Chapter 1

Introduction

Mechatronics field consists of the synergistic integration of three distinct traditional engineering fields for system level design process. These three fields are

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

Mechatronics field is not simply the sum of these three major areas, but the field defined as the intersection of these areas when taken in the context of systems design (Fig.1.1). It is the current state of evolutionary change of the engineering fields that deal with the design of controlled electro-mechanical systems. The word mechatronics was first coined by engineers at Yaskawa Electric Company [1,2]. Virtually every modern electro-mechanical system has an embedded computer controller. Therefore, computer hardware and software issues (as far as they are applied to the control of electro-mechanical systems) are part of the field of mechatronics. Had it not been the widespread availability of the low cost microcontrollers for the mass market, the field of mechatronics as we know it today would not have existed. The availability of embedded microprocessors for the mass market at an ever reducing cost and increasing performance makes the use of computer control in thousands of consumer products possible.

The old model for an electro-mechanical product design team includes

1. engineer(s) who designs the mechanical components of a product,
2. engineer(s) who design the electrical components such as actuators, sensors, amplifiers etc, as well as design 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 from mechanical design, followed by electrical and computer control system designs, but rather all aspects (mechanical, electrical and computer control) of design is done simultanenously for optimal product design. Clearly, mechatronics is not a new engineering discipline, but the current state of the evolutionary process of engineering disciplines needed in design of electro-mechanical systems. The end product of a mechatronics engineer's work is a working prototype of an embedded computer controlled electro-mechanical device or system. This book covers the fundamental technical topics needed 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, the book has sections in mechanical design of various mechanisms used in automated machines and robotic applications. Such mechanisms are almost a century old designs and the basic designs are still used in modern applications. Mechanical design forms the "skelleton" of the electro-mechanical product, upon which the rest of the functionalities are built (such as "eyes", "musculles", "brains"). These mechanisms are discussed in terms of their functionality and common design parameters. Detailed stress or force analysis of them is omitted which are covered in traditional streess analysis and machine design courses.

The analogy between a human controlled system and computer control system is shown in Fig.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 a particular control action is taken. One could view the outcome of decision making process as a low power control or decision signal, and the action of the muscules 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, actuators replace the muscules, and the computer replaces the human brain. Every closed loop control system has these four basic functional blocks:

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

The microprocessor and digital signal processing (μP/DSP) technology had two types of impact in 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, 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 electro-mechanical systems for the measurement of temperature, pressure, force, stress, position, speed, acceleration, flow etc (Fig.1.3). This list does not attempt to cover every conceivable sensor available in the current state of 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 the hydraulic and electric power actuators in detail. Pneumatic power (compressed air power) actuation systems are not discussed. They are typically used in low performance, ON/OFF type control applications. The component functionalities of pneumatic systems are similar to those of hydraulic systems. However, the construction detail of each are 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 than those used in pneumatic systems.

Finally, the hardware and software fundamentals for embedded computers, microprocessors and digital signal processors (DSP), are covered with applications to the control of electro-mechanical devices in mind. Hardware I/O interface, microprocessor hardware architecture, and software concepts are discussed in detail. The basic electronics circuit components are discussed since they form the foundation of interface between the digital world of computers and 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 only. Therefore, the importantance of software, especially as it applies to embedded systems, can not be over emphasized.

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

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

Early automatic control systems performed an automated function completely with mechanical means. For instance, a water level regulator for a water tank uses a float connected to a valve via a linkage (Fig.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 around when the water reaches the required level. Another classic automatic control system that is made of compeletly mechanical components (no electronics) is the Watt's flyball governor which is used to regulate the speed of an engine (Fig.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 much fuel to inject based on the difference between the desired and actual engine speed (Fig.1.8).

Analog servo controlller using operational amplifiers made the second major change in mechatronic systems. Now, the 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 a voltage) and actuates an electrical device (solenoid or electric motor) based on the difference. This brought about many electro-mechanical servo control systems (Fig.1.6,1.7). In figure 1.6 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, a certain tension is to be 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 tention (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 operation amplifier controller. In addition, the digital controller may 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.

In figure 1.7 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 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 the relay does not turn ON and OFF due to small variations about the set temperarure, 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 late 1970s, the programmable control and intelligent decision making were introducted to the automatic devices and systems. Digital computers not only duplicated the automatic control functionality of previous mechanical and electro-mechanical devices, but also brought about new possibilities of device designs that were not possible before. The control functions incorporated into the designs included not only the servo control capabilities but also fault diagonotics, component health monitoring, network communication, non-linear, optimal, and adaptive control strategies (Fig.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.

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 needed labor and increasing the productivity. The product itself, cars, have also changed significantly. Before the wide spread introduction of 8-bit and 16-bit microcontrollers into the embedded control mass warket, the only electrical components in a car were radio, starter, alternator and battery charging system. Engine, transmission, brake subsystems were all controlled by mechanical or hydro-mechanical means. Today, the engine on 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, temperature and pressure sensors in real time. Thus, it improves the fuel efficieny, reduces emissions, and increases performance (Fig.1.8). Similarly, automatic transmission is controlled by an embedded controller. Braking system include ABS (anti-lock braking system), TCS (traction-control system), DVSC (dynamic vehicle stability control) systems which use dedicated microcontrollers to modulate the control of brake and engine in order to maintain better control of the vehicle. It is estimated that an average car today has over thirty embedded microprocessor controller aboard. This number continue to increase as more intelligent functions are added to cars. It is clear that the traditionally all mechanical devices in cars have now become computer controlled electro-mechanical 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 electro-mechanical devices and systems. The field of mechatronics is defined as the intergration of these areas to serve the design process.

Robotic manipulator is a good example of a mechatronic system. Low-cost, high computational power and wide availablity 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 mechanism, 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 serves as a good example of mechatronic system. A robotic manipulator has four major sub-systems (Fig.1.3), and every modern mechatronic system has the same sub-system functionalities,

1. a mechanism to transmit motion from actuator to tool,
2. actuator (i.e. a motor and power amplifer, 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. controller (DSP or microprocessor) along with operator user interface devices and communication capabilities to other intelligent devices.

Let us consider a electric servo motor driven robotic manipulator with three axis. The robot would have a predefined mechanical structure, i.e. cartesian, cylindrical, spherical, SCARA type robot (Fig.1.9,1.10). Each of the three electric servo motors (i.e. brush type DC motor with integrally mounted position sensor such as encoder or stepper motor with separately mounted 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, amplifer 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 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 extrnal sensor not directly linked to the actuator motions, such as a vision sensor or a force sensor or various proximity sensors, are used by the supervisory controller to coordinate the robot motion with other events. While each axis may have a dedicated closed loop control algorithm, there has to be a supervisory controller which coordinates the motion of the three motors in order to generate a coordinated motion by the robot, i.e. straight line motion, 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. The figure 1.11 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 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).

Fig.1.12 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 power from 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 ger mechanism is linked via a torque converter. In other designs, the transmission may be a hydrostatic design where the mechanical power is converted 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 engine deals with maintaining an engine speed commanded by the operator pedal. As the load increases and engine needs more power, the ECM automatically commands more fuel to the engine to regulate the desired speed. The transmsission ECM deals with control of which set of solenoid actuated pressure valves 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.

Agricultural industry uses harvesting equipment where the equipment technology has the same basic components used in automotive industry. Therefore, automotive technology feeds and benefits the agricultural production. Using global positioning systems (GPS) and land mapping for optimal ustilization, 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 a 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 relatively mature for autonomous construction equipment and farm equipment operation (Fig.1.13). Modern agricultural machinery incorporates very sophisticated computer controls, much more than the mechanical tractor.

Chemical process industry involves many large scale computer controlled plants. The early application of computer controlled plants were based on a large central computer controlling most of the activities. This is called the *centralized control* model. In recent years, as the microcontrollers became more powerful and low cost, the control systems for large plants are designed using many layers of hierarchy of controllers. In other words, 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 applications of optimized computer control. Home appliances are more and more microprocessor controlled, instead of being just an electro-mechanical applicances. 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 occur in many other appliances used in homes such as washers, driers.

Micro electro mechanical 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, intelligent drills, is perhaps one of the most promissing field in the next century.

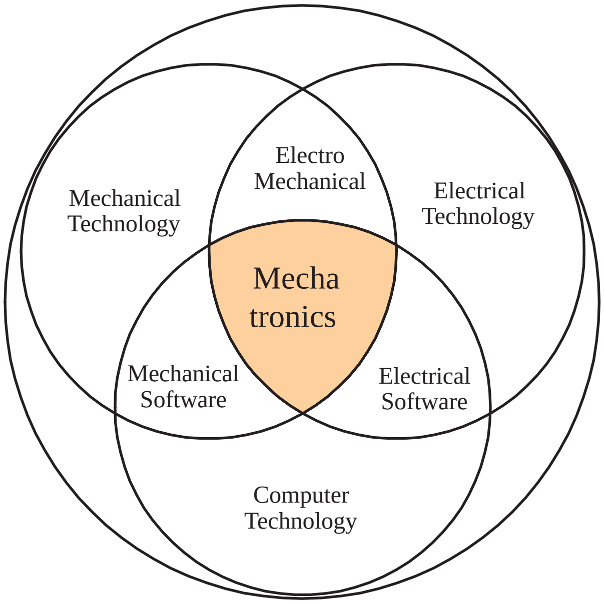

Figure 1.1: The field of mechatronics: intersection of mechanical, electrical and computer science.

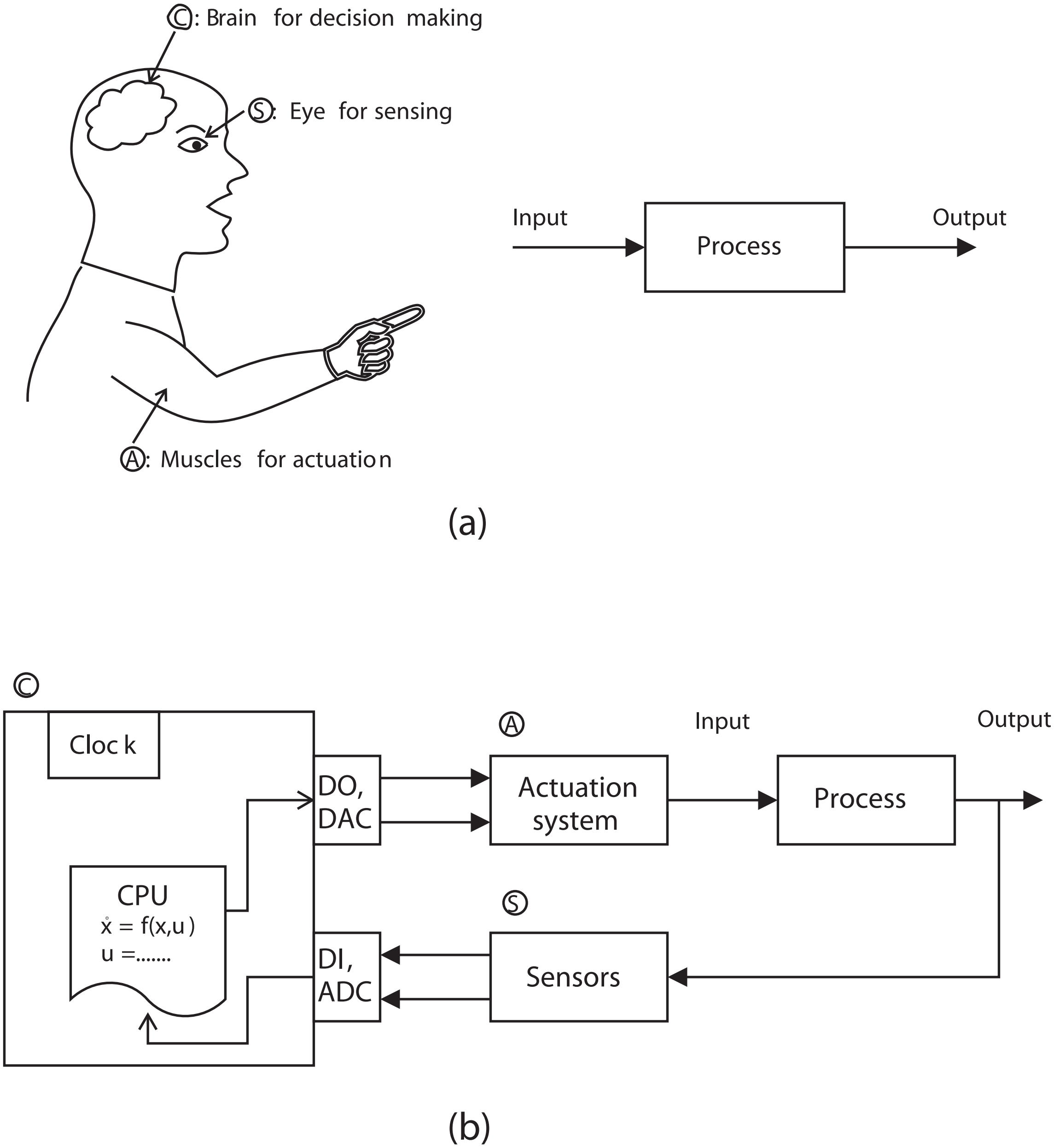

Figure 1.2: Manual and automatic control system analogy: a) human controlled, b) computer controlled.

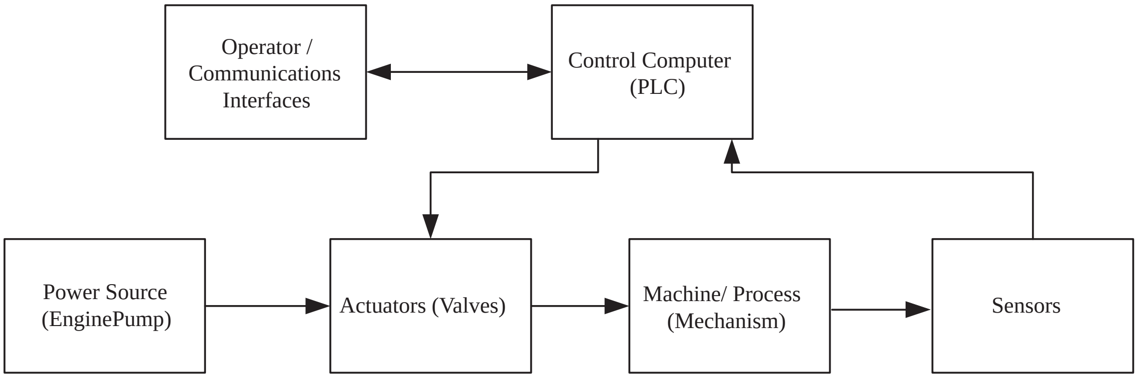

Figure 1.3: Main components of any mechatronic system: mechanical structure, sensors, actuators, decision making component (microcontroller), power source, human/supervisory interfaces.

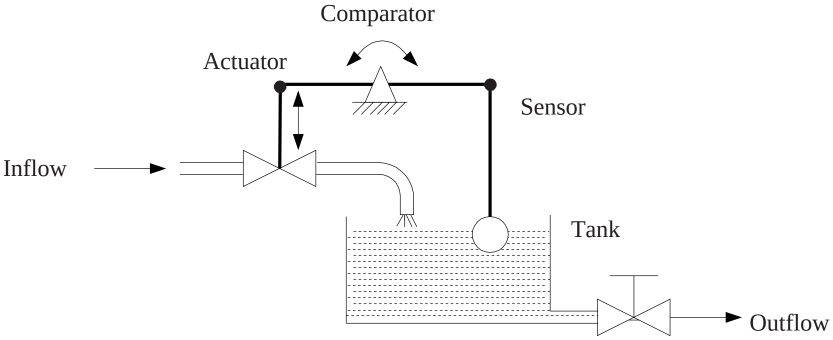

Figure 1.4: A completely mechanical closed loop control system for liquid level regulation.

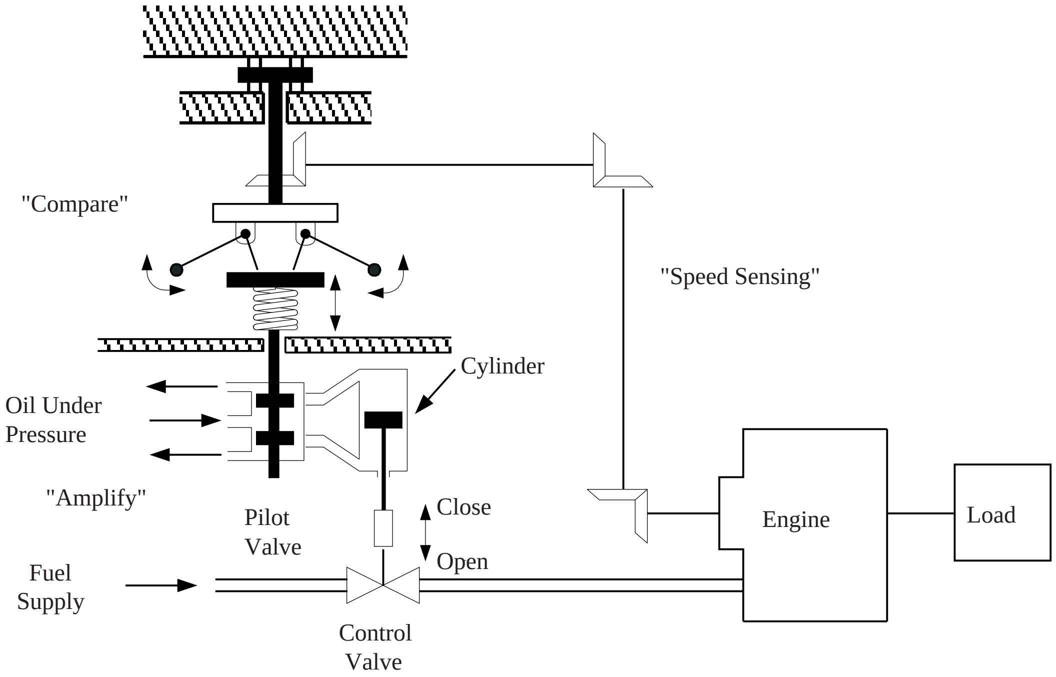

Figure 1.5: Mechanical “governor” concept for automatic engine speed control using all mechanical components.

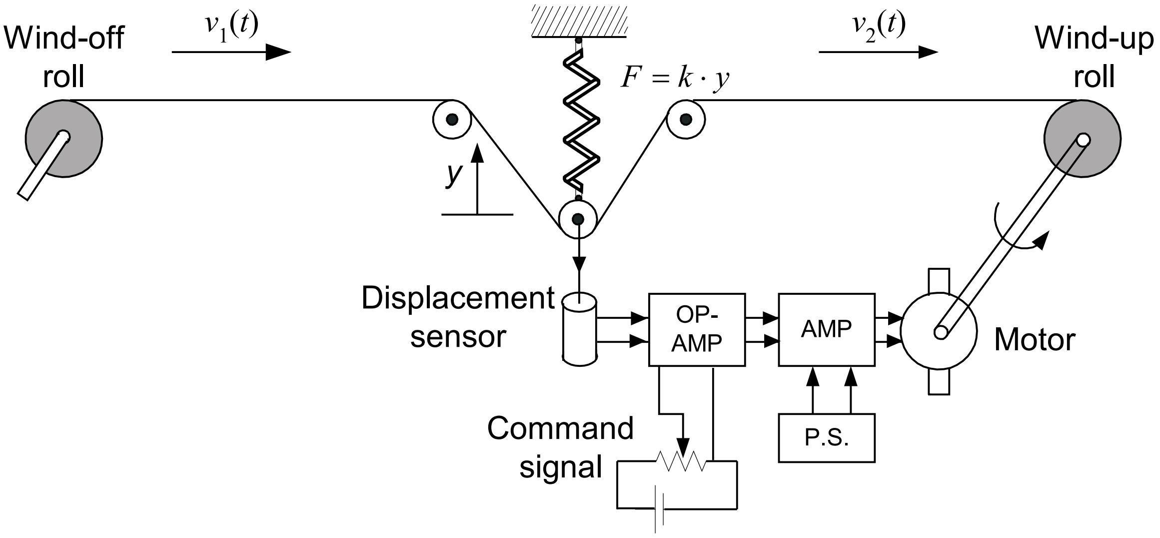

Figure 1.6: A web handling motion control system. Web is moved at high speed while maintaining a desired tension. The tension control system can be considered as a mechatronic system where the control decision is made by an analog op-amp, not a digital computer.

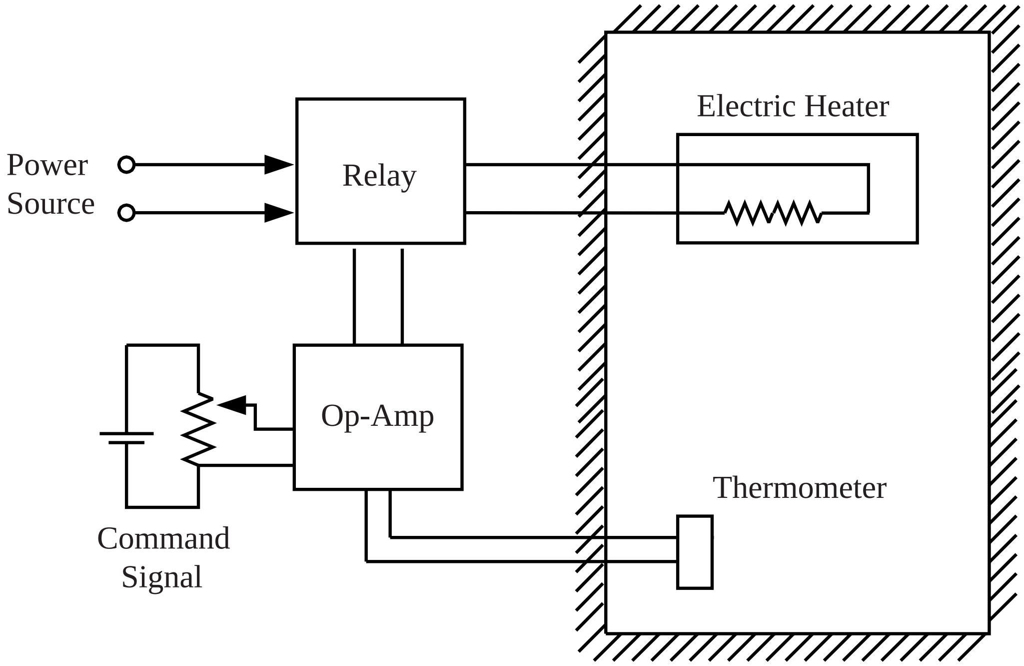

Figure 1.7: A furnace or room temperature control system and its components using analog op-amp as controller.

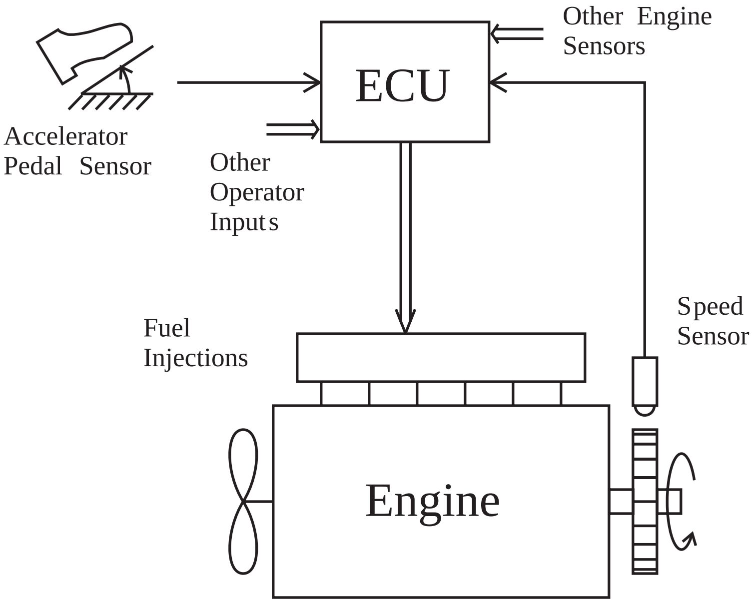

Figure 1.8: Electronic "governor" concept for engine control using embedded microcontrollers. Electronic control unit decides on fuel injection timing and amount in real time based on sensor information.

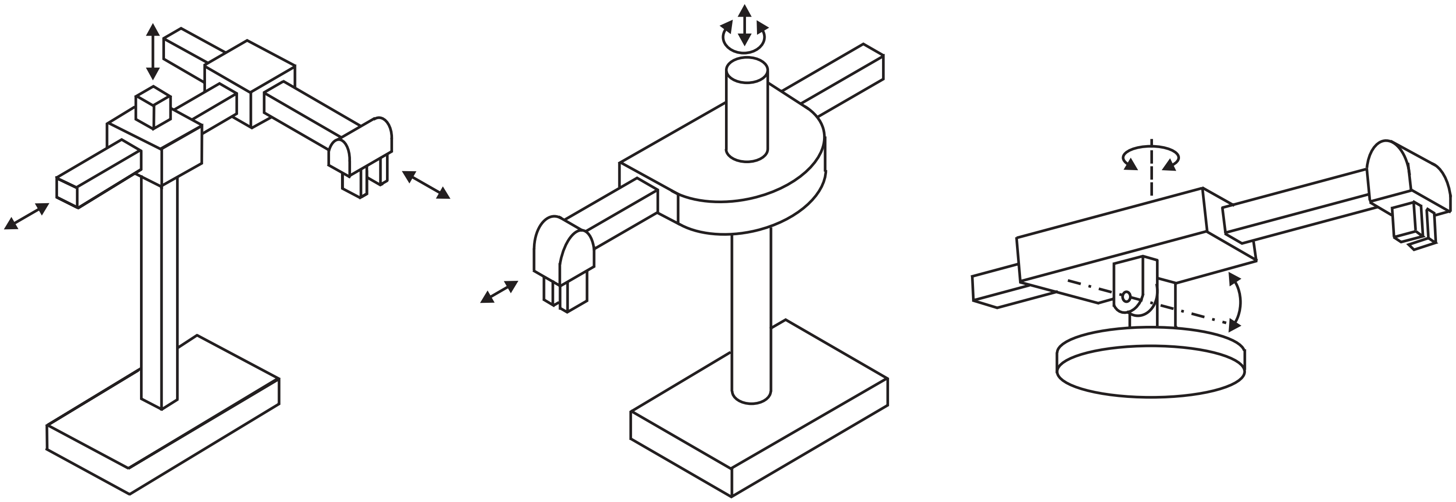

Figure 1.9: Three major robotic manipulator mechanisms: cartesian, cylindrical, spherical coordinate axes.

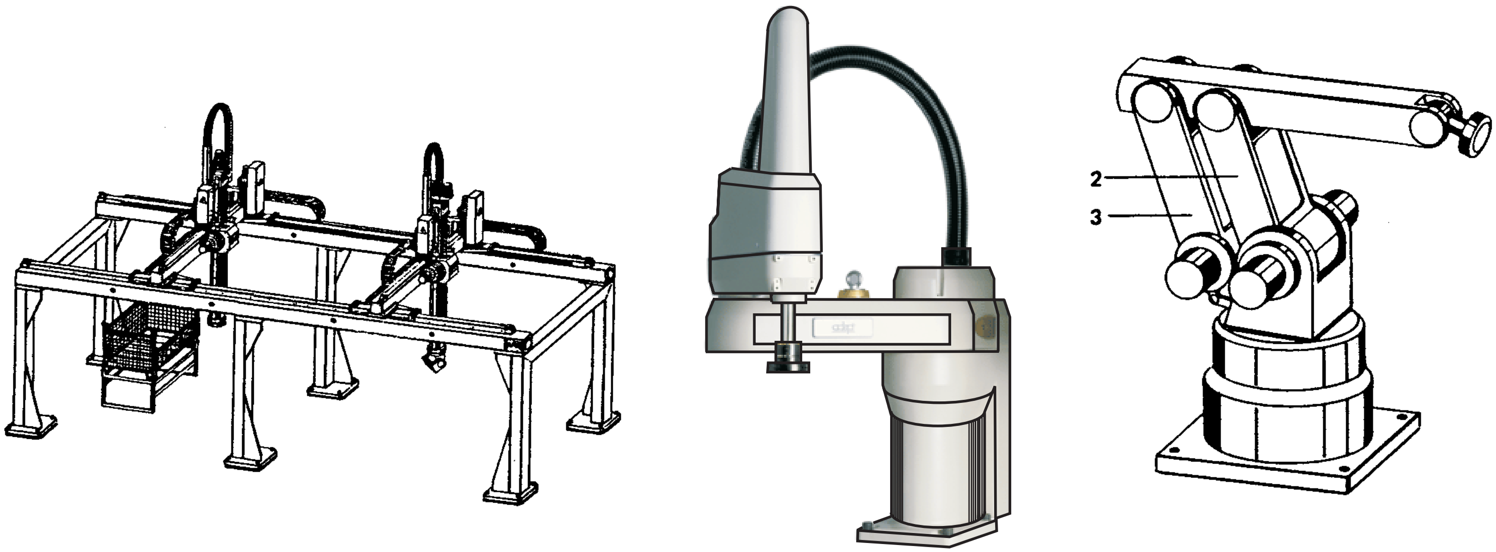

Figure 1.10: Gantry, SCARA and parallel linkage drive robotic manipulators.

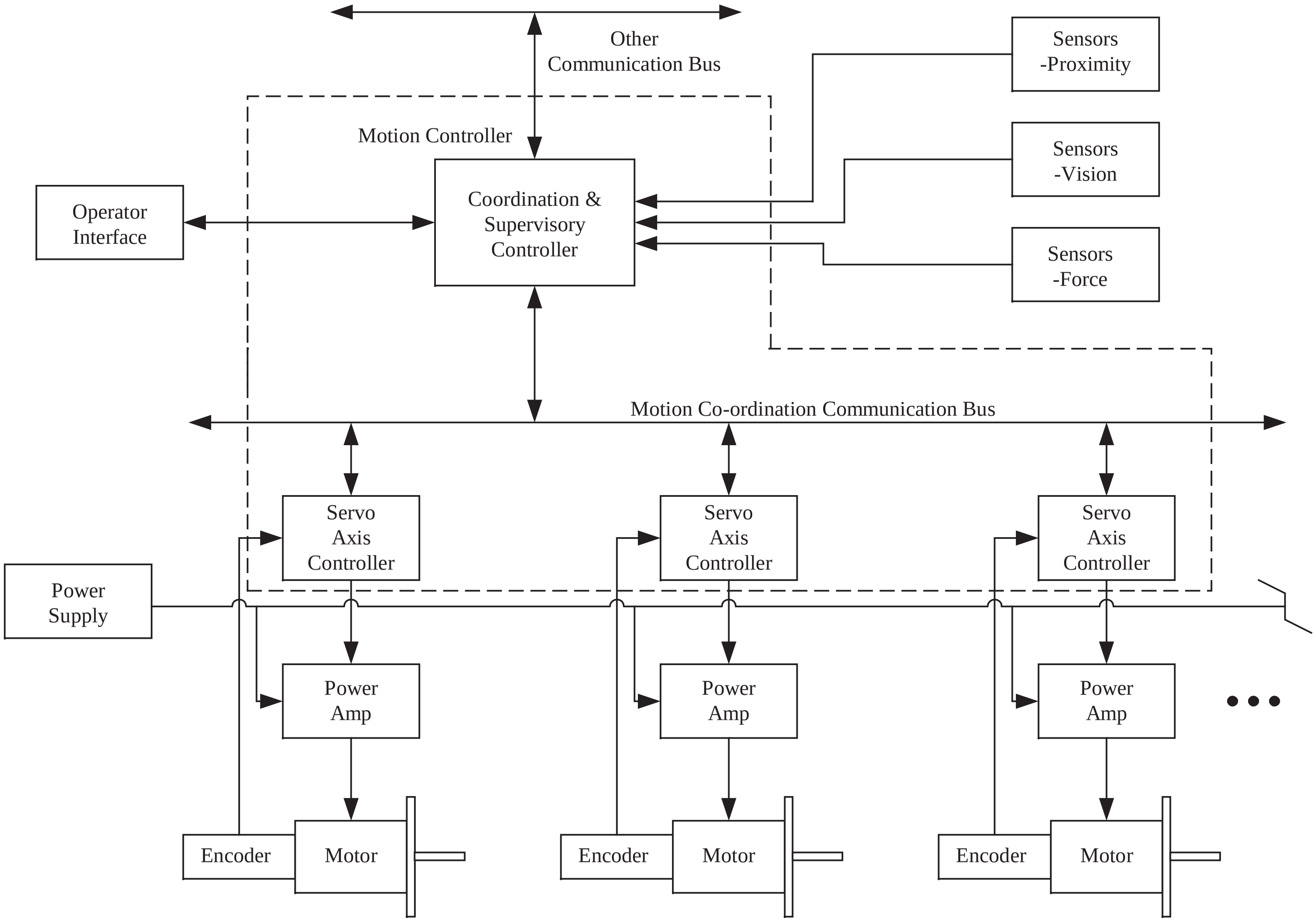

Figure 1.11: Block diagram of the components of a computer controlled robotic manipulator.

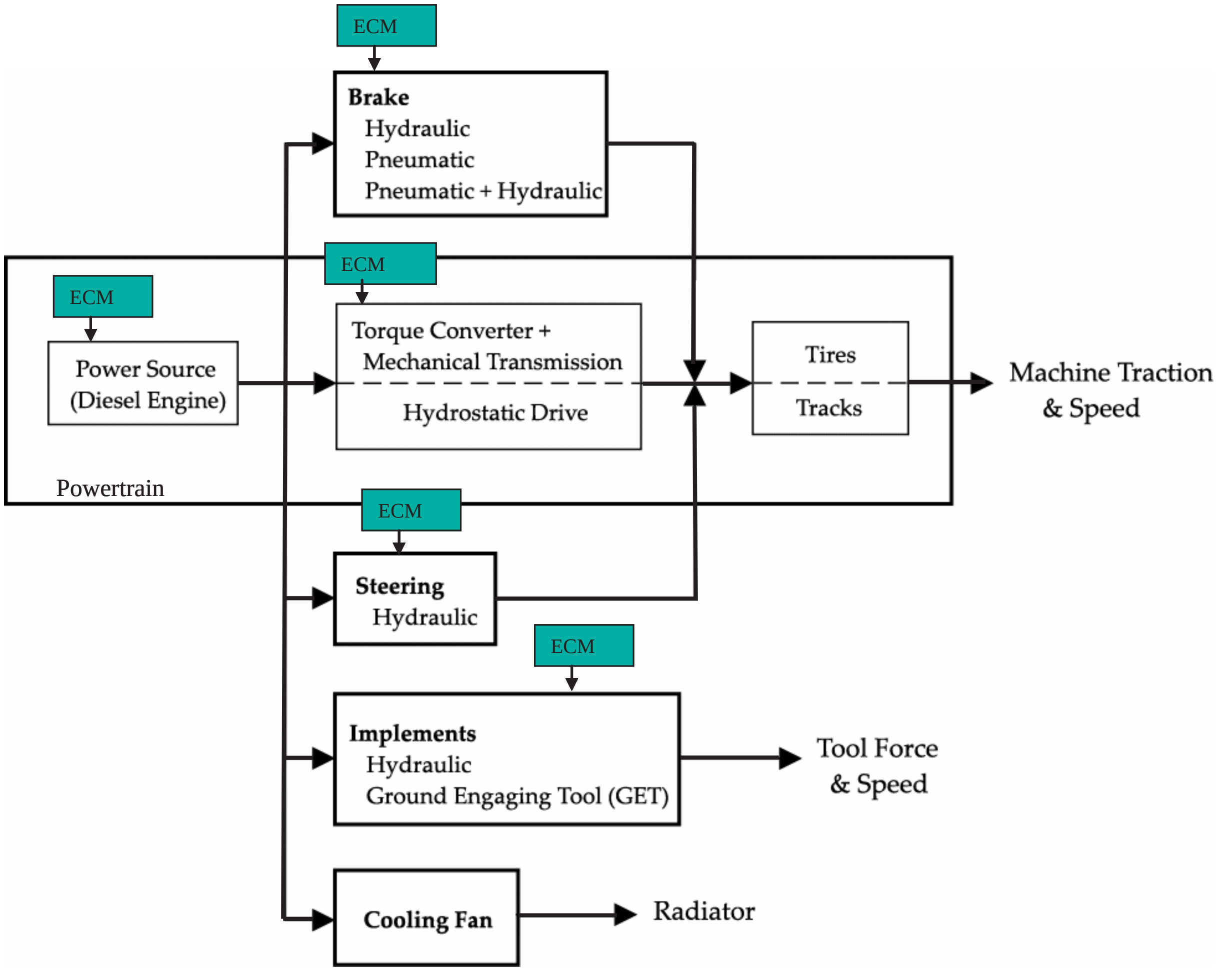

Figure 1.12: Block diagram controlled power flow in a construction equipment. Power flow in automotive applications is similar. Notice that modern construction equipment have electronic control modules (ECMs) for most major sub-systems such as engine, transmission, brake, steering, implement sub-systems.

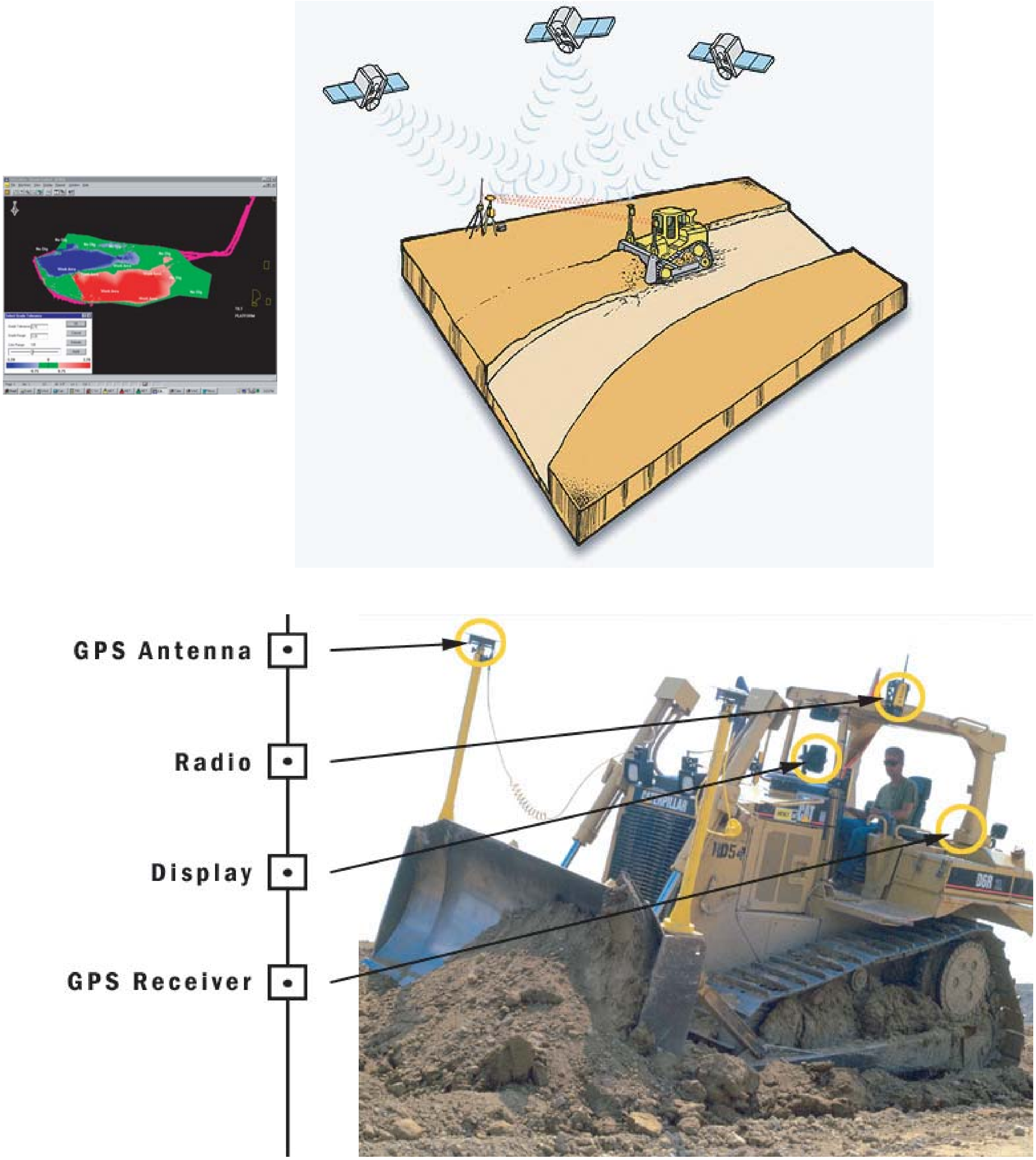

Figure 1.13: Semi-autonomous construction equipment operation using global positioning system (GPS), local sensors and on-vehicle sensors fro closed loop sub-system control.