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# Editor

**Kun Bai** received his B.S. degree from Zhejiang University, China in 2006 and earned his M. S. and Ph. D. degrees from the Woodruff School of Mechanical Engineering at Georgia Institute of Technology, Atlanta, US in 2009 and 2012 respectively. Currently, he is Associate Professor with the State Key Laboratory of Digital Manufacturing Equipment and Technology and the School of Mechanical Science and Engineering at Huazhong University of Science and Technology, China.

Dr. Bai's research areas include actuators, sensing and control systems, in which he has published over 30 peer-viewed papers and held over 10 patents. He has extensive expertise and experience in developing spherical motors for a variety of applications, ranging from manufacturing to robotics. These successful attempts have led to systems/equipments with superior advantages in terms of structural simplicity and dynamic response, comparing to their counterparts built with conventional single-axis motors. Dr. Bai has also made major contributions in developing novel multi-DOF sensing/control methods and systems which significantly improve the feedback control performance and efficiency of spherical motors.

**Professor Kok-Meng** Lee earned his B.S. degree from the University at Buffalo, the State University of New York, Buffalo, NY, USA, in 1980, and M.S. and Ph.D. degrees from Massachusetts Institute of Technology, Cambridge, MA, USA, in 1982 and 1985, respectively. He is currently Professor of Mechanical Engineering at Georgia Institute of Technology, Atlanta, GA, USA. He is also Distinguished Professor with the State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, China, under Thousand Talents Plan.

Prof. Lee's research interests include system dynamics/control, robotics, automation, and mechatronics. He is a world renowned researcher with more than 30 years of research experience in magnetic field modeling and design, optimization and implementation of electromagnetic actuators. He has published over 150 peer-reviewed papers and holds 8 patents in machine vision, three degrees of freedom (DOF) spherical motor/encoder, and live-bird handling system. He is IEEE/ASME Fellow and was the Editor-in-Chief for the IEEE/ASME Transactions on Mechatronics from 2008 to 2013. Recognitions of his research contributions include the National Science Foundation (NSF) Presidential Young Investigator, Sigma Xi Junior Faculty Research, International Hall of Fame New Technology, and Kayamori Best Paper awards.

# Preface

In recent years, "Intelligent manufacturing+tri-co robots" are particularly eye-catching, presenting the characteristics of the era of the perception of things,the interconnect of things,the intelligence of thing.Intelligent manufacturing and tri-co robots industry will be the strategic emerging industry with priority development,it is also a huge engine for "Made in China 2049". It's remarkable that the large-scale tri-co robots industry formed by smart cars ,drones and underwater robots will be a strategic areas of countries to compete in the next 30 year, and have influence on economic development, social progress, and war forms. The related manufacturing sciences and robotics are comprehensive disciplines that links and covers material sciences, information sciences, and life sciences. Like other engineering sciences and technical sciences, tri-co robots industry also will be the big sciences that provide a way to understand and transform the world. In the mid-20th century,the publication of Cybernetics and Engineering Cybernetics created a new era of engineering sciences.Since the 21th century,the manufacturing sciences, robotics and artificial intelligence and other fields have been extremely active and far-reaching,they are the sources of the innovation of "Intelligent manufacturing+ tri-co robots".

Huazhong University of Science and Technology Press follows the trend of the times, aiming at the technological frontiers of intelligent manufacturing and robots, organizes and plans this series of Intelligent Manufacturing and Robot Theory & Technology Research Series .The series covers a wide range of topics,experts and professors are warmly welcome to write books from different perspectives,different aspects, and different fields.The key points of the topics include but are not limited to:the links of intelligent manufacturing,such as research, development, design, processing, molding and assembly, etc;the fields of intelligent manufacturing,such as intelligent control, intelligent sensing, intelligent equipment, intelligent systems, intelligent logistics and intelligent automation, etc;development and application of robots,such as industrial robots, service robots, extreme robots, land-sea-air robots, bionics/artificial/robots, soft robots and micro-nano robots;artificial intelligence, cognitive science, big data, cloud manufacturing, Internet of things and Internet,etc.

This series of books will become a platform for academic exchange and cooperation between experts and scholars in related fields, a zone where young scientists thrive, and an international arena for scientists to display their research results.Huazhong University of Science and Technology Press will cooperate with international academic publishing organizations such as Springer Publishing House to publish and distribute this series of books. Also, the company has established close  with relevant international academic conferences and journals, creating a good environment to enhance the academic level and practical value,expand the international influence of the series.

In recent years, people from all walks of life, university teachers and students, experts, scientists and technicians in various fields are more and more enthusiastic about intelligent manufacturing and robotics.This series of books will become the link between experts, scholars, university teachers and students and technicians, enhance the connection between authors, editors and readers, speed up the process of discovering, imparting , increasing and updating knowledge, contribute to economic construction, social progress, and scientific and technological development.

Finally,I sincerely thank the authors, editors and readers who have contributed to this series of books,for adding,gathering,and exerting positive energy for innovation-driven development, thank the relevant personnel of Huazhong University of Science and Technology Press for their hard work in the process of organizing and scheming of the series of book.

Professor of Huazhong University of Science and Technology
Academician of Chinese Academy of Sciences

Youlun Xiong
September, 2017

# Preface

Rapid advances of intelligent machines for smart manufacturing equipment, driverless vehicles, robotics, and medical industries continue to motivate new designs and applications of multi-degree-of-freedom (DOF) actuators capable of complex motion and precise force/torque manipulations to complete tasks that have never been automated before. Extensive efforts to develop novel actuators with compact designs and dexterous manipulations can be found in both academic research and industrial development. Unlike multi-DOF systems with designs based on bulky serial/parallel combinations of single-axis spin motors and transmission mechanisms, spherical motors/actuators are direct-drive and can achieve multi-DOF rotational motions in a single ball joint. Because of these attractive features, along with the structural simplicity and the capability to achieve quick singularity-free motion, spherical motors are expected to play a significant role in the development of intelligent machines.

In this book, we provide fundamentals for practical designs of spherical motors with the intent to push forward the development of high-performance spherical motors. This book is organized into three parts: The first part begins with the methods for modeling the three-dimensional (3D) electromagnetic fields involved in a spherical motor, and the multi-dimensional forces and torques generated electromechanically between its rotor and stator. The second part presents the sensing techniques for measuring the multi-DOF joint motion in real time. The third part offers methods for controlling the coupled rotational motions of spherical motors. While this book is primarily intended for students, researchers, and engineers studying/developing spherical motors, those who work in the area of electric machines should find the modeling, sensing and control methods presented here relevant to the development of various electromagnetic motion systems.

This book is an outcome of the research work accomplished by the authors on spherical motors over the years in Georgia Institute of Technology (USA) and Huazhong University of Science and Technology (China). The authors sincerely appreciate the institutional support received from the two organizations. Part of the work on DMP model and orientation sensing has also built on research works by many former students, particularly Dr. Hungsun Son and Dr. Shaohui Foong, during their studies at Georgia Institute of Technology.

Wuhan, China<br>Atlanta, USA

Kun Bai<br>Kok-Meng Lee

# Nomenclature

## Symbols (Uppercase)

| | |
|---|---|
| $\mathbf{A}$ | Magnetic vector potential |
| $\mathbf{B}$ | Magnetic flux density |
| $\mathbf{H}$ | Magnetic field intensity |
| $I$ | Moment of inertia |
| $\mathbf{J}$ | Current density |
| $[\mathbf{K}]$ | Torque characteristic matrix |
| $\mathbf{K}$ | Torque characteristic vector |
| $\mathbf{K}_{\mathrm{P}}$, $\mathbf{K}_{\mathrm{I}}$, $\mathbf{K}_{\mathrm{D}}$ | Proportional, integral, and derivative gain matrices |
| $\mathbf{M}$ | Magnetization |
| $M_0$ | Magnetization strength |
| $[\mathbf{M}]$ | Inertia matrix |
| $N_E$ | Number of electromagnets |
| $N_P$ | Number of permanent magnets |
| $N_W$ | Number of turns in the winding of an EM |
| $\mathbf{S}$ | Sensor index vector |
| $\mathbf{T}$ | Motor torque |
| XYZ | Stator coordinate frame |
| $\Gamma$ | Bijective domain |
| $\Omega$ | MFD-defined domain |
| $\Phi$ | Magnetic scalar potential |
| $\Lambda$ | Magnetic flux linkage |

## Symbols (Lowercase)

| | |
|---|---|
| $\mathbf{g}$ | Gravity torque vector |
| $i$ | EM/coil current input |
| $m$ | Magnetic dipole strength |
| $\mathbf{n}$ | Normal vector |
| $\mathbf{q}$ | Rotor orientation |

| | |
|---|---|
| **u** | Current input vector |
| *xyz* | Rotor coordinate |
| $\alpha, \beta, \gamma$ | XYZ Euler angles |
| $\theta, \phi, r$ | Spherical coordinates in rotor frame |
| $\lambda$ | Pole separation angle |
| $\mu$ | Permeability of magnetic material |
| $\mu_0$ | Permeability of free space (air) |

## Abbreviations

| | |
|---|---|
| DC | Direct current |
| DFC | Direct field-feedback control |
| DMP | Distributed multi-pole |
| DOF | Degree of freedom |
| EM | Electromagnetic magnet |
| MFD | Magnetic flux density |
| PM | Permanent magnet |
| PMSM | Permanent magnet spherical motor |
| TCV | Torque characteristic vector |
| WCR | Weight-compensating regulator |

# Contents

## Part III Control Methods

# Chapter 1
# Introduction

Spherical motors which can achieve multi-DOF rotational motion in one joint have wide potential applications in modern manufacturing, robotics, automobile and medical industries. To provide systematic approaches for developing high-performance spherical motors, the basic concepts and solutions for the modeling, sensing and control are the focus of this book. This chapter begins with the motivations along with the exemplary applications of spherical motors, which is followed by a state-of-the-art review and a brief introduction of some fundamental concepts and operational principles of spherical motors. Finally, the outline of the book is presented.

## 1.1 Background

Multi-degree-of-freedom (DOF) actuators are widely used in industry, particularly in emerging applications where the end-effectors must be re-oriented smoothly, rapidly and precisely. In modern manufacturing industries, the trend to downscale equipment for manufacturing products on "desktops" has motivated the development of compact mechatronic platforms capable of performing various machining tasks. Figure 1.1a shows a micro-factory system [1, 2] which consists of a high-speed spindle cutter and a multi-DOF rotational stage. The multi-DOF actuator provides dexterous motions to manipulate the work-piece mounted on the stage for sophisticated machining by the cutter. Similar manipulation can also be found in conformal printing on 3D/flexible surfaces (Fig. 1.1b) where the substrate must be continuously re-orientated to align the surface normal with the print head direction, which allows conformal printing of circuits onto 3D substrates with a high level of surface topography [3].

Besides manufacturing applications, multi-DOF actuators are essential components in medical fields. Figure 1.1c shows a handheld micromanipulator for surgery. The end-effector (needle) must be controlled in up to 6-DOF (both position



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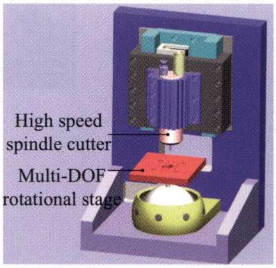
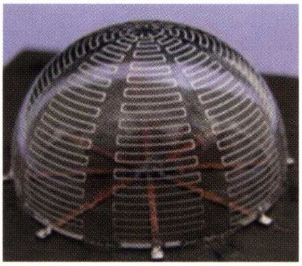
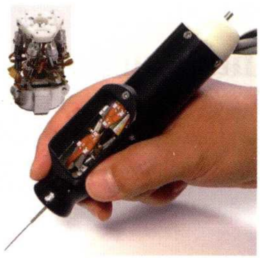


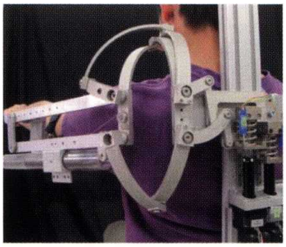

(a) Desk-top machining



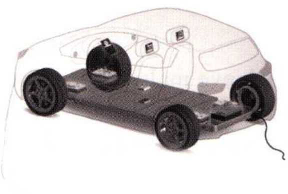
(b) Conformal printing [3]. © 2011 IEEE.



(c) Surgical device [4]. © 2015 IEEE.



(d) Exo-skeleton [5]. © 2016 IEEE.



(e) In-wheel motor

(f) Robotic joints (DLR HASy [7]). © 2015 IEEE.

**Fig. 1.1** Multi-DOF systems

and orientation) in order to actively compensate the hand tremor during surgical operations [4]. In Fig.1.1d, an exo-skeleton which accommodates the joint motion of human shoulders can be used in the rehabilitation process for post-stroke patients [5]. The actuator systems must offer dexterous motion and direct force/torque manipulation in order to actively cooperate with the human motion. Apart from these applications, multi-DOF actuators with novel topology and advanced control efficiencies continue to play a leading role in advancing the development of many modern systems such as automobile in-wheel motors [6] in Fig. 1.1e and robotic joint motors [7] in Fig. 1.1f.

Although multi-DOF motions can be generated by means of multiple single-axis spin-motors connected in serial or in parallel with external linkages or transmission mechanisms, such systems have some intrinsic disadvantages:

- The structural complexity of the multi-DOF mechanism, which often results in kinematic singularities in their workspace, greatly degrades its motion dexterity.
- The added mass and moment-of-inertia associated with the moving linkages for connecting the multiple single-axis actuators in a multi-DOF mechanism are the primary causes of its bulky size and poor dynamic performance.
- The friction between the moving parts results in wears which, along with the backlash in the motion transmission mechanisms (such as gears, timing belts

and external linkages between the motors and the end-effectors), seriously affect motion control accuracies and robustness in practical applications.

- Furthermore, the (friction and backlash) nonlinearities in the transmission mechanisms make the force/torque manipulation extremely difficult to control, which are essential for applications like rehabilitation and haptic uses.

To overcome these problems, a number of novel actuators have been developed. Among these are the ball-joint-like spherical motors capable of providing 3-DOF rotational motions in a single joint. By eliminating the transmission mechanisms (and thus the associated frictions and moment-of-inertia), the spherical motor is simple/compact in structure, has no singularities except at the boundaries of its workspace and thus can offer continuous rotational motion essential for dexterous manipulation tasks with high dynamic performance. As the driving forces and torques are directly applied on the rotor, the spherical motors can be used for applications where precise force/torque manipulation of the end-effector is required. Originally proposed in [8] as a robotic wrist actuator, a variety of spherical motors have been developed since then. Recent spherical-motor applications include actuation for digital cameras [9], robotic joints [10], machining stages [11], satellite attitude control [12], a haptic interface for snap-fit designs [13], and a traction motor for an electrical wheelchair [14].

Permanent magnet spherical motors (PMSMs) take many forms and have been studied by many researchers in the past decades. Inheriting the merits of spherical motors capable of offering multi-DOF rotational motions in a single joint, PMSMs incorporating PM poles in the rotor have the advantages such as high force/torque density (due to the strong magnetic field of rare-earth PMs), brushless and wire-free rotor design and compact size. PMSMs have drawn more and more attention, and are expected to be employed in a variety of industrial applications. In this book, we focus on the fundamental studies and technical issues from the perspectives of modeling, sensing and control of a PMSM. The materials offered here are essential bases for developing practical PMSMs; their effective applications will contribute to and benefit manufacturing, robotics, automobile as well as medical industries.

## 1.2 The State of the Art

Spherical motors take a number of forms which can be categorized into electromagnetic, piezoelectric (or ultrasonic) [15, 16] and cable/wheel-driven systems [17, 18]. Most of the spherical motors are based on the principle of electromagnetism, which include induction [19–25], direct current (DC) [26, 27], stepper [28–30], variable-reluctance (VR) [31, 32], and permanent magnet spherical motors (PMSMs) [33, 34]. The earliest form of electromagnetic spherical motors was designed as an induction motor. The first induction motor in spherical form with a tiltable angle between stator and rotor axes was introduced by Williams et al. [19]. The spin shaft of the motor was fixed (thus with 1-DOF rotor motion) and the stator