12

Material Handling

Material handling is defined by the Materials Handling Institute as the movement of bulk packaged and individual goods, as well as their in-process and postprocess storage, by means of manual labor or machines within the boundaries of a facility. Although this field of study includes the handling of bulk (solid- or liquid-phase) material and individual goods, this chapter will only focus on the latter (i.e., ''unit loads''), with a primary emphasis on material handling equipment, as opposed to facility planning and movement control.

Material handling does not add value to the product but only cost. Thus the objective of material handling is the efficient movement of goods for the on-time delivery of correct parts in exact quantities to desired locations in order to minimize associated handling costs. It is not uncommon to have parts/subassemblies moving around a plant several kilometers prior to their shipment. Manufacturing plants must therefore eliminate all unnecessary part movements, as well as in-process inventories, for just-in-time (JIT) production.

Material handling equipment can be classified according to the movement mode: above-floor transportation (e.g., belt conveyors, trucks, etc.), on-floor transportation (e.g., chain conveyors), and overhead transportation (e.g., cranes). In the following sections, we will review industrial trucks (including automated guided vehicles), conveyors, and industrial robots as

the primary mechanized/automated material handling equipment. We will also briefly review the automated storage and retrieval of goods in high-density warehouses, as well as the important issue of automatic part identification (including bar codes). The chapter will be concluded with a discussion on automobile assembly.

12.1 INDUSTRIAL TRUCKS

Industrial powered trucks are the most versatile and flexible material handling devices in manufacturing. They can transport small or large loads over short distances in a plant with minimal restrictions on their movements. Powered trucks are generally classified into two broad categories: lift trucks and tow tractors.

12.1.1 Lift Trucks

Powered (lift) fork trucks are the most common industrial trucks used in the manufacturing industry for the transportation of parts placed on pallets (Fig. 1). The basic elements of a fork truck are (1) the mast assembly—a one-stage or multistage mechanism that lifts the forks, most commonly,
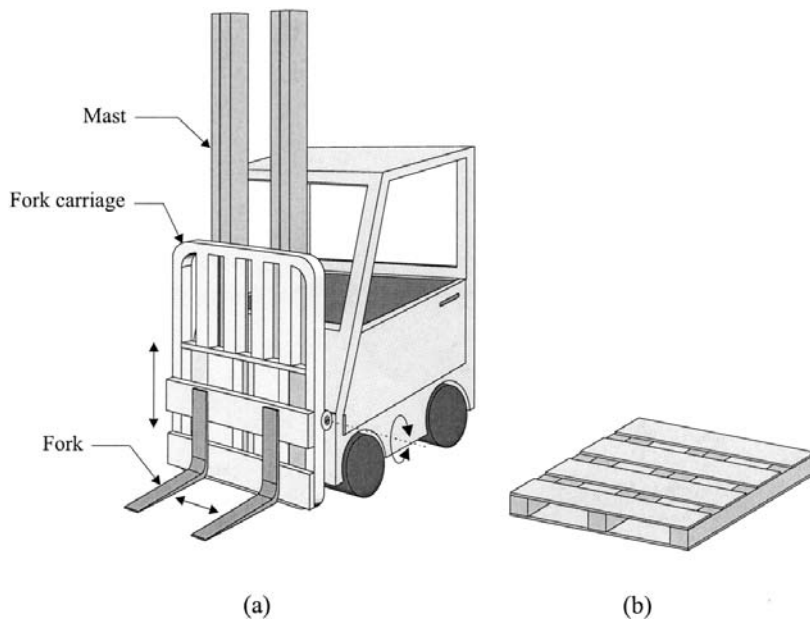

FIGURE 1   (a) A forklift truck; (b) a typical industrial pallet.

through hydraulic power; (2) the fork carriage—a carriage that is mounted on the mast, to which the forks are attached, with a primary objective of preventing loads from falling backward once they have been lifted off the ground; and, (3) the forks—the two forks can be of fixed configuration or with variable horizontal distance to accommodate varying load sizes. On most trucks, the mast assembly, including the forks, can be tilted backwards (4 to 12°) for increased security during motion.

The load capacity of forklift trucks is defined as the maximum weight carried at the maximum elevation of the forks. Typical forklifts can carry weights in the range of 1000 to 5000 kg at lift heights of up to 6 m and move at speeds of 5 to 10 km/hr. A large number of forklift trucks are counterbalanced at their rear for increased load capacity and more secure transportation, though at the expense of a larger footprint and potential difficulty working in confined spaces.

The primary advantage of forklift trucks is their path independence. A trained driver can transport parts by following the shortest available route, though their being driver-operated vehicles is also the greatest disadvantage of industrial trucks owing to increased costs.

12.1.2 Tow Tractors

A variety of wheeled vehicles are utilized in the manufacturing industry for towing (pulling) single- (or multi-)trailer cart attachments. Most tractors (like forklift trucks) are battery operated for maintaining clean-air environments within closed plants. The load carried can be palletized or (manually) placed directly on the trailer. The typical load-carrying capacity of electric-powered tow tractors ranges from 5,000 to 25,000 kg. As with forklift trucks, the primary disadvantage of tow tractors is their dependence on human drivers. In the following subsection, automated guided vehicles will be presented as a potential answer to this disadvantage.

12.1.3 Automated Guided Vehicles

The Materials Handling Institute defines an automated guided vehicle (AGV) as a driverless vehicle equipped with an on-board automatic-guidance device (electro-optical or electromagnetic) capable of following preprogrammed paths. The path information can be uploaded onto an on-board computer through (radio-frequency, RF) wireless communication or through a temporary (physical) connection to the plant's computer network. Reprogrammability of AGVs is their primary asset. Occasionally, AGVs are referred to as mobile robots owing to their reprogrammabilty. This is an erroneous classification, since AGVs mostly do not include a robotic manipulator arm capable of interacting with the environment.

The first AGV was developed by Barrett Electronics, U.S.A., in the early 1950s and installed at Mercury Motor Freight in 1954. These towing vehicles received poor acceptance by the manufacturing industry owing to their limited controllers and difficulty in their reprogammability. The subsequent period of 1960 to 1980, however, was marked by the introduction of a large number of AGVs in Europe, which was further accelerated during the following decade because of better (compact and reliable) on-board computers and electronics. As expected, the automotive industry (e.g., Volvo, Fiat) was the leader in the use of AGVs (more than 50% of over 10,000 installations).

General Motors (GM) has been the largest user of AGVs in North America since the late 1980s, with over 3,000 installations in their automotive plants. Most of GM's AGVs have been in their assembly lines (engine and body assemblies). Other main North American companies, on the other hand, have been utilizing AGVs since the early 1990s, largely in their warehousing/receiving/shipping activities, as opposed to on their factory floors.

AGVs have been intended to replace industrial trucks operated by human drivers. Thus they can be found in the following configurations: unit-load carriers, towing tractors, and forklift trucks (Fig. 2). The first two configurations are the more common types of AGVs in manufacturing environments. Despite their different intended usage, however, the operation of all AGVs is subject to a set of common constraints, some of which will be detailed below.

Basic vehicle design: AGVs are battery-powered wheeled vehicles that can automatically navigate through a network of paths (preinstalled) on the factory floor. The batteries can be recharged, commonly as the AGV is waiting between tasks (at distributed recharging locations) or when it is about to be depleted (at a central recharging location). The vehicles can be designed for forward-motion only or for forward and backward motions, as

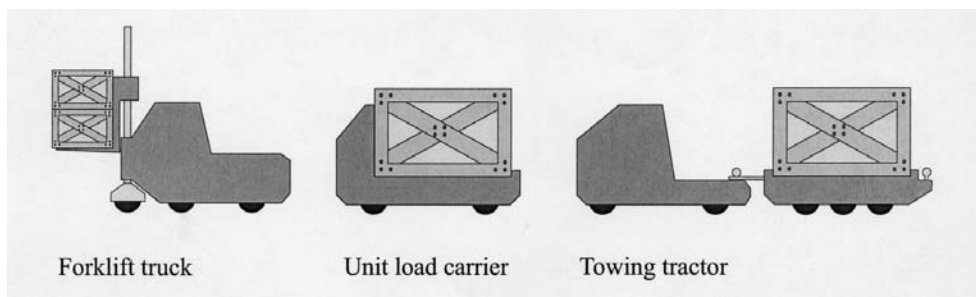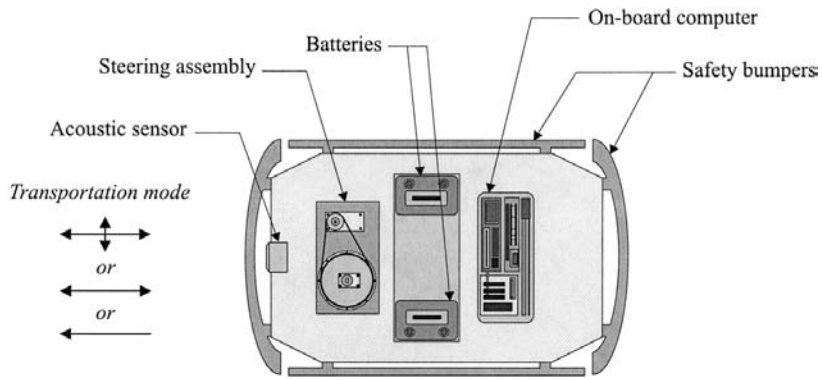Forklift truck   Unit load carrier   Towing tractor

FIGURE 2   AGV types.

FIGURE 3 Basic AGV design.

well as for sideways motions. Steering is achieved by an on-board computer executing a prespecified motion trajectory, which is communicated to it from a central area controller, normally via RF. The vehicles are equipped with acoustic sensors to detect obstacles (for collision avoidance) as well as with safety bumpers that can detect contact and stop their motion in an emergency manner (Fig. 3).

Navigation guidance: Navigation guidance for AGVs can be in two forms: passive or active tracking of a guidepath. Both methods rely on noncontact tracking of a guidepath installed on or in the floor of the manufacturing plant. Optical passive tracking is the most economical and flexible method, where the guidepath is defined by a painted or taped-on strip. An optical detection device mounted underneath the vehicle follows the continuous guidepath (a collection/network of branched paths) and guides the vehicle to its destination (Fig. 4). Naturally, such a method can only be employed if the painted/taped-on guidepaths can be maintained reasonably well for prolonged periods of time.
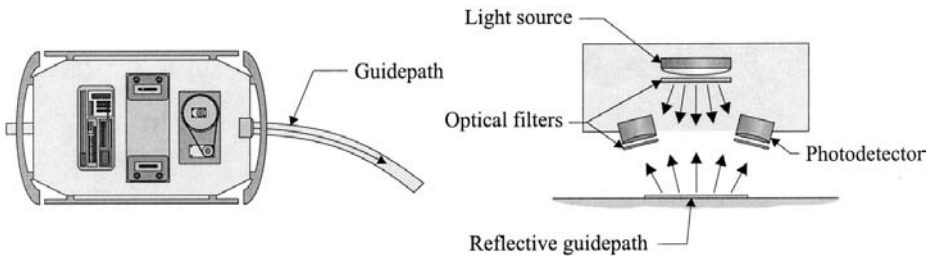
FIGURE 4 Optical guidance for AGVs.

Active tracking of a guidewire buried in a below-surface slot must be utilized for floors that cannot be easily kept clean. In this method, a network of paths is created using low-voltage, low-current-carrying wires that emit low-frequency (1 to 2 kHz) AC signals. In a networked environment, branching of a path can be specified by having the different paths emit different-frequency signals. Active tracking, however, is more expensive and less flexible than optical methods. Thus any reconfiguration of the factory floor would require reinstallation of a new network of buried wires (up to 40 mm deep).

Load carrying capacity: Most unit-load carrying AGVs have been designed to cope with weights in the range of 500 to 1,000 kg, though some custom-made vehicles can carry up to 50,000 kg. Tractor-type AGVs have been commonly designed to pull weights of up to 20,000 kg. AGVs can achieve typical speeds of up to 2 to 4 km/hr.

Applications

Several applications of AGVs for material handling in manufacturing environments are described below.

Car-engine assembly: A number of automotive manufacturers (including GM and Fiat) have utilized unit-load carrying AGVs for car-engine assembly (Fig. 5). On such assembly lines, AGVs transport in-process engines from one assembly station to another in an asynchro-
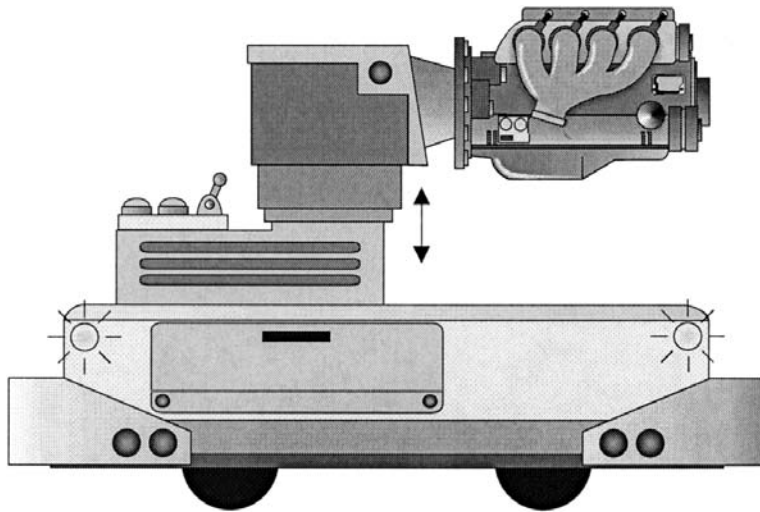

FIGURE 5 Car engine assembly.

nous manner—intermittent transfer. AGVs remain at a station until the specific assembly task is finished, which varies in time from engine to engine and from one operation to another. In a multi-car-model environment, bar codes placed on the engine or on the pallet indicate to the operator (or robot) the exact types of parts to be assembled.

Car-body assembly: Volvo has been the pioneer in replacing moving-conveyor-based assembly lines with AGV-based lines, where the entire car is assembled on a dedicated AGV that moves from one assembly station to another in an asynchronous mode (see Sec. 12.6). This original concept was also applied by GM in the late 1980s in their car assembly plants in Oshawa, Canada, and Lansing, U.S.A.

Electronics manufacturing: A number of electronics manufacturers (including Intel) have frequently used AGVs for the transportation of wafers, parts in magazines, printed circuit boards, etc., from one processing station to another and from storage to factory floor and vice versa. AGVs are very suitable to work in such clean-room environments in comparison to other material handling equipment.

Machining: AGVs, some with on-board robotic manipulators, have also been utilized by the metal-cutting industry in the transport of large workpieces, palletized batches of parts, and cutting tools. Most such AGVs are equipped with automatic transfer mechanisms that allow them to link to conveying devices (or other transfer mechanisms) for the automatic transfer of unit loads.

12.2   CONVEYORS

Conveyors are a broad class of material handling (conveying) equipment capable of transporting goods along fixed paths. Although conveyors are the least flexible material handling equipment (owing to their path inflexibility), they provide manufacturers with a cost-effective and reliable alternative. Conveying equipment is generally classified as above-floor conveyors versus on-floor or overhead tow-line conveyors. Both classes allow horizontal and inclined conveying, while tow-line type conveyors also allow vertical conveying (e.g., bucket elevators). In the following subsections, several examples of conveyors will be discussed with the emphasis being on conveying for manufacturing.

12.2.1   Above-Floor Conveyors

Above-floor conveyors have been also classified as package handling conveyors owing to their primary application of transporting cartons, pallets, and totes. On the factory floor, they are utilized to transport (palletized/

fixtured) workpieces (e.g., engine blocks, gearboxes, household items) from one assembly station to another. In a networked environment, where branching occurs, automatic identification devices must be utilized to route parts correctly to their destination along the shortest possible path.

Roller Conveyors

Powered roller conveyors are line-restricted conveying devices comprising a set of space rollers mounted between two side frame members and elevated from the floor by a necessary distance (Fig. 6). Rolling power can be achieved by having a moving flat belt underneath the rollers or a set of drive belts rotating the rollers individually, yielding speeds of up to 30 to 40 m/min.

Belt Conveyors

The early use of belt conveyors can be traced back to late 1800s in the mining industry. Today, the flat-belt version of such conveyors (versus the ones used in bulk-material transfer with side-inclined rollers—''troughing'' idlers) are commonly used in the manufacturing industry for the transfer of individual (unpalletized) workpieces, as well as cartons/bins/etc. The highly durable, endless belt is placed in tension between two pulleys and normally operated in uni-directional motion (Fig. 7).

The belt is the most important and expensive component of a belt conveyor. A carcass, enclosed between top and bottom covers, provides the tensile strength necessary for conveying and absorbs the impact forces by workpieces being loaded onto the belt. The top cover protects the carcass against tear and wear and against high temperatures when needed (up to $200°C$). Steel is commonly used in the construction of the carcass for high-tension applications.
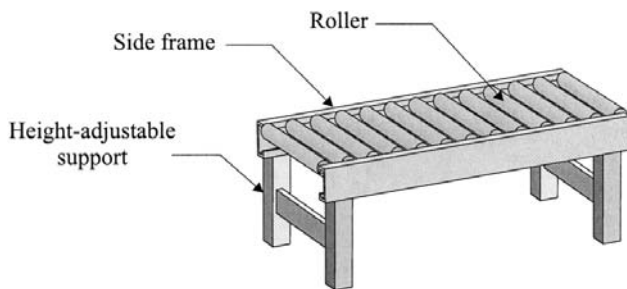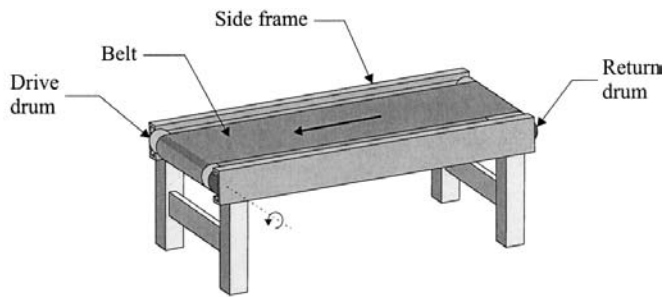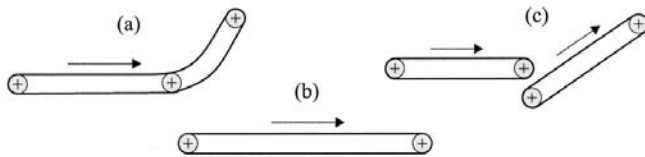

FIGURE 6   Roller conveyor.

FIGURE 7 Belt conveyor.

Belt conveyors can be inclined up to 30 to 40° and operate at speeds of 10 to 40 m/min, over lengths of 20 to 30 m, while carrying loads of up to 800 kg/m.

12.2.2 On-Floor and Overhead Conveyors

On-floor towline conveyors provide manufacturers with versatile transportation systems for conveying goods unsuitable (large, irregular geometry, etc.) for above-floor conveyors. They normally comprise one, two, or multiple chains running in parallel tracks (in shallow trenches). Goods can be directly placed on the chains or on pallets. Towline carts of a variety of sizes and shapes have also been used in on-floor conveying using chain conveyors. Traditionally, chain conveyors have been configured to operate along straight lines, horizontally and at low speeds (typically, 1 to 5 m/min for large loads and less than 25 to 30 m/min for small loads).

Overhead conveyors maximize utilization of three-dimensional workspaces (Fig. 8). Although most are configured for the point-to-point transportation of unit loads directly mounted on the conveyor via hooks
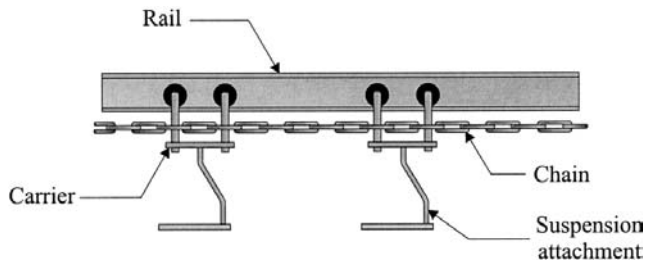
FIGURE 8 Overhead conveyor.

(e.g., automobile doors) or placed on suspension pallets, they can also provide a favorable environment for certain manufacturing applications, such as the on-the-fly spray-painting of workpieces. Overhead conveyors can operate horizontally or in inclined modes. The drive mechanisms employ chains or worm-screws. Occasionally, these conveyors also employ individually powered carriers capable of moving along monorails.

Overhead conveyors can reach speeds up to 80 to 100 m/min, though typically they operate in the range of 10 to 20 m/min.

12.3 INDUSTRIAL ROBOTS

Robotics is a multidisciplinary engineering field dedicated to the development of autonomous devices, including manipulators and mobile vehicles. In this section, our focus will be on robotic manipulators developed for industrial tasks. Although these devices are reprogrammable and multifunctional manipulators of goods and tools, the issues of planning, programming, and control will be addressed later in Chap. 14. Herein we will primarily address the mechanical design of manipulators and various applications of industrial robots in manufacturing environments.

The word robot has been often traced to the Czech word for forced labor mentioned by Karel Capek in his science fiction play Rossum's Universal Robots around 1921. The modern concept of industrial robotic manipulators was only introduced in late 1950s by G. C. Devol (U.S. Patent 2988237) and later championed by J. Engelberger—originators of the first industrial robot by Unimation Inc. in the 1959. The first installation of the Unimate robot for loading/unloading a die-casting machine at GM was in 1961. Today industrial robots can be found in almost all manufacturing applications, ranging from machine servicing to welding to painting.

12.3.1 Mechanical Design

An industrial robotic manipulator is typically an open-chain mechanism (fixed at one end to a base and free at the other end with an attached end-effector), whose mobility is defined by the number of independent joints in its configuration. As can human arms, these robotic mechanisms can manipulate objects/tools within a workspace defined by the geometry of the arm, via the end effector/gripper attached to the last link of the arm. The mobility of the end-effector is formally defined by the number of degrees of freedom (dof) of the robotic arm. In its most generic form, an end-effector can attain any position and orientation in three-dimensional Cartesian space (X, Y, Z, R_x, R_y, R_z), if the robotic arm has at least six independent dof. This mobility can also be described as the ability of the robot arm to relocate a Cartesian frame attached to its end-effector to any location (position and orientation) in its workspace with respect to a fixed "world" coordinate frame (Fig. 9).

Configurations

Industrial robots have been (mechanically) designed in several distinct configurations, each with a corresponding set of advantages. These robots can operate in point-to-point (PTP) or continuous-path (CP) motion mode: that is, they can move their end-effectors from one location (F_1) to another (F_2) in the fastest possible way without following any specified trajectory—i.e., PTP motion, or follow a specified continuous trajectory
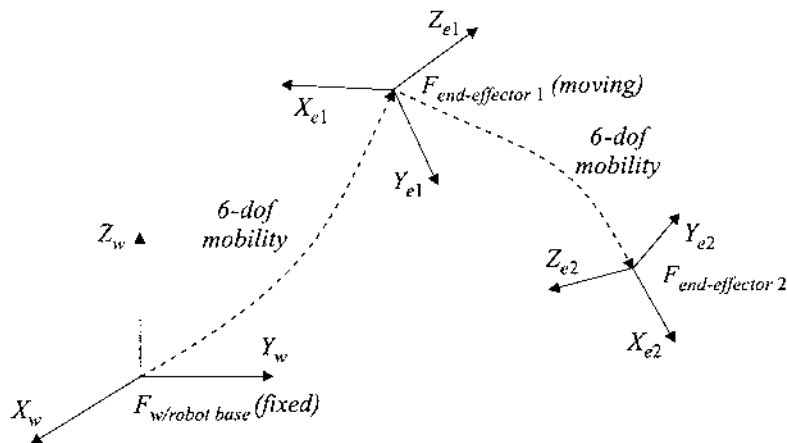

FIGURE 9 Six-dof mobility.

(e.g., a straight line) when moving their end-effector from F_1 to F_2—i.e., CP motion.

Classification of industrial robots is carried out according to their configuration based on the geometry of their workspace, primarily, defined by the first three joints:

Rectangular-geometry robots: There exist two primary robot configurations that belong to this group: Cartesian and gantry (Figs. 10a, 10b). Both configurations employ three linear joints assembled orthogonally for best achievable repeatability. The gantry type configuration is reserved for increased payload capacity due to its better structural stiffness and for better workspace utilization (e.g., electronic components assembly).

Rectangular-geometry robots can have up to three additional (closely located) rotary joints following the first three linear joints for a total of six-dof mobility.

Cylindrical-geometry robots: There exist two primary robot configurations that belong to this group: cylindrical and SCARA (Figs. 11a, 11b). The former has a sequence of rotary-linear-linear joints assembled orthogonally, while the latter has a sequence of rotary-rotary-linear joints. The cylindrical robot configuration was originally developed for fast peripheric access with good repeatability (due to the linear joints). The SCARA (selective compliance assembly robot arm) configuration, on the other hand, was developed in the late 1970s for vertical insertion of small parts (e.g., watch components) placed on a plane, thus requiring a maximum of four dof.

SCARA robots provide manufacturers with complete three-dof mobility in the part-placement plane and one-dof (vertical motion) linear mobility to reach the plane, for a total of four-dof mobility. In contrast, most cylindrical robots would have three additional (rotary) dof at their
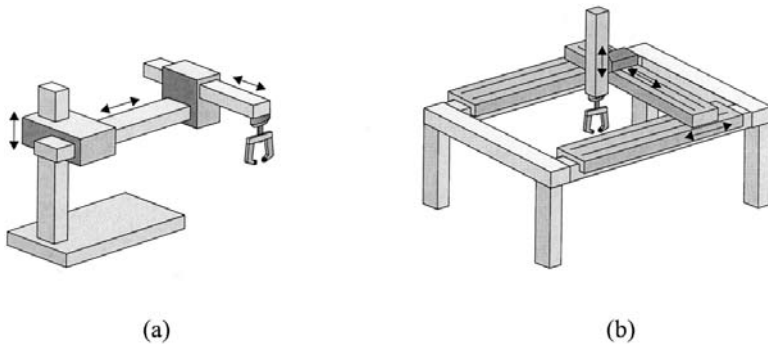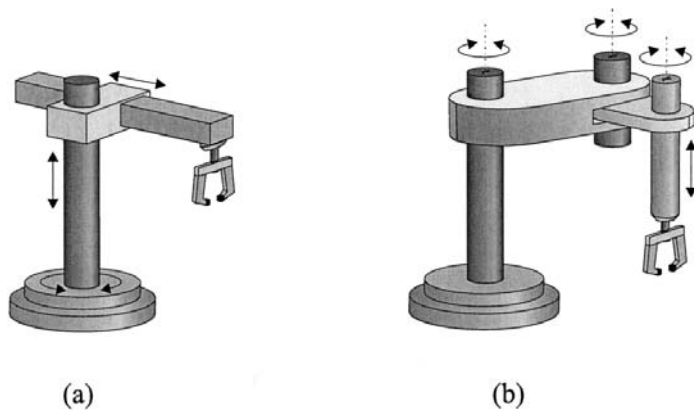

(a)   (b)

**FIGURE 10** (a) Cartesian; (b) gantry robot configurations.

FIGURE 11   (a) Cylindrical; (b) SCARA robot configurations.

configuration end for a total six-dof mobility necessary for an arbitrary motion in three-dimensional space.

   Spherical-geometry robots: There exist several robot configurations that yield spherical workspace geometries: spherical and articulated (anthropomorphic, human-like) types are the most common (Figs. 12a, 12b). The former (the first commercial robot configuration) has a sequence of rotary-rotary-linear joints assembled orthogonally to provide manufacturers with a fast reach-in/at capability along simple trajectories (e.g., machine loading/unloading). The latter articulated robot configuration provides maximum reachability among all available manipulator geometries (e.g., reaching into automobile bodies for spray painting) with a sequence of three rotary joints.
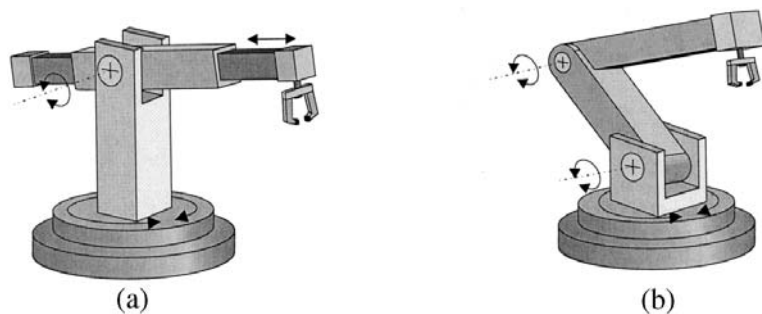
**FIGURE 12**   (a) Spherical; (b) articulated robot configurations.
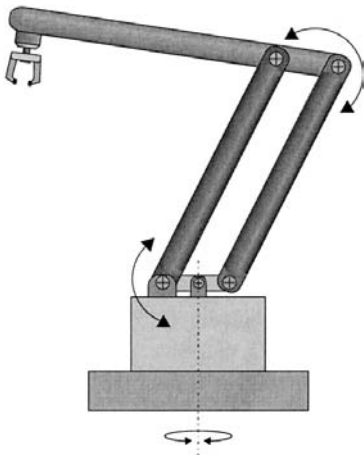
FIGURE 13 An articulated robot with parallelogram linkages.

Both robot configurations shown in Fig. 12 would have three additional (rotary type) joints for a total of six-dof mobility.

In comparison to other configurations, an articulated configuration robot would not be suitable for carrying large loads owing to its sequential employment of three rotary joints. In response to this drawback, a number of robot manufacturers redesigned their articulated configurations: better joint stiffness is achieved by employing two parallelogram linkages, for the "shoulder" and the "elbow" movements (Fig. 13).

Actuators

The three types of actuators used to power the primary (first three) joints of industrial robots are pneumatic, hydraulic, and electric. Pneumatic actuators are only suitable for light-load-carrying applications owing to the compressibility of air. As discussed in Chap. 10 (Sec. 10.6, Automatic Assembly), such actuators are frequently used in 1- to 2-dof pick-and-place mechanisms for the transportation of small parts. At the other extreme, hydraulic actuators are, normally reserved for heavy-load-carrying applications (up to 100 to 150 kg) owing to the incompressibility of hydraulic fluids. Electric motors are the most commonly used robotic actuators, despite their limited load-carrying capability, because of their low maintenance demand and low noise operation. Electric robots can carry loads up to 40 to 50 kg (but typically less than 10 kg). Most industrial robots can achieve end-effector speeds above 1 m/s, some achiev-
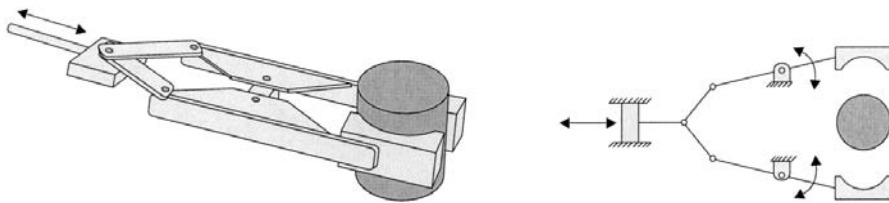
FIGURE 14 Slider-crank gripper.

ing up to 10 m/s in electronic component placement. End-effector repeatability of 0.005 to 0.1 mm can be achieved for linear electric-motor actuated robots.

Grippers

Industrial robotic applications require manipulators to be equipped with a variety of tools and grippers (end-effectors). Here our emphasis is on grippers designed for the handling of workpieces (i.e., their grasping, transportation, and placement). Stable grasping of objects can be achieved through mechanical grippers with one or multiple dof (depending on workpiece geometry complexity) or through vacuum/magnetic type gripping devices.

The slider-crank mechanism shown in Fig. 14 can be used for the grasping of cylindrical objects and, when adjusted accordingly, for the grasping of constant-width prismatic objects. This is a simple one-dof gripper, normally operated using pneumatic power (for lightweight objects) or hydraulic power. The gear-and-rack mechanism shown in Figure 15 can be very effectively used for the grasping of different width prismatic workpieces, without any adjustment, owing to the parallel motion of the jaws.
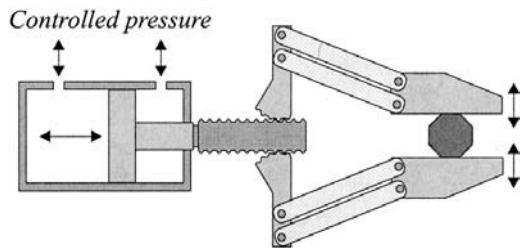
FIGURE 15 Gear-and-rack gripper.
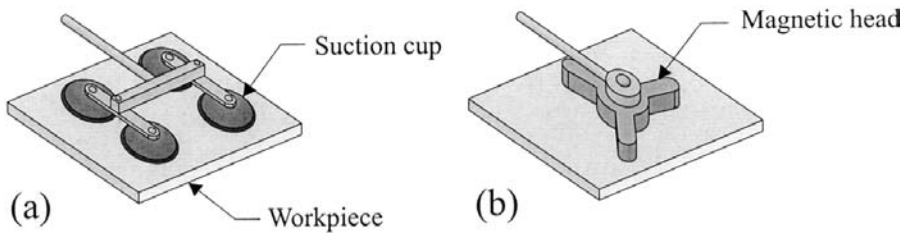
FIGURE 16 Grippers: (a) vacuum; (b) magnetic.

Vacuum type grippers can be used for the grasping of large nonferrous workpieces that cannot be handled using mechanical grippers (Fig. 16a). The workpieces must have appropriate flat surfaces, and a sufficient number of suction cups must be used for the successful grasping of heavy objects. For large ferrous objects, the use of magnetic grippers would be more suitable (Fig. 16b).

In a large number of applications, the industrial robot would be required to carry out an insertion operation—i.e., insert a peg held by the gripper into a hole on a fixtured object. In the absence of closed-loop force-feedback control, it would be recommended to use a passive alignment mechanism that would facilitate the insertion of the peg. One such facilitator is the remote–center compliance (RCC) device placed between the last link of the manipulator and the gripper (Fig. 17). The principle of an operation of an RCC device is to obtain compliance by employing flexible elements (spring, elastomer columns, etc.) between two (originally) parallel plates.

12.3.2 Applications

Industrial robots are automated mechanical manipulators that can be programmed to carry out a variety of material handling tasks, as well as production operations. As discussed earlier, the two primary end-effector-
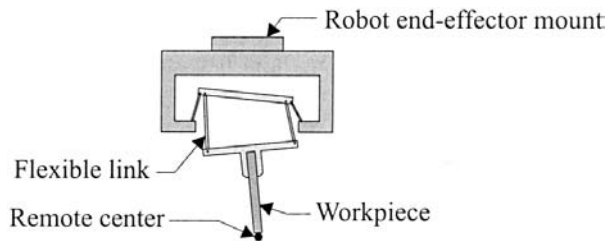
FIGURE 17 Remote-center compliance.

motion categories common to all industrial applications of robotic manipulators are PTP and CP. PTP motion implies the relocation of the end-effector from one position to another, such as in pick-and-place assembly operations, loading/unloading of machines, spot welding, riveting, and so on. CP motion, on the other hand, requires controlled movement of the end-effector (e.g., constant speed) along a prespecified trajectory defined in three-dimensional Cartesian space, such as in spray painting, arc welding, and so on.

Prior to a more detailed review of several industrial robot applications, a brief discussion of robot programming methods is provided below.

Robot Teaching

The majority of industrial robots can only be programmed after having been taken off the production line. The robot is taught to interact with its environment in show-and-teach mode and expected to operate subsequently in playback mode. In order to avoid this extremely time-consuming teaching process by carrying out an off-line teaching process, the following conditions must be satisfied:

> The kinematic model of the robot describing the mobility of its end-effector (i.e., its Cartesian frame, $F_{\text{end-effector}}$, Fig. 9) with respect to its base (i.e., $F_{\text{robot-base}}$) must be known.
> The locations of all devices (including the robot) must be accurately defined with respect to a fixed "world" coordinate frame and must not vary during the interactions of the robot end-effector with its environment.
> The motion controller of the industrial robot must allow for off-line programming.

Only in a very limited number of occasions are all above three conditions satisfied. Thus in industry most robot teaching is still carried out by show-and-teach methods.

The most common robot teaching method relies on moving the end-effector to a series of points using a teach pendant (a sophisticated joystick) and asking the robot controller to memorize these locations in terms of robot joint positions. Then the operator compiles a program in a high-level (robot-dependent) language, specifying a set of time-dependent PTP motion segments or a set of CP trajectories (e.g., a straight line) between these points. A typical teach pendant would allow the programmer to move each joint individually or move the end-effector along individual Cartesian axes in the end-effector or in the world-frame coordinates in order to position the robot end-effector at a desired location.

Material Handling and Machine Loading

For a large number of industrial robot applications, the manipulator arm moves a workpiece from one location to another. The objective here is the safest and fastest transportation of the workpiece in PTP-motion mode with no particular emphasis on the trajectory followed by the end-effector. Typical tasks include picking and placing components from and onto conveyors, indexing tables, pallets, and bins, and loading and unloading lathes, milling machines, forging presses and casting machines (Fig. 18).

Today, a large number of manufacturing machines (milling machines, lathes, etc.) can be purchased with built-in robotic arms that allow the automatic loading and unloading of workpieces or even tools. On a number of occasions, material handling robots have also been mounted on AGVs for increased mobility and as an important step toward humanless autonomous factory floors.

Welding

Spot welding is one of the primary industrial robot applications especially in the automotive industry. Most commonly, the robot end-effector is a
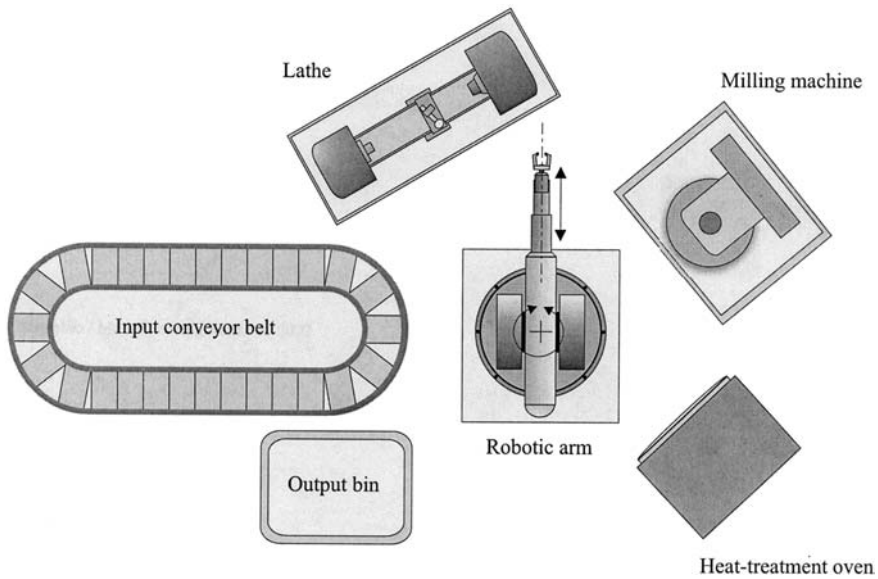
FIGURE 18 A robotic workcell.
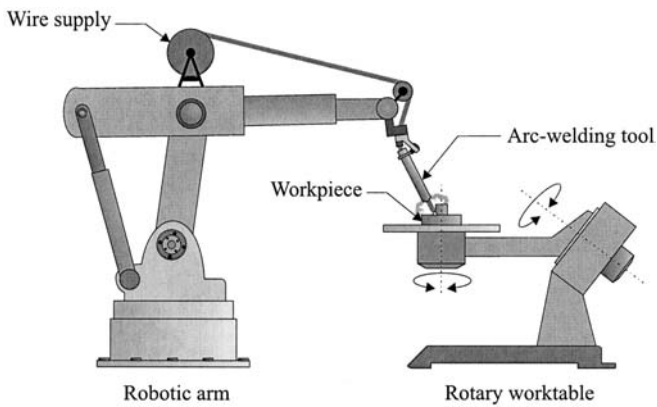
FIGURE 19 Robotic arc welding.

(resistance-weld) gun with two electrodes that joins two fixtured work-pieces by squeezing their surfaces, while an electric current generates sufficient fusion heat (Chap. 10). The motion of such a robotic spot welder is of the PTP type—moving the welding gun from one spot to another. Occasionally, the industrial robot moves the two workpieces held in its gripper to a fixed spot welder, instead of moving the welding gun to fixed workpieces. Spot welding of automotive bodies (up to 1,500 to 3,000 spots per vehicle) is the most common example for robotic welding.

A large number of industrial robots have also been used in arc welding (Chap. 10). The robot end-effector is the arc welder fusing workpieces fixtured on stationary or rotary tables that themselves may have up to three rotational dof (Fig. 19). The robot end-effector is normally programmed to follow a CP trajectory at a constant speed. Most robot end-effectors for such arc welding tasks are equipped with proximity sensors to follow the seam (i.e., seam tracking). Typical product examples for robotic arc welding include water boilers, bicycle frames, gearbox casings, and car-seat frames.

Spray-Painting

Industrial robots dominate the spray-painting activities in manufacturing companies since they provide a clean-room environment and they are very repeatable. The CP motion trajectories followed by the robot end-effector (i.e., the spray gun), however, are difficult to teach to a conventional robot. Thus most robotic painters are taught through a lead-through technique.

An expert painter (literally) holds the end-effector of the robot and moves it through a desired complex trajectory, while the robot controller memorizes a large set of points on this trajectory. If the mechanical design of the robot does not allow such a lead-through motion because of the large gear ratios, these robots can be taught via a stripped-down version of the industrial robot (i.e., a "slave") with no gears or motors. Data collected using the slave robot is then transferred to the actual (master) robot, which is designated to carry out the spray-painting operation.

12.4 AUTOMATED STORAGE AND RETRIEVAL

The storage of goods until they are required for a manufacturing operation or shipment to a customer is commonly referred to as warehousing. The three common objectives of warehousing are ease of accessibility for random retrieval, effective protection of goods while they are stored and transported, and maximum utilization of space.

There are a variety of racks that can be used in the construction of high-density storage areas. Such structures could be as high as 20 to 30 meters and be totally automated in terms of storage of goods and their random retrieval based on an order issued by the warehousing computer—automated storage and retrieval systems (AS/RS).

Storage and retrieval equipment in high-density warehouses can be categorized into single-masted (single-column), double-masted, and human-aboard machines (stacker canes). Single-masted and double-masted machines are normally supported from the ceiling for accurate vertical alignment. All such machines are equipped with telescopic extraction devices for the loading/unloading of unit loads onto/from the racks based on an address defined by the warehousing computer (e.g., *X12, Y7, Z22* m) (Fig. 20).

12.5 IDENTIFICATION AND TRACKING OF GOODS

Effective material handling in flexible manufacturing systems requires automatic identification and tracking of goods that are stationary or in motion. This information must be transferred into a computer that oversees the transportation of goods in a timely manner. Some exemplary scenarios that necessitate automatic identification are listed below as a preamble to the descriptions of available technologies.

Unit loads (cartons, bins, pallets, etc.) moving on a conveyor network must be identified for correct branching.

A product arriving at an assembly substation must be identified for the correct assembly of parts by human or robotic operators.
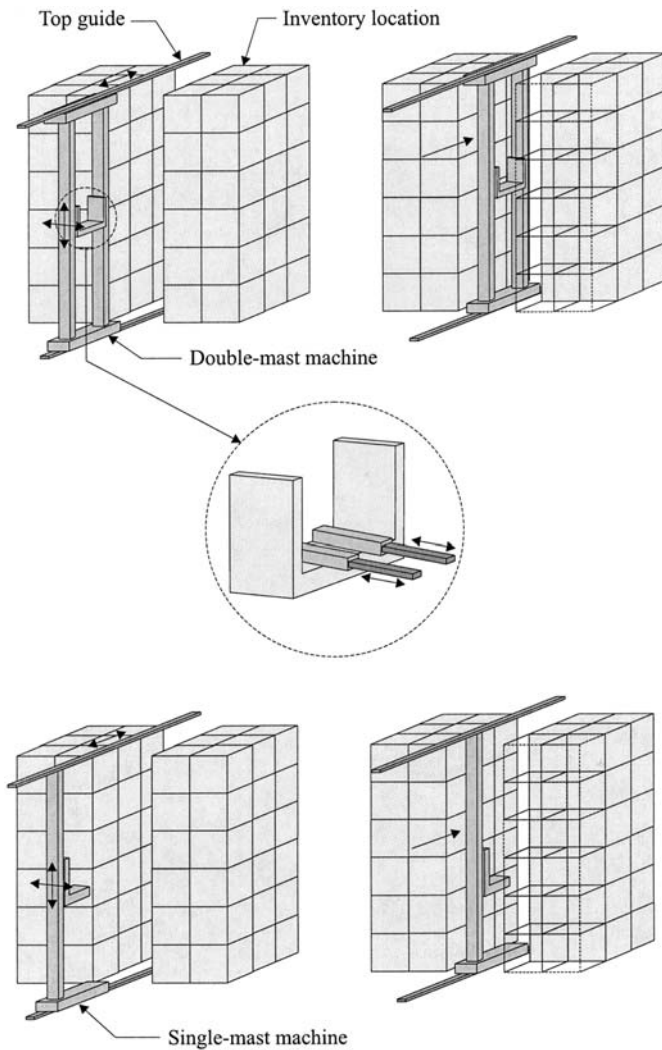
FIGURE 20 High-density warehousing.

A product arriving at a warehouse must be correctly identified for its automatic storage.

Automatic identification can be carried out by directly observing the geometry of the object or by indirectly reading an alphanumeric code attached to the object or onto the pallet/fixture carrying it. The former is, normally, carried out using a computer vision system or a collection of
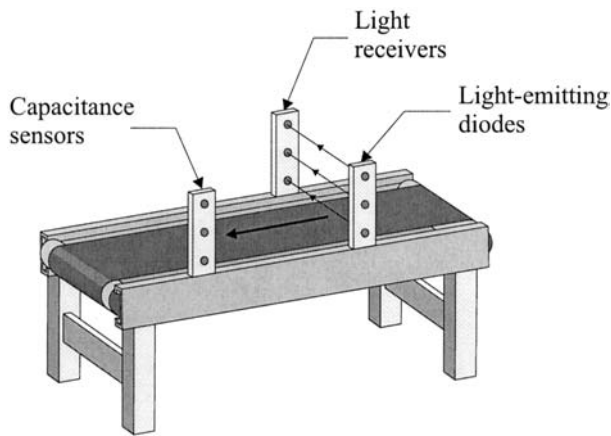
FIGURE 21 Direct object identification.

electro-optical or electromagnetic sensors that can detect a limited number of features on the object (Chap. 13).

Part identification through computer vision is a complex procedure and cannot be effectively utilized in high-volume, high-speed applications. Identification through individual noncontact sensors, on the other hand, can only differentiate among a limited number of object features, for example,

Electro-optical sensors mounted on both sides of a conveyor can differentiate among a number of different-height objects (Fig. 21).

Electromagnetic (e.g., capacitance) sensors mounted on one side of a conveyor can differentiate between conductive and nonconductive objects (metals versus plastics) (Fig. 21).

Bar Codes

Bar codes are the most commonly used identifiers of unit loads in manufacturing environments. Their primary advantage is the near-impossibility of incorrect identification—for most codes, a less than one in a million chance. Even if a bar-code scanner does not succeed in reading a code owing to improper printing or dirt, it will almost never read it as a different existing code.

A bar code is a collection of vertical printed bars (white and black) of two distinct thickness that form a constant-length string. Alphanumeric information is represented by assembling (combinatorically) different fixed-length subsets of vertical bars (i.e., characters) into a code. Almost

all bar-code strings are provided with a check digit at their end for minimizing the occurrence of errors.

The 3-of-9 code is the most commonly used coding technique in manufacturing. A 3-of-9 bar-code character utilizes 3 wide and 6 narrow bars (black or white) to define a character. The symbology comprises the numbers 0 to 9, the letters A to Z, and six additional symbols, for a total of 43 characters. The Universal Product Code (UPC) symbology, on the other hand, is an all-numeric bar code, in which each digit is represented by 2 black and 2 white (narrow or wide) bars.

Bar codes printed on the highest possible quality printers are normally attached onto cartons/boxes that contain the goods or onto the pallets/fixtures that carry the goods and only very rarely onto the object itself. They must be placed on locations that are visible to the bar-code readers, preferably on the flattest parts of the goods/pallets/etc.

Bar-code readers (also known as "scanners") can be of the handheld type or the fixed-in-place type (e.g., stationed on the side of the conveyor). They must be placed at correct heights for effective reading. The reader scans through the bar code horizontally utilizing a light beam of circular cross section (reflected back for interpretation) with a diameter that is much smaller than the height of the bars. This relative dimensionality allows the bar-code reader to scan codes that are not well placed—misaligned and/or above or below their expected location (Fig. 22).

For increased effectiveness of bar-code reading (i.e., increased robustness to label misalignments), there are omnidirectional moving-beam scanners that use multiple light-beam scanners: one light beam is perpendicular to the motion direction of the good, while two other light beams
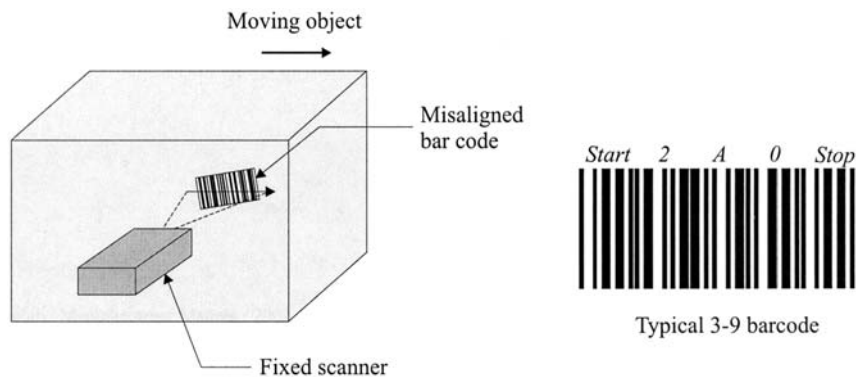

FIGURE 22 Bar-code scanning.

scan parallel to the motion direction of the good. There are also fixed-position moving-beam scanners that can project a scan line onto the good's surface in a rotating pattern to allow maximum flexibility of placing bar-code labels.

In certain circumstances, when the environmental and product constraints do not allow the use of optical devices, manufacturers have to use identifiers based on electromagnetic or RF-emission technologies (e.g., magnetic cards, tags). Such active (battery-powered) tags (transponders) are normally attached to the carriers of the goods (boxes, bins, pallets) that are reusable through reprogramming of the tag or the identifier (or both) for new goods.

12.6   AUTOMOBILE ASSEMBLY

Final assembly of automobiles has long been seen as the most complex manufacturing activity to automate because of high dexterity requirements, even long after the introduction of robotic manipulators on the factory floors. The typical car body is not assembly friendly; it requires individual components and subassemblies to follow complex paths to be fitted into their necessary locations. As discussed in Chap. 1, although the transfer of car bodies has been highly mechanized for their mass production since the 1910s, most direct assembly operations are still carried out manually.

12.6.1   Brief History

Today, the North American customer may erroneously assume that the name bearer of an automobile make manufactures and assembles the vehicle. In practice, however, a car maker is only primarily responsible for the design and assembly of the vehicles—the manufacturing of the individual components has long been the responsibility of independent or subsidiary suppliers (with some limited exceptions). Therefore major car makers are continually faced with low profit margins and thus must control assembly costs very carefully.

Historically, assembly plants have been set up as single-car-model plants, with most having large presses for the fabrication of the "white body" prior to its welding and painting on the same premises. The beginnings of these plants in the late 1880s and early 1900s were marked by the utilization of craft-production strategy; i.e., individual vehicles were assembled at specific fixed locations by highly skilled craftspeople who machined, matched, and assembled components with no great concern for interchangibility. Although this strategy was rapidly discontinued in favor of Ford's moving assembly line in the 1910s, one can still find recent

examples of such neo-craft systems in the production of low-volume sports cars or luxury cars.

The early part of the 20th century was marked by the total dominance of conveyor lines in the transfer of vehicles from one assembly station to another. The vehicle was brought to the employee but almost always kept in motion, in order to maintain targeted productivity numbers. The 1960s witnessed the mechanization of two additional activities, complementary to mechanical assembly: painting and spot welding, which were eventually totally automated in the 1970s with the introduction of industrial robots and highly repeatable positioning mechanisms.

The period of 1975–1995 witnessed many innovations on the assembly floors, ranging from common-sense production strategies to modern material handling systems. The era was marked by intense competition between the Japanese auto makers and their U.S. counterparts, as well as drastic management changes in Europe. In hindsight, however, many concluded that these intense and varied changes had little impact on the productivity of assembly operations. The most important experiment was the concept of teamwork-based assembly introduced by Volvo at its plant in Uddevalla. The basic premise was to empower teams in decision making and subsequently increase their motivation in the faster assembly of high-quality cars (Sec. 12.6.3 below). Although concepts developed in this plant were adopted by others, including GM, the Uddevalla plant was closed in 1993.

12.6.2 Strategies for Automation

Although automation has been traditionally introduced in North America, as turnkey systems for improved productivity, in some European countries it has been introduced onto factory floors as human-motivating automation. The latter strategy aims at alleviating stress and boredom caused by repetitive jobs and then increasing employee satisfaction and job attractiveness. Companies such as Volvo that have adopted this strategy see automation as a tool that makes the assembly work station more human-friendly, where the human operator is expected to be always in control. The high-tech automation strategy adopted by companies such as GM, VW, and Fiat, on the other hand, emphasizes the eventual elimination of human operators from the factory floors.

Car assembly operations range from engine mounting, to suspension mounting, to windshield placement, to bumper mounting, to battery placement, to spare tire storage, and to a variety of wire harnessing operations. The characteristics of each are different in terms of weight, bulkiness, shape complexity, and alignment tolerances. Thus while some

can be (and need to be) automated, most assembly tasks are not easy to automate with current technologies.

Statistics collected during the period of 1985 to 1995 indicated that less than 30% of assembly tasks have been automated. Among all automated tasks, welding is the leading operation (80 to 100% automated), while painting is the second leading automated task (100% of electrocoating and 70 to 100% of topcoat painting). In contrast to welding and painting, normally less than 2% of component insertion/mounting tasks have been automated: among those that are automated, windshield placement and sealing is the most automated task, while others include, rear-glass placement/sealing, engine mounting, suspension assembly, and spare tire placement. Some of these are further discussed below:

Body assembly: Levels of automation and technologies used in spot welding automation are very similar in the world auto industry. Although Japanese plants tend to have framing stations, where the roof, sides, and underbody of the vehicle are joined at once, U.S. and European plants usually have sequential lines. Furthermore, Japanese plants tend to automate a large portion of their arc welding operations, which may not be the case with U.S. plants.

Painting: The electrocoating process, the first coat of paint applied, primarily for rust protection, is always automated. The subsequent primer application and the last topcoat painting are also very widely automated. However, the interior painting of a vehicle is a challenging task and only infrequently automated (except in newer plants). Manual painting is usually required for finishing touch-ups at hard-to-reach interior places.

Final assembly: Despite massive investments in the past two decades, progress in the automation of final assembly has been very slow. However, modern plants do employ state-of-the-art conveying systems. For example, most plants utilize overhead conveyors with tilt-over mechanisms to allow efficient underbody work. For work on the upper body and interior of the car, most plants remove the doors at the start of the line and reattach them later. Most plants also utilize platform-type conveyors that carry the vehicle only or both the vehicle and the assembly person. Some newer plants allow for variable-speed conveying, for more efficient assembly, according to the task at hand. In carrying out the assembly tasks, the employees are provided with a variety of assistance tools for lifting, placing, bolting, and so on.

12.6.3 The Uddevalla System

Volvo's Uddevalla plant was initially planned to be a complete auto assembly plant with a body welding shop and paint shop. However, in

1989, the plant opened only as a final assembly plant, which eventually was shut down in 1993 because of a cyclic downturn in demand. Some have argued that a contributing factor to the closure was the lack of body and paint shops. However, all agree that the radical changes experimented with in this plant have been adopted by other Volvo plants and other auto makers, so Uddevalla's death has not been the end of the story!

As discussed above, the assembly strategy adopted by the designers of the Uddevalla plant was based on human-motivating automation, which attempted to make assembly work attractive by moving from a moving-line-type assembly to stationary assembly. Thus first came the development of such an implementable assembly strategy. The concept necessitated the empowerment of a small team (planned to be 5 to 10 people) to assume total assembly responsibility for the vehicle. However, due to efficiency limitations, the assembly of the vehicle had to be planned as a division into 8 sequential stations (as opposed to a single assembly station), where workers were to carry out assembly tasks for a duration of 20 minutes on each car (an upper time limit to human efficiency in learning and performing a sequence of tasks). Each station was to be supplied with complete component kits (prepared at a central location) for each 1/8th of the vehicle, respectively.

Next came the difficult task of factory layout. The first planned cost-effective layout comprised parallel assembly shops, each for complete car assembly. Each shop was to house four stations allowing eight separate teams to work in parallel on four stationary cars. In each shop, labor teams specializing on 1/8th of the assembly were to move from one station to another and complete the assembly of four cars at a time. Each team was to comprise 8 to 10 people. Stations were to be equipped with lifting and tilting mechanisms for maximum utilization of space.

The eventual shop layouts, however, employed only four teams (versus eight) working sequentially at four stations within the shop, for a total assembly time of almost two hours, repeated four times a day. The teams worked in an asynchronous manner deciding when to start to work on the next car and even occasionally switching tasks among themselves between cars.

Prior to its closure, Uddevalla had the following statistics: complaints per car reduced from 1.32 to 0.87, productivity of 32 hours per car assembly versus 42 in other European plants and above 50 in North American plants; 25% lower tooling costs per car and lead-time reductions of almost 50% on delivery of ordered cars.

Although the plant no longer exists in its intended form, many European and Japanese auto makers have adopted the principles of Uddevalla—a combination of low-cost technology and skilled labor for

human-oriented automotive assembly. The use of AGVs, instead of conveyor lines, in automotive assembly has also been commonly attributed to the Uddevalla experience.

REVIEW QUESTIONS

1. What is the fundamental objective of material handling? Is this objective compatible with just-in-time manufacturing? Explain.
2. Why can industrial trucks be considered "flexible" equipment?
3. Define automated guided vehicles (AGVs). Can AGVs be considered industrial robots?
4. What has been the primary purpose of developing and using AGVs in industrial settings that typically employ industrial trucks, such as lift trucks and tow tractors?
5. Describe navigation guidance for AGVs.
6. Why should one consider overhead conveying?
7. Compare the use of AGVs versus conveyors in asynchronous manufacturing environments. Consider car engine assembly as an example application.
8. What is an industrial robot?
9. Define mobility for open-chain robotic (spatial) manipulators.
10. Define point-to-point (PTP) versus continuous-path (CP) motion for industrial robots.
11. Why can rectangular geometry robots (with linear joints) provide users with better end-effector accuracy than that achievable with nonrectangular geometry robots (with rotary joints)? Discuss the use of parallelogram linkages in this context.
12. Describe the use of a remote-center compliance device in robotic component insertion processes.
13. Discuss the limitations of robot teaching on the implementation of industrial manipulators. Consider the assembly of a multicomponent toy car as an example.
14. Why are industrial robots ideal for use in welding and painting applications?
15. What is automated storage and retrieval?
16. What are bar codes and how can they be used in manufacturing environments?
17. Discuss the use of nonoptical goods tracking devices in manufacturing environments.
18. Why has automobile assembly been so intensely studied? Discuss its historical development in the 20th century.

19. What are the most commonly automated tasks in automobile assembly?
20. Briefly review the Uddevalla automobile assembly system and discuss its innovations.

DISCUSSION QUESTIONS

1. Computers and other information management technologies have been commonly accepted as facilitators for the integration of various manufacturing activities. Define/discuss integrated manufacturing in the modern manufacturing enterprise and address the role of computers in this respect. Furthermore, discuss the use of intranets and extranets as they pertain to the linking of suppliers, manufacturers, and customers.
2. Manufacturing flexibility can be achieved at three levels: operational flexibility, tactical flexibility, and strategic flexibility. Discuss operational flexibility. Is material handling automation a necessary or a desirable tool in achieving this level of flexibility?
3. Explain the importance of investigating the following factors in the establishment of a manufacturing facility: availability of skilled labor, availability and closeness of raw materials and suppliers, closeness of customers/market, and availability of logistical means for the effective distribution of products.
4. Discuss strategies for retrofitting an existing manufacturing enterprise with automation tools for material as well as information processing. Among others, consider issues such as buying turn-key solutions versus developing in-house solutions and carrying out consultations in a bottom-up approach, starting on the factory floor, versus an top-to-bottom approach, starting on the executive board of the company and progressing downward to the factory floor.
5. Several fabrication/assembly machines can be physically or virtually brought together to yield a manufacturing workcell for the production of a family of parts. Discuss the advantages of adopting a cellular manufacturing strategy in contrast to having a departmentalized strategy, i.e., having a turning department, a milling department, a grinding department, and so on. Among others, an important issue to consider is the transportation of parts (individually or in batches).
6. In the factory of the future, it is envisioned that production and assembly workcells would be frequently reconfigured based on the latest manufacturing objectives without the actual physical relocation

of their machines/resources. Discuss the material handling options that should be available to the users of such workcells, whose boundaries may exist only in the (computer's) virtual space.

7. Discuss the advantages of utilizing reusable pallets and other temporary storage means in a manufacturing environment. Propose a number of features that would improve the usability, transportation, storage, removal, and so on of such pallets/boxes/magazines/etc.

8. AGVs have been accepted as being more flexible and less space restrictive than networks of conveyors. Discuss this comparison and extend it to include human-operated material handling vehicles (e.g., forklifts) in manufacturing environments as well as overhead conveying (i.e., three-dimensional material handling solutions).

9. Welding, soldering, and painting are manufacturing operations that rely on maintaining consistent and repeatable process parameters. Discuss the use of automation (including the use of industrial robots) for these and other processes that have similar requirements as replacements for manual labor.

10. The majority of industrial robots can be programmed using a high-level language that allows users to define end-effector trajectories between a priori taught points in Cartesian space. Lack of earlier standardization in NC machine controllers that have been frequently used as the basis for robot controllers, however, has also led to the absence of a single programming language common to all industrial robots. In trying to protect their markets, industrial robot makers have developed proprietary programming languages. Discuss the potential negative impact of the proliferation of programming languages on the use of industrial robots in manufacturing environments.

11. The necessary programming of robot task space locations by physically moving the robot's end-effector to these positions, while it is taken off the manufacturing line, has severely limited their use to mass-production environments. Thus although industrial robots provide a high level of automation, they cannot be time efficiently programmed and used for one-of-a-kind or small-batch productions. Discuss potential remedies that would allow robots to be programmed for their next task, while they are performing their current task.

12. Industrial robots have traditionally been designed and marketed as "all-capable" (generic) manipulators. That is, they have the necessary mobility to manipulate objects in three-dimensional space (position and orientation), the necessary workspace to replace a human operator, the necessary load carrying capability for a large number of applications, and so on. In most manufacturing environments, however, such robots would be overqualified. Discuss an alternative approach to industrial

robot design and marketing that is based on modularity and reconfigurability, a possibility of manufacturing industrial robots that are made to order based on the employment of standardized modular components: cut-to-length links and properly sized actuators assembled to the extent of the mobility (frequently less than six degrees of freedom) that is required and in an optimal geometrical architecture.

13. Industrial robots are normally sold with no end-effectors (grippers or other tools). Discuss the advantages/disadvantages of using generic humanlike multifingered hands versus simple single-purpose, limited-mobility (possibly, quick-exchange) end-effectors.

14. Industrial robots have been often labeled as being deaf and blind operators with no tactile feedback detection capability. Discuss in general terms what would be the benefits of having a variety of visual and nonvisual sensors monitoring the robot's working environment and feeding back accurate and timely information to the motion controller of such manipulators.

15. Human operators have been argued to be intelligent, autonomous, and flexible when compared to industrial robots. Discuss several manufacturing applications where one would tend to utilize human operators rather than industrial robots (even those supported by a variety of sensors) in the context of these three properties.

16. Industrial robots have been often designed to replace the human operator in manufacturing settings. The past several decades have shown us, however, that there still exist significant gaps between humans' and robots' abilities, primarily owing to the unavailability of artificial perception technologies. Compare humans to pertinent anthropomorphic robots in terms of the following and other issues: mechanical configuration and mobility, power source, workspace, payload capacity, accuracy, communications (wireless!), supervisory control ability, sensory perception, ability to process data, coping with uncertainties, and working in hazardous environments.

17. Discuss the need of having effective tracking means, distributed throughout a manufacturing facility, that would provide users (and even customers) with timely feedback about the status and location of products in motion. Include several examples of such sensing and feedback devices in your discussion. Furthermore, discuss the advantages/disadvantages of using wireless solutions.

18. It has been long argued that manufacturing inventories hide production problems, and that their elimination would expose the sources of chronic problems. Despite this understanding, what manufacturing scenarios would still require the use of large (automated or manually operated) warehouses?

19. Material handling has been always argued to be a cost adding (versus value adding) activity in manufacturing. Despite this acceptance, however, many manufacturers, including numerous vehicle assemblers, continue to utilize several-kilometer-long paths that their product must travel prior to their shipment. Discuss the reasons that fabricators and assemblers of many manufactured products continue to utilize long material handling paths. Consider several examples and propose remedies. In your discussion include a comparison of the assembly concepts of bringing the work to the operator versus bringing the operator to the work, as well as a comparison of the fabrication concepts of departmentalized facility layout (i.e., milling department, grinding department, heat-treatment department, etc.) versus flexible manufacturing workcell layout.

20. The 20th century has witnessed a historical trend in the strong reduction of manual labor in the agricultural industry with the introduction of a variety of (mechanized) vehicles, irrigation systems, crop treatment techniques, and so on. Discuss the current trend on continuing reduction in the (manual) labor force involved in materials handling activities. Can you identify similarities to what has happened in the agricultural industry (and even in the book publishing, textile, and other industries in earlier centuries) to what may happen in the manufacturing industry in the 21st century?

BIBLIOGRAPHY

Apple, James M. (1977). *Plant Layout and Materials Handling*. New York: Ronald Press.

Asfahl, Ray C. (1992). *Robots and Manufacturing Automation*. New York: John Wiley.

Stephen, Cameron, Penelope, Probert, eds. (1994). *Advanced Guided Vehicles*. River Edge, NJ: World Scientific.

Eastman, Robert M. (1987). *Materials Handling*. New York: Marcel Dekker.

Engstrom, T., Medbo, L., Jonsson, D. (July 1994). Extended work cycle assembly—a crucial learning experience. *International Journal of Human Factors in Manufacturing* 4(3):293–303.

Engstrom, T., Medbo, L., Jonsson, D. (1998). Volvo Uddevalla plant and interpretations of industrial design processes. *Journal of Integrated Manufacturing Systems* 9(5–6):279–295.

Groover, Mikell P. (2001). *Automation, Production Systems, and Computer-Integrated Manufacturing*. Upper Saddle River, NJ: Prentice Hall.

Fayed, M. E., Skocir, Thomas S. *Mechanical Conveyors: Selection and Operation*. Lancaster, PA: Technomic.

Hammond, Gary (1986). *AGVS at Work: Automated Guided Vehicle Systems*. Bedford: UK: IFS.

Hollier, R. H., ed. (1987). *Automated Guided Vehicle Systems*. Bedford, UK: IFS.

Holzbock, Werner G. (1986). *Robotic Technology, Principles and Practice*. New York, NY: Van Nostrand Reinhold.

Hunt, V. Daniel (1988). *Robotics Sourcebook*. New York: Elsevier.

Koren, Yoram (1985). *Robotics for Engineers*. New York: McGraw-Hill.

Kulwiec, Raymond A., ed. (1985). *Materials Handling Handbook*. New York: John Wiley.

Lundesjo, Gregor, ed. (1985). *Handbook of Materials Handling*. New York: Halsted Press.

Miller, Richard Kendall, Subrin, Rachel, ed. (1987). *Automated Guided Vehicles and Automated Manufacturing*. Dearborn, MI: Society of Manufacturing Engineers.

Mulcahy, David E. (1999). *Materials Handling Handbook*. New York: McGraw-Hill.

Müller, Willi (1985). *Integrated Materials Handling in Manufacturing*. Bedford, UK: IFS.

Nayak, Nitin, Asok, Ray (1993). *Intelligent Seam Tracking for Robotic Welding*. New York: Springer-Verlag.

Nof, Shimon Y., ed. (1999). *Handbook of Industrial Robotics*. New York: John Wiley.

Pham, D. T., Heginbotham, W. B. (1986). *Robot Grippers*. Bedford, UK: IFS.

Rembold, Ulrich (1990). *Robot Technology and Applications*. New York: Marcel Dekker.

Rivin, Eugene I. (1988). *Mechanical Design of Robots*. New York: McGraw-Hill.

Shimokawa, K., Jürgens, U. Fujimoto, T., eds. (1997). *Transforming Automobile Assembly: Experience in Automation and Work Organization*. New York: Spring-Verlag.

Todd, D. J. (1986). *Fundamentals of Robot Technology: An Introduction to Industrial Robots, Teleoperators and Robot Vehicles*. London: Kogan Page.