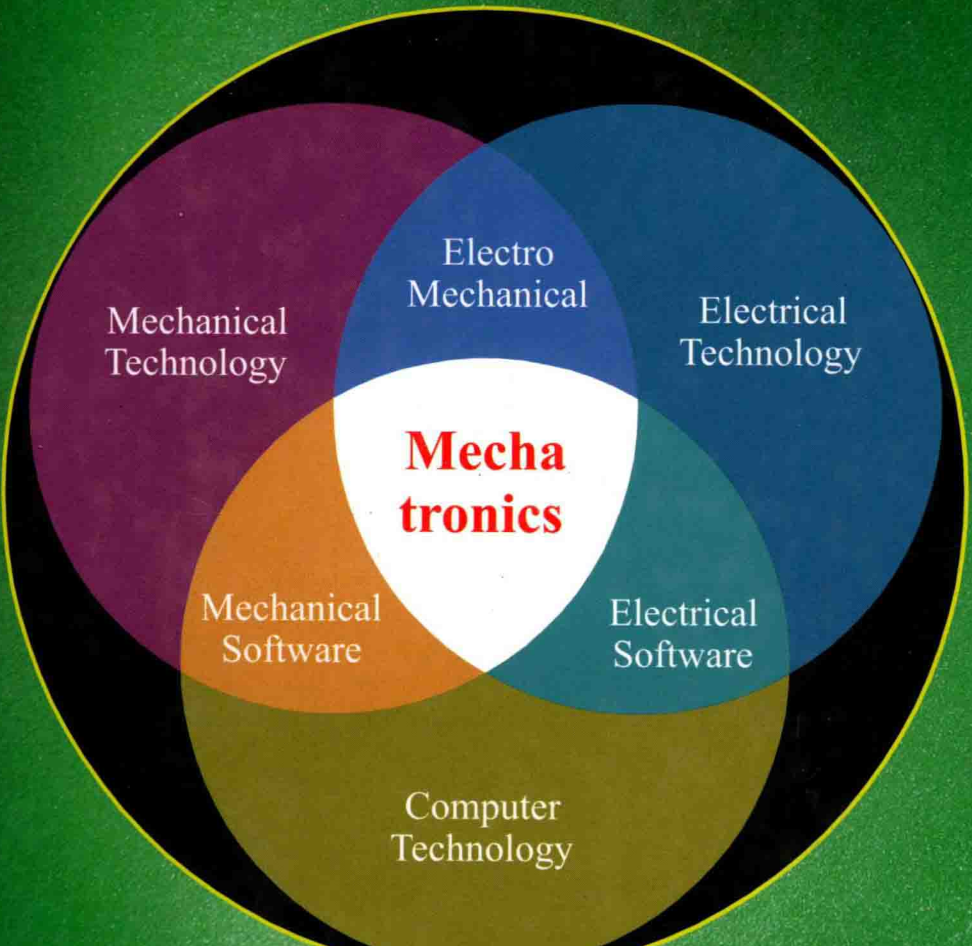
Second Edition

MECHATRONICS with Experiments



Sabri Cetinkunt

with website

WILEY

SECOND EDITION

MECHATRONICS

with Experiments

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WILEY

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MECHATRONICS

PREFACE

This second edition of the textbook has the following modifications compared to the first edition:

- Twelve experiments have been added. The experiments require building of electronic interface circuits between the microcontroller and the electromechanical system, writing of real-time control code in C language, and testing and debugging the complete system to make it work.
- All of the chapters have been edited and more examples have been added where appropriate.
- A brief tutorial on MATLAB®/Simulink®/Stateflow is included.

I would like to thank Paul Petralia, Tom Carter and Anne Hunt [Acquisitions Editor, Project Editor and Associate Commissioning Editor, respectively] at John Wiley and Sons for their patience and kind guidance throughout the process of writing this edition of the book.

Sabri Cetinkunt
Chicago, Illinois, USA
March 19, 2014

ABOUT THE COMPANION WEBSITE

This book has a companion website:

www.wiley.com/go/cetinkunt/mechatronics

The website includes:

- A solutions manual

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CHAPTER 1

INTRODUCTION

THE MECHATRONICS field consists of the synergistic integration of three distinct traditional engineering fields for system level design processes. These three fields are

1. mechanical engineering where the word "mecha" is taken from,
2. electrical or electronics engineering, where "tronics" is taken from,
3. computer science.

The file of mechatronics is not simply the sum of these three major areas, but can be defined as the intersection of these areas when taken in the context of systems design (Figure 1.1). It is the current state of evolutionary change of the engineering fields that deal with the design of controlled electromechanical systems. A mechatronic system is a computer controlled mechanical system. Quite often, it is an *embedded computer*, not a general purpose computer, that is used for control decisions. The word mechatronics was first coined by engineers at Yaskawa Electric Company [1,2]. Virtually every modern electromechanical system has an embedded computer controller. Therefore, computer hardware and software issues (in terms of their application to the control of electromechanical systems) are part of the field of mechatronics. Had it not been for the widespread availability of low cost microcontrollers for the mass market, the field of mechatronics as we know it today would not exist. The availability of embedded microprocessors for the mass market at ever reducing cost and increasing performance makes the use of computer control in thousands of consumer products possible.

The old model for an electromechanical product design team included

1. engineer(s) who design the mechanical components of a product,
2. engineer(s) who design the electrical components, such as actuators, sensors, amplifiers and so on, as well as the control logic and algorithms,
3. engineer(s) who design the computer hardware and software implementation to control the product in real-time.

A mechatronics engineer is trained to do all of these three functions. In addition, the design process is not sequential with mechanical design followed by electrical and computer control system design, but rather all aspects (mechanical, electrical, and computer control) of design are carried out simultaneously for optimal product design. Clearly, mechatronics is not a new engineering discipline, but the current state of the evolutionary process of the engineering disciplines needed for design of electromechanical systems. The end product of a mechatronics engineer's work is a working prototype of an embedded computer controlled electromechanical device or system. This book covers the fundamental

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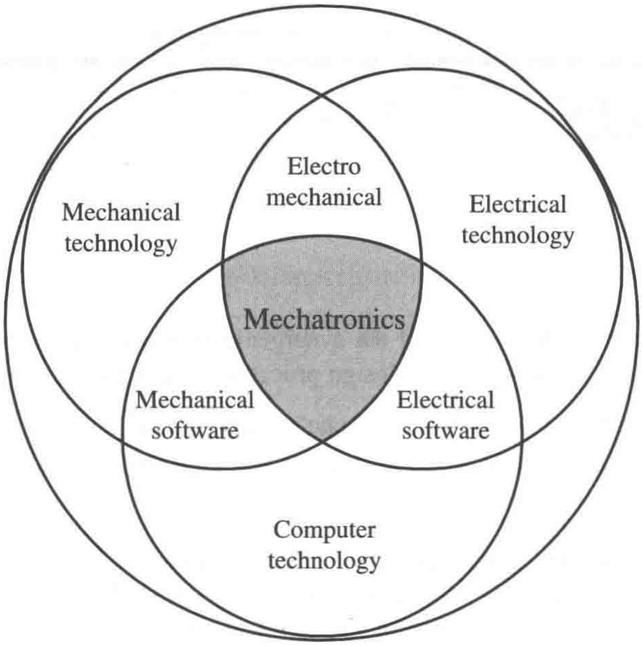

FIGURE 1.1: The field of mechatronics: intersection of mechanical engineering, electrical engineering, and computer science.

technical topics required to enable an engineer to accomplish such designs. We define the word *device* as a stand-alone product that serves a function, such as a microwave oven, whereas a *system* may be a collection of multiple devices, such as an automated robotic assembly line.

As a result, this book has sections on mechanical design of various mechanisms used in automated machines and robotic applications. Such mechanisms are designs over a century old and these basic designs are still used in modern applications. Mechanical design forms the "skeleton" of the electromechanical product, upon which the rest of the functionalities are built (such as "eyes," "muscles," "brains"). These mechanisms are discussed in terms of their functionality and common design parameters. Detailed stress or force analysis of them is omitted as these are covered in traditional stress analysis and machine design courses.

The analogy between a human controlled system and computer control system is shown in Figure 1.2. If a process is controlled and powered by a human operator, the operator observes the behavior of the system (i.e., using visual observation), then makes a decision regarding what action to take, then using his muscular power takes a particular control action. One could view the outcome of the decision making process as a low power control or decision signal, and the action of the muscles as the actuator signal which is the amplified version of the control (or decision) signal. The same functionalities of a control system can be automated by use of a digital computer as shown in the same figure.

The sensors replace the eyes, the actuators replace the muscles, and the computer replaces the human brain. Every computer controlled system has these four basic functional blocks:

1. process to be controlled,
2. actuators,
3. sensors,
4. controller (i.e., digital computer).

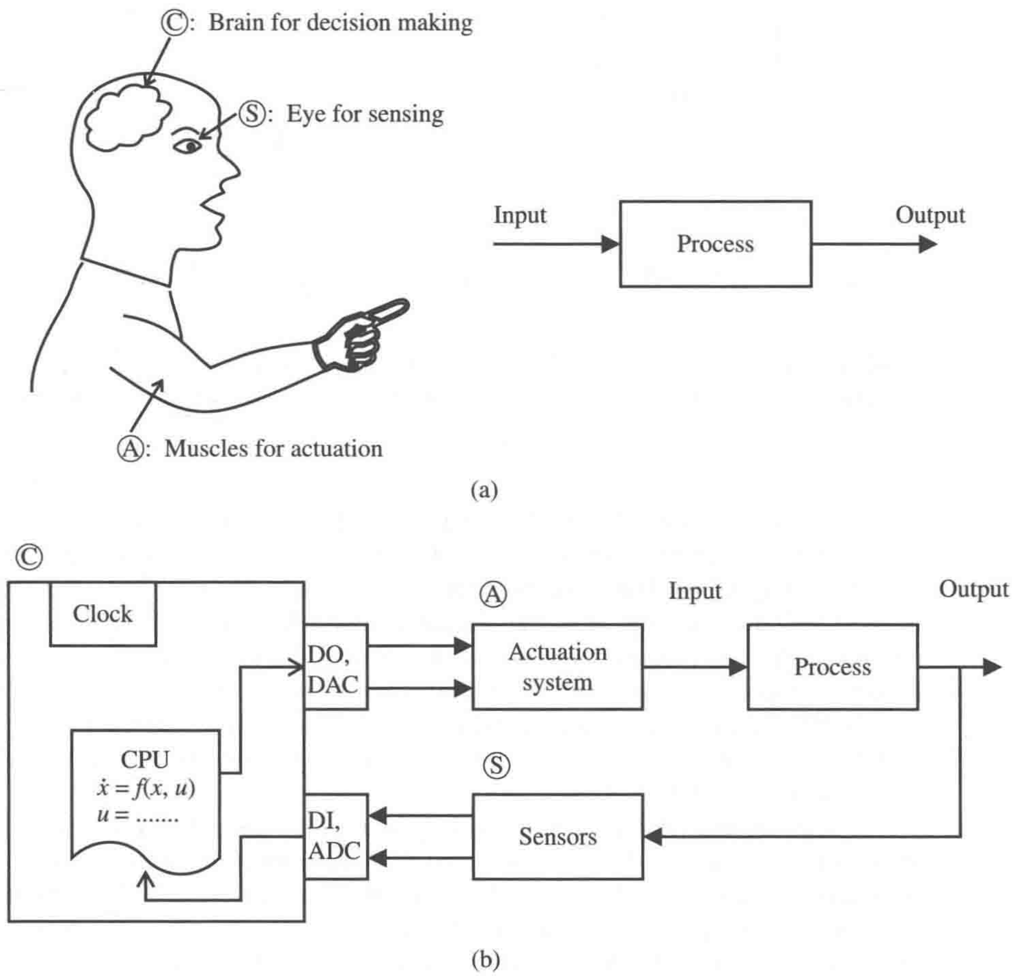

FIGURE 1.2: Manual and automatic control system analogy: (a) human controlled, (b) computer controlled.

The microprocessor (μP) and digital signal processing (DSP) technology had two impacts on control world,

1. it replaced the *existing* analog controllers,
2. prompted *new* products and designs such as fuel injection systems, active suspension, home temperature control, microwave ovens, and auto-focus cameras, just to name a few.

Every mechatronic system has some sensors to measure the status of the process variables. The sensors are the "eyes" of a computer controlled system. We study most common types of sensors used in electromechanical systems for the measurement of temperature, pressure, force, stress, position, speed, acceleration, flow, and so on (Figure 1.3). This list does not attempt to cover every conceivable sensor available in the current state of the art, but rather makes an attempt to cover all major sensor categories, their working principles and typical applications in design.

Actuators are the "muscles" of a computer controlled system. We focus in depth on the actuation devices that provide high performance control as opposed to simple ON/OFF actuation devices. In particular, we discuss hydraulic and electric power actuators in detail. Pneumatic power (compressed air power) actuation systems are not discussed.

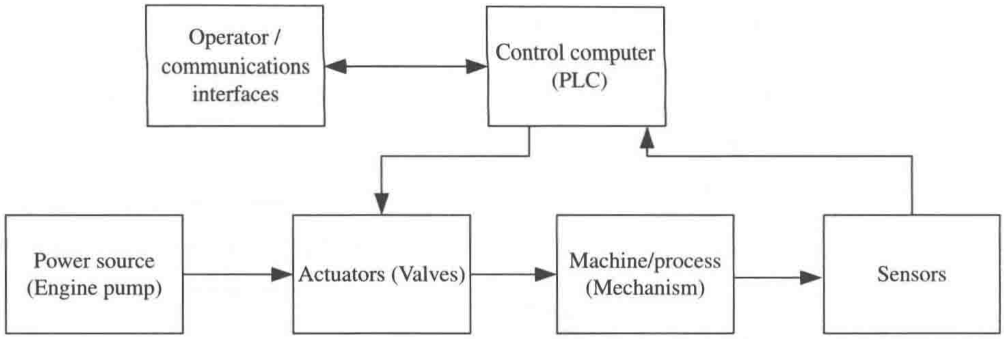

FIGURE 1.3: Main components of any mechatronic system: mechanical structure, sensors, actuators, decision making component (microcontroller), power source, human/supervisory interfaces.

They are typically used in low performance, ON/OFF type control applications (although, with advanced computer control algorithms, even they are starting to be used in high performance systems). The component functionalities of pneumatic systems are similar to those of hydraulic systems. However, the construction detail of each is quite different. For instance, both hydraulic and pneumatic systems need a component to pressurize the fluid (pump or compressor), a valve to control the direction, amount, and pressure of the fluid flow in the pipes, and translation cylinders to convert the pressurized fluid flow to motion. The pumps, valves, and cylinders used in hydraulic systems are quite different to those used in pneumatic systems.

Hardware and software fundamentals for embedded computers, microprocessors, and digital signal processors (DSP), are covered with applications to the control of electromechanical devices in mind. Hardware I/O interfaces, microprocessor hardware architectures, and software concepts are discussed. The basic electronic circuit components are discussed since they form the foundation of the interface between the digital world of computers and the analog real world. It is important to note that the hardware interfaces and embedded controller hardware aspects are largely standard and do not vary greatly from one application to another. On the other hand, the software aspects of mechatronics designs are different for every product. The development tools used may be same, but the final software created for the product (also called the application software) is different for each product. It is not uncommon that over 80% of engineering effort in the development of a mechatronic product is spent on the software aspects alone. Therefore, the importance of software, especially as it applies to embedded systems, cannot be over emphasized.

Mechatronic devices and systems are the natural evolution of automated systems. We can view this evolution as having three major phases:

1. completely mechanical automatic systems (before and early 1900s),
2. automatic devices with electronic components such as relays, transistors, op-amps (early 1900s to 1970s),
3. computer controlled automatic systems (1970s–present)

Early automatic control systems performed their automated function solely through mechanical means. For instance, a water level regulator for a water tank uses a float connected to a valve via a linkage (Figure 1.4). The desired water level in the tank is set by the adjustment of the float height or the linkage arm length connecting it to the valve. The float opens and closes the valve in order to maintain the desired water level. All the functionalities of a closed loop control system ("sensing-comparison-corrective actuation"

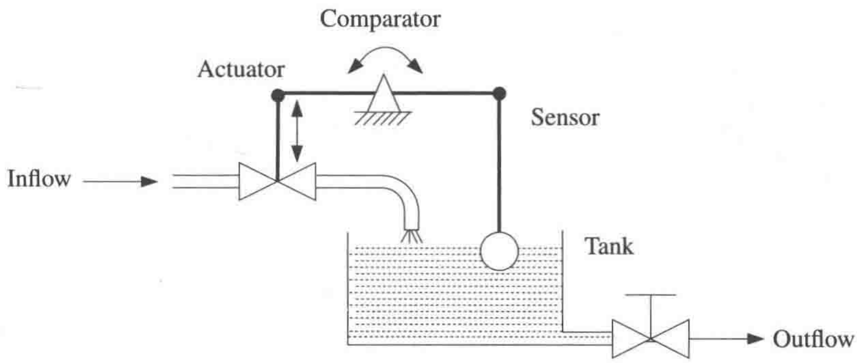

FIGURE 1.4: A completely mechanical closed loop control system for liquid level regulation.

or "sensor-logic-actuation") may be embedded in one component by design, as is the case in this example.

Another classic automatic control system that is made of completely mechanical components (no electronics) is Watt's flyball governor, which is used to regulate the speed of an engine (Figure 1.5). The same concept is still used in some engines today. The engine speed is regulated by controlling the fuel control valve on the fuel supply line. The valve is controlled by a mechanism that has a desired speed setting using the bias in the spring in the flywheel mechanism. The actual speed is measured by the flyball mechanism. The higher the speed of the engine is, the more the flyballs move out due to centrifugal force. The difference between the desired speed and actual speed is turned into control action by the movement of the valve, which controls a small cylinder which is then used to control the fuel control valve. In today's engines, the fuel rate is controlled directly by an electrically actuated injector. The actual speed of the engine is sensed by an electrical sensor (i.e., tachometer, pulse counter, encoder) and an embedded computer controller decides on how

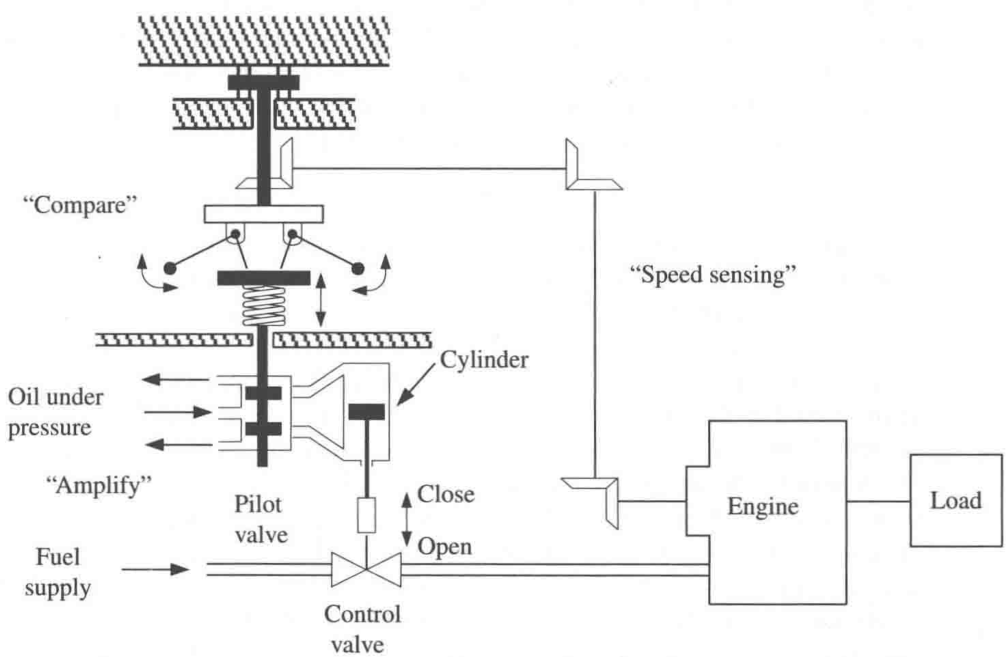

FIGURE 1.5: Mechanical "governor" concept for automatic engine speed control using all mechanical components.