Advances in Industrial Control

Tong Heng Lee
Wenyu Liang
Clarence W. de Silva
Kok Kiong Tan

Force and Position Control of Mechatronic Systems

Design and Applications in Medical Devices

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Department of Electrical, Computer and Biomedical Engineering, University of Pavia, Via Ferrata 1, 27100 Pavia, Italy
e-mail: antonella.ferrara@unipv.it

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Tong Heng Lee
Department of Electrical and Computer Engineering
National University of Singapore
Singapore, Singapore

Wenyu Liang
Department of Electrical and Computer Engineering
National University of Singapore
Singapore, Singapore

Clarence W. de Silva
Department of Mechanical Engineering
University of British Columbia
Vancouver, BC, Canada

Kok Kiong Tan
Department of Electrical and Computer Engineering
National University of Singapore
Singapore, Singapore

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To our families

Series Editor's Foreword

Mechatronics is a discipline that includes elements of mechanics, electronics, computer science, and control. It is a complex discipline simply because its nature combines the essences of so many others but it is extremely fascinating and relevant for our daily life and for industrial production. We live in a world pervaded by mechatronic systems: our cars are an example, as are the robots that contribute to their assembly, the robotic systems that process the food we eat, the automated cells involved in the manufacture of fabrics and leather to create the clothes and the shoes we wear, the machines that make the work of farmers in agriculture less laborious, and many home automation systems and smart components associated with the Internet of Things; all these are mechatronic systems.

Apart from the aforementioned applications, there is no doubt that one of the fields in which mechatronics has taken hold significantly in recent decades is healthcare. Many fundamental medical devices are mechatronic systems. Think, for example, of prosthetic limbs that allow realistic movements, restoring to amputees a quality of life that would have been unbelievable decades ago. Think of robotic surgery devices, which support surgeons in surgical activities that are extremely complex to perform by laparoscopy, also allowing the surgeon to operate while sitting and with a perfect vision of the operating field, which is often impossible with conventional surgery. In addition, since robot-assisted surgery is minimally invasive, it enables quicker patient recovery.

Among the possible medical applications of mechatronics, we cannot omit the use of machines for rehabilitation, including wearable robot systems such as exoskeletons and rehabilitation robots, which nowadays are increasingly combined with advanced communication systems, even allowing the patient to be rehabilitated remotely. It is no coincidence that, at present, the term bio-mechatronics is more and more often used in the related technical literature.

In writing this Foreword, I cannot ignore the difficult moment in which this book is being prepared. A historic moment marked by the heavy social and economic impact of COVID-19. In this dramatic situation, medical mechatronics has played a crucial role, supporting hospital workers in carrying out their duties despite difficult and risky conditions. The pandemic has further motivated researchers and technologists from all over the world to investigate new possibilities in the medical mechatronics. Given that the pandemic caused by SARS-CoV-2 is still ongoing and that future disease outbreaks cannot be excluded, nascent ideas of new mechatronic medical applications deserve to be sustained and brought to realization whether these be directly related to patient care—in the automation of taking nasal swabs without undue patient discomfort, for example—or in more general preventative measures such as the automated sanitization of daily work spaces without damage to nearby equipment. In scenarios in which the risk of contagion is high, and effective personal protection devices are not always available, the role of machines equipped with a certain level of autonomy, reliability, and finesse becomes of utmost importance.

The application of mechatronics to the healthcare sector and medicine, in general, brings formidable challenges, both from the point of view of the development of the underlying theory, and of the realization of the devices at affordable cost. To this end, the use of accurate kinematic and dynamic models is fundamental. The theoretical implications of controlling the interaction between the device and the environment, and of the hybrid force/position control of the parts of the machine which come in contact with the patient cannot be overlooked.

Turning to economic and productivity concerns, the production volumes of these machines, especially of those which perform niche operations or very-high-precision tasks such as ophthalmic surgical robots, may not be enormous. Therefore, the research and development phase must also address cost containment, in order to guarantee a competitive advantage for producers. Achieving a fair balance between costs and benefits is also assisted by dedicating attention to the theoretical aspects and following a rigorous methodological approach in the design and development phase.

From this perspective, this book plays two important roles. It provides the user with the methodological tools that can help understand the functioning and characteristics of a certain mechatronic device, specifically a device of medical type. It also reviews theoretical tools relevant to ensuring that mechanical and control design is reliable and efficient. It is a very thoroughgoing book, covering a broad spectrum of topics, from force and position control to observer-based force estimation, encompassing supervisory and vision-based motion and interaction control strategies.

If, at first glance, the book may appear to be a classic robotics book, a more careful reading reveals that this is absolutely not true. All parts, even those that refer to very classic topics, are made modern and interesting thanks to their being customized for the specific case of mechatronic medical devices.

With this volume, *Advances in Industrial Control* is enriched with a new monograph that contributes strongly to broadening the scope of the series, confirming that the meaning of the adjective "industrial" that we agree on in this context is very broad and inclusive of the control of machines, devices, and systems that do not fall under the conventional classification of industrial applications.

Antonella Ferrara
University of Pavia, Italy

Preface

Mechatronic systems have been increasingly used in many industrial and medical applications, where they are designed to work for various tasks in different environments. Significantly, many applications are required to carry out the contact operation and handle the interaction between the mechatronic systems and the environments (contacting objects) in order to complete the specific task successfully, such as grasping, polishing, assembly, robotic surgery, injection, etc. During the contact operation, the interaction force needs to be regulated carefully to avoid the undesirable effects and ensure the success of the performed task. As a consequence, force control is needed and designed delicately to meet specific requirements and achieve desired performance.

To achieve an appropriate or desired interaction, force feedback control is an effective way to regulate contact behavior. In recent years, huge numbers of research works report various force feedback schemes, which show good effectiveness of applying force controller in different applications. The explicit force controllers can achieve low force overshoot good force tracking performance, especially when the contact model is established accurately. However, it is noted that the motion/position of the actuation system is unconstrained or uncontrolled for pure force controllers (i.e., only the force is controlled directly). To deal with the applications where both force control and position control are required, force and position control is the major approach.

In this book, we offer systematic coverage of theoretical and practical aspects in the area of force and position control, which gives the readers an overview on the concepts, design, and implementation approaches of such control system. This book totally consists of nine chapters. More specifically, the first chapter of this book introduces the general concepts and technologies related to the force sensing, interaction modeling, and control strategy. In the following chapters from Chap. 2 to Chap. 8, the novel ideas and innovations related to the force estimation and the force and position control (includes direct force control, force–position control and impedance control) are reported in detail. Significantly, Chaps. 3–8 are technical chapters that are presented along with specific applications in medical devices. These chapters not only offer the readers various general knowledge and new thinking to solve their application challenges or control problems, but also provide the readers detailed references and examples on the ways to integrate the suitable control approaches into the practices. Lastly, the final chapter concludes this book.

In summary, this book gives an overview of the force and position control techniques; shows the readers our several recent novel ideas and innovations on the design and implementation of the force control and the force and position control for mechatronics; and uses the practical applications as case studies where detailed experimental verifications and results are given. From this book, readers can expect to learn how to design and implement new techniques of force control or force and position control for mechatronic systems, especially, medical devices. In particular, application-oriented readers can benefit more from this book.

Besides, we would like to take the opportunity to many thank Dr. Sunan Huang for his help and constructive suggestions in the writing of this book. Also, this book would not be possible without the generous assistance of the following colleagues and friends: Mr. Chee Siong Tan, Dr. Lynne Hsueh Yee Lim, Mr. Chee Wee Gan, Dr. Cailin Ng, Mr. Zhao Feng, Dr. Wenchao Gao, Dr. Jun Yik Lau, Dr. Jun Ma, and Dr. Silu Chen. Moreover, we are grateful for the help provided by the Editors. Finally, we thank our families for their love and support.

May the force be with you!

Singapore, Singapore — Tong Heng Lee
Singapore, Singapore — Wenyu Liang
Vancouver, Canada — Clarence W. de Silva
Singapore, Singapore — Kok Kiong Tan
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Chapter 1
Introduction

Forces result from interactions between objects. Interactions with other objects play a significant role in the proper and successful completion of various specific tasks for mechatronic systems. To deal with the interaction problems, force control is an effective and good way to guarantee the acceptable or desired contact. In recent years, the force control plays a more and more important role in mechatronic systems as the tasks of these systems become more complex and have increasing needs for handling the interaction between their contacting objects (e.g., environment, human) and themselves.

1.1 Overview

With the rapid development of mechatronics, mechatronic systems have been increasingly used in healthcare and medical applications due to their capabilities of automating processes with precise and fast motions, such as ear surgical device [1], surgical robot for laparoscopic surgery [2], robot-assisted beating heart surgery [3, 4], robot-assisted vitreoretinal surgery [5, 6], palpation probe for minimally invasive surgery (MIS) [7], hand-held ultrasound probe [8], cell injection system [9–11], powered exoskeleton [12], and so on. Remarkably, advancements in mechatronic systems of the medical devices allow surgeons/doctors to conduct the surgical treatments in a more efficient way.

Meanwhile, the tasks of medical devices become more complex, and higher dexterity as well as higher adaptability to different circumstances are needed with the increase of various applications. Therefore, they are not only required to generate precise motions to complete their tasks but also required to handle the interactions between the environment or human and themselves (e.g., robot–environment inter-

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action and human–robot interaction) in the sophisticated tasks. To this end, the force control plays an important role in these mechatronic systems.

Force control is essentially a kind of approach that controls the dynamic interaction between a mechatronic system and its contacting object. Its main objectives are to maintain the contact force within an acceptable range or control the applied force to follow a desired reference. There are enormous numbers of research works on force control. For example, in [3], a model reference adaptive force control was designed suitably for beating heart surgery. In [10], a force control strategy for cell injection system was proposed based on the cell model of polynomial function and feedback linearization technique, so that an explicit force tracking was achieved. Also of interest is the work in [13] where an inversion-free force tracking controller for a variable physical damping actuator was proposed without complicated modeling. Nevertheless, although suitable individual force controllers can achieve fast response and low force overshoot, the position of the actuated device is typically unconstrained and uncontrolled for pure force controllers; and such a situation (while obviously possibly posing certain dangers) is oftentimes part of the trade-off for the actuated device to reach the desired location to complete the overall task [14]. Furthermore, many applications need to perform the position tracking in certain directions while the force control is required in other directions. To deal with such cases, the force and position control is the major approach, where both force and position are considered in the control system.

In moving beyond pure force control, it can be noted that the regulation of both position and force can be realized through employing the hybrid force–position (force/position) control approach [15] or the parallel force–position (force/position) control approach [16], which includes a position controller and a force controller to track position and force, respectively. Such force–position control approaches are widely used in various mechatronic systems. In [17], a hybrid force/position control scheme is designed and implemented in a flexible parallel manipulator. In [18], through employing a suitably optimized algorithm, a selective force–position control approach was applied on an ear surgical device. In [19], a parallel force/position control approach was designed and used in a parallel wire robot for epicardial interventions. In [20], a proportional–integral–derivative (PID) force controller and an adaptive sliding mode position controller were combined to penetrate zebrafish embryos.

Alternatively, the methodology of impedance control proposed by Hogan in [21] is an effective and practical approach to regulate the position and force simultaneously without direct force control. Through establishing a virtual mass–spring–damper system containing position error and contact force, a delicate and compliant interaction control is achieved. Large numbers of research works on the impedance control are reported in various publications, and some examples of which are listed as follows. In [22], a force tracking impedance control was designed for a robot manipulator contacting with a rigid environment. In [23], a robust impedance control was proposed to handle parametric uncertainties, unknown force conversion function and hysteresis nonlinearity for a piezo-actuated flexure-based four-bar mechanism. Additionally too, discrete-time sliding mode impedance controllers have also been designed to complete microassembly in [24, 25].