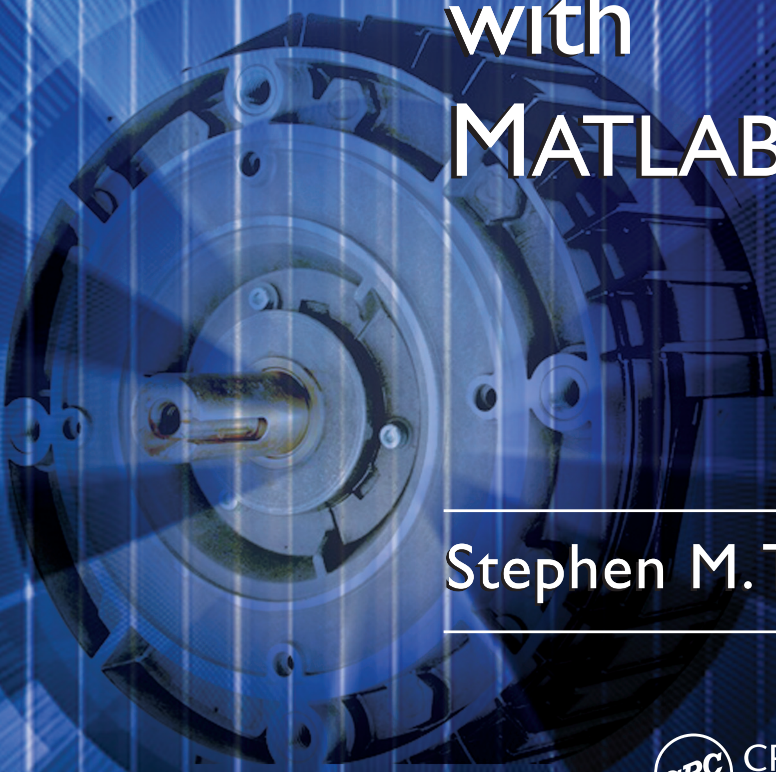
DC SERVOS

Application and Design with MATLAB®



Stephen M. Tobin

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Dedication

To Elisa

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Preface

The idea for this book came from years of frustration as I tried to find an authoritative source for how to design a custom servomechanism, using a few reference designs with detailed explanations and electrical schematics that can be readily built, tested, and changed if necessary by the reader. These designs would use modern, easily accessible parts. The primary focus would be on the use of commonly available brushed DC motors in position and velocity control systems. There was a particular void in the literature regarding the application of optical encoders. Many texts would describe these feedback transducers in some detail, yet fail to show how they are used in a real system. In this new book, there would be an even treatment of the theoretical and practical sides of application and design, seemingly unavailable to the author, even though this work has been going on for more than 50 years.

When I graduated from the University of New Hampshire in 1983, robots were doing real work inside automobile manufacturing plants. During our senior year, a few fellow student friends and I decided to build a small robot to see what was going on with all this "motion control" stuff. We were hooked, and our senior project took two semesters to complete. Early on in the project, we decided that we would use step motors for the prime movers in our robot. The reason was that our advisor for the project, Charles K. ("Charlie") Taft, was a respected authority in the modeling and use of steppers. Charlie had friends in industry who could supply us with free motors. It was simply the quickest means to our end, and even though three of us had taken and passed EE/ME 781 (the UNH Control Systems course), we had no idea how to implement a DC servo. At the time, the course was too theoretical for us to absorb. We had a gut feeling that DC servos would give us a more flexible, robust solution but did not know why. Charlie simply did not have the time or the energy to teach us. He was in high demand in the UNH ME department and had several graduate students to attend to, in addition to his regular undergraduate course load. In the end, we created a step motor–controlled robot that had very limited capabilities (see Figure P.1).

Despite our relative inexperience as students in 1982, I continue to believe our instincts were correct. Motion control mattered in the real world. This is borne out by a prediction made by Caxton C. Foster in his 1981 book *Real Time Programming—Neglected Topics* (see bibliography). In the book, he explored subjects that defied classification into engineering curriculums at that time. Nominally, his audience was computer science majors

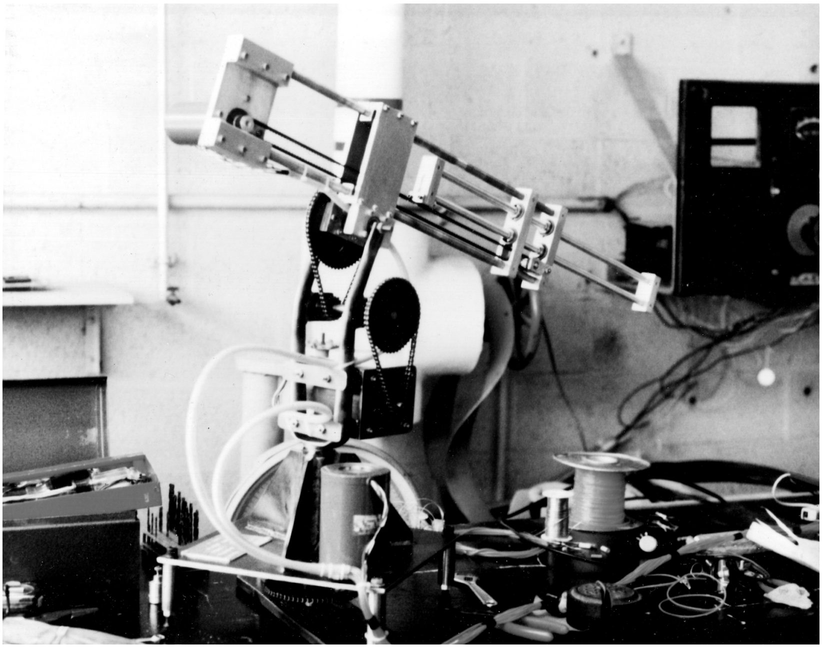

FIGURE P.1
A step motor–controlled robot, designed and built in 1983 at UNH by the author and three other collaborators.

and computer hobbyists. One relevant question he posed was "Why study servomechanisms?" His answer still holds true:

> With the dramatic decline in the price of computers over the past ten years, they have moved out of the accounting departments of business and the ivy-covered walls of academia into private homes and industrial assembly lines. One of the major applications of the new micros has been, and will continue to be, in controlling physical devices of one sort or another. Now the fundamental idea behind a servomechanism is the application of feedback to controlling position or velocity or some other attribute of the device in question.

Foster goes on to give an eloquent, concise introduction to the fundamental aspects of control and what role the new digital computers could play in it. In retrospect, it would have been great to have taken a course like his as a mechanical engineering major, or at least be exposed to his book at the time. However, I truly believe that learning is a lifetime endeavor. I admit it—I still get a rush every time I see the motion of an object being controlled. That is why I wrote this book.

Today, DC servos are working all over the world in countless applications—CD players, ink-jet printers, robotics, machining centers, vending machines, eyeglass manufacturing, home appliances, automotive seat positioning. How are all these machines being designed? In my experience working at a number of small to mid-sized companies, there are one or two key people who have been through "servo school." How did they get there? What was their path to learning all the nuances of servo design? How did they find out how to implement these design techniques in a real-world product? The fact is that successful servo control of mechanisms draws from so many different engineering disciplines that it is difficult for anyone to master it all. It takes years of experience (for most of us) to grasp all of the details necessary. This book is an attempt to distill some, if not most, of the practical knowledge required from the various branches of applied science—electrical engineering, analog electronics, mechanical engineering, mechanics, control theory, digital electronics, embedded computing, and firmware design—into a cohesive framework. The goal of this book is to take you on a short journey through servo school and to teach you what I had to learn on my own. I feel compelled to do this, so that more engineers, students, scientists, and hobbyists can feel confident designing the ever more complex machines of the 21st century. With this book, I hope both author and reader will make meaningful contributions to society at large.

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Acknowledgments

I wish to thank my publisher, Taylor & Francis, as well my editor, Jonathan Plant, project coordinator, Amber Donley, and project editor, Andrea Demby of CRC Press. They stuck with me even though this project took twice as long to complete as first anticipated. I also wish to thank Judy Bass at McGraw-Hill, who patiently taught this first-time author how to promote a work such as this one within the publishing community. Diane Trevino at National Semiconductor was very generous with permission to use and reproduce several application notes. Harprit Sandhu (along with his editor at McGraw-Hill, Roger Stewart) was extremely generous with his sharing of firmware, without which Chapter 8 could not have been written in such a reasonable length of time. I also wish to thank The MathWorks and their book program staff for complimentary copies of MATLAB® and Control System Toolbox software used throughout the book.

Some personal associations and friendships must be duly noted. My illustrator, Bob Conroy of Mantis Design Associates, has become a trusted collaborator and guide throughout the entire project. Charles K. ("Charlie") Taft was my first great teacher, and truly inspired me while an undergraduate at UNH. One of my senior project partners at UNH, Brian Butler, continues to be a great friend and source of wisdom. His statement to me some years ago, "Your best is good enough," has helped sustain me throughout my adult life. Samuel Fuller and Michael Hunter were my other two partners on the UNH robot project. Finally, I wish to thank my wife, Elisa, for her unwavering support over the past two years, making this book the best it could possibly be.

Since no book, human being, or DC servo system is perfect, errors and omissions are unavoidable. Your feedback would be very much appreciated. Please forward your comments to me directly at optical-tools@comcast.net.

About the Author

Stephen M. Tobin is the founder and president of Optical Tools Corporation. He received his B.S. degree in mechanical engineering from the University of New Hampshire in 1983. He spent the first five years of his career in the motion control field, holding positions in step motor and optical encoder design engineering with divisions of Allied-Signal and Dresser Industries. He then turned his attention to the development of electro-optical instrumentation. He joined General Eastern Instruments (now a division of General Electric) in 1988, working on closed-loop optical humidity measurement systems. He received his M.S. degree in electrical engineering with a concentration in electro-optics from Tufts University in 1994. He later spent six years developing medical devices at Arthur D. Little, a world-renowned consulting firm based in Cambridge, MA. Optical Tools Corporation (http://www.optical-tools.net) was founded by Tobin in 2004, and he continues to consult to the medical device and manufacturing automation communities. He holds four U.S. patents and is a member of the Tau Beta Pi National Engineering Honor Society. Motion control continues to be his life long passion.

1

DC Servo Systems Defined

1.1 Scope and Definition

In the roughly 40 years between man landing on the moon and today, the DC servo has been implemented in countless applications in industry. The invention of solid-state amplifiers, as well as the microprocessor, has given rise to the idea of preprogrammed machines running on direct current. The more recent resurgence of smaller DC servos running on less than 100 watts can be attributed to a few factors: (1) the revolution of personal computers and the need for their "peripheral" electromechanical devices; (2) market demand for miniaturization and portability of increasingly complex machines; and (3) recent worldwide concern for electrical safety, where governmental approvals are much easier to obtain when a device runs on less than 48 volts DC. A typical example is the print head positioning relative to the paper on an ink-jet printer. *Servo* is derived from the Latin noun *servus*, which means "slave." For now, we define the servo as a machine that can perform a predefined action of larger power output than that exerted by the operator.

1.2 The Concept of Feedback Control

Consider the simple act of boiling water for a morning cup of tea. A modern automatic teakettle uses a temperature sensor to detect the onset of boiling and turns itself off. In Figure 1.1, an electrical signal representing the water temperature is constantly measured with respect to a reference value (i.e., fed back), and an action is taken upon reaching that value. Contrast this with the standard whistling kettle that requires human intervention to hear the whistle, walk to the cooktop, and shut down the power source.

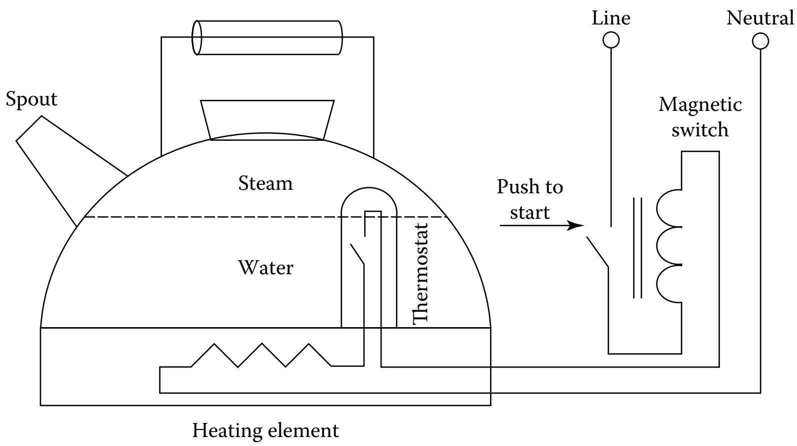

FIGURE 1.1
Electric teakettle control schematic.

1.3 Types of Control

We further classify the natural control types as (1) open loop vs. closed loop control and (2) on/off vs. continuous control. Brief descriptions of these follow, using the teakettle as an example.

1.3.1 Open Loop vs. Closed Loop Control

As described above, if the water is boiled with human intervention, we refer to this as an "open loop" process, since no feedback is employed. Conversely, if the kettle is automatically shut off after the boiling task is completed, this process is a "closed loop" one.

1.3.2 On/Off vs. Continuous Control

The automatic teakettle is a simple on/off or "bang-bang" control system. Power is either applied fully or not applied at all. In a continuous control process, the amount of power applied can be dependent on the magnitude of the feedback signal, its sign, its rate of change (derivative), or its accumulation (integral), along with various combinations of these.

1.4 Comments on Motion Control

As considered in this book, the DC servo is fundamentally concerned with the concept of motion, either translational or rotational. The motion to be controlled will usually be the position, or its first derivative, velocity of a