# 1

Introduction

Motion control is widely used in all types of industries including packaging, assembly, textile, paper, printing, food processing, wood products, machinery, electronics, and semiconductor manufacturing. It is the heart of just about any automated machinery and process. Motion control involves controlling mechanical movements of a load. For example, in case of an inkjet printer, the load is the ink cartridge that has to be moved back-and-forth across the paper with high speed and precision. On the other hand, in a paper-converting machine, the load can be the large parent roll of paper that is loaded into the machine for processing. In this case, the load rotates as the paper is unwound from the roll and rewound into smaller processed rolls such as embossed paper towels.

Each motor moves a segment of the mechanical components of the machine. The segment of the machine along with the motor that moves it is called an *axis*. Considering an inkjet printer as an example, the mechanical components involved in the sliding motion of the print cartridge and the motor driving them collectively make up an axis of the machine. Another axis of the printer consists of all mechanical components and the motor that feed paper into the printer. In case of the paper-converting machine, the mandrel that holds the roll of paper, the pulleys, and belts that connect it to the motor and the motor make up an axis.

A typical motion control system manages position, velocity, torque, and acceleration of an axis. Often the machine consists of multiple axes whose position and/or velocity must be controlled in a synchronized fashion. For example, the *X*-axis and *Y*-axis of the table of a CNC machine need to be controlled in a coordinated way so that the machine can cut a round corner in the work piece. The ability to precisely control and coordinate complex motions of multiple axes enables design of industrial machines such as those in Figure 1.1.

Prior to the programmable motion controllers, coordination was achieved through mechanical means [14]. A central line shaft was connected to a large electric motor or an engine that ran at constant speed. This motion source was then used to drive all the axes of the machine by coupling them to the line shaft through pulleys, belts, gears, cams, and linkages (Figure 1.2). Clutches and brakes were used to start or stop the individual axes. The gear ratios between the line shaft and the individual axes determined the speed of each axis. Drive-trains, which were often long shafts, transferred the coordinated motion to the appropriate part of the
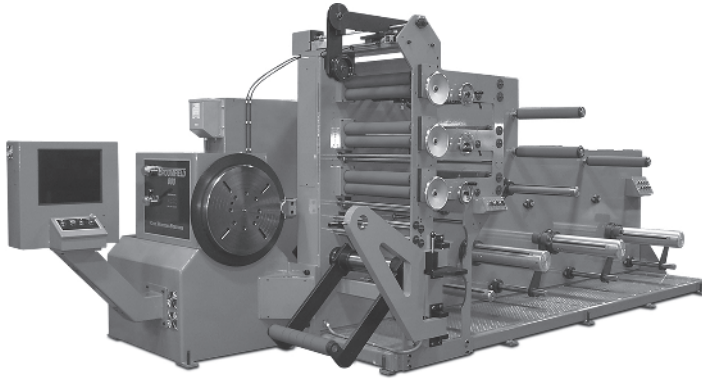
(a)
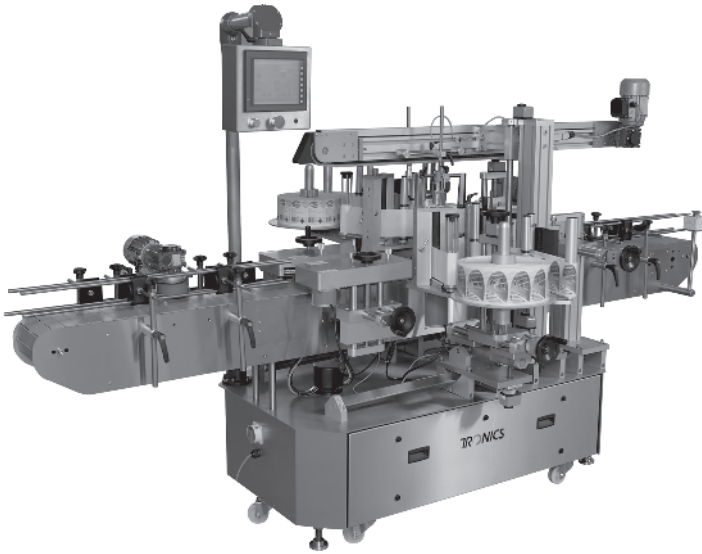
(b)

Figure 1.1 Complex machines with multiple axes are made possible with the ability of the controller to precisely coordinate motion of all axes. (a) Foil and wire winding machine (Reproduced by permission of Broomfield, Inc. [3]). (b) Pressure sensitive labeling machine (Reproduced by permission of Tronics America, Inc. [19])

machine. Complex machinery required sophisticated mechanical designs. Backlash, wear, and deflections in the long shafts were problematic. The biggest challenge was when a change in the product had to be introduced into the production system. It required physically changing the gear reducers, which was costly and very time consuming. Also, realigning the machine for accurate timing was difficult after drive-train changes.

As computers became main-stream equipment through the inexpensive availability of electronics, microprocessors, and digital signal processors, coordination of motion in multiaxes
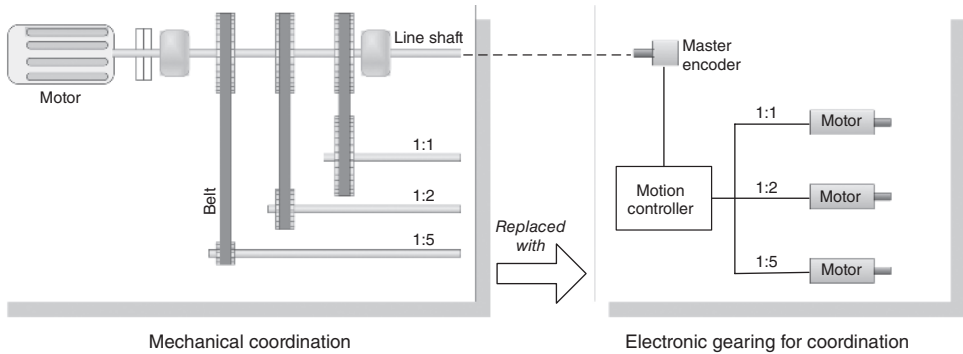
Figure 1.2   Multiaxis coordination

machines began to shift into a computer-controlled paradigm. In a modern multiaxis machine, each axis has its own motor and electric drive. Coordination between the axes is now achieved through electronic gearing in software. The drive-trains with long shafts are replaced by short and much more rigid shafts and couplings between the motor and the mechanism it drives. The motion controller interprets a program and generates position commands to the drives of the axes. These motion profiles are updated in real-time as the drives commutate the motors and close the control loops. In today's technology it is typical for an ordinary motion controller to coordinate up to eight axes at a time. Controllers with 60+ axis capabilities are available.

1.1   Components of a Motion Control System

The complex, high-speed, high-precision control required for the multiaxis coordinated motion is implemented using a specialized computer called **motion controller**. As shown in Figure 1.3, a complete motion control system consists of:

1. Human–machine interface (HMI),
2. Motion controller
3. Drives
4. Actuators
5. Transmission mechanisms
6. Feedback.

1.1.1   Human–Machine Interface

The HMI is used to communicate with the motion controller. The HMI may serve two main functions: (i) Operating the machine controlled by the motion controller, and (ii) Programming the motion controller.

Control panels as shown in Figure 1.4a with pilot lights, push buttons, indicators, digital readouts, and analog gauges are common hardware-based HMIs to serve the purpose of operating a machine. Chapter 5 discusses operator interface devices such as pilot lights, push buttons,
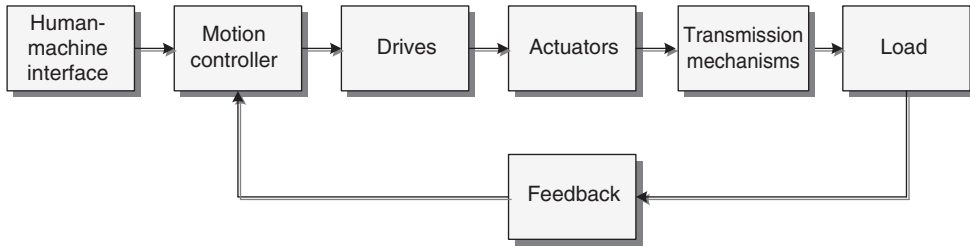
Figure 1.3   Components of a motion control system

(a)   (b)

Figure 1.4   Human–machine interfaces (operator panels) are used to operate the machine. (a) Hardware-based control panel [7]. (b) Software-based control panel with touch screen (Reproduced by permission of American Industrial Systems, Inc. [2])

and selector switches. Control panels can also be software-based as shown in Figure 1.4b. These panels can have touch screens and embedded computers that run a graphical user interface developed using software [10, 13, 15]. The advantage of this type of panel is the ease of reconfiguration of the HMI as new features may be added to the machine in the future.

A computer is interfaced to the motion controller for programming purposes. Custom software provided by the manufacturer of the controller is used to write, edit, download, and test the machine control programs. The software also includes features to test motors, monitor input/output (I/O) signals, and tune controller gains. Chapter 7 presents programming approaches for motion, machine I/O management, and multiaxis coordination.

1.1.2   Motion Controller

The motion controller is the "brains" of the system. It generates motion profiles for all axes, monitors I/O, and closes feedback loops. As presented in Chapter 2, the controller generates the motion profile for an axis based on the desired motion parameters defined by the user or the programmer. While the machine is running, it receives feedback from each axis motor. If there is a difference (following error) between the generated profile and the actual position or
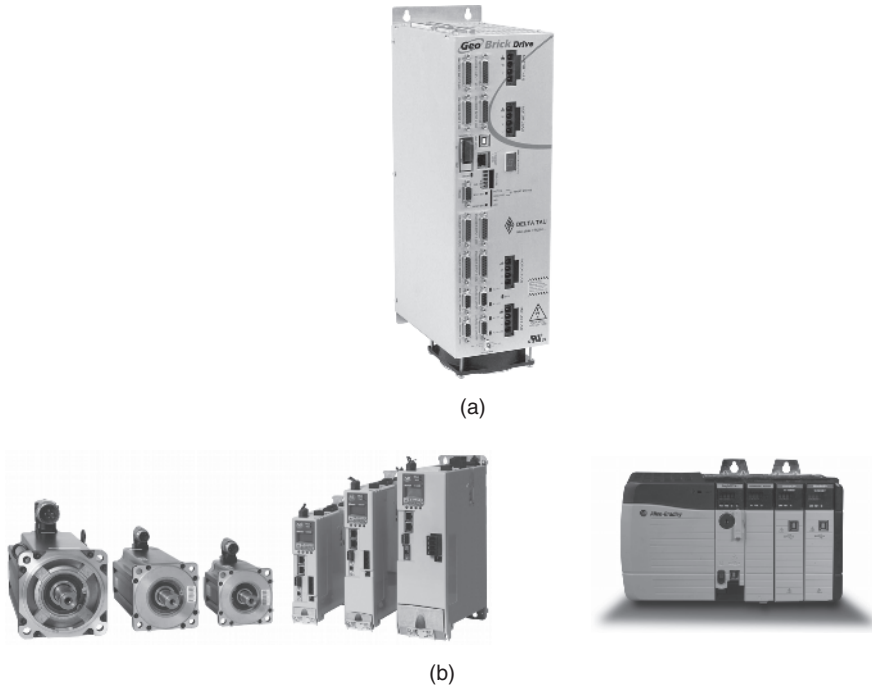
(a)

(b)

Figure 1.5   Motion controllers can have the various form factors. (a) Integrated form factor (Reproduced by permission of Delta Tau Data Systems, Inc. [5]). (b) Modular form factor. (Left) motors and drives [16], (Right) controller [17] (Courtesy of *Rockwell Automation, Inc.*)

velocity of an axis, the controller generates correction commands, which are sent to the drive for that axis. Chapter 6 discusses various control algorithms used to act on the following error to generate command signals to eliminate the error. As discussed in Chapter 7, the controller can also generate and manage complex motion profiles including electronic camming, linear interpolation, circular interpolation, contouring, and master–slave coordination.

Motion controllers are available in different form factors (Figure 1.5). The integrated form factor incorporates the computer, the drive electronics for the axes, and the machine I/O into a single unit. This unit is called motion controller or drive. In a modular system, the computer, the drives, and the machine I/O are separate units connected to each other via some type of communication link. In this case, just the computer is called the motion controller.

A complete motion controller consists of the following:

1. Computer
    - Interpretation of user programs
    - Trajectory generation
    - Closing the servo loops
    - Command generation for the drives (amplifiers)
    - Monitoring axis limits, safety interlocks
    - Handling interrupts and errors such as excessive following (position) error.

2. I/O for each axis
   - Motor power output
   - Servo I/O for command output to amplifiers
   - Input terminals for feedback signals from motor or other external sensors
   - Axis limits, homing signals, and registration.
3. Machine I/O
   - Digital input terminals for various sensors such as operator buttons and proximity sensors
   - Digital output terminals to drive external devices (usually through relays)
   - Analog inputs (often optional) for analog sensors such as pressure, force
   - Analog outputs (often optional) to drive analog devices.
4. Communication
   - Network communications with other peripheral devices, the host computer, and/or supervisory system of the plant using protocols such as DeviceNet®, Profibus®, ControlNet®, EtherNet/IP®, or EtherCAT®
   - USB or serial port communications, and
   - HMI communications.

1.1.3   Drives

The command signals generated by the controller are small signals. The drive (Figure 1.6) amplifies these signals to high-power voltage and current levels necessary to operate a motor. Therefore, the drive is also called an amplifier. The drive closes the current loop of the servo system as discussed in Chapter 6. Therefore, it must be selected to match the type of motor

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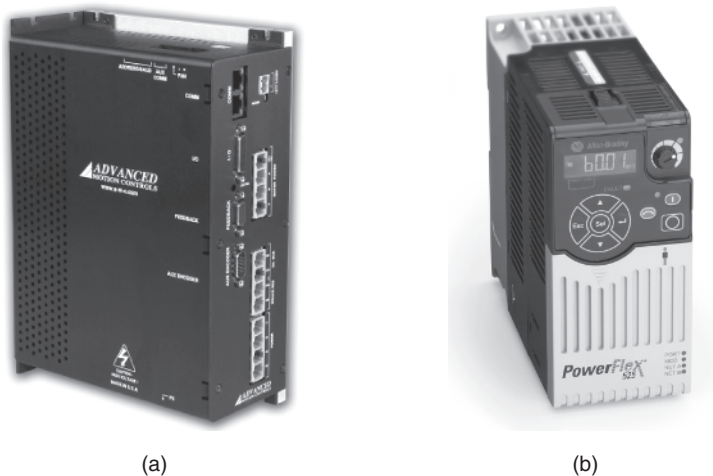
Figure 1.6   Drives are used to provide high voltage and current levels necessary to operate motors. (a) Digital servo drive (Reproduced by permission of ADVANCED Motion Controls®) [1]. (b) AC drive (Courtesy of *Rockwell Automation, Inc.*) [18]

to be driven. In recent trends, the line between a drive and a controller continues to blur as the drives perform many of the complex functions of a controller. They are expected to handle motor feedback and not only close the current but also the velocity and position loops.

1.1.4 Actuators

An actuator is a device that provides the energy to move a load. Motion control systems can be built using hydraulic, pneumatic, or electromechanical (motor) technologies. This book presents three-phase AC servo and induction motors (Figure 1.7). Underlying concepts of electromechanical operation of these motors along with mathematical models are presented in Chapter 6. Specific control algorithms implemented in the drive to control each type of motor are explored in Chapter 6. When a machine for a motion control application is designed, motors must be carefully selected for proper operation of the machine. Chapter 3 presents torque–speed curves for each of these motors and design procedures for proper motor sizing.

1.1.5 Transmission Mechanisms

A transmission mechanism is used to connect the load to the motor of an axis. It helps meet the motion profile requirements. Chapter 3 presents gearboxes (Figure 1.8), lead/ball-screw drives, linear belt drives, pulley-and-belt drives, and conveyors. When a load is coupled to a motor through a transmission mechanism, the load inertia and torque are reflected through the mechanism to the motor. Chapter 3 provides extensive discussion on the mathematical models for this. Motor, gearbox, and transmission selection procedures are also provided.

1.1.6 Feedback

Feedback devices are used to measure the position or speed of the load. Also, the drive and the controller use feedback to determine how much current needs to be applied to each phase of the motor as explained in detail in Chapters 4 and 6. Most common feedback devices are resolvers, tachometers, and encoders. Chapter 5 explains encoders, which can be rotary or

(a)   (b)

Figure 1.7 AC servo and induction motors are used in motion control applications as actuators. (a) AC servo motors (Reproduced by permission of Emerson Industrial Automation [8]). (b) AC induction motor (Reproduced by permission of Marathon™ Motors, A Regal Brand) [12]
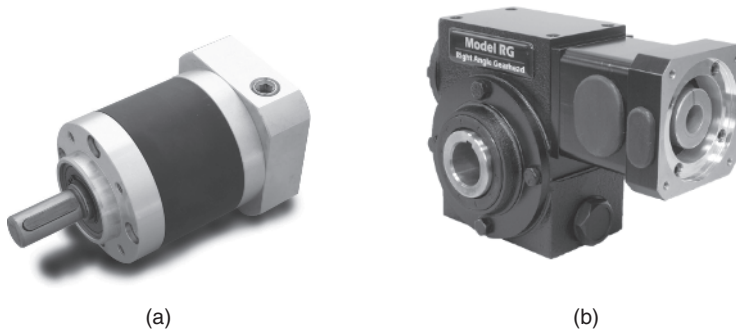
       (a)   (b)

Figure 1.8   Gearboxes are used in motion control applications to help achieve speed and torque requirements. (a) In line gearhead for servo motors (Reproduced by permission of DieQua Corp. [6]). (b) Right-angle worm gear reducer for AC induction motors (Reproduced by permission of Cone Drive Operations, Inc. [4])

       (a)   (b)

Figure 1.9   Encoders are used in motion control applications as feedback devices. (a) Rotary encoder (Reproduced by permission of US Digital Corp. [20]). (b) Linear encoder (Reproduced by permission of Heidenhain Corp. [9])

linear as shown in Figure 1.9. In addition, encoders can be incremental or absolute. Selection of the feedback device depends on the desired accuracy, cost, and environmental conditions of the machine.

    A different type of feedback is provided to the controller from detection sensors such as proximity switches, limit switches, or photoelectric sensors. These devices detect presence or absence of an object. For example, a photoelectric sensor such as the one in Figure 1.10 may detect arrival of a product on a conveyor and signal the motion controller to start running the conveyor.

Figure 1.10   Photoelectric sensors are used for detection of presence of an object [11]

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