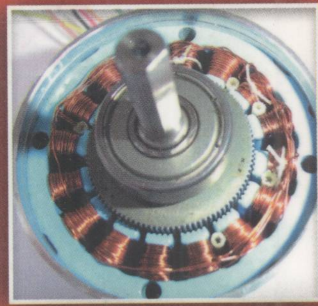
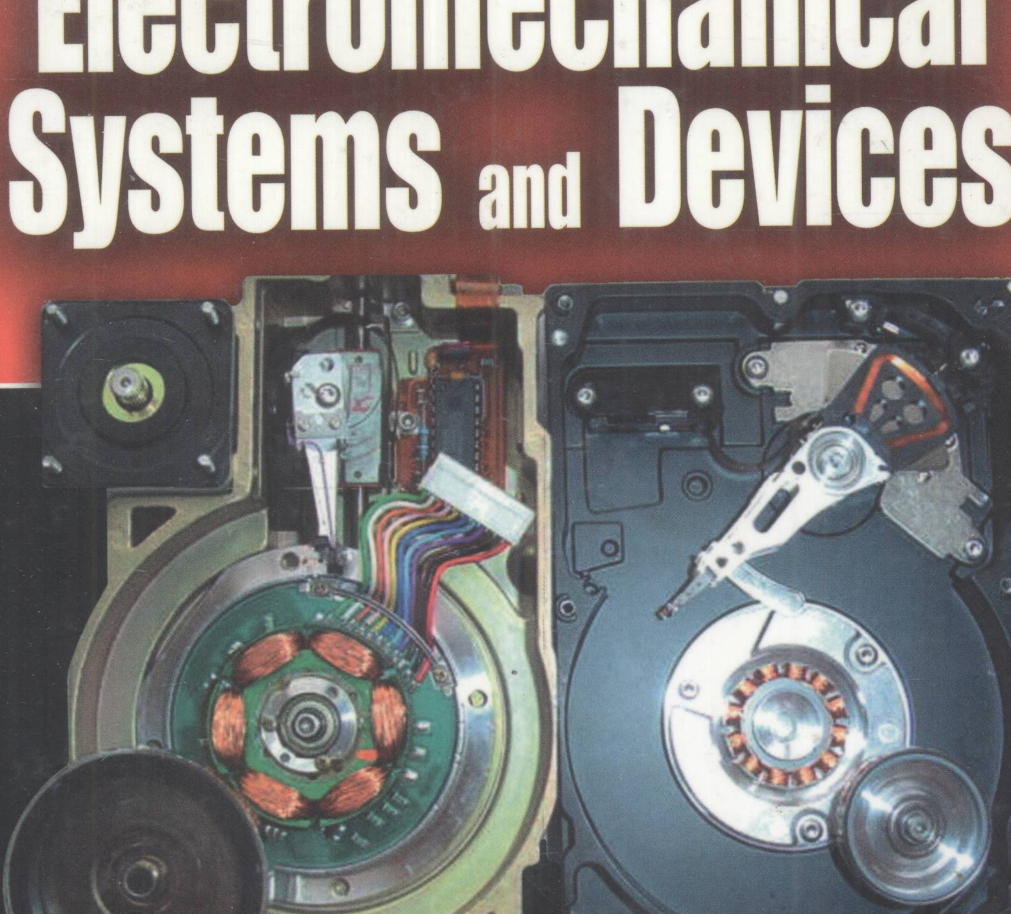



Electromechanical Systems and Devices



Sergey E. Lyshevski

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Electromechanical Systems and Devices

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Electromechanical Systems and Devices

Dedication

Dedicated to my family with a deep appreciation and admiration of their love, devotion, and support

Preface

We encounter electromechanical systems in daily activities. Because of the enormous impact of electromechanical systems, which has been signified in recent years, as well as enabling actuation/sensing/control/fabrication technologies, this book is written. The overall goal is to introduce and coherently cover electromechanical systems and their components. In particular, we will examine motion devices (actuators, motors, transducers, sensors, and others), power electronics, controllers, and so on. The major emphasis is focused on high-performance electromechanical systems addressing analysis, design, and implementation issues. Different electromechanical systems are widely used as electric drives and servosystems. A variety of enabling electromechanical systems and devices are covered. Recent trends in engineering have increased the emphasis on integrated analysis, design, and control. The scope of electromechanical systems has been expanded, and systems integrate actuators, sensors, power electronics, integrated circuits (ICs), microprocessors, digital signal processors (DSPs), and so on. Even though the basic fundamentals have been developed, some urgent areas were downgraded or less emphasized. This book aims to ensure descriptive features, extend the results to the modern hardware-software developments, utilize enabling solutions, place the integrated system perspectives in favor of a sound engineering, as well as focus on the unified studies.

This book facilitates comprehensive studies and covers the design aspects of electromechanical systems with high-performance motion devices. We combine traditional engineering topics and subjects with the latest technologies and developments in order to stimulate new advances in design of state-of-the-art systems. The major objective of this book is to provide a deep understanding of the engineering underpinnings of integrated technologies. The modern picture of electromechanics, energy conversion, electric machines, and electromechanical motion devices is provided.

The demand for an educational book in electromechanical systems and devices far exceeds what was previously expected by the academy, industry, and the engineering community. Although excellent textbooks in electric machines, power electronics, ICs, microcontrollers, and DSPs were published, and outstanding books about control are available, the need for a comprehensive study of electromechanical systems is evident. There is a lack of books that comprehensively cover and examine high-performance electromechanical systems. This book targets the frontiers of electromechanical engineering and science examining basic theory, emerging technologies, advanced software, and enabling hardware. The author is disturbed by the recent increase in the number of students whose good programming skills and sound theoretical background are matched with their complete inability to solve the simplest engineering problems. The major aims of this book are to demonstrate the application of cornerstone fundamentals in analysis and design of electromechanical systems, cover emerging software and hardware, develop and introduce the rigorous theory, and help the reader to develop strong problem-solving skills. This book offers an in-depth presentation and contemporary coverage facilitating the developments of problem-solving skills. This book is readable, comprehendible, and accessible to students and engineers because it develops a thorough understanding of integrated perspectives, and, by means of practical worked-out examples, documents how to use the results. Engineers and students who master this book will know what they are doing, why they are doing it, and how to do it. To avoid possible difficulties, the material is presented in sufficient details. In particular, basic results (needed to fully understand, appreciate, and apply the knowledge) are covered for use by those whose background and expertise could be deficient to some extent. Step-by-step, this book guides the reader through various aspects, for example, from rigorous theory to advanced applications, from coherent design to systems analysis, and so on.

Analysis and optimization are very important in designing advanced systems. Competition has prompted cost and product cycle reductions. To accelerate analysis and design, ensure productivity and creativity, integrate advanced control algorithms, attain rapid prototyping, generate C codes, and visualize the results, MATLAB® (with embedded Simulink®, Real-Time Workshop®, Control, Optimization, Signal Processing, Symbolic Math, and other application-specific environments and toolboxes) is used. The book demonstrates the MATLAB capabilities and helps the reader to master this viable environment, studies important practical examples, helps increase designer productivity by showing how to use the advanced software, and so on. MATLAB offers a rich set of capabilities to efficiently solve a variety of complex design and analysis problems. The reader can easily modify the studied application-specific problems and utilize the reported MATLAB files for particular systems. The examples covered in this book consist of a wide spectrum of practical systems and devices. Users can easily apply these results, modify the findings, and develop new MATLAB files and Simulink block diagrams. For various enterprise-wide practical examples, efficient analysis and design methods to solve practical problems are demonstrated. The documented results provide the solutions for various simulation, analysis, control, and optimization tasks as applied to electromechanical systems and devices.

In line with the specifically related topics philosophy and flexibility of course content, this book is adaptable to a wide variety of courses fulfilling overall and specific objectives as well as goals. *Electromechanical Systems and Devices* forms a versatile and modular basis for the following courses:

- Energy Conversion
- Electric Machines
- Electromechanics
- Electromechanical Systems
- Mechatronics

The above-listed courses are offered as undergraduate and graduate courses by many electrical and mechanical engineering departments around the world. This book is balanced and works nicely for one- and two-semester courses because the material is arranged to guarantee the greatest degree of flexibility in the choice of topics. Different course settings are possible at the undergraduate and graduate levels.

The revision of this book depends on students, engineers, scholars, and faculty who would be kind enough to provide their suggestions. This valuable communication, especially concerning potential deficiencies and shortcomings, will be greatly appreciated. The author welcomes any comments and corrections to ensure the highest degree of quality and accuracy. Your comments and suggestions are very welcome. It was a great pleasure to work on this book, and I hope readers will enjoy and will like this book.

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Sincere gratitude goes to MathWorks, Inc. for supplying the MATLAB® environment (MathWorks, Inc., 24 Prime Park Way, Natick, MA 01760-15000 http://www.mathworks.com.) Many thanks to all of you.

About the Author

Sergey Edward Lyshevski was born in Kiev, Ukraine. He received his M.S. (1980) and Ph.D. (1987) degrees from Kiev Polytechnic Institute, both in electrical engineering. From 1980 to 1993, Dr. Lyshevski held faculty positions at the Department of Electrical Engineering at Kiev Polytechnic Institute and the Academy of Sciences of Ukraine. From 1989 to 1993, he was the microelectronic and electromechanical systems division head at the Academy of Sciences of Ukraine. From 1993 to 2002, he was with Purdue School of Engineering as an associate professor of electrical and computer engineering. In 2002, Dr. Lyshevski joined Rochester Institute of Technology as a professor of electrical engineering. Dr. Lyshevski serves as a full professor faculty fellow at the U.S. Air Force Research Laboratories and Naval Warfare Centers.

Dr. Lyshevski is the author of 14 books. He is the author or coauthor of more than 300 journal articles, handbook chapters, and regular conference papers. His current research and teaching activities include the areas of electromechanical and electronic systems, micro- and nanoengineering, intelligent large-scale systems, molecular processing, systems informatics, and biomimetics. Dr. Lyshevski has made significant contributions in the devising, design, application, verification, and implementation of various advanced aerospace, electromechanical, and naval systems. He has made more than 30 invited presentations nationally and internationally.

Contents

1

Introduction to Electromechanical Systems

Every day, one utilizes and largely depends on thousands of electromechanical systems. More than 99.9% of electricity is produced by electric machines (generators) that convert one form of energy (nuclear, hydro, solar, thermal, wind, and other) into electric energy. By increasing the efficiency of power generators by 1%, one will reduce the oil and coal consumption by millions of barrels and tons per day. Synchronous generators, which induce the voltage in power systems, are covered in this book. Conventional synchronous generators are utilized in power plants, whereas permanent-magnet synchronous generators are widely used in auxiliary power units, low/medium-power alternative energy modules, and so on. Our major emphasis is focused on high-performance electromechanical systems and motion devices for electric drives and servosystems. For example, in "high-end" applications such as computer and camera hard drives, two electromechanical systems (drive and servo) are utilized, as reported in Figure 1.1. Without those electromechanical systems and actuators, one would not be able to assess the hard drive memory. In cars, there are hundreds of electromechanical systems, from the starter/alternator to various solenoids, fans, microphones, speakers, and even a traction electric drive in hybrid cars.

A phenomenal growth in electromechanical systems has been accomplished as a result of:

1. Raising industrial/societal needs and growing market;
2. Affordability and overall superiority of electromechanical systems as compared to any other (hydraulic, pneumatic, and other) drives and servos;
3. Rapid advances in actuators, sensors, power electronics, integrated circuits (ICs), microprocessors, and digital signal processors (DSPs) hardware;
4. Matured cost-effective fabrication technologies.

Fundamental and applied developments in actuators, electric machines, sensors, and power electronics notably contributed and motivated current

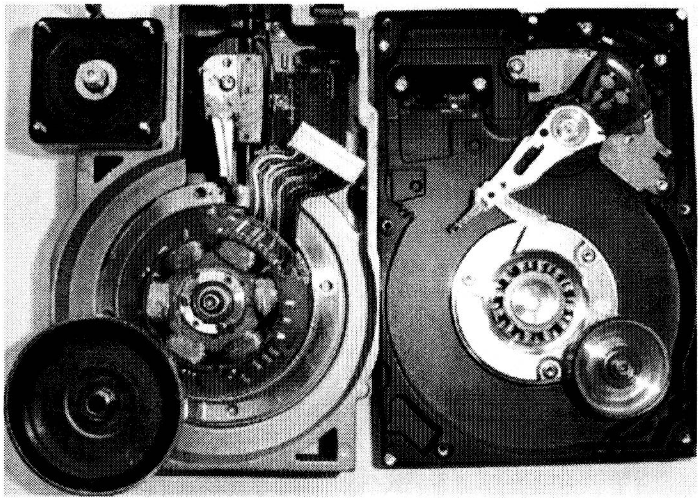

FIGURE 1.1
Two hard drives. In the hard drive on the left, to displace the pointer, the rotational motion of the stepper motor (at the top left) is converted to the translational motion (displacement) by using a gear (mechanical kinematics). The direct-drive limited-angle axial topology actuator is illustrated in the hard drive on the right. Permanent-magnet synchronous motors (at the center of the hard drives), controlled by power electronics, rotate the disk. As documented, the phase windings are on the stator (stationary machine member), whereas the radial segmented permanent magnets are on the rotor.

societal progress, welfare, and technological advances. There is a need to further expand meaningful developments by:

1. Devising, advancing and integrating leading-edge actuation and sensing paradigms;
2. Enhancing/devising device physics of electromechanical motion devices, thereby ensuring enabling performance and capabilities;
3. Advancing hardware and developing novel software;
4. Developing and implementing advanced fabrication technologies;
5. Applying enabling energy conversion concepts, and so on.

The concurrent design provides the end-users with the needed coherency integrating subsystems and components within high-performance electromechanical systems. With the stringent requirements on electromechanical systems performance and capabilities, the designer applies the advanced concepts in analysis, design, and optimization. This introductory chapter discusses the electromechanical systems and their components reporting introductory and conceptual features.

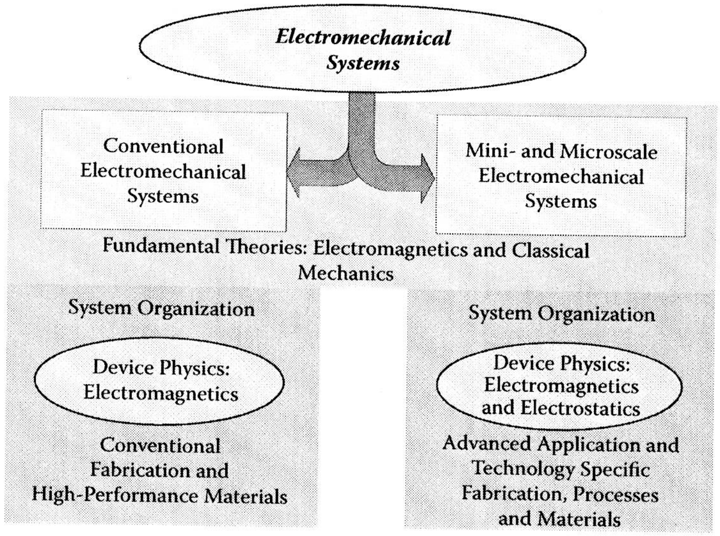

FIGURE 1.2
Electromechanical systems.

In general, electromechanical systems are classified as:

- Conventional electromechanical systems,
- Mini-/micro-scale electromechanical systems.

The operating principles and basic foundations of conventional and mini-/micro-scale electromechanical systems are identical or similar. The overall device physics and analysis are based on the electromagnetics and classical mechanics. However, the device physics specifics (electromagnetic phenomena and effect utilized, for example, electromagnetics versus electrostatics), system organization, and fabrication technologies (including processes and materials used) can be profoundly different. Figure 1.2 illustrates those features.

The structural and organizational complexity of electromechanical systems has been increased drastically as a result of hardware advancements and stringent performance requirements imposed. To meet the rising demands on the system complexity and performance, novel solutions and design concepts have been introduced and applied. In addition to the coherent choice of system components (subsystems, modules, devices, etc.), there are various issues that must be addressed in view of the constantly evolving nature of integrated developments in design, analysis, optimization, complexity, diagnostics, packaging, and so on. The *optimum-performance* systems can be designed only by applying the advanced hardware and software. Integrated multidisciplinary features approach quickly. As documented in Figure 1.3,