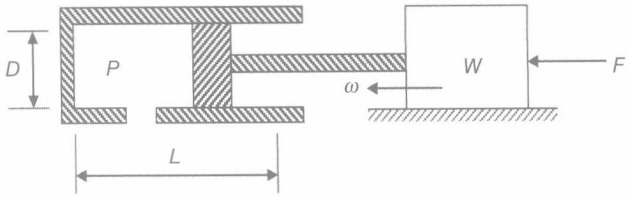

FIGURE 1.2 A pneumatic cylinder

Example 1.2: Partially unknown system The pneumatic cylinder, widely existing in manufacturing industry, is used to move a load of weight W along a horizontal surface, as shown in Figure 1.2. There exists the friction force F between the load and the surface, and the unknown disturbance force w is caused by other uncertain factors, such as leakage. The load is accelerated within a distance L to attain a steady-state velocity V. If the supply pressure is P, the actuator size D will be designed for a robust performance.

The performance V may be expressed as the sum of the known nominal model f and the model uncertainty Δf

$$V = f + \Delta f \tag{1.2}$$

with $f = \sqrt{\frac{gL(\pi D^2 P - 4F)}{2W}}$, $\quad \Delta f = \sqrt{\frac{gL}{2W}}\left(\sqrt{\pi D^2 P - 4(F + w)} - \sqrt{\pi D^2 P - 4F}\right)$.

The nominal model f is derived from the force balance in the absence of the disturbance force w. The model uncertainty Δf is caused by unknown disturbance force w, and thus it, including its structure, is unknown as a black box to designers. For a desirable performance, a robust design is needed to properly handle all these uncertainties coming from the design variable D and the parameters W and F in the system. ■

In past decades, much effort has been dedicated to robust design of the static system. Design on this aspect can be classified into two main categories: the experiment-based robust design and the model-based robust design.

The experiment-based methods, as indicated in Figure 1.3a, design system robustness using experimental data. These methods have the advantage that no accurate system model is required. Typical examples include the Taguchi method (Ross, 1988; Taguchi, 1987, 1993) and the response surface method (Box, 1988; Tsui, 1992; Engel and Huele, 1996; Choi, 2005). All these methods are developed generally based on experiment data without process knowledge. Thus, the cost could be high if a large number of experiments are needed, and the method may not be accurate, especially for the strongly nonlinear system. Moreover, they cannot handle variations of design variables (Chen et al., 1996a). All these disadvantages may limit their applications and make it difficult to be applied for the nonlinear system described in Example 1.1, or the partially known system with variations of design variables described in Example 1.2.

The second class of methods is the model-based robust design, as shown in Figure 1.3b, which uses the model information to design the system robustness.