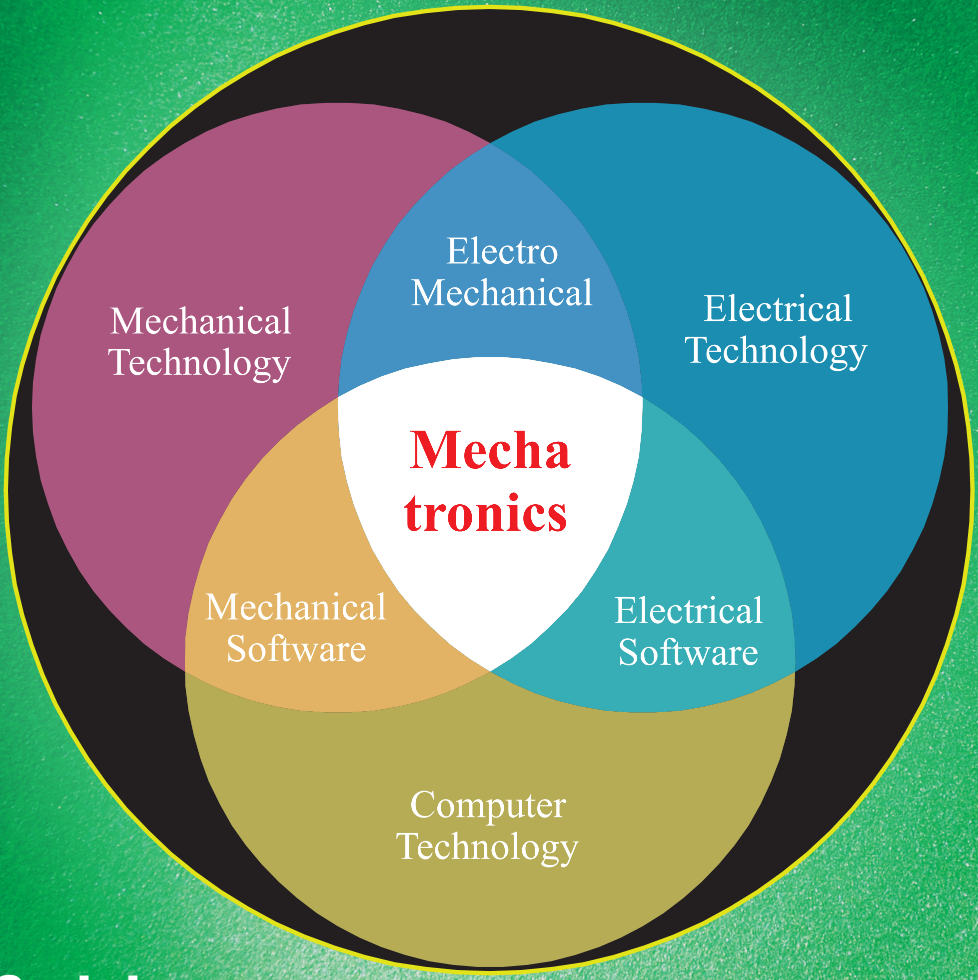
Second Edition

MECHATRONICS

with Experiments



Sabri Cetinkunt

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SECOND EDITION

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with Experiments

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WILEY

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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

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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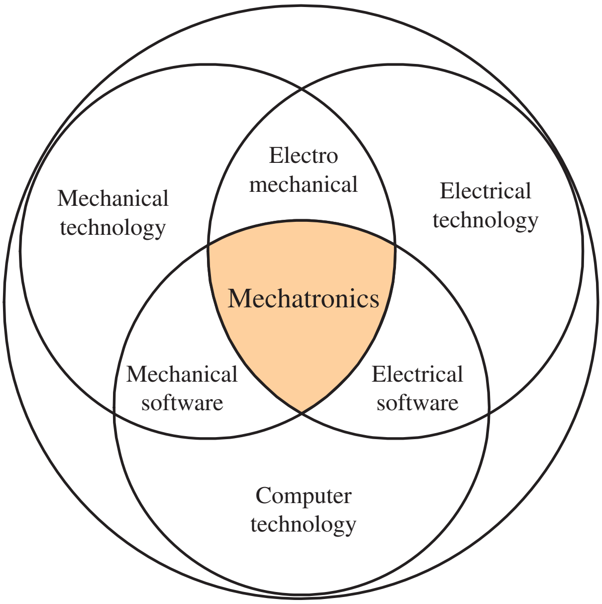


FIGURE 1.1: The field of mechatronics: intersection of mechanical engineering, electrical engineering, and computer science.

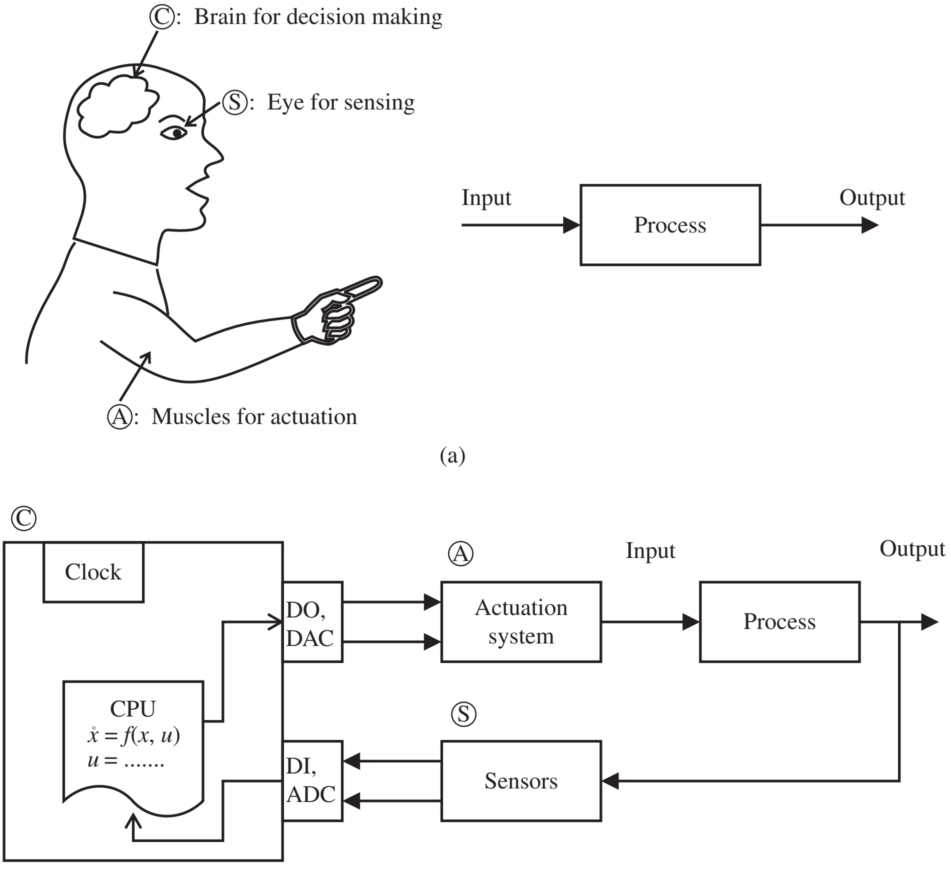
technical topics required to enable an engineer to accomplish such designs. We define the word *device* as a stand-alone product that serves a function, such as a microwave oven, whereas a *system* may be a collection of multiple devices, such as an automated robotic assembly line.

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).



(a)

(b)

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.

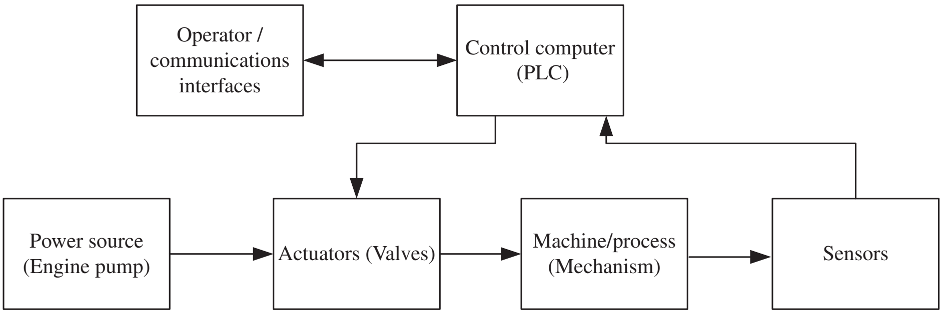


FIGURE 1.3: Main components of any mechatronic system: mechanical structure, sensors, actuators, decision making component (microcontroller), power source, human/supervisory interfaces.

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"

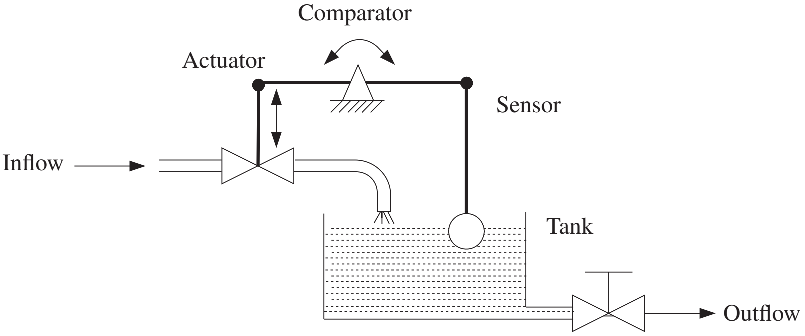


FIGURE 1.4: A completely mechanical closed loop control system for liquid level regulation.

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

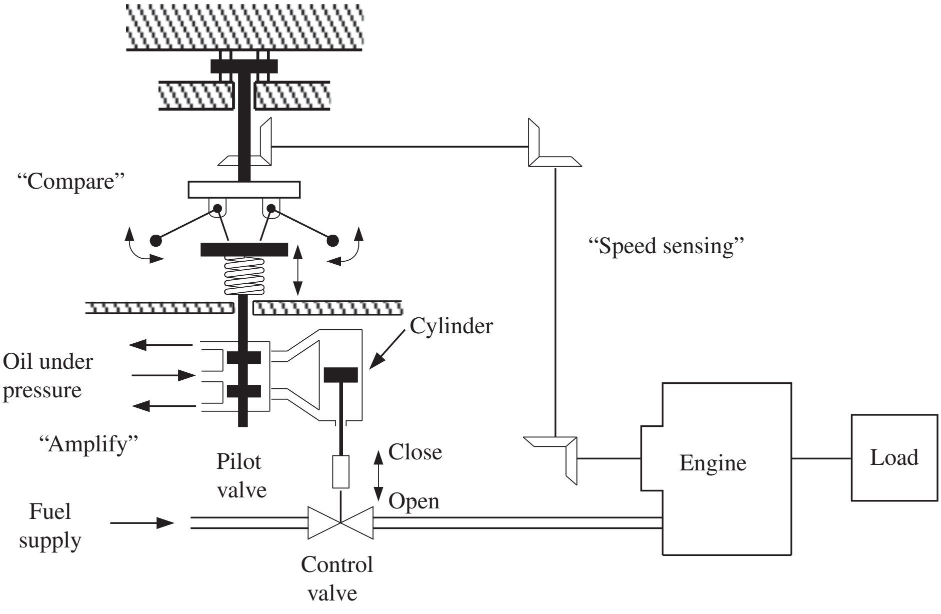


FIGURE 1.5: Mechanical "governor" concept for automatic engine speed control using all mechanical components.

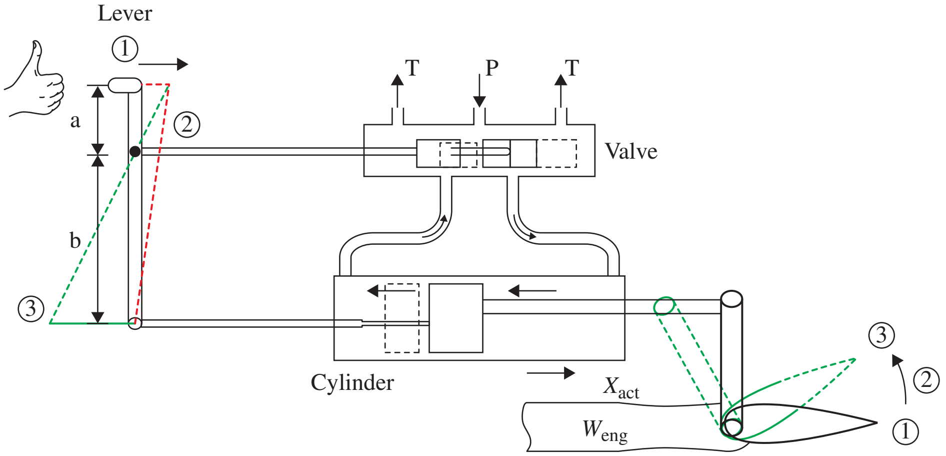


FIGURE 1.6: Closed loop cylinder position control system with mechanical feedback used in the actuation of the main valve.

much fuel to inject based on the difference between the desired and actual engine speed (Figure 1.9).

Figure 1.6 shows a closed loop cylinder position control system where the position feedback is mechanical. The command signal is the desired cylinder position and is generated by the motion of the lever moved by the pilot, and converted to the actuation power to the valve spool displacement through the mechanical linkage. The position feedback is provided by the mechanical linkage connection between the cylinder rod and the lever arm. When the operator moves the lever to a new position, it is the desired cylinder position (position 1 to position 2 in the figure). Initially, that opens the valve, and the fluid flow to the cylinder makes the piston move. As the piston moves, it also moves the linkage connected to the lever. This in turn moves the valve spool (position 2 to position 3 in the figure) to neutral position where the flow through the valve stops when the cylinder position is proportional to the lever displacement. In steady-state, when the cylinder reaches the desired position, it will push the lever such that the valve will be closed again (i.e., when the error is zero, the actuation signal is zero). The proportional control decision based on error is implemented hydro-mechanically without any electronic components.

$$x_{valve}(t) = \frac{1}{a} \cdot x_{cmd}(t) - \frac{1}{b} \cdot x_{actual}(t) \tag{1.1}$$

Analog servo controllers using operational amplifiers led to the second major change in mechatronic systems. As a result, automated systems no longer had to be all mechanical. An operational amplifier is used to compare a desired response (presented as an analog voltage) and a measured response by an electrical sensor (also presented as an analog voltage) and send a command signal to actuate an electrical device (solenoid or electric motor) based on the difference. This brought about many electromechanical servo control systems (Figures 1.7, 1.8). Figure 1.7 shows a web handling machine with tension control. The wind-off roll runs at a speed that may vary. The wind-up roll is to run such that no matter what the speed of the web motion is, a certain tension is maintained on the web. Therefore, a displacement sensor on the web is used to indirectly sense the web tension since the sensor measures the displacement of a spring. The measured tension is then compared to the desired tension (command signal in the figure) by an operational amplifier. The operational amplifier sends a speed or current command to the amplifier of the motor based on the tension error. Modern tension control systems use a digital computer controller in place of the analog operational amplifier controller. In addition, the digital controller may

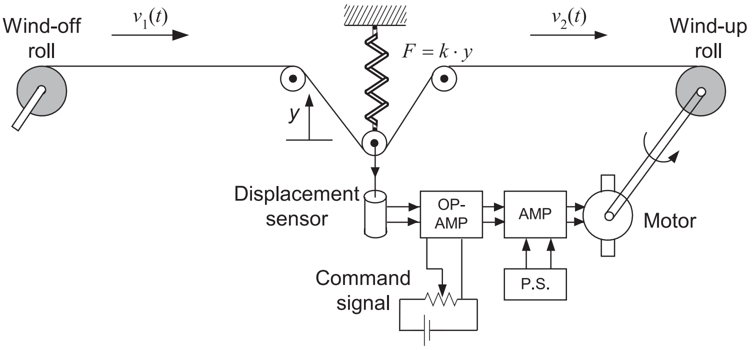


FIGURE 1.7: A web handling motion control system. The web is moved at high speed while maintaining the desired tension. The tension control system can be considered a mechatronic system, where the control decision is made by an analog op-amp, not a digital computer.

use a speed sensor from the wind-off roll or from the web on the incoming side in order to react to tension changes faster and improve the dynamic performance of the system.

Figure 1.8 shows a temperature control system that can be used to heat a room or oven. The heat is generated by the electric heater. Heat is lost to the outside through the walls. A thermometer is used to measure the temperature. An analog controller has the desired temperature setting. Based on the difference between the set and measured temperature, the op-amp turns ON or OFF the relay which turns the heater ON/OFF. In order to make sure

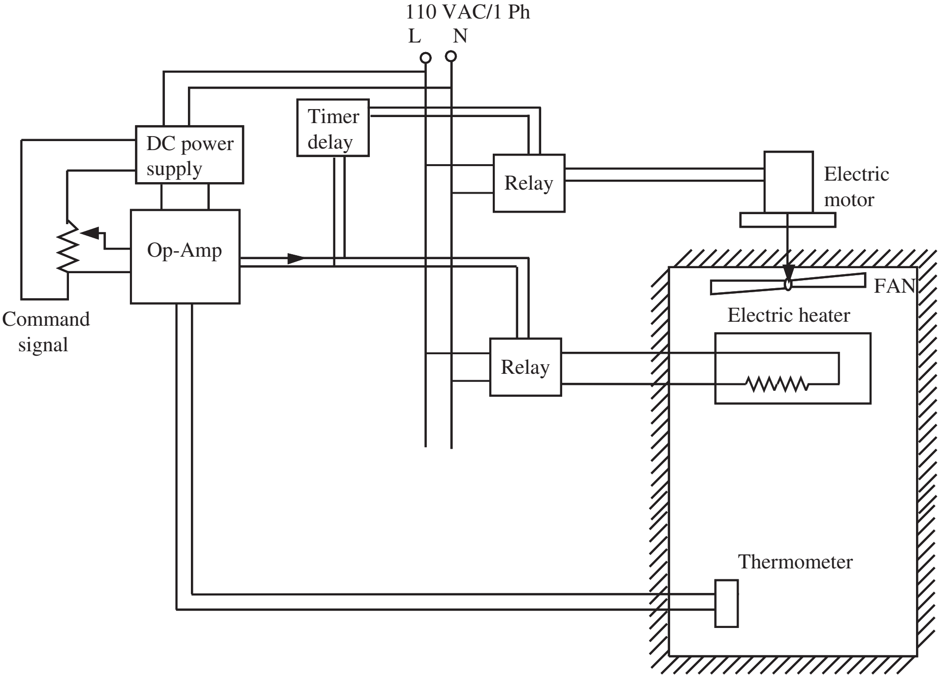


FIGURE 1.8: A furnace or room temperature control system and its components using analog op-amp as the controller. Notice that a fan driven by an electric motor is used to force the air circulation from the heater to the room. A timer is used to delay the turn ON and turn OFF time of the fan motor by a specified amount of time after the heater is turned ON or OFF. A microcontroller-based digital controller can replace the op-amp and timer components.

the relay does not turn ON and OFF due to small variations around the set temperature, the op-amp would normally have a *hysteresis* functionality implemented on its circuit. More details on the relay control with hysteresis will be discussed in later chapters.

Finally, with the introduction of microprocessors into the control world in the late 1970s, programmable control and intelligent decision making were introduced to automatic devices and systems. Digital computers not only duplicated the automatic control functionality of previous mechanical and electromechanical devices, but also brought about new possibilities for device designs that were not possible before. The control functions incorporated into the designs included not only the servo control capabilities but also many operational logic, fault diagnostics, component health monitoring, network communication, nonlinear, optimal, and adaptive control strategies (Figure 1.3). Many such functions were practically impossible to implement using analog op-amp circuits. With digital controllers, such functions are rather easy to implement. It is only a matter of coding these functionalities in software. The difficulty is in knowing what to code that works.

The automotive industry, the largest industry in the world, has transformed itself both in terms of its products (the content of the cars) and the production methods of its products since the introduction of microprocessors. Use of microprocessor-based embedded controllers significantly increased the robotics-based programmable manufacturing processes, such as assembly lines, CNC machine tools, and material handling. This changed the way the cars are made, reducing the necessary labor and increasing the productivity. The product itself, cars, has also changed significantly. Before the widespread introduction of 8-bit and 16-bit microcontrollers into the embedded control mass market, the only electrical components in a car were the radio, starter, alternator, and battery charging system. Engine, transmission, and brake subsystems were all controlled by mechanical or hydro-mechanical means. Today, the engine in a modern car has a dedicated embedded microcontroller that controls the timing and amount of fuel injection in an optimized manner based on the load, speed, temperaturem and pressure sensors in real time. Thus, it improves the fuel efficiency, reduces emissions, and increases performance (Figure 1.9). Similarly, automatic transmission is controlled by an embedded controller. The braking system includes ABS (anti-lock braking system), TCS (traction-control system), DVSC (dynamic vehicle

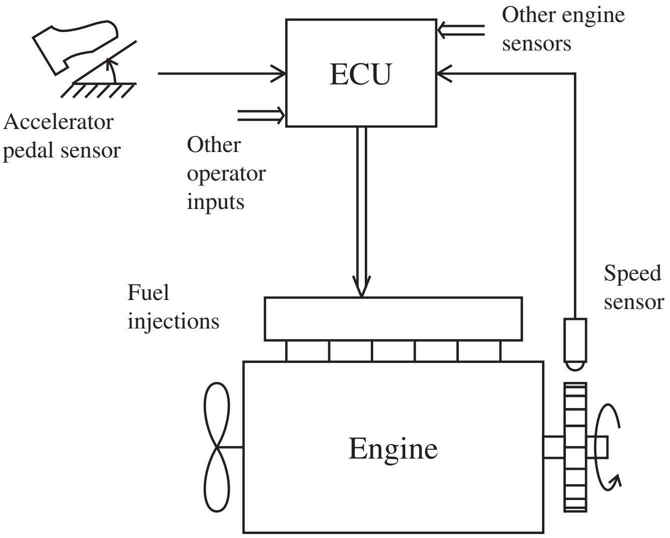


FIGURE 1.9: Electronic "governor" concept for engine control using embedded microcontrollers. The electronic control unit decides on fuel injection timing and amount in real time based on sensor information.

stability control) systems which use dedicated microcontrollers to modulate the control of brake, transmission and engine in order to maintain better control of the vehicle. It is estimated that an average car today has over 30 embedded microprocessor-based controllers on board. This number continues to increase as more intelligent functions are added to cars, such as the autonomous self driving cars by Google Inc and others. It is clear that the traditionally all-mechanical devices in cars have now become computer controlled electromechanical devices, which we call mechatronic devices. Therefore, the new generation of engineers must be well versed in the technologies that are needed in the design of modern electromechanical devices and systems. The field of mechatronics is defined as the integration of these areas to serve this type of modern design process.

Robotic manipulator is a good example of a mechatronic system. The low-cost, high computational power, and wide availability of digital signal processors (DSP) and microprocessors energized the robotics industry in late 1970s and early 1980s. The robotic manipulators, the reconfigurable, programmable, multi degrees of freedom motion mechanisms, have been applied in many manufacturing processes and many more applications are being developed, including robotic assisted surgery. The main sub-systems of a robotic manipulator serve as a good example of mechatronic system. A robotic manipulator has four major sub-systems (Figure 1.3), and every modern mechatronic system has the same sub-system functionalities:

1. a mechanism to transmit motion from actuator to tool,
2. an actuator (i.e., a motor and power amplifier, a hydraulic cylinder and valve) and power source (i.e., DC power supply, internal combustion engine and pump),
3. sensors to measure the motion variables,
4. a controller (DSP or microprocessor) along with operator user interface devices and communication capabilities to other intelligent devices.

Let us consider an electric servo motor-driven robotic manipulator with three axes. The robot would have a predefined mechanical structure, for example Cartesian, cylindrical, spherical, SCARA type robot (Figures 1.10, 1.11, 1.12). Each of the three electric servo motors (i.e., brush-type DC motor with integrally mounted position sensor such as an encoder or stepper motor with position sensor) drives one of the axes. There is a separate power amplifier for each motor which controls the current (hence torque) of the motor. A DC power supply provides a DC bus at a constant voltage and derives it from a standard AC line. The DC power supply is sized to support all three motor-amplifiers.

The power supply, amplifier, and motor combination forms the actuator sub-system of a motion system. The sensors in this case are used to measure the position and velocity

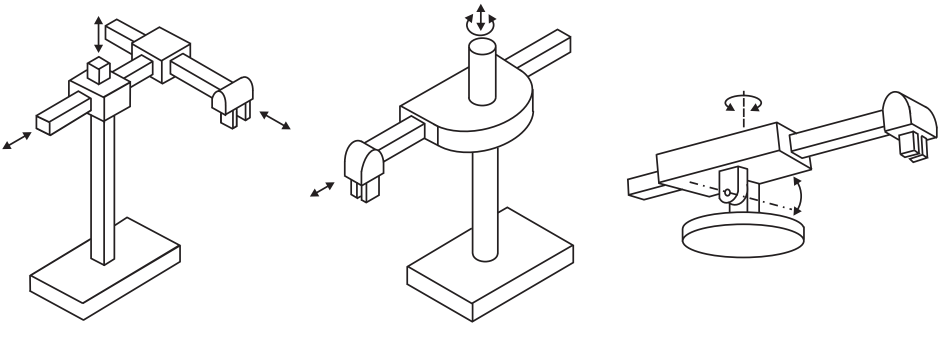


FIGURE 1.10: Three major robotic manipulator mechanisms: Cartesian, cylindrical, spherical coordinate axes.

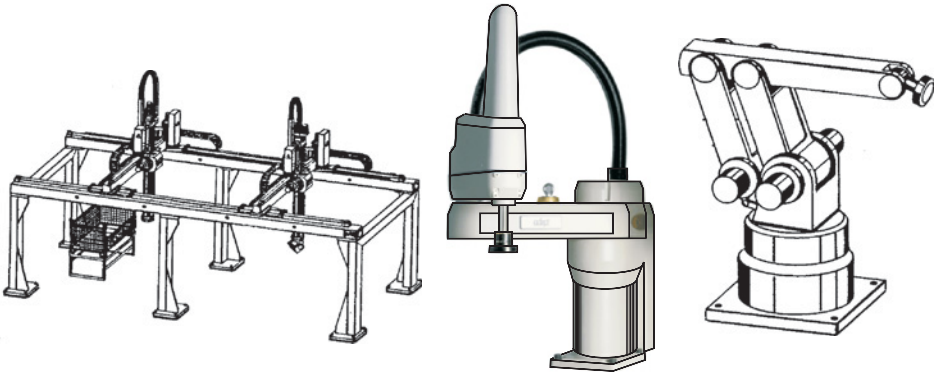


FIGURE 1.11: Gantry, SCARA, and parallel linkage drive robotic manipulators.

of each motor so that this information is used by the axis controller to control the motor through the power amplifier in a closed loop configuration. Other external sensors not directly linked to the actuator motions, such as a vision sensors or a force sensors or various proximity sensors, are used by the supervisory controller to coordinate the robot motion with other events. While each axis has a dedicated closed loop control algorithm, there has to be a supervisory controller that coordinates the motion of the three motors in order to generate a coordinated motion by the robot, that is straight line motion, and so on circular motion etc. The hardware platform to implement the coordinated and axis level controls can be based on a single DSP/microprocessor or it may be distributed over multiple processors as shown. Figure 1.12 shows the components of a robotic manipulator in block diagram form. The control functions can be implemented on a single DSP hardware or a distributed DSP hardware. Finally, just as no man is an island, no robotic manipulator is an

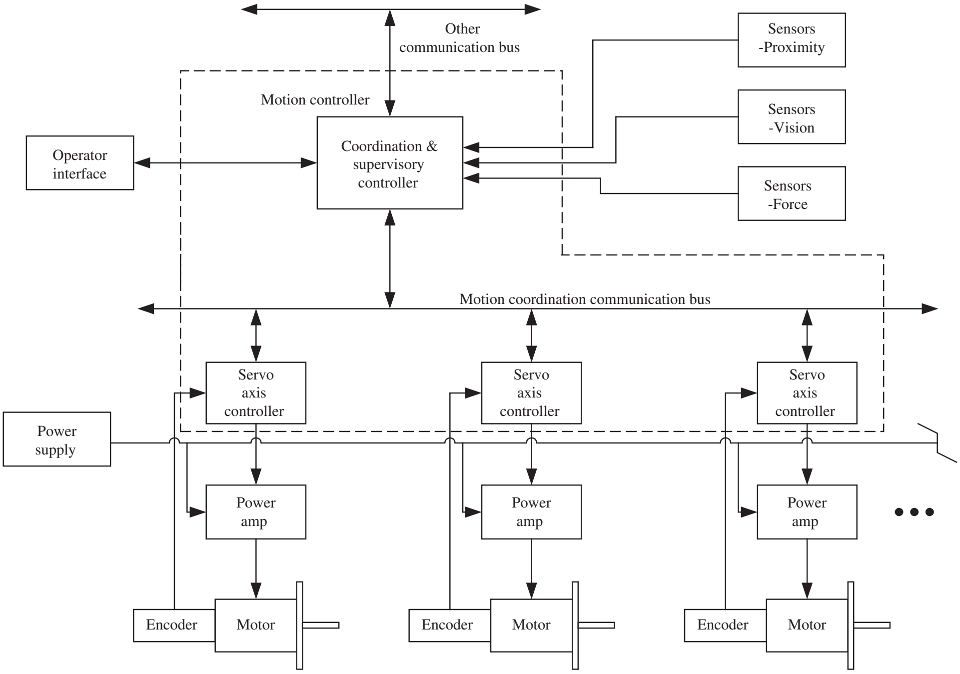


FIGURE 1.12: Block diagram of the components of a computer controlled robotic manipulator.

island. A robotic manipulator must communicate with a user and other intelligent devices to coordinate its motion with the rest of the manufacturing cell. Therefore, it has one or more other communication interfaces, typically over a common fieldbus (i.e., DeviceNET, CAN, ProfiBus, Ethernet). The capabilities of a robotic manipulator are quantified by the following;

1. workspace: volume and envelope that the manipulator end effector can reach,
2. number of degrees of freedom that determines the positioning and orientation capabilities of the manipulator,
3. maximum load capacity, determined by the actuator, transmission components, and structural component sizing,
4. maximum speed (top speed) and small motion bandwidth,
5. repeatability and accuracy of end effector positioning,
6. manipulator's physical size (weight and volume it takes).

Figure 1.13 shows a computer numeric controlled (CNC) machine tool. A multi axis vertical milling machine is shown in this figure. There are three axes of motion controlled precisely (i.e., within $1/1000$ in or 25 micron $= 25/1000$ mm accuracy) in x, y and z directions by closed loop controlled servo motors. The rotary motion of each of the servo motors is converted to linear motion of the table by the ball-screw or lead-screw

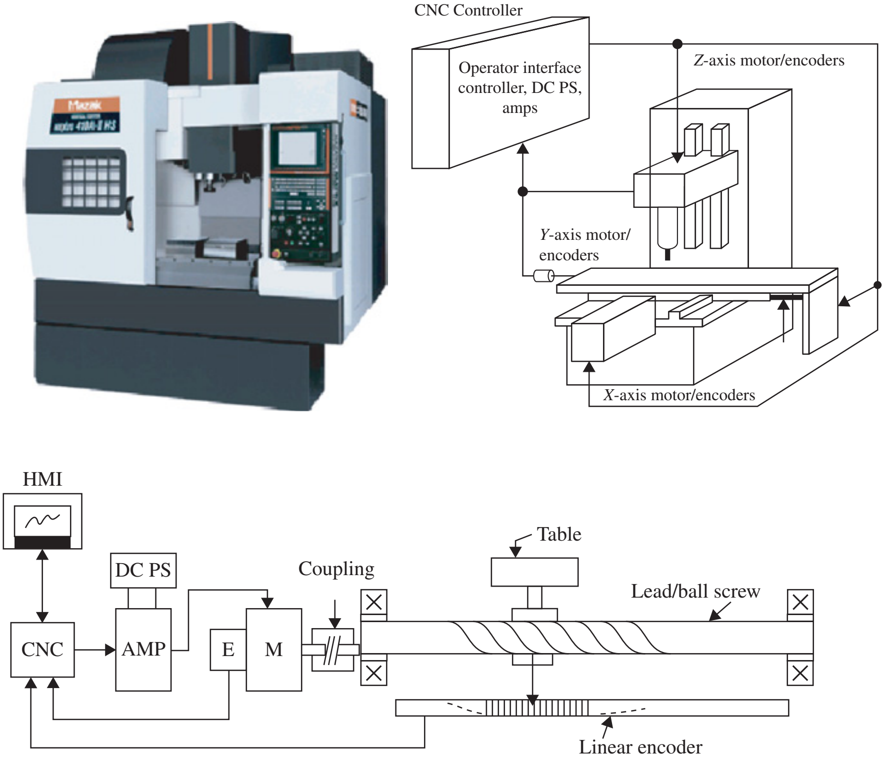
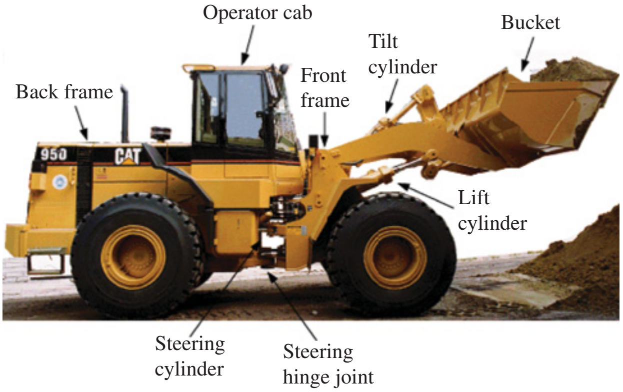


FIGURE 1.13: Computer numeric controlled (CNC) machine tool: (a) picture of a vertical CNC machine tools, reproduced with permission from Yamazaki Mazak Corporation, (b) *x-y-z* axes of motion, actuated by servo motors, (c) closed loop control system block diagram for one of the axis motion control system, where two position sensors per axis (motor-connected and load-connected) are shown (also known as dual position feedback).

mechanism in each axis. The fourth motion axis is the spindle rotation which typically runs at a constant speed. Each axis has its own servo motor (i.e., brushless DC motor with position feedback), amplifier and DC power supply. In high precision machine tools, in addition to the position sensors integral to the servo motor, there are also linear position sensors (i.e., linear encoders) attached to the moving part of the table on each axis in order to measure the translational position of the table directly. Using this measurement, the controller can compensate for position errors due to backlash and mechanical transmission errors in the lead-screw/ball-screw. The CNC controller implements the desired motion commands for each axis in order to generate the desired cut-shape, as well as the closed loop position control algorithm such as a PID controller. When two position sensors are used for one degree of motion (one located at the actuator point (on the motor shaft) and one located at the actuated-tool point (table)), it is referred to as *dual position feedback control system*. A typical control logic in dual-position feedback system is to use the motor-based encoder feedback in velocity loop, and load-based encoder feedback in position loop control. Current state of the art technology in CAD/CAM and CNC control is such that a desired part is designed in CAD software, then the motion control software to run on the CNC controller (i.e., G-code or similar code which defines the sequence of desired motion profiles for each axis) is automatically generated from the CAD file of the part, downloaded to the CNC controller, which then controls each motion axis of the machine in closed loop to cut the desired shape.

Figure 1.14 shows the power flow in a modern construction equipment. The power source in most mobile equipment is an internal combustion engine, which is a diesel engine in large power applications. The power is hydro-mechanically transmitted from engine to transmission, brake, steering, implement, and cooling fan. All sub-systems get their power in hydraulic form from a group of pumps mechanically connected to the engine. These pumps convert mechanical power to hydraulic power. In automotive type designs, the power from engine to transmission gear mechanism is linked via a torque converter. In other designs, the transmission may be a hydrostatic design where the mechanical power is converted to hydraulic power by a pump and then back to mechanical power by hydraulic motors. This is the case in most excavator designs. Notice that each major sub-system has its own electronic control module (ECM). Each ECM deals with the control of the sub-system and possibly communicates with a machine level master controller. For instance, ECM for engines deals with maintaining an engine speed commanded by the operator pedal. As the load increases and the engine needs more power, the ECM automatically commands more fuel to the engine to regulate the desired speed. The transmission ECM deals with the control of a set of solenoid actuated pressure valves which then controls a set of clutch and brakes in order to select the desired gear ratio. Steering ECM controls a valve which controls the flow rate to a steering cylinder. Similarly, other sub-system ECMs controls electrically controlled valves and other actuation devices to modulate the power used in that sub-system.

The agricultural industry uses harvesting equipment where the equipment technology has the same basic components used in the automotive and construction equipment industry. Therefore, automotive technology feeds and benefits agricultural technology. Using global positioning systems (GPS) and land mapping for optimal utilization, large scale farming has started to be done by autonomous harvesters where the machine is automatically guided and steered by GPS systems. Farm lands are fertilized in an optimal manner based on previously collected satellite maps. For instance, the planning and execution of an earth moving job, such as road building or a construction site preparation or farming, can be done completely under the control of GPSs and autonomously driven machines without any human operators on the machine. However, safety concerns have so far delayed the introduction of such autonomous machine operations. The underlying technologies are



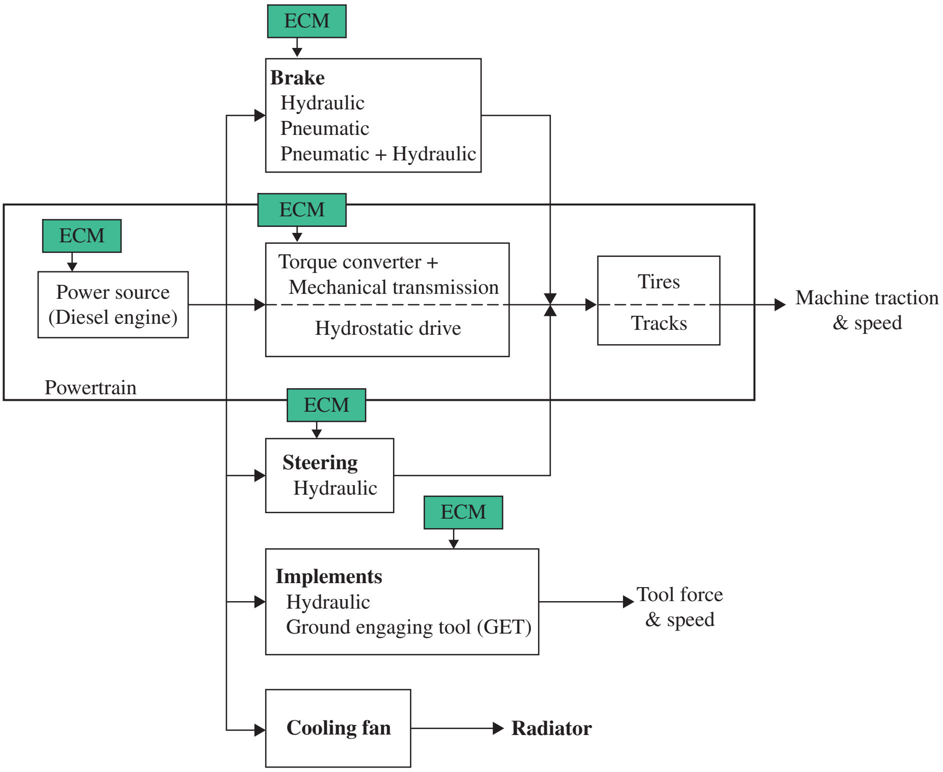


FIGURE 1.14: Block diagram controlled power flow in a construction equipment. Power flow in automotive applications is similar. Notice that modern construction equipment has electronic control modules (ECMs) for most major sub-systems such as engine, transmission, brake, steering, implement sub-systems.

relatively mature for autonomous construction equipment and farm equipment operation (Figure 1.15).

The chemical process industry involves many large scale computer controlled plants. The early application of computer controlled plants was based on a large central computer controlling most of the activities. This is called the *centralized control* model. In recent years, as microcontrollers became more powerful and low cost, the control systems for large plants have been designed using many layers of hierarchy of controllers. In other words,

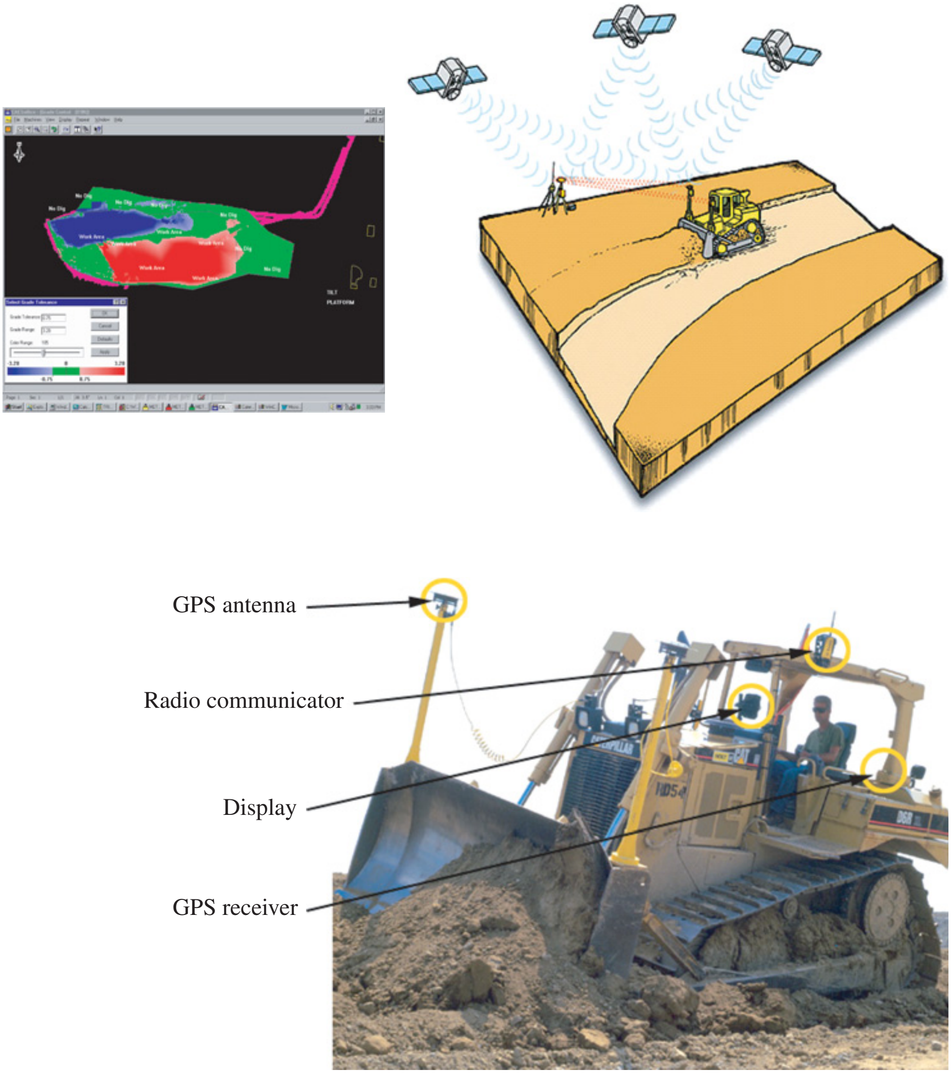


FIGURE 1.15: Semi-autonomous construction equipment operation using global positioning system (GPS), local sensors and on-vehicle sensors for closed loop sub-system control.

the control logic is distributed physically to many microcomputers. Each microcomputer is physically closer to the sensors and actuators it is responsible for. Distributed controllers communicate with each other and higher level controllers over a standard communication network. There may be a separate communication network at each layer of the hierarchical control system. The typical variables of control in process industry are fluid flow rate, temperature, pressure, mixture ratio, fluid level in tank, and humidity.

Energy management and control of large buildings is a growing field of application of optimized computer control. Home appliances are more and more microprocessor controlled, instead of being just an electromechanical appliances. For instance, old ovens used relays and analog temperature controllers to control the electric heater in the oven. The new ovens use a microcontroller to control the temperature and timing of the oven operation. Similar changes have occurred in many other appliances used in homes, such as washers and driers.

Micro electromechanical systems (MEMS) and MEMS devices incorporate all of the computer control, electrical and mechanical aspects of the design directly on the silicon substrate in such a way that it is impossible to discretely identify each functional component. Finally, the application of mechatronic design in medical devices, such as surgery assistive devices, robotic surgery, and intelligent drills, is perhaps one of the most promising field in this century.

Computer controlled medical devices (implant and external assistive, rehabilitation equipment) have been experiencing exponential growth as the physical size of sensing and computing devices becomes very tiny such that they can be integrated with small actuators as implant devices for human body. The basic principle of the sensing-decision-actuation is being put to many uses in embedded computer controlled medical devices (also called bio-mechatronic devices, Figure 1.16). In time these devices will be able to integrate a growing set of tiny sensors, and make more sophisticated real-time decisions about what (if any) intervention action to take to assist the functioning of the human body. For instance, implant defibrillators and pace-makers for heart patients are examples of such devices. A pace-maker is a heart implant device that provides electrical pulses to the heart muscules to regulate its rate when it senses that the heart rate has fallen below a critical level. The

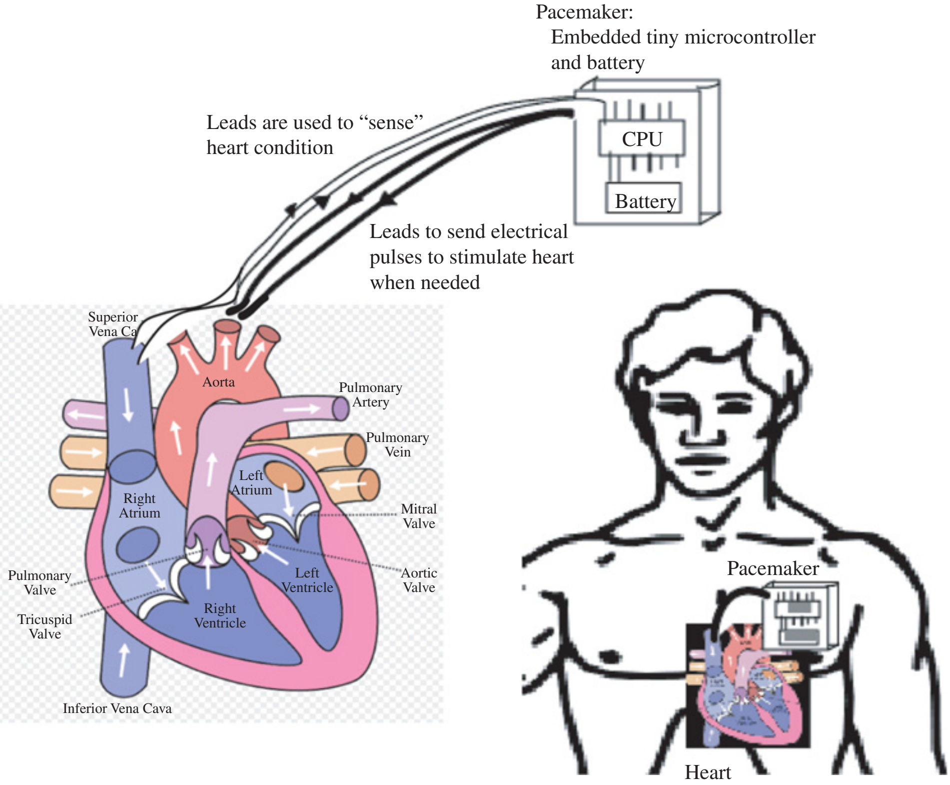


FIGURE 1.16: Example of an embedded computer controlled medical device: a bio-mechatronic device. The pulse generator houses the battery (electrical power source) and a tiny embedded computer. The electrical wires between the heart and the pulse generator (pace-maker) are for both sensing the heart condition (sensor cables) and actuating the heart beat by electrical pulse signal shocks to the heart muscle. The sensing-decision-actuation functions are integrated via the pulse generator and electrical signal leads. Wapcaplet, Yaddah [GFDL (www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia.

pace-maker senses the heart rate, and if the heart rate is below a critical rate, it sends electrical pulses to the heart in order to increase the heart rate. The sensing and actuation components are interfaced to the heart through electrical wires. The embedded computer, battery (electrical power source for the pulse power) and pulse generator circuit is one integrated unit which is implanted under the skin somewhere close to the heart.

In addition, many computer controlled orthopeadic devices are in the process of development as implanted aid devices as well as rehabilitative devices. For example, in artificial hand devices, the embedded computer senses the desired motion signals in the remaining muscles which are sent from the brain, then interprets them to actuate the mechanical hand like it would function in a natural hand. The compact electromechanical design of the hand mechanism, its integrated actuation and sensing (position and force sensors) devices are *electromechanical design problems*. Measurement and interpretation of the desired motion signals from human brain to the residual muscles and, based on that information, determining the desired motion of the hand is an *intelligent signal processing and control problem* (see National Geographic Magazine, ... issue).

1.1 CASE STUDY: MODELING AND CONTROL OF COMBUSTION ENGINES

The internal combustion engine is the power source for most of the mobile equipment applications including automotive, construction, and agricultural machinery. As a result, it is an essential component in most mobile equipment applications. Here, we discuss the modeling and basic control concepts of internal combustion engines from a mechatronics engineering point of view. This case study may serve as an example of how a dynamic model and a control system should be developed for a computer controlled electromechanical system. Basic modeling and control of any dynamic system invariably involves use of Laplace transforms. As a result, detailed analysis using Laplace transforms is minimized here in this introductory chapter.

We will discuss the basic characteristics of a diesel engine from a mechatronics engineer's point of view. Any modeling and control study should start with a good physical understanding of how a system works. We identify the main components and sub-systems. Then each component is considered in terms of its input and output relationship in modeling. For control system design purposes, we identify the necessary sensors and controlled actuators. With this guidance, we study

1. engine components – basic mechanical components of the engine,
2. operating principles and performance – how energy is produced (converted from chemical energy to mechanical energy) through the combustion process,
3. electronic control system components: actuators, sensors, and electronic control module (ECM),
4. dynamic models of the engine from a mechatronics engineer's point of view,
5. control algorithms – basic control algorithms and various extensions in order to meet fuel efficiency and emission requirements.

An engine converts the chemical energy of fuel to mechanical energy through the combustion process. In a mobile equipment, sub-systems derive their power from the engine. There are two major categories of internal combustion engines: (i) Clerk (two-stroke) cycle engine; (ii) Otto (four-stroke) cycle engine. In a two-stroke cycle engine, there is a combustion in each cylinder once per revolution of the crankshaft. In a four-stroke cycle engine, there is a combustion in each cylinder once every two revolutions of the crankshaft. Only four-stroke cycle engines are discussed below.