

Industrial Motion Control

Motor Selection, Drives,
Controller Tuning, Applications

Hakan Gürocak

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INDUSTRIAL MOTION CONTROL

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Preface

Over the past couple of decades, the academic community has made significant advances in developing educational materials and laboratory exercises for fundamental mechatronics and controls education. Students learn mathematical control theory, board-level electronics, interfacing, and microprocessors supplemented with educational laboratory equipment. As new mechanical and electrical engineering graduates become practicing engineers, many are engaged in projects where knowledge of industrial motion control technology is an absolute must since industrial automation is designed primarily around specialized motion control hardware and software.

This book is an introduction to industrial motion control, which is a widely used technology found in every conceivable industry. It is the heart of just about any automated machinery and process. Industrial motion control applications use specialized equipment and require system design and integration where control is just one aspect. To design such systems, engineers need to be familiar with industrial motion control products; be able to bring together control theory, kinematics, dynamics, electronics, simulation, programming and machine design; apply interdisciplinary knowledge; and deal with practical application issues. Most of these topics are already covered in engineering courses in typical undergraduate curricula but in a compartmentalized nature, which makes it difficult to grasp the connections between them.

As I wrote this book, my goal was to bring together theory, industrial machine design examples, industrial motion control products and practical guidelines. The context of studying industrial motion control systems naturally brought separately taught topics together and often crossed disciplinary lines. The content came from my personal experience in developing and teaching mechatronics and automation courses, working with undergraduate students and from many discussions with engineers in the motion control industry. For example, even though many types of motors are available, I chose to concentrate on three-phase AC servo and induction motors based on input from the motion control industry. By no means this is a comprehensive book on any of the topics covered. It is not an in-depth examination of control theory, motor design, or power electronics. Rather, it is a balanced coverage of theory and practical concepts. Much of this material is available in manufacturer data sheets, manuals, product catalogs, fragments in various college courses, websites, trade magazines, and as know-how among practicing engineers. The book presents these pieces in a cohesive way to provide the fundamentals while supplementing them with solved examples based on practical applications.

The book starts with an introduction to the building blocks of a typical motion control system in Chapter 1. A block diagram is provided and the basic function of each building block is explained.

Chapter 2 examines how the motion profile is generated when an axis of a machine makes a move. After an overview of basic kinematics, two common motion profiles are explained. The chapter concludes with two approaches for multi-axis coordination.

As the mechanical design of each axis and the overall machine are significant factors in achieving the desired motion, Chapter 3 focuses on drive-train design. Concepts of inertia reflection, torque reflection, and inertia ratio are introduced. Five types of transmission mechanisms are explored in depth. Torque-speed curves of motors, gearboxes, and motor selection procedures for different types of motors and axes with transmission mechanisms are provided.

Electric motors are by far the most commonly used actuators in industrial motion control. Chapter 4 begins with fundamental concepts such as electrical cycle, mechanical cycle, poles, and three-phase windings. Construction and operational details of AC servo and induction motors are provided. Torque generation performance of AC servo motors with sinusoidal and six-step commutation is compared. The chapter concludes with mathematical and simulation models for both types of motors.

Motion control systems employ an assortment of sensors and control components along with the motion controller. Chapter 5 starts with the presentation of various types of optical encoders for position measurement, limit switches, proximity sensors, photoelectric sensors, and ultrasonic sensors. Sinking or sourcing designations for sensor compatibility to I/O cards are explained. Next, control devices including push buttons, selector switches, and indicator lights are presented. The chapter concludes with an overview of motor starters, contactors, overload relays, soft-starters, and a three-wire motor control circuit.

A drive is the link between the motor and the controller. It amplifies small command signals generated by the controller to high-power voltage and current levels necessary to operate a motor. Chapter 6 begins by presenting the building blocks of drive electronics. The popular pulse width modulation (PWM) control technique is explained. Then, basic closed-loop control structures implemented in the drive are introduced. Single-loop PID position control and cascaded velocity and position loops with feedforward control are explored in depth. Mathematical and simulation models of the controllers are provided. Control algorithms use gains that must be tuned so that the servo system for each axis can follow its commanded trajectory as closely as possible. The chapter concludes by providing tuning procedures for the control algorithms presented earlier and includes practical ways to address integrator saturation.

The book concludes with Chapter 7, which is about programming and motion control applications. Linear, circular, and contour move modes of a motion controller are explored. The chapter continues by introducing algorithms for basic programmable logic controller (PLC) functionality that are commonly used in motion controller programs. The chapter concludes by reviewing how a motion controller can control a non-Cartesian machine, such as a robot, by computing its forward and inverse kinematics in real-time.

One of the challenges in writing a book like this is the variety of motion controller hardware and software in the market and their proprietary nature. Each controller manufacturer has its own programming language and programming environment for their products. Since the programming details are very specific to each hardware, I attempted to provide algorithmic outlines rather than complete programs in a specific programming language or structure. The product manuals and manufacturer suggestions must be closely followed in adapting these

algorithms to a specific choice of motion controller hardware. Another challenge was the digital control systems implemented in the controllers. These sampled data systems would be modeled using the z -transform (z -domain). However, almost all undergraduate engineering programs include only coverage of the continuous-time systems modeled using the Laplace transform (s -domain). Therefore, I chose to use the s -domain in presenting the control system models. This approach provides a good approximation since today's controllers have very fast sampling frequencies and the mechanical systems they control have relatively slow dynamics.

As I presented concepts, especially for the solved drive-train examples, I used data for industrial products from datasheets and catalogs. Today, most of these resources are available on the Internet as provided in the references of the chapters. Over time, manufacturers will change their products and these catalogs may not be available anymore. However, the theoretical coverage and the practical selection procedures should equally apply to the similar, newer future products.

This book is intended to be an introduction to the topic for undergraduate mechanical and electrical engineering students. Since many practicing engineers are involved in motion control systems, it should also be a resource for system design engineers, project managers, industrial engineers, manufacturing engineers, product managers, field engineers, mechanical engineers, electrical engineers, and programmers in the industry. For example, the tuning procedures in Chapter 4 were demonstrated using mathematical simulations. But if a real system with a motion controller is available, then these procedures can simply be used to tune the controller of the real system without the need for any of the simulations. Similarly, Chapter 7 provides algorithms for common types of motion control applications such as winding. These algorithms can be a starting point to develop the control programs in the programming language of the real system. As stated earlier, the product manuals and manufacturer suggestions must be closely followed in adapting these algorithms to a specific choice of real motion controller hardware.

I am indebted to many people who helped me through the journey of writing this book. Many thanks to Mr. Ken Brown, President of Applied Motion Systems, Inc., Mr. Ed Diehl, President of Concept Systems, Inc., for our discussions about motion control systems, for the valuable suggestions and materials they provided. Special thanks goes to Mr. Dimitri Dimitri, President of Delta Tau Data Systems, Inc., and Mr. Curtis Wilson, Vice President of Engineering and Research at Delta Tau Data Systems, Inc. for their contributions to our laboratory, to this book and for their in-depth technical guidance. I would also like to acknowledge the contributions by Mr. Dean Ehnes, Mechanical Engineer, Mr. John Tollefson, Electrical Engineer, and Mr. Brian Hutton, General Manager of Columbia/Okura, LLC through insightful discussions about material handling systems, motors, and for ideas for example problems. My colleague Dr. Xiaodong Liang from electrical engineering provided a detailed review of the chapters on motors and electric drives, which was much appreciated. I received tremendous help from Mr. Ben Spence, my former student from a long time ago and now Systems Engineer at Applied Motion Systems, Inc. I learned a lot from him as we spent countless hours working together on laboratory machines and discussing many technical aspects of motion control. Also, I am grateful to Mr. Matthew Bailie, Mechanical Engineer at Applied Motion Systems, Inc. for his guidance about the motor sizing procedures and for ideas for some of the example problems. Many thanks to the companies that provided the product photographs used in the book. I would like to thank Mr. Paul Petralia, Senior Editor at John Wiley & Sons and the Wiley staffs Sandra Grayson, Clive Lawson and Siva Raman Krishnamoorthy, for their guidance

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As I discovered through this process, writing a textbook is a major undertaking. I am very grateful to my wife for her endless patience, support, and encouragement while I was writing this book for the last 3 years.

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1

Introduction

Motion control is widely used in all types of industries including packaging, assembly, textile, paper, printing, food processing, wood products, machinery, electronics, and semiconductor manufacturing. It is the heart of just about any automated machinery and process. Motion control involves controlling mechanical movements of a load. For example, in case of an inkjet printer, the load is the ink cartridge that has to be moved back-and-forth across the paper with high speed and precision. On the other hand, in a paper-converting machine, the load can be the large parent roll of paper that is loaded into the machine for processing. In this case, the load rotates as the paper is unwound from the roll and rewound into smaller processed rolls such as embossed paper towels.

Each motor moves a segment of the mechanical components of the machine. The segment of the machine along with the motor that moves it is called an *axis*. Considering an inkjet printer as an example, the mechanical components involved in the sliding motion of the print cartridge and the motor driving them collectively make up an axis of the machine. Another axis of the printer consists of all mechanical components and the motor that feed paper into the printer. In case of the paper-converting machine, the mandrel that holds the roll of paper, the pulleys, and belts that connect it to the motor and the motor make up an axis.

A typical motion control system manages position, velocity, torque, and acceleration of an axis. Often the machine consists of multiple axes whose position and/or velocity must be controlled in a synchronized fashion. For example, the *X*-axis and *Y*-axis of the table of a CNC machine need to be controlled in a coordinated way so that the machine can cut a round corner in the work piece. The ability to precisely control and coordinate complex motions of multiple axes enables design of industrial machines such as those in Figure 1.1.

Prior to the programmable motion controllers, coordination was achieved through mechanical means [14]. A central line shaft was connected to a large electric motor or an engine that ran at constant speed. This motion source was then used to drive all the axes of the machine by coupling them to the line shaft through pulleys, belts, gears, cams, and linkages (Figure 1.2). Clutches and brakes were used to start or stop the individual axes. The gear ratios between the line shaft and the individual axes determined the speed of each axis. Drive-trains, which were often long shafts, transferred the coordinated motion to the appropriate part of the

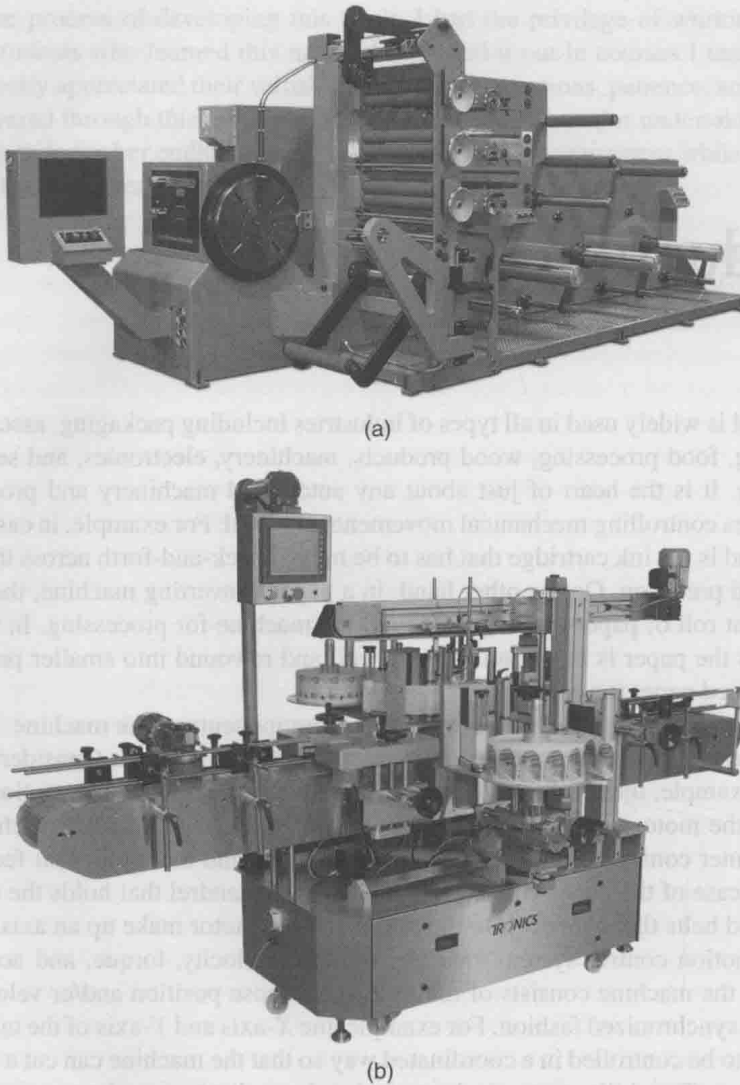


Figure 1.1 Complex machines with multiple axes are made possible with the ability of the controller to precisely coordinate motion of all axes. (a) Foil and wire winding machine (Reproduced by permission of Broomfield, Inc. [3]). (b) Pressure sensitive labeling machine (Reproduced by permission of Tronics America, Inc. [19])

machine. Complex machinery required sophisticated mechanical designs. Backlash, wear, and deflections in the long shafts were problematic. The biggest challenge was when a change in the product had to be introduced into the production system. It required physically changing the gear reducers, which was costly and very time consuming. Also, realigning the machine for accurate timing was difficult after drive-train changes.

As computers became main-stream equipment through the inexpensive availability of electronics, microprocessors, and digital signal processors, coordination of motion in multiaxes

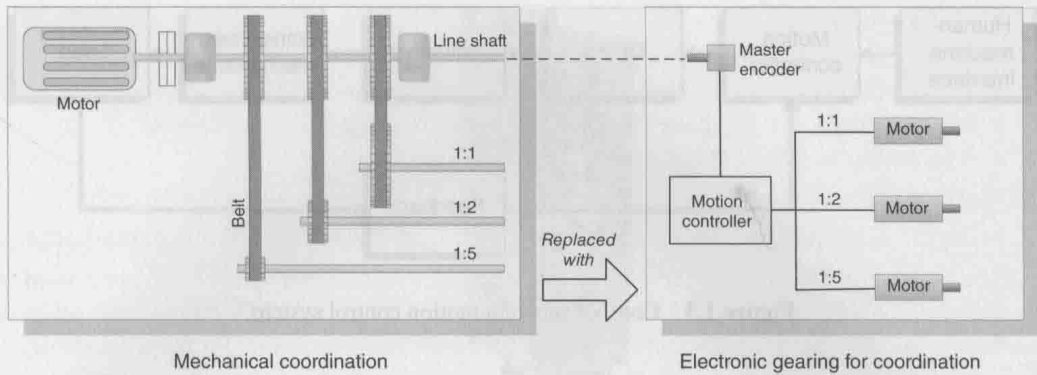


Figure 1.2 Multiaxis coordination

machines began to shift into a computer-controlled paradigm. In a modern multiaxis machine, each axis has its own motor and electric drive. Coordination between the axes is now achieved through electronic gearing in software. The drive-trains with long shafts are replaced by short and much more rigid shafts and couplings between the motor and the mechanism it drives. The motion controller interprets a program and generates position commands to the drives of the axes. These motion profiles are updated in real-time as the drives commutate the motors and close the control loops. In today's technology it is typical for an ordinary motion controller to coordinate up to eight axes at a time. Controllers with 60+ axis capabilities are available.

1.1 Components of a Motion Control System

The complex, high-speed, high-precision control required for the multiaxis coordinated motion is implemented using a specialized computer called **motion controller**. As shown in Figure 1.3, a complete motion control system consists of:

1. Human-machine interface (HMI),
2. Motion controller
3. Drives
4. Actuators
5. Transmission mechanisms
6. Feedback.

1.1.1 Human-Machine Interface

The HMI is used to communicate with the motion controller. The HMI may serve two main functions: (i) Operating the machine controlled by the motion controller, and (ii) Programming the motion controller.

Control panels as shown in Figure 1.4a with pilot lights, push buttons, indicators, digital readouts, and analog gauges are common hardware-based HMIs to serve the purpose of operating a machine. Chapter 5 discusses operator interface devices such as pilot lights, push buttons,

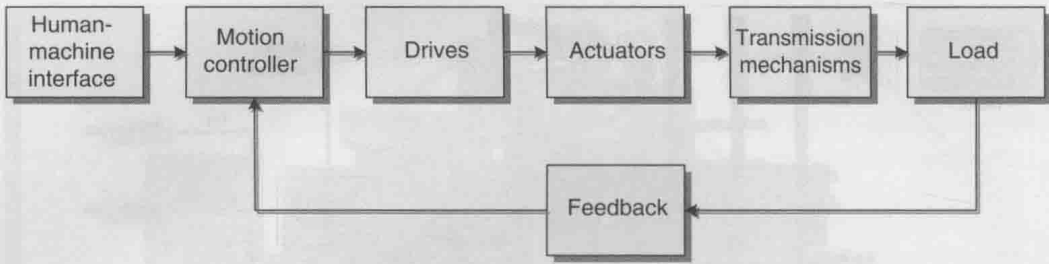
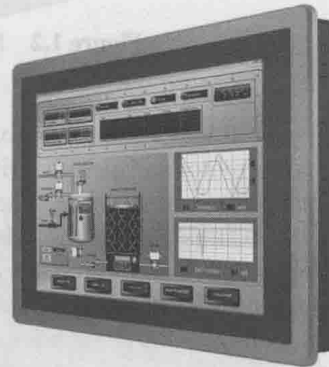


Figure 1.3 Components of a motion control system



(a)



(b)

Figure 1.4 Human-machine interfaces (operator panels) are used to operate the machine. (a) Hardware-based control panel [7]. (b) Software-based control panel with touch screen (Reproduced by permission of American Industrial Systems, Inc. [2])

and selector switches. Control panels can also be software-based as shown in Figure 1.4b. These panels can have touch screens and embedded computers that run a graphical user interface developed using software [10, 13, 15]. The advantage of this type of panel is the ease of reconfiguration of the HMI as new features may be added to the machine in the future.

A computer is interfaced to the motion controller for programming purposes. Custom software provided by the manufacturer of the controller is used to write, edit, download, and test the machine control programs. The software also includes features to test motors, monitor input/output (I/O) signals, and tune controller gains. Chapter 7 presents programming approaches for motion, machine I/O management, and multiaxis coordination.

1.1.2 Motion Controller

The motion controller is the “brains” of the system. It generates motion profiles for all axes, monitors I/O, and closes feedback loops. As presented in Chapter 2, the controller generates the motion profile for an axis based on the desired motion parameters defined by the user or the programmer. While the machine is running, it receives feedback from each axis motor. If there is a difference (following error) between the generated profile and the actual position or

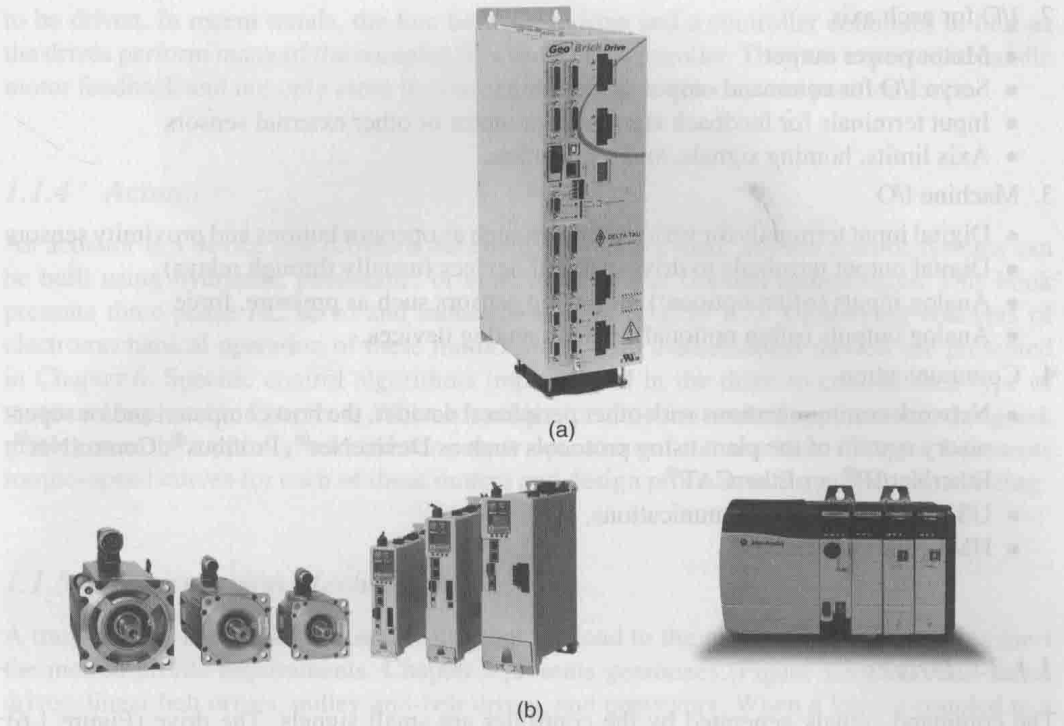


Figure 1.5 Motion controllers can have the various form factors. (a) Integrated form factor (Reproduced by permission of Delta Tau Data Systems, Inc. [5]). (b) Modular form factor. (Left) motors and drives [16], (Right) controller [17] (Courtesy of Rockwell Automation, Inc.)

velocity of an axis, the controller generates correction commands, which are sent to the drive for that axis. Chapter 6 discusses various control algorithms used to act on the following error to generate command signals to eliminate the error. As discussed in Chapter 7, the controller can also generate and manage complex motion profiles including electronic camming, linear interpolation, circular interpolation, contouring, and master–slave coordination.

Motion controllers are available in different form factors (Figure 1.5). The integrated form factor incorporates the computer, the drive electronics for the axes, and the machine I/O into a single unit. This unit is called motion controller or drive. In a modular system, the computer, the drives, and the machine I/O are separate units connected to each other via some type of communication link. In this case, just the computer is called the motion controller.

A complete motion controller consists of the following:

1. Computer

- Interpretation of user programs
- Trajectory generation
- Closing the servo loops
- Command generation for the drives (amplifiers)
- Monitoring axis limits, safety interlocks
- Handling interrupts and errors such as excessive following (position) error.