Mechatronics

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Mechanical System Interfacing

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Preface

In the philosophy of mechatronics from which this text evolved the (embedded) control computer is the central component, and the core of the technology that makes mechatronics a unique discipline. Digital and analog circuitry, and actuation and instrumentation elements immediately surround the control computer and serve as the "interface" between the computer and the target physical system. These form the focus for this book.

The characteristics that differentiate modern mechanical systems from one another in the marketplace are strongly determined by the creativity and effectiveness of the embedded software. The interface elements described in this book support the embedded software by providing it with timely information from the target system and by translating its commands into effective delivery of modulated power.

The book covers the major mechanical system interface areas from the perspective of engineers not trained in electrical or computer engineering. A substantial segment of the material is also of interest to electrical or computer engineers seeking exposure to mechanical systems. It is used as a text for a graduate course in mechanical engineering; students in the course have already had a class in real time software for control so there is a basic understanding of the operation of mechatronic systems. The material needn't be limited to graduate level, however. It is appropriate in whole or in part for use in a variety of undergraduate situations as well.

On a professional level, this material is of interest in situations where performance specifications are being tightened at the same time that productivity and reliability are stressed as primary market expectations. It is of particular relevance to engineers in those industries where system coordination has been based on mechanical components, gears, linkages, etc., and is now coming under computer control. Broad segments of industry have found that converting to electronic (computer) control can improve system accuracy and operating speed, and that substantial productivity benefits are realized from reduced downtime for product changeover.

Use of the book, either as a class text or for self study, is heavily lab based. Most of the problems and exercises involve laboratory work and many of them are design oriented.

The first and largest section of the book is devoted to digital electronics. This is the circuitry that is closest to the computer since that is how computers are built. Somewhere in its passage between the physical world and the computer, all information passes through digital interface circuitry. Mechatronic system designers need to be concerned with digital interface circuitry when data rates exceed the processing capability of software, a fairly common occurrence!

Digital electronics is initially introduced through Boolean algebra, including design and minimization methods based on maps and realization in circuit form with common logic families and programmable logic devices (PLDs). Sequential logic forms the "calculus" that builds on Boolean algebra. Most of the interesting problems fall into this domain! Synchronous sequential logic is by far the most common form and is discussed next. Because use of this material in a mechatronics context will almost always require input from asynchronous devices (such as limit switches, optical sensors, etc.) problems associated with bringing asynchronous signals into synchronous circuits are discussed as is the related problem of metastability. Design of asynchronous sequential logic is discussed next, for the same reason. In mechatronics systems there are instances of small, stand-alone logic circuits for which design with a clock is not necessary or desirable. The final topic under digital electronics is register transfer logic. This is a means of system organization for problems that are too complex to treat holistically. It is used in computer processor design, and design principles for simple processors are shown.

Embedded computers bridge the gap between computers and circuit elements. This chapter discusses various types of embedded computers and typical applications. At the simplest end, where hundreds of millions are sold every year, embedded microcontrollers look very much like circuit elements that are plugged onto the system board. They are very small and low cost, but their function is software based. At the upper end, they are more identifiably computers, but still intimately connected to the lowest level of system function. The microcontrollers (single-chip computers designed primarily for minimum size) are joined by digital signal processors (DSPs), reduced instruction set processors (RISC) as well as embedded PC systems to provide a rich set of alternatives for system designers.

The next two chapters shift attention from the computer and its closest interface components to the actuation side by examining stepper motors and DC motors. These motors account for a large majority of mechanical positioning applications. The presentations focus first on how these motors operate, including variant configurations such as linear motors, then presents material relating to typical usage situations and how control is exerted on the motors in a variety of situations.

Despite the increasing "digitization" of the technological world, there remain many interactions in mechatronic systems that depend on analog signals. The chapter on analog/digital conversion explores the avenues available for producing analog command signal originating as digital information inside the computer and for gathering information generated by instruments in analog form and converting it to digital information. The basic technology is introduced for digital-to-analog form and converting it to digital information. The basic technology is introduced for digital-to-analog conversion and for flash, successive approximation, integrating, and sigma-delta analog-to-digital conversion. Operating characteristics leading to choice of technology in various situations are discussed as well.

Instrumentation, the counterpart of actuation in mechatronics systems, is the source of ongoing information for the software decision-maker. Because many mechatronic systems utilize mechanical motion, regardless of the final technology of the target system, the discussion of measurement is limited to the most basic quantities of mechanics, velocity and position. Both analog and digital instruments are discussed, including tachometers, resistive measurement, variable reluctance devices, Hall effect, encoders, and resolvers.

The final section is devoted to manipulation of analog electrical signals, both low level for information and at high level for power. Usage of operational amplifiers (op-amps) is explored in both the computing and the follower configurations. General circuit design methods are discussed for a variety of linear and nonlinear applications. Amplifier selection is addressed through a discussion of the specifications of various types and classes of operational amplifiers. While op-amps serve the critical signal processing role for analog information, power amplifiers actually deliver the "goods." That is, the modulated power that allows precise control of mechanical elements. Because all information must go through the electrical medium before reaching the computer, many actuators are of the electro-*something* type, electro-mechanical, electro-thermal, etc. Operation of these elements requires the delivery of large amounts of controlled electrical power. The last chapter of the book is devoted to this subject. Basic operating principles of bipolar junction transistors (BJT) as well as field-effect transistors (FET) are discussed. The crucial factors that come into play when the amplifier has to control large currents at high voltages are brought forward, then configurations found in typical mechatronic applications are explored. Linear (proportioning) amplifiers are discussed as are switching amplifiers for pulse-width modulation (PWM) usage.

In the graduate course taught for mechanical engineers at Berkeley, this material is presented more-or-less in the order in the book. The course is heavily lab oriented and includes a design project for the last third of the semester. The material in each of the major sections, however, is reasonably independent, so the order of study can be varied to meet individual needs.

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1

Mechanical System Interfacing: Introduction

Mechanical systems have become increasingly dependent on computers and electronics to achieve the degree of function, flexibility, and reliability demanded by users. The combination of mechanics and electronics has been called mechatronics, a term that has come to include computers as well. A mechanical system can be characterized as

system = mechanics + electronics + software

The mechanics includes the mechanisms, electromagnetic components, thermal components, flow elements, and so on. The most notable function of the system is usually realized through the mechanics section. The instruments and actuators are considered part of the system mechanics.

The overall control of the mechanical system is expressed in the software. It is the unique role of software that differentiates modern mechanical systems from their forebears. Control of mechanical system through software affords a degree of flexibility unknown to the traditional machine designer. Changing, for example, from manufactured parts of one dimension to parts with another dimension is only a matter of changing numbers in a program. In traditional machines it might have required changing gears, resetting linkages, or other mechanical operations that could take many hours. In addition to this flexibility in usage, such a machine will have fewer moving parts, improving its reliability and probably decreasing its cost.

With this perspective, a new definition for mechatronics can be formulated:

> *Mechatronics* is the application of complex decision making to the operation of physical systems.

This definition recognizes the central role played by software and computers, the decision makers in the design and implementation of mechanical systems. It also recognizes the possibilities of using other technologies for decision making in the future.

Electronics forms the glue that connects the mechanics to the software. At the time the term *mechatronics* was coined, by combining mechanics and electronics, the electronic components themselves were so much more flexible and easy to program than mechanical components that a new class of machine was defined. Software has, however, eclipsed electronics in flexibility and decision making, defining yet another level of intelligent machines. Electronics continues to play a crucial role. That is the role of interface between mechanical components and the computers that run the system software. This role, that of *mechanical system interface*, is the subject of exploration in this book.

1.1 THE INTERFACE

At the lowest level, the interface requires conversion from one energy medium to another and from one power level to another. Because computers are internally electronic, the conversion must have electrical energy as one of its modes. Many conversions require electronics closely coupled to the conversion device, instrument or actuator. Slightly decoupled from the actual energy conversion, electronics provides signal conditioning. This can include change of level for device compatibility, spectral filtering to remove unwanted information, and modulation or demodulation to convert the signal to a more desirable form.

Although software is usually cheaper than custom electronics to design and implement, it has severe speed constraints. Many aspects of processing needed in mechanical systems are simply too fast for software. Electronics can take over data processing chores when software is too slow. These processing chores are usually relatively simple, but crucial. Electronic processing can be either digital or analog, covering such functions as counting (a very common operation), integration, differentiation, generalized logic, selection, and so on.

The ability to build electronics and computing capability directly into a system is leading to new classes of instruments and actuators, *smart instruments*. For example, the traditional boundaries between ac and dc motors are breaking down as the ability to create excitation signals of arbitrary complexity increases. Motors in this category can be made to have the simplicity of dc motors as viewed externally, but actually use ac motor technology internally for a motor with fewer mechanical parts.

1.2 MECHANICAL SYSTEM DESIGN PHILOSOPHY

Mechanical system design has the goals of producing systems with superior performance while minimizing time to market and manufacturing cost, and maximizing reliability.

This suggests the following priority order for choice of medium at the design level:

- Software
- Electronics
- Mechanics

Assigning computational functions to the mechanics, for example, leads to machines with more moving parts and therefore generally lower reliability and higher manufacturing costs. Traditional cam grinding machines, for example, use a master cam and a follower mechanism. Changeover to different cam profiles requires replacement of the master cam and readjustment of the mechanism. Masterless cam grinders use a software (data table) representation of the cam profile to be ground. There is no follower mechanism, and changeover to a new cam profile requires only a new table. New design problems arise as well, however. These involve measurements of tool position and extremely accurate control of the motion of the grinding mechanism to synchronize it with the rotation of the cam blank.

Another example of this is the increasing popularity of brushless dc motors for precision motion applications. The essence of dc motor operation is in the change of electrical excitation to the windings to match the angular position of the motor's rotor. In the Faraday dc motor, this is done mechanically with a set of electrically conducting brushes sliding on an electrically split ring. This commutator changes the excitation every time the brush moves to a new section of the ring. Brushless motors replace mechanical commutation with electrical commutation, improving reliability, particularly in the brushes, which can wear rapidly. But to accomplish the same function, explicit measurement of the rotor angular position is required along with means to change the electrical excitation on command.

Another example arises in controllers themselves. These devices are used to control process or motion variables (pressure, flow, temperature, velocity, position). Historically, mechanics were used for all aspects of the control, measurement, computation, and actuation, as in the Watt governor for steam engines. Controller technology has evolved from mechanical to use of hydraulic or pneumatics, then electronics, and now software.

The operator interface is of critical importance to successful system function and it, too, has changed in response to this design philosophy. Fixed meters, pushbuttons, thumbwheels, and so on, are being replaced with computer display screens, touch-sensitive screen input, keyboards, mice, and trackballs. These computer-based operator interfaces have the potential of providing vastly more effective operator interfaces because information can be grouped according to the immediate needs of the operator, allowing a focus that was not possible in a system with hundreds of fixed elements. On the other hand, the design of the interface becomes even more critical since the operator must have the correct information and controls available to make the right decision.

Overall, this design philosophy can produce systems that:

- Have more functionality
- Are easier to change
- Have a faster development cycle
- Are more reliable
- Give better information and control to the user

However.

- There are new kinds of design problems.
- Different skills are required.
- Unexpected failure modes exist.
- Testing can be more difficult.

1.3 MECHANICAL SYSTEM TIME SCALES

The need for customized electronics in mechanical systems is governed primarily by two factors:

- Signal level
- Time scale

Signal level is connected directly to the conversion process. Standard components. analog-to-digital converters, and other such devices can be used where the signal has a high enough power level to be relatively immune to local electrical noise contamination. Otherwise, electronic signal conditioning is required before these standard devices can be used.

Time scales control the speed with which decisions must be made and actions taken, and thus the speed with which computations must be carried out. The crossover between electronics and software occurs somewhere in the range 1 to 100 μs. Any decisions required below the low end of that range will usually require dedicated electronics. Above the high end, software will generally be used.

A number of time scales are important. Typical time scales for primary actions in representative mechanical systems are:

- *Process systems*: seconds to minutes
- *Large mechanical systems*: tenths of seconds
- *Medium mechanical systems*: milliseconds
- *Small mechanical systems*: 10 μs

The instrument and actuator decision rates can be many times faster than the primary rate. For example, consider the incremental encoder, a common means of measuring linear or rotary position in mechanical systems. It generates a change of state in a digital signal for each specified increment in motion. Even large mechanical systems can generate these changes at maximum rates, in the million per second range. Thus the most basic level of processing must be able to keep up with these rates even though the higher-level decision making can be much slower.

It is interesting that the data rates are often determined by precision/dynamic range considerations rather than raw speed or size of the device being controlled. Precision refers to the size of the smallest change that must be recognized; *dynamic range* refers to the maximum number of such changes that a system must be able to undergo. Precision in such systems is often determined by the need to characterize velocity for low-speed operation. Dynamic range is then determined from the maximum distance the device has to move. The maximum data rate is then dependent on the fastest speed at which the device has to move. One reason for the importance of incremental encoders, for example, is that as digital devices, their dynamic range is limited primarily by the processing equipment rather than by the device itself.

1.4 MAJOR TOPICS

Mechanical system interfacing thus centers on electronics but includes those devices closest to the computational part of the system, primarily instruments and actuators. The book starts with digital logic. With computers playing the central role in mechanical systems, there is a strong motivation in system and component design to use as much digital electronics as possible to simplify the interface. As computers get smaller and cheaper, they can be integrated directly with instruments and actuators. The exploration thus follows naturally from digital logic to this most important application of digital logic, computer architecture. Microcontrollers are designed specifically for such integration and are a hybrid—programmed like computers but used as circuit elements. Motors, the next topics, are the most common actuation elements in mechanical systems. Despite inroads from direct digital instruments and actuators, analog signals are still widely used but must be converted to digital form for computational use. Even in process systems, mechanical motion measurement plays such an important role for such tasks as valve positioning that position and velocity measurement are treated specifically. The final chapters deal with analog electronics, first at the signal level using operational amplifiers and then at the power level.

- Boolean logic
- Sequential logic
- Computer architecture
- Microcontrollers
- Stepping motors
- dc motors
- Analog-to-digital conversion
- Position and velocity measurement
- Analog signal processing (operational amplifiers)
- Power amplification

1.5 PROBLEMS AND DISCUSSION TOPICS

1. Automobile cruise control devices relieve the driver of the need to monitor and control speed. Refer to Figure 1.1 and discuss the following issues:
   (a) Where in the actual vehicle are the signals indicated in the block diagram?
   (b) Identify instrumentation, computation, actuation, and the target system.
   (c) Indicate the power flows in the system and how they are regulated.
   (d) Which aspects of the system are possible candidates for hardware or software control?