

# INDUSTRIAL ROBOTS AND ROBOT SYSTEM SAFETY

## I. INTRODUCTION.

Industrial robots are programmable multifunctional mechanical devices designed to move material, parts, tools, or specialized devices through variable programmed motions to perform a variety of tasks. An industrial robot system includes not only industrial robots but also any devices and/or sensors required for the robot to perform its tasks as well as sequencing or monitoring communication interfaces.

Robots are generally used to perform unsafe, hazardous, highly repetitive, and unpleasant tasks. They have many different functions such as material handling, assembly, arc welding, resistance welding, machine tool load and unload functions, painting, spraying, etc. Most robots are set up for an operation by the teach-and-repeat technique. In this mode, a trained operator (programmer) typically uses a portable control device (a teach pendant) to teach a robot its task manually. Robot speeds during these programming sessions are slow.

This instruction includes safety considerations necessary to operate the robot properly and use it automatically in conjunction with other peripheral equipment. This instruction applies to fixed industrial robots and robot systems only.

### A. ACCIDENTS: PAST STUDIES.

1. Studies in Sweden and Japan indicate that many robot accidents do not occur under normal operating conditions but, instead during programming, program touch-up or refinement, maintenance, repair, testing, setup, or adjustment. During many of these operations the operator, programmer, or corrective maintenance worker may temporarily be within the robot's working envelope where unintended operations could result in injuries.
2. Typical accidents have included the following:
  - A robot's arm functioned erratically during a programming sequence and struck the operator.
  - A materials handling robot operator entered a robot's work envelope during operations and was pinned between the back end of the robot and a safety pole.
  - A fellow employee accidentally tripped the power switch while a maintenance worker was servicing an assembly robot. The robot's arm struck the maintenance worker's hand.

### B. ROBOT SAFEGUARDING.

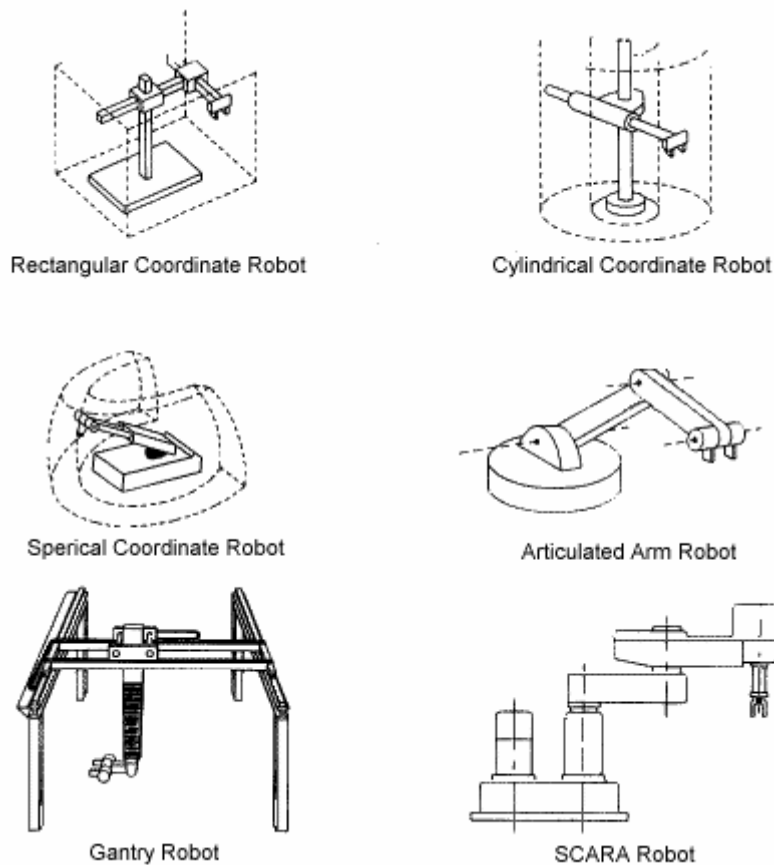
1. The proper selection of an effective robotic safeguarding system should be based upon a hazard analysis of the robot system's use, programming, and maintenance operations. Among the factors to be considered are the tasks a robot will be programmed to perform, start-up and command or programming procedures, environmental conditions, location and installation requirements, possible human errors, scheduled and unscheduled maintenance, possible robot and system malfunctions, normal mode of operation, and all personnel functions and duties.
2. An effective safeguarding system protects not only operators but also engineers, programmers, maintenance personnel, and any others who work on or with robot

systems and could be exposed to hazards associated with a robot's operation. A combination of safeguarding methods may be used. Redundancy and backup systems are especially recommended, particularly if a robot or robot system is operating in hazardous conditions or handling hazardous materials. The safeguarding devices employed should not themselves constitute or act as a hazard or curtail necessary vision or viewing by attending human operators.

## II. TYPES AND CLASSIFICATION OF ROBOTS.

Industrial robots are available commercially in a wide range of sizes, shapes, and configurations. They are designed and fabricated with different design configurations and a different number of axes or degrees of freedom. These factors of a robot's design influence its working envelope (the volume of working or reaching space). Diagrams of the different robot design configurations are shown in Figure 1.

**FIGURE 1. ROBOT ARM DESIGN CONFIGURATIONS.**



### A. SERVO AND NONSERVO.

All industrial robots are either servo or nonservo controlled. Servo robots are controlled through the use of sensors that continually monitor the robot's axes and associated components for position and velocity. This feedback is compared to pretaught information which has been programmed and stored in the robot's memory. Nonservo robots do not have the feedback capability, and their axes are controlled through a system of mechanical stops and limit switches.

**B. TYPE OF PATH GENERATED.** Industrial robots can be programmed from a distance to perform their required and preprogrammed operations with different types of paths generated

through different control techniques. The three different types of paths generated are Point-to-Point Path, Controlled Path, and Continuous Path.

**1. Point-to-Point Path.** Robots programmed and controlled in this manner are programmed to move from one discrete point to another within the robot's working envelope. In the automatic mode of operation, the exact path taken by the robot will vary slightly due to variations in velocity, joint geometries, and point spatial locations. This difference in paths is difficult to predict and therefore can create a potential safety hazard to personnel and equipment.

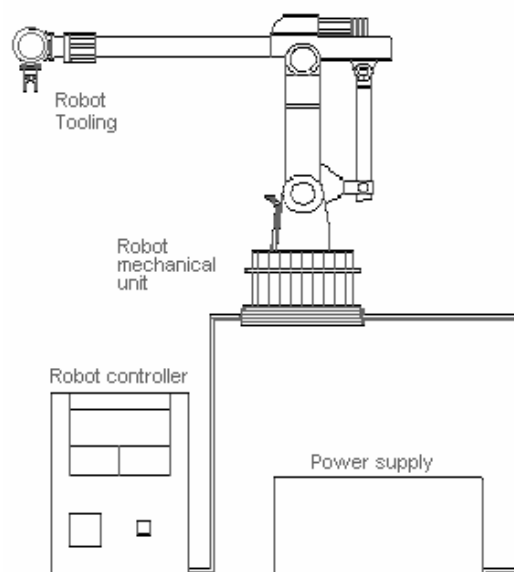
**2. Controlled Path.** The path or mode of movement ensures that the end of the robot's arm will follow a predictable (controlled) path and orientation as the robot travels from point to point. The coordinate transformations required for this hardware management are calculated by the robot's control system computer. Observations that result from this type of programming are less likely to present a hazard to personnel and equipment.

**3. Continuous Path.** A robot whose path is controlled by storing a large number or close succession of spatial points in memory during a teaching sequence is a continuous path controlled robot. During this time, and while the robot is being moved, the coordinate points in space of each axis are continually monitored on a fixed time base, e.g., 60 or more times per second, and placed into the control system's computer memory. When the robot is placed in the automatic mode of operation, the program is replayed from memory and a duplicate path is generated.

**C. ROBOT COMPONENTS.** Industrial robots have four major components: the mechanical unit, power source, control system, and tooling (Figure 2).

**1. Mechanical Unit.** The robot's manipulative arm is the mechanical unit. This mechanical unit is also comprised of a fabricated structural frame with provisions for supporting mechanical linkage and joints, guides, actuators (linear or rotary), control valves, and sensors. The physical dimensions, design, and weight-carrying ability depend on application requirements.

**FIGURE 2. INDUSTRIAL ROBOTS: MAJOR COMPONENTS.**



## **2. Power Sources.**

a. Energy is provided to various robot actuators and their controllers as pneumatic, hydraulic, or electrical power. The robot's drives are usually mechanical combinations powered by these types of energy, and the selection is usually based upon application requirements. For example, pneumatic power (low-pressure air) is used generally for low weight carrying robots.

b. Hydraulic power transmission (high-pressure oil) is usually used for medium to high force or weight applications, or where smoother motion control can be achieved than with pneumatics. Consideration should be given to potential hazards of fires from leaks if petroleum-based oils are used.

c. Electrically powered robots are the most prevalent in industry. Either AC or DC electrical power is used to supply energy to electromechanical motor-driven actuating mechanisms and their respective control systems. Motion control is much better, and in an emergency an electrically powered robot can be stopped or powered down more safely and faster than those with either pneumatic or hydraulic power.

## **D. CONTROL SYSTEMS.**

1. Either auxiliary computers or embedded microprocessors are used for practically all control of industrial robots today. These perform all of the required computational functions as well as interface with and control associated sensors, grippers, tooling, and other associated peripheral equipment. The control system performs the necessary sequencing and memory functions for on-line sensing, branching, and integration of other equipment. Programming of the controllers can be done on-line or at remote off-line control stations with electronic data transfer of programs by cassette, floppy disc, or telephone modem.

2. Self-diagnostic capability for troubleshooting and maintenance greatly reduces robot system downtime. Some robot controllers have sufficient capacity, in terms of computational ability, memory capacity, and input-output capability to serve also as system controllers and handle many other machines and processes. Programming of robot controllers and systems has not been standardized by the robotics industry; therefore, the manufacturers use their own proprietary programming languages which require special training of personnel.

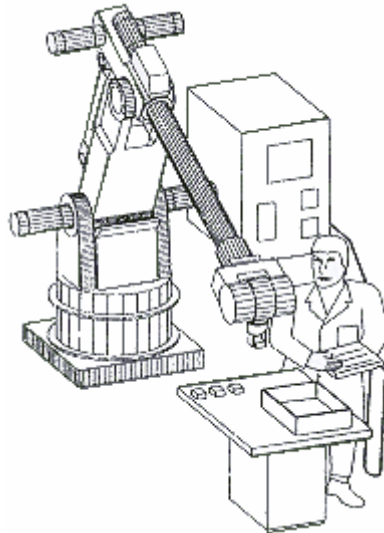
**E. ROBOT PROGRAMMING BY TEACHING METHODS.** A program consists of individual command steps which state either the position or function to be performed, along with other informational data such as speed, dwell or delay times, sample input device, activate output device, execute, etc.

When establishing a robot program, it is necessary to establish a physical or geometrical relationship between the robot and other equipment or work to be serviced by the robot. To establish these coordinate points precisely within the robot's working envelope, it is necessary to control the robot manually and physically teach the coordinate points. To do this as well as determine other functional programming information, three different teaching or programming techniques are used: lead-through, walk-through, and off-line.

**1. Lead-Through Programming or Teaching.** This method of teaching uses a proprietary teach pendant (the robot's control is placed in a "teach" mode), which allows trained personnel physically to lead the robot through the desired sequence of events by activating the appropriate pendant button or switch. Position data and functional information are "taught" to the robot, and a new program is written (Figure

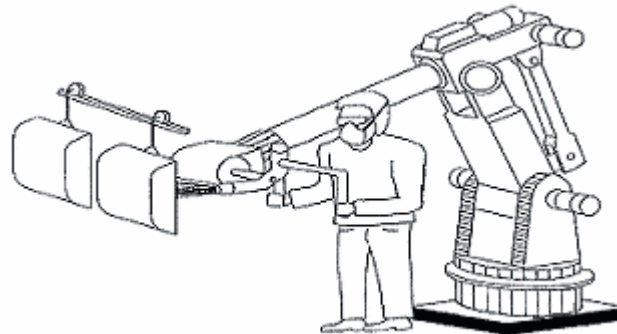
3). The teach pendant can be the sole source by which a program is established, or it may be used in conjunction with an additional programming console and/or the robot's controller. When using this technique of teaching or programming, the person performing the teach function can be within the robot's working envelope, with operational safeguarding devices deactivated or inoperative.

**FIGURE 3. ROBOT LEAD-THROUGH PROGRAMMING OR TEACHING.**



**2. Walk-Through Programming or Teaching.** A person doing the teaching has physical contact with the robot arm and actually gains control and walks the robot's arm through the desired positions within the working envelope (Figure 4).

**FIGURE 4. WALK-THROUGH PROGRAMMING OR TEACHING.**

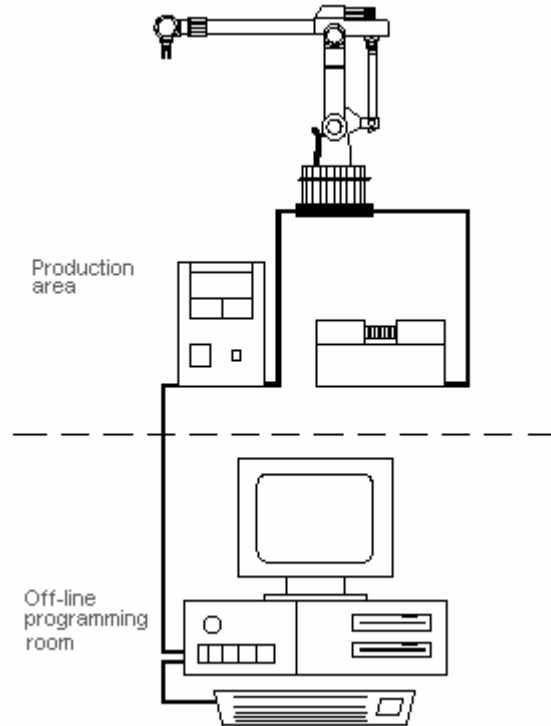


During this time, the robot's controller is scanning and storing coordinate values on a fixed time basis. When the robot is later placed in the automatic mode of operation, these values and other functional information are replayed and the program run as it was taught. With the walk-through method of programming, the person doing the teaching is in a potentially hazardous position because the operational safeguarding devices are deactivated or inoperative.

**Off-Line Programming.** The programming establishing the required sequence of functional and required positional steps is written on a remote computer console (Figure 5). Since the console is distant from the robot and its controller, the written program has to be transferred to the robot's controller and precise positional data

established to achieve the actual coordinate information for the robot and other equipment. The program can be transferred directly or by cassette or floppy discs. After the program has been completely transferred to the robot's controller, either the lead-through or walk-through technique can be used for obtaining actual positional coordinate information for the robot's axes.

**FIGURE 5. OFF-LINE PROGRAMMING OR TEACHING.**



When programming robots with any of the three techniques discussed above, it is generally required that the program be verified and slight modifications in positional information made. This procedure is called program touch-up and is normally carried out in the teach mode of operation. The teacher manually leads or walks the robot through the programmed steps. Again, there are potential hazards if safeguarding devices are deactivated or inoperative.

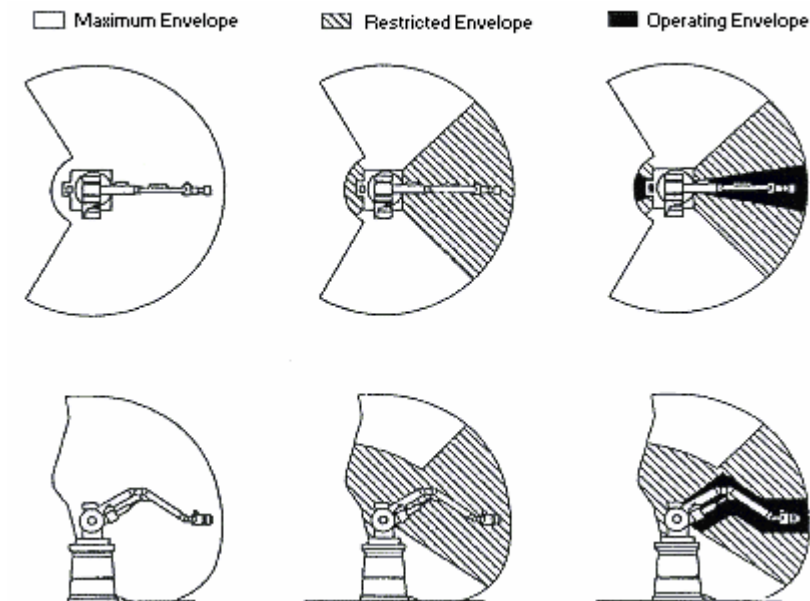
**3. DEGREES OF FREEDOM.** Regardless of the configuration of a robot, movement along each axis will result in either a rotational or a translational movement. The number of axes of movement (degrees of freedom) and their arrangement, along with their sequence of operation and structure, will permit movement of the robot to any point within its envelope. Robots have three arm movements (up-down, in-out, side-to-side). In addition, they can have as many as three additional wrist movements on the end of the robot's arm: yaw (side to side), pitch (up and down), and rotational (clockwise and counterclockwise).

### **III. HAZARDS.**

The operational characteristics of robots can be significantly different from other machines and equipment. Robots are capable of high-energy (fast or powerful) movements through a large volume of space even beyond the base dimensions of the robot (see Figure 6). The pattern and initiation of movement of the robot is predictable if the item being "worked" and the environment are held

constant. Any change to the object being worked (i.e., a physical model change) or the environment can affect the programmed movements.

**FIGURE 6. A ROBOT'S WORK ENVELOPE.**



Some maintenance and programming personnel may be required to be within the restricted envelope while power is available to actuators. The restricted envelope of the robot can overlap a portion of the restricted envelope of other robots or work zones of other industrial machines and related equipment. Thus, a worker can be hit by one robot while working on another, trapped between them or peripheral equipment, or hit by flying objects released by the gripper.

A robot with two or more resident programs can find the current operating program erroneously calling another existing program with different operating parameters such as velocity, acceleration, or deceleration, or position within the robot's restricted envelope. The occurrence of this might not be predictable by maintenance or programming personnel working with the robot. A component malfunction could also cause an unpredictable movement and/or robot arm velocity.

Additional hazards can also result from the malfunction of, or errors in, interfacing or programming of other process or peripheral equipment. The operating changes with the process being performed or the breakdown of conveyors, clamping mechanisms, or process sensors could cause the robot to react in a different manner.

**I. TYPES OF ACCIDENTS.** Robotic incidents can be grouped into four categories: a robotic arm or controlled tool causes the accident, places an individual in a risk circumstance, an accessory of the robot's mechanical parts fails, or the power supplies to the robot are uncontrolled.

**1. Impact or Collision Accidents.** Unpredicted movements, component malfunctions, or unpredicted program changes related to the robot's arm or peripheral equipment can result in contact accidents.

**2. Crushing and Trapping Accidents.** A worker's limb or other body part can be trapped between a robot's arm and other peripheral equipment, or the individual may be physically driven into and crushed by other peripheral equipment.

**3. Mechanical Part Accidents.** The breakdown of the robot's drive components, tooling or end-effector, peripheral equipment, or its power source is a mechanical accident. The release of parts, failure of gripper mechanism, or the failure of end-effector power tools (e.g., grinding wheels, buffing wheels, deburring tools, power screwdrivers, and nut runners) are a few types of mechanical failures.

**4. Other Accidents.** Other accidents can result from working with robots. Equipment that supplies robot power and control represents potential electrical and pressurized fluid hazards. Ruptured hydraulic lines could create dangerous high-pressure cutting streams or whipping hose hazards. Environmental accidents from arc flash, metal spatter, dust, electromagnetic, or radio-frequency interference can also occur. In addition, equipment and power cables on the floor present tripping hazards.

**II. SOURCES OF HAZARDS.** The expected hazards of machine to humans can be expected with several additional variations, as follows.

**1. Human Errors.** Inherent prior programming, interfacing activated peripheral equipment, or connecting live input-output sensors to the microprocessor or a peripheral can cause dangerous, unpredicted movement or action by the robot from human error. The incorrect activation of the "teach pendant" or control panel is a frequent human error. The greatest problem, however, is overfamiliarity with the robot's redundant motions so that an individual places himself in a hazardous position while programming the robot or performing maintenance on it.

**2. Control Errors.** Intrinsic faults within the control system of the robot, errors in software, electromagnetic interference, and radio frequency interference are control errors. In addition, these errors can occur due to faults in the hydraulic, pneumatic, or electrical subcontrols associated with the robot or robot system.

**3. Unauthorized Access.** Entry into a robot's safeguarded area is hazardous because the person involved may not be familiar with the safeguards in place or their activation status.

**4. Mechanical Failures.** Operating programs may not account for cumulative mechanical part failure, and faulty or unexpected operation may occur.

**5. Environmental Sources.** Electromagnetic or radio-frequency interference (transient signals) should be considered to exert an undesirable influence on robotic operation and increase the potential for injury to any person working in the area. Solutions to environmental hazards should be documented prior to equipment start-up.

**6. Power Systems.** Pneumatic, hydraulic, or electrical power sources that have malfunctioning control or transmission elements in the robot power system can disrupt electrical signals to the control and/or power-supply lines. Fire risks are increased by electrical overloads or by use of flammable hydraulic oil. Electrical shock and release of stored energy from accumulating devices also can be hazardous to personnel.

**7. Improper Installation.** The design, requirements, and layout of equipment, utilities, and facilities of a robot or robot system, if inadequately done, can lead to inherent hazards.