SKEM4153
ROBOT TECHNOLOGY FOR AUTOMATION

CHAPTER 9
Safety in Robotics and Manufacturing Automation

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The Three Laws of Robotics:

The laws were developed by Isaac Asimov (in 1940s and 1950s), the science fiction writer:

1. A robot must not harm a human being, nor through inaction allow one to come to harm
2. A robot must always obey human beings, unless that is in conflict with the first law
3. A robot must protect itself from harm, unless that is in conflict with the first and second law

These laws are still valid today, and safety considerations must be included.

Situations requiring safety

1. When repairing malfunctioning robot
2. When other equipment fails
3. During maintenance of robots
4. During reprogramming of robots
5. During robot operations

ROBOTS
REQUIRE
RESPECT

Group	Standard	Subject
1. ANSI/RIA	R1056-1986	American national standards for industrial robots and robot systems
2. BSR/RIA	BSR/RIA R15-06-19XX	Proposed standard for industrial robots and robot systems
3. ANSI/RIA	R15.02-1990	American national standard human engineering design criteria for hand-held robot control pendants
4. OSHA	Pub. 2254 (revised)	Training requirements in standards and training guidelines
5. NIOSH	Pub. 88-108	Safe maintenance guidelines for robotics workstations
6. OSHA	Pub. 8-1.3, 1987	Guidelines for robotics safety
7. OSHA	29 CFR 1910.147	Control of hazardous energy source (lockout/tagout final rule)
8. AFOSH	127-12, 1991	Occupational safety machinery

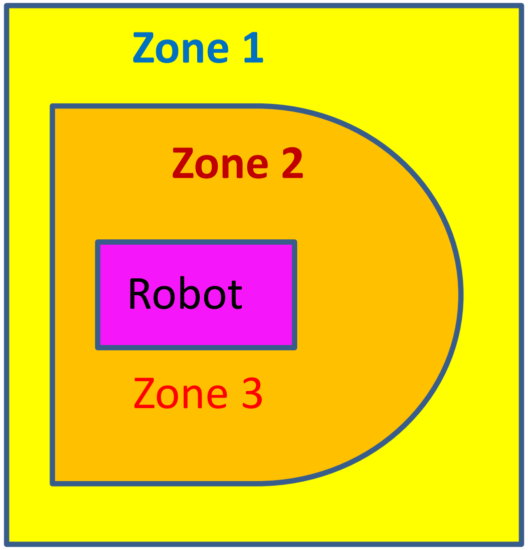
ANSI/RIA = American National Standards Institutes/Robotics Industrial Association.
BSR/RIA = Bureau of Standards Review/Robotics Industrial Association.
NIOSH = National Institute for Occupational Safety and Health.
OSHA = Occupational Safety and Health Administration.
AFOSH = Department of the Air Force.

SAFEGUARDING A WORK CELL

- The responsibility for safeguarding a robotic cell falls on the user. The standards address safeguarding by considering four points:

1. Devices to be used
2. Operator safety
3. Safety of the teacher
4. Safeguarding maintenance and repair personnel

Safety Zones



- **Zone 1** : is the area outside the work cell and has no restrictions on human traffic
- **Zone 2:** is the area inside the work cell but out of reach of the robot arm. Only programmers, work-cell operators, and maintenance personnel are allowed in this area.
- **Zone 3**: is the area inside the robot work envelope, and it cannot be entered as long as the robot is in the automatic or run mode. Penetration is permitted during programming or maintenance but only after safety standards established for the type of robot present have been satisfied.

Zone 1: typically distinguished by signs and yellow lights. A continuous barrier with electrical interlocks is usually installed to separate zones 1 and 2.

Zone 3: usually distinguished by an outline on the floor indicating the robot's maximum reach. In addition, awareness alarm electronic detectors are frequently used in zones 2 and 3.

Safety hardware

Physical Barriers: Physical barriers are the first line of defense in protecting people from hazards. These include:

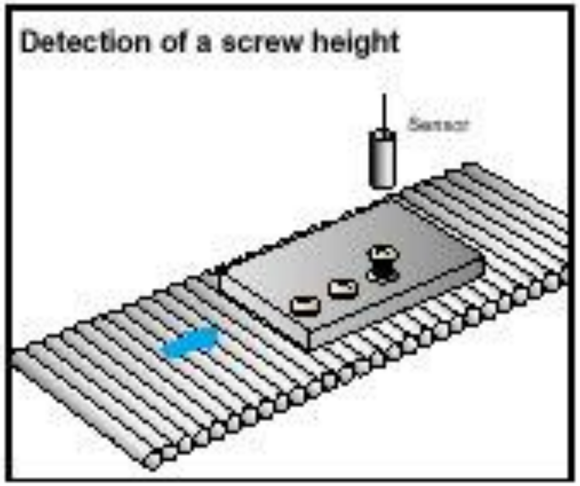
- Chains and guard posts
- Safety rails
- Wire mesh fencing
- Equipment within the work cell

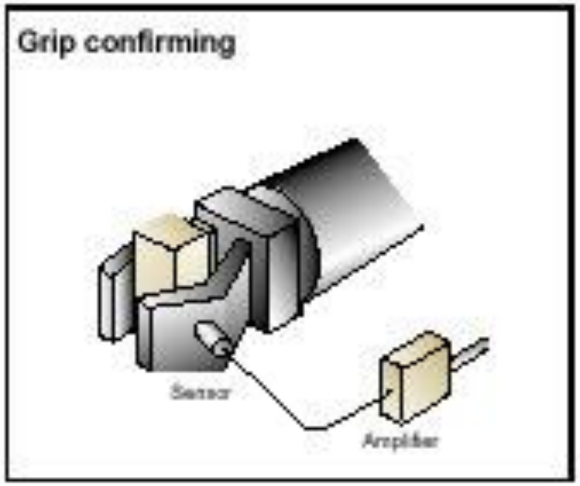
The last item, when combined with guard rails and fences, provides effective safety protection at reduced cost.

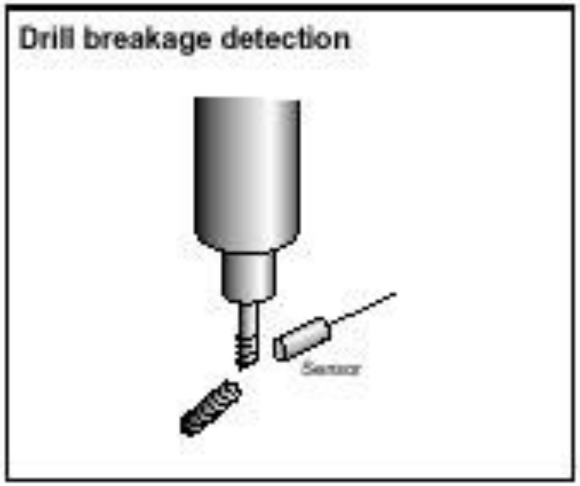
E-stop Devices: switches with various tripping mechanisms remove power to production machines in emergency situations. The most common E-stop devices are the mushroom pushbutton and grab wire switches.

Safety hardware

Presence Sensing Devices: sense the presence of a person and cause the appropriate action to safeguard the person from any hazardous condition. The common examples include light curtains, pressure sensing pads, and proximity sensing devices.







Safety hardware

Interlock Devices: these are switches that interlock a guard door with the power source of the hazard. Power interlocking and control interlocking are the two types of control most frequently used. Contact and non-contact switches are used with various tripping mechanism that include actuator operated, hinge operated, cam operated, active actuator non-contact, unconditional guard unlocking, and conditional guard unlocking.

Figure : Special limit switches designed for work in safety system (Omron Electronics, LLC)

Safety Control Units: are the intelligent controllers that link elements of the safety system together and interface the safety system to the rest of the automated cell hardware.

Presence Sensing Devices

Three devices commonly used in automated work cells to sense the presence of a human: proximity sensing devices, light curtains and pressure sensitive mats.

Proximity Sensing Devices: uses ultrasonic and laser technologies used to sense the presence of human from a single sensing location.

Proximity laser sensor (PLS) is a programmable single point safety device that can pattern a protective field to an irregularly shaped production area. It covers a 180 degree field of view without reflectors or separate receivers.

The PLS creates 3 independent user-defined sensing fields, using an infrared laser beam and time-of-flight measurements. The fields include two programmable protected zones (the safety zone and the early warning zone) and a surveyed area zone. (See Figure below).

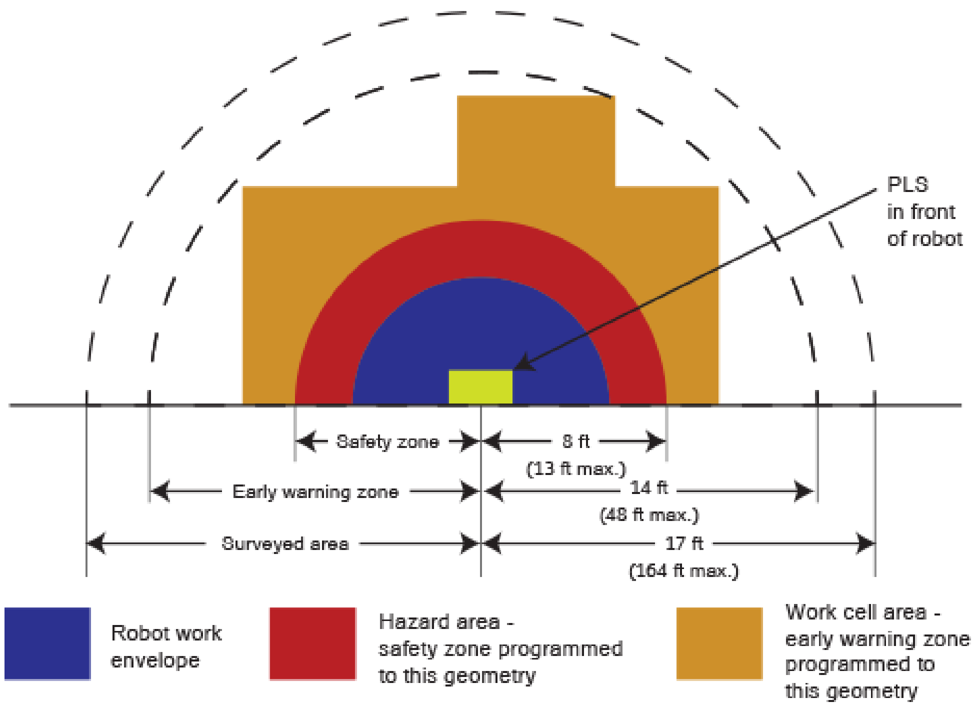


Figure: Typical Layout of the PLS System.

- Entrance into the early warning zone initiates a warning signal, and movement into the safety zone would stop any hazardous machine motion.

  The surveyed area is used to support positioning and navigation for AGVs.

  The safe guarded zone are set using a learn mode in the PLS, or they are defined by the programmer using a Windows-based programming language in the graphic input mode or the coordinate input mode.

Technical specification of the PLS System

Scanning range	Safety zone radius Early warning zone radius Surveyed area radius	4 m (13 ft) 15 m (48 ft) 50 m (164 ft)
Object sensitivity	70 mm (2.75 in.) at 4 m scanning range (variable at closer range)	
Response time	Less or equal to 80 mm safety zone. Less or equal to 40 mm safety zone	
Safety category	Single component failure detectability; EN 954, Category 3	

Light curtains

Light curtain Introduction

- Light curtains (also called light screens, optical guards, and presence sensing devices) provide guarding with a degree of flexibility and reduced operator fatigue when compared to traditional guarding methods such as mechanical barriers, gates, and pull-back restraints. Safety light curtains simplify routine tasks such as machine setup, maintenance, and repair by replacing solid guards.

Light curtain Operation

- In a light curtain a photoelectric transmitter sends an array of synchronized parallel infrared light beams to a receiver unit. If an opaque object interrupts one or more beams, the light curtain controller sends a stop signal to the guarded machine. The light curtain in Figure illustrates this concept. Light emitting diodes (LEDs) in the transmitter are energized by the light curtain's timing and logic circuitry and emit pulses of invisible infrared light.

Light curtains

The light pulses of individual diodes are energized one after another and are modulated at the specific frequency. Phototransistors and logic circuitry in the receiving unit detect only the specific pulse and designated frequency of the sending diode. This technique ensures safe operation and rejection of external light sources.

A controller interfaces the curtain to guarded machine and work cell hardware, and provides user controls, status and diagnostic indication, and power from curtain operation. A light curtain from Omron is pictured in the Figure .

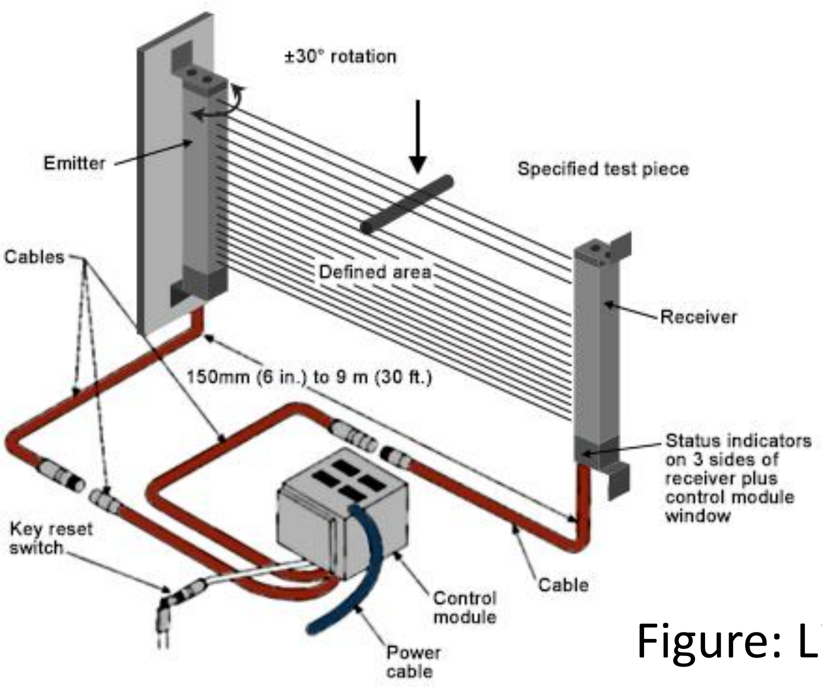


Figure: Light curtain System components

Light curtains

- The light curtain is different from a standard photoelectric sensor because of a concept called control reliability. Control reliability is a design standard from OSHA and ANSI (ANSI B11.19-1990, 5.5) for safety related machine control system. It stated that:
- *The device, system, or interface shall be designed, constructed, and installed such that a single component failure within the device, interface, or system shall not prevent normal stopping action from taking place but shall prevent a successive machine cycle.*

Example of control reliability design include self-checking circuitry, which monitors the curtain from internal faults by using lockouts to stop the guarded machine until the fault is corrected and the system is reset. Redundant output relays are other example of control reliability design. If one relay fails, a second is used to stop the guarded machine.

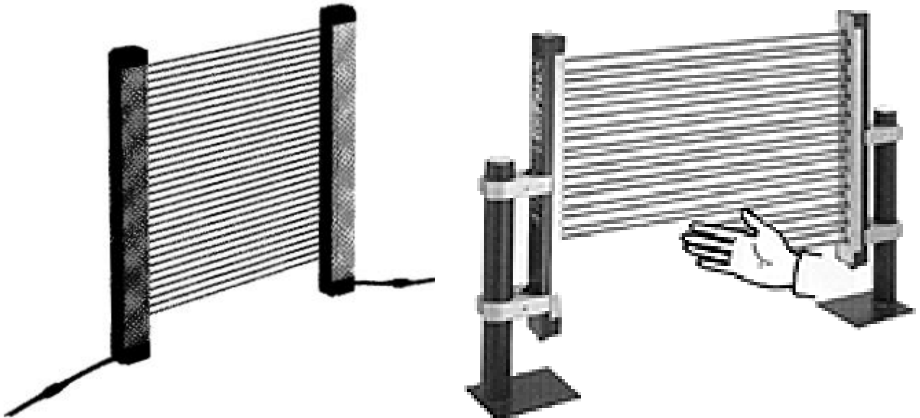


Figure: Light curtain model from Omron

Light curtain applications

- Light curtain applications are often grouped by the type of guarding required. Guarding for the point of operation, also called the zone of hazardous operation or the pinch point, protects and operator from the hazards located where the process is performed. Finger and hand protection is the primary goal for light curtains used to guard presses, stamping, forming and automated assembly machinery.
- Perimeter guards are used to guard the boundary defined by a machine or robot. The goal is to detect the presence of humans and to control the machine to prevent hazardous conditions while personnel are present in the area. Perimeter guarding applications are usually designed to detect arm and body elements. The entrance to the robot cell in Figure is guarded by a horizontal light curtain.

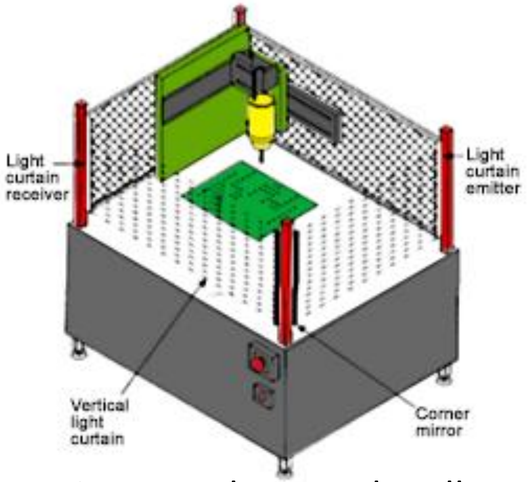


Figure: Robot Work Cell Guarded by a Horizontal Light Curtain

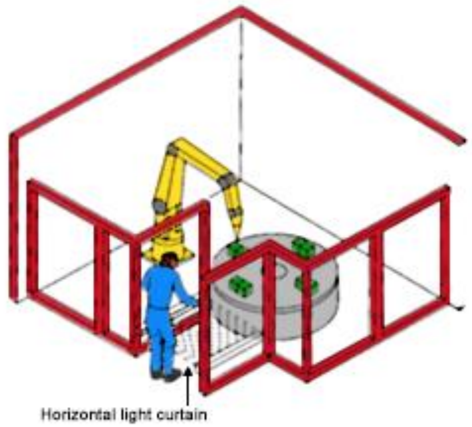
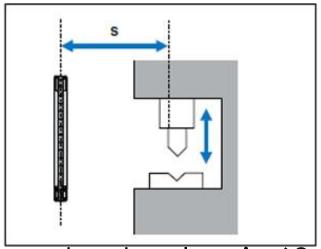


Figure: Automatic Drilling Machine Protected by a Vertical Light Curtain

Calculating Safe Curtain Distance

One of the most important concepts related to the use of light curtains in machine guarding is the calculation of the minimum safe distance. The ANSI standard B11.19-1990 (4.2.33.3.5) describes the safe distance as:



$$D_{pf} = \frac{S - 0.3}{0.3}$$

The ANSI minimum formula is:

$$D_s = K * (T_s + T_c + T_r + T_{bm}) + D_{pf}$$

where

D_s = Minimum safe distance.

K = Hand speed constant in inches per second. The ANSI standard value is 63 inches per second.

T_s = The stop time of the machine in seconds measured from the final reenergized control element.

T_c = The response time in second, of the press or machine control circuit to activate the machine's brake.

Note: $T_s + T_c$ are usually measured together with stopwatch.

T_r = The response, in seconds, of the safety light curtain. Use the value of 0.045 seconds in planning an installation or use the actual response time of the light curtain provided in the installation manual.

T_{bm} = The additional stopping time, in seconds, allowed by the brake performance monitor. If excessive brake wear is present, a brake monitor will halt the machine when the stop time of the machinery exceeds the brake monitor limit. Therefore, T_{bm} = brake monitor set point – ( )

D_{pf} = The added distance for the depth penetration factor in inches. This compensates for small objects, like fingers, that can move through a curtain because the curtain's sensitivity is not sufficient to detect the presence of the objects. The minimum object resolution S of the light curtain is substituted into the following equation (S has units of inches):

Example 9.1

- A mechanical press has a stopping time for the press brake mechanism (T_s) of 0.35seconds, and a stopping time for the control circuits (T_C) of 0.05 seconds. The brake monitor is set for 0.49 seconds. The response time of the light curtain selected is 0.045 seconds and the minimum object sensitivity (S) is 0.80 inches. Determine the safe distance D_s for the curtain to be mounted to the press.

Solution

K = 63 in/s (chosen)

T_{lim} = brake monitor setpoint – (T_s + T_c)
= 0.49 s – (0.35 s + 0.05 s) = 0.09 s

D_{pf} = (S-0.3) / 0.3 = (0.8 in – 0.3)/0.3 = 1.67 in.

D_s = K x (T_s + T_c + T_t + T_{bm}) + D_{pf}
= 63 in/s x (0.35 s + 0.05 s + 0.045 s + 0.09 s) + 1.67 in.
= 33.705 in + 1.67 in = 35.375 in.

Pressure Sensing Mats

- A pressure sensing mat is a simple solution to many safety issues associated with sensing the presence of humans in an area. The full visibility and access to the work area offered by mats is their primary advantage. Another advantage is their simple mode of operation.

- **Sensing Mat Operation**

- The electrical model for a mat is a normally open switch that closes when a specified minimum weight is applied to the mat. The guarded machine is halted by the mat control system when the system senses that the mat switch is closed. The mat switch is formed by two conductors separated by small insulators. Each conductor is connected to a pair of wires that are used to interface to the control circuits.

- The mat components are molded into a PVC structure to create a strong assembly. The resistance of the mat switch circuits falls to zero (a closed switch) when pressure is applied to the active mat area. This switch closing in the mat causes a relay in the mat controller to de-energize. When the mat controller relay turns off, contacts open and the guarded machine has power removed.

Pressure Sensing Mats (cont.)

- Mats are available in various sized and can be linked together by joining strips to provide presence sensing for a large area. Mat controllers permit multi mat layouts to be combined electrically for a single machine stop signal when any mat in the group receives the minimum force. Mat controllers offer the following safety features:

- Control reliable circuitry.
- Corroded-mat electrode monitor.
- Mat-wiring integrity monitors.
- Remote access to status, test, and reset functions.
- Built-in diagnostic indicators.

Interlocking Devices

- The safety interlock switch is one of the most important types of protective devices because it interlocks the machine guard door with the power source of the machine. When the guard door is opened, the power to the machine is removed, which ensures the safety of the operator. There are many different types of interlock switches, and it is important to select the device type that matches the application. The general features and requirements of switches used for interlocking duties are described in the following sections.

Interlocking Devices cont.

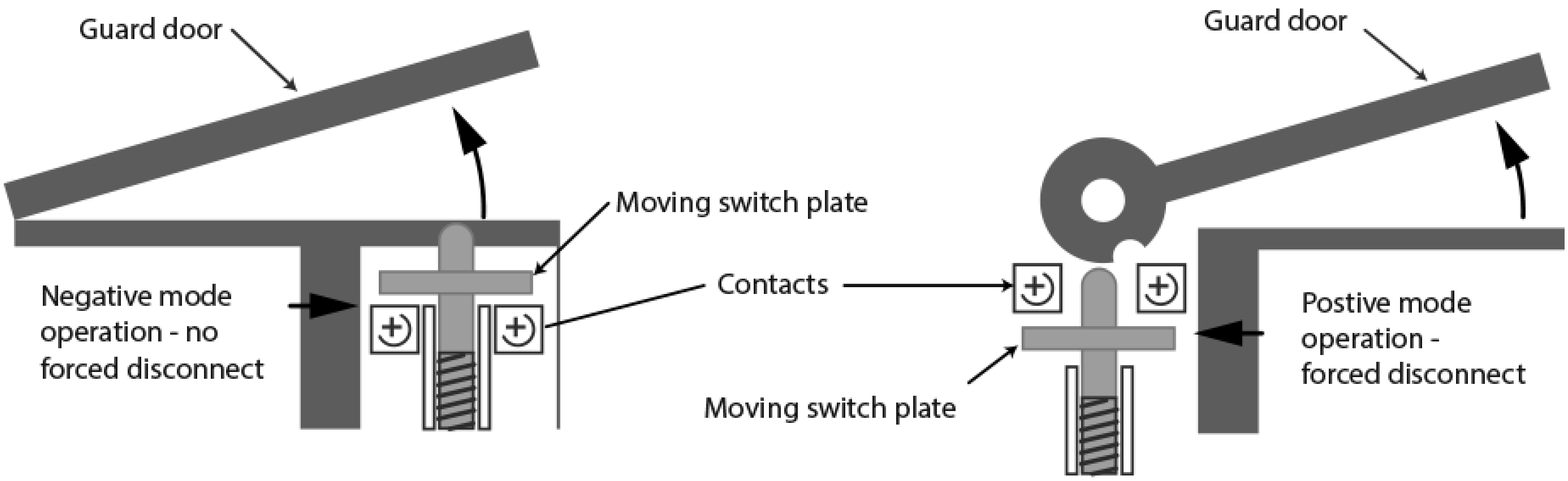
- **Interlock Switch Operation**

The European Standard EN 1088, interlocking devices associated with guards, and EN-60947-5-1 from electromechanical switches are used to design interlocks in robot and machine safety situations. The first requirement of interlocks switches is reliable operation under extreme conditions and rough treatment.

A second requirement relates to security. The interlock switch must be able to overcome all attempts to cheat or defeat the mechanism. Personnel often attempt to override an interlock switch to expedite an order or to save production time. Machine usage information gathered at the risk assessment stage of the design process will help to determine if cheating is likely. Switch security levels range from resistance to impulsive tampering to being almost impossible to defeat. Interlock device that are not accessible when the guard door is open provide the highest degree of security.

Interlock Positive Mode Operation

The standard defines positive mode as the movement of one object by another through direct contact or via rigid elements. In single mechanical type interlocking switches, the movement of the guard and the switch safety contacts exhibit positive mode operation, This ensures that the contact physically pulled apart or force disconnected by the movement of the guard, and that the contacts do not rely on spring pressure to open. This feature, required by the standard, overcomes the problem of sticking or welded contacts or a weak or broken spring in the switch. Figure below illustrates negative and positive mode operation.



(a) Negative mode

(b) Positive mode

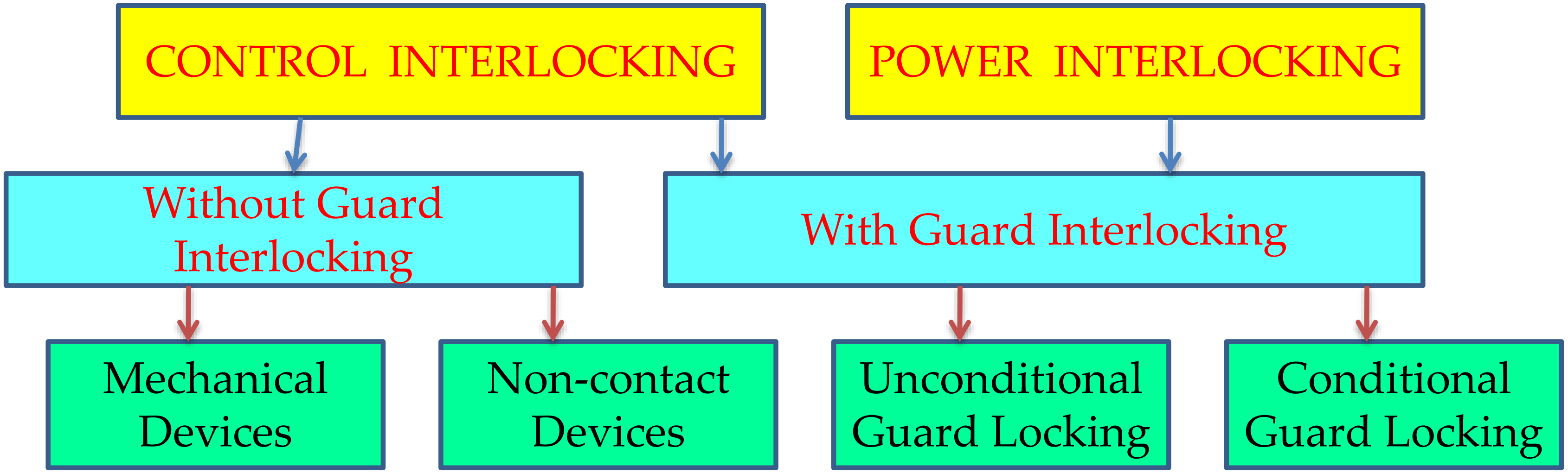
Interlocking Devices cont.

Forms of Interlock Devices

There are two basic types of electrical interlocking systems:

- ***Power interlocking*** – the power source of the machine is directly interrupted when the guard is opened.
- ***Control interlocking*** – the power source of the hazard is interrupted by a power control device activated by interlock device.

All the current forms of interlocking are illustrated in Figure below:



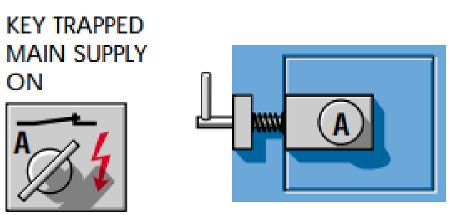
Interlocking Devices cont.

Power Interlocking

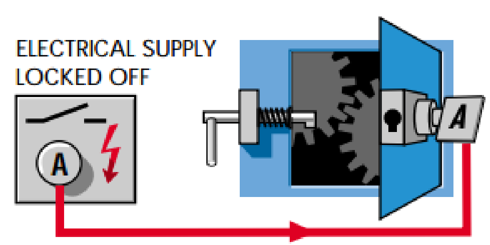
In this technique, guard movement is interlocked directly with the switching of the power to the machine. This means that the interlock device must be capable of switching the voltage and current required by the production machine.

This works only with a small percentage of industrial machines because most machines use a three-phase voltage supply with relatively high current. When high power switching is required, one approach is to use trapped key system, in which a key is used to open the guarded area and also to switch power to machine.

The key is trapped in position while the switch is in the on position (guard door is closed) but can be removed when the guard door is open and the machine is off.



MACHINE IS RUNNING.
ELECTRICAL SUPPLY IS ON.
ACCESS DOOR IS LOCKED.

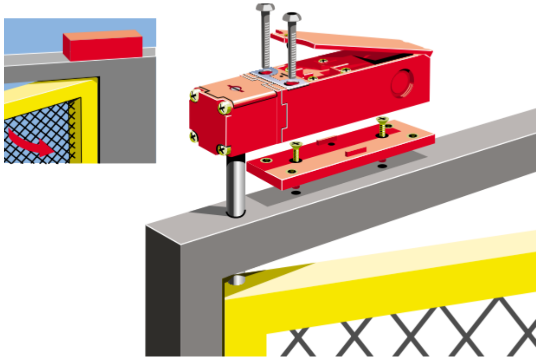


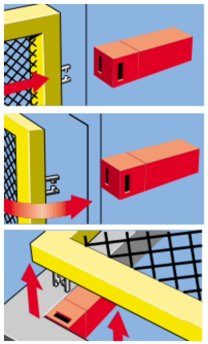
MACHINE IS NOW STOPPED AND THE ELECTRICAL SUPPLY HAS BEEN ISOLATED.
ACCESS DOOR CAN NOW BE OPENED.
WHEN DOOR IS OPEN, KEY IS TRAPPED.

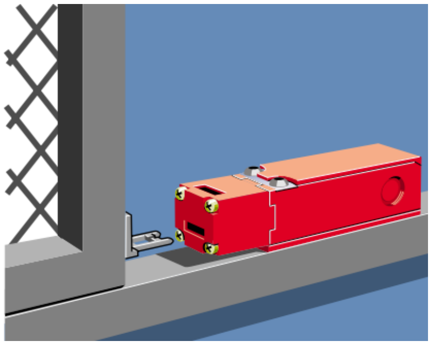
Interlocking Devices cont.

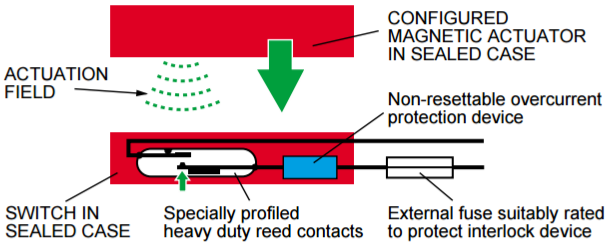
Control Interlocking

Control Interlocking, the most commonly used method, has an interlock switch attached to the guard that opens the switch contacts whenever guard movement is sensed. The interlock switch contacts trigger a control circuit that removes power from the motor starter or contactor that switches the primary machine power. Control interlocking can be applied with or without a physical lock on the guard door.









Interlocking Devices cont.

Calculating Safe Guard Distance

The draft European standard prEN 999 addresses the distance between protective guards and the hazards used to overcome the maximum speed an operator would use to approach a machine. The formula is

$$S = (K \times T) + C$$

Where,

S = The minimum distance in mm from the danger zone to the opening edge of the guard.

K = 1600 millimeters per second. Research data indicates that 1600 is a reasonable assumption for an approach speed by an operator. The actual application might yield a different value, but as a general guideline, a value for K from 1600 to 2500 millimeters per second is commonly used.

T = The total time in (seconds) from the opening of the interlock switch contact to the cessation of the hazard.

C = An additional distance in millimeters based on how far an operator could reach over, around, or through the guard before the stop action of the safety device is initiated.

Interlocking Devices cont.

Example 9.2

A robot system has a protective barrier enclosing the work-cell area. The total time fro the system to come to a full halt after power is removed is 1 second, and an additional distance of 4 feet is required because of the height of the guard gate.

Determine the minimum distance from the guard gate to the closed part of the robot work envelope.

Solution 9.2

Solution:

K = 1600 mm/s (chosen)
T = 1 s
C = 4 ft
C = 4 ft x 304.8 mm/ft = 1219 mm
S = (KxT)+C
= (1600 mm/s x 1 s) + 1219 mm
= 2819 mm

Interlocking Devices cont.

Mechanical Interlock Devices

Vendors supply another group of mechanical interlock devices that link movement in the guard door to positive mode switch operation. There are three main types of mechanical actuation devices:

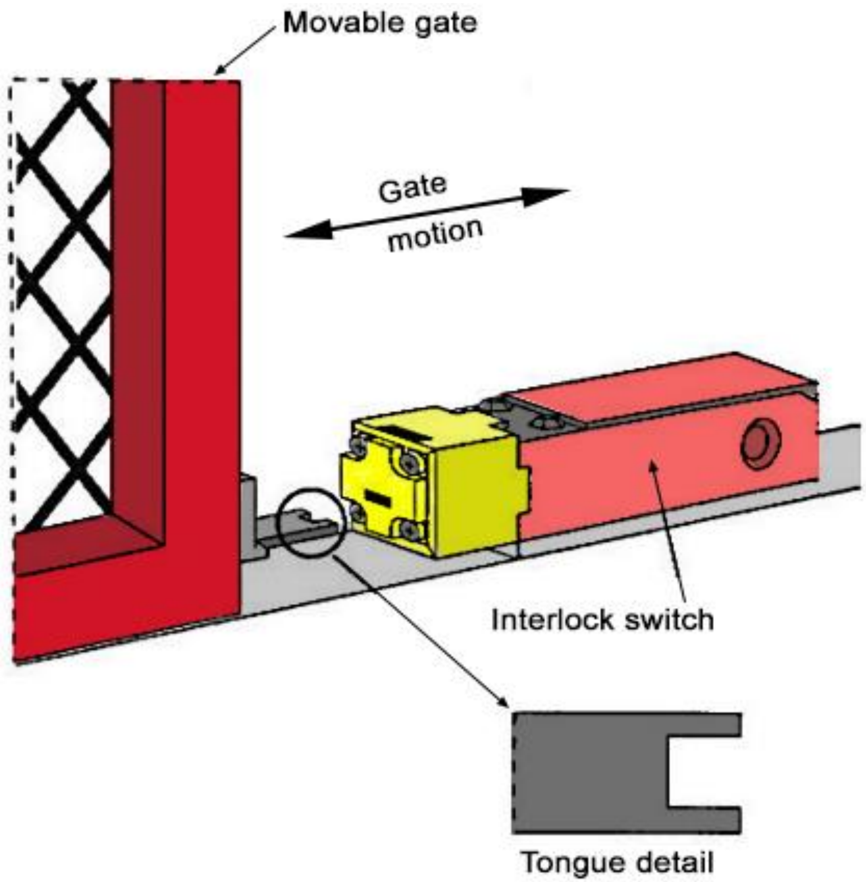
1. **actuator operated**
2. **hinge operated**
3. **cam operated**

The actuator operated device, the most common mechanical safety switch, has an actuator tongue mounted to the guard gate. When the gate is closed, the tongue slides into the switch and closes the switch contacts. The contacts open when the tongue is pulled out of the switch by opening the gate.

Interlocking Devices cont.

Characteristics of this switch include the following:

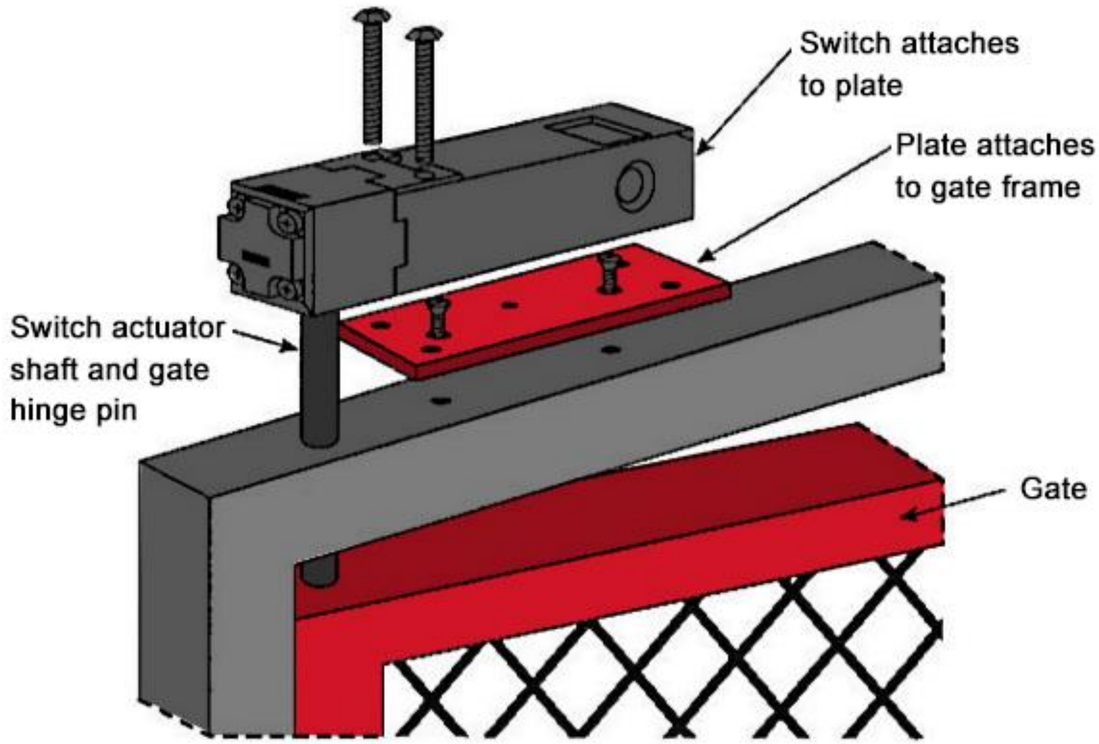
- Designed to make cheating of the switch difficult.
- Easy to install
- Reliable operation
- Can be used on sliding, hinged, and lift-off guards.
- Alignment between the guard and switch must be maintained.
- Difficult to clean thoroughly.



This is an example of this type of mechanical safety switch.

Interlocking Devices cont.

The hinge operated actuation device in Figure below is mounted over the hinge pin of a hinge guard door. When the door is opened, the rotation of the hinge pin inside the switch causes a positive mode operation mechanism to open the switch include the following:



Ideal for hinged guard doors where access to the hinge centerline is possible.

Provides protection with only 3 degrees of guard door movement.

Extremely difficult to defeat without dismantling the guard door.

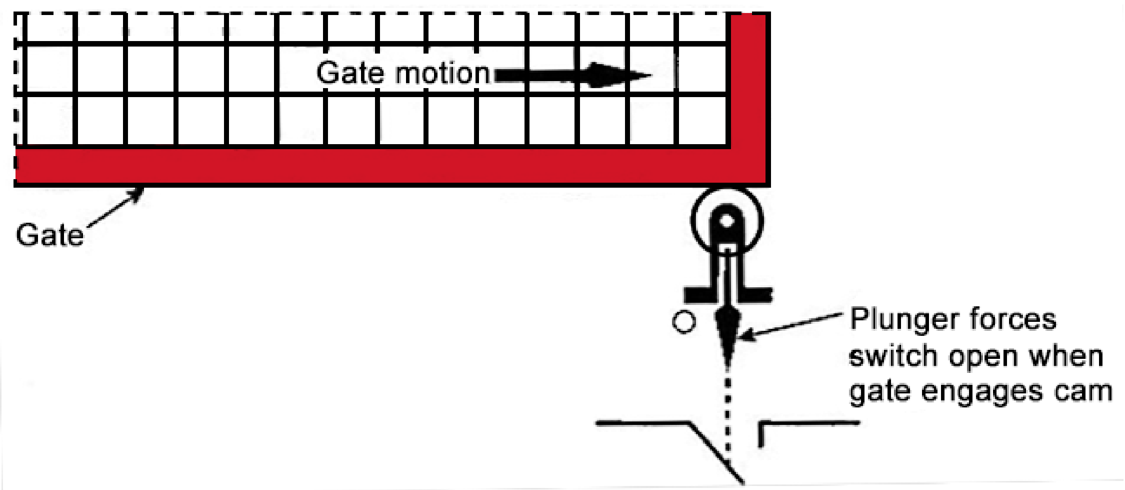
Wide guard doors have too great an opening with the 3 degree door rotation.

Heavy doors can put too great a strain on the switch actuator shaft.

Interlocking Devices cont.

- The cam operated actuation in Figure below is a positive mode, acting limit switch with a linear or rotary cam. As illustrated, the cam operator is most often used on sliding guards where the cam forces the plunger down to open the control circuit contacts when the guard is opened. Characteristics of this switch include the following:

- Small but reliable system.
- Not suitable for hinged or lift type guards.
- Design must ensure that cam and guard always remain in contact.
- Wear on the cam can cause failure or improper operation.



Human–Robot Cooperation for Handling Tasks

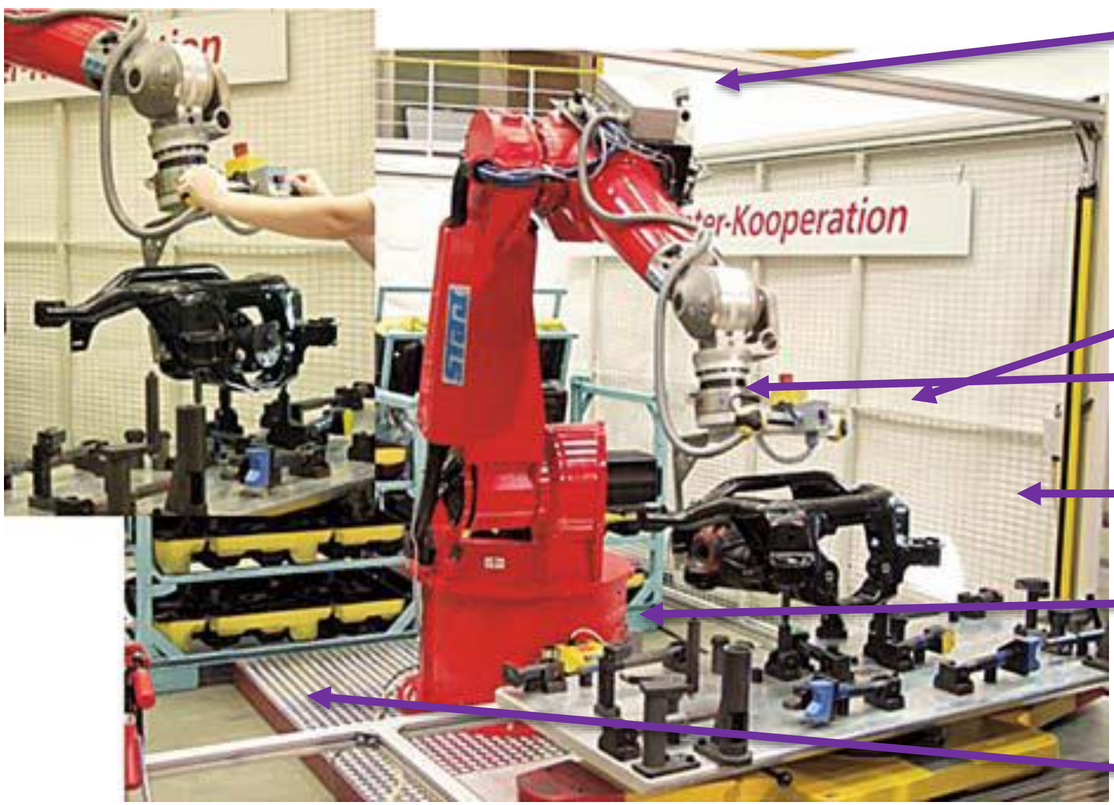
Robots for human augmentation (force or precision augmentation) stretch from fully automated operation to acting as a servo-controlled balancer. As an example: in a car drive train assembly the heavy gear box is grasped by the robot which balances it softly so the worker can insert it precisely into the housing (see Fig. on next slide).

Preprogrammed virtual walls give the worker a realistic feeling of constraints. The central interface for the worker's tactile commands is a handle equipped with safety switches. These switches trigger the force-torque sensor that is attached to the robot's flange. Upon touching both safety switches (two-handed operation) the force-torque sensor is activated and the robot control is set to a safe reduced end-effector speed (of some 50mm/*s)*.

Thus, the sensor scales the applied force/torque information into a compliant robot motion. Obviously the physical human–robot cooperation has to obey safety precautions as the robot's and worker's workspaces overlap.

Human–Robot Cooperation for Handling Tasks

Fig. Human-robot-cooperation for handling tasks. Inside a regular workcell which is secured by light curtains, the robot handles gear boxes at regular speed in fully automated mode. Upon approaching the light curtain at reduced speed, the worker grasps the safety switch which activates both the reduced-speed mode and the force-torque sensor. The worker guides the robot almost effortlessly by its handle so that the gear-box is balanced with precision into the rear axle frame for final assembly (Fraunhofer IPA, Stuttgart)



Human–Robot Cooperation for Handling Tasks (cont. 1)

The ISO standard specifies requirements and guidelines for the inherent safe design, protective measures, and information for use of industrial robots. It describes basic hazards associated with robots, and provides requirements to eliminate or adequately reduce the risks associated with these hazards. A novel element of this revised standard is the regulation of so-called collaborative operation, where the robot works in direct cooperation with a human within a defined workspace.

Basically the collaborative operation depends on several criteria, which have to be met by the robot work cell:

1. The hand-guiding equipment shall be located in the area of the end-effector.
2. The robot moves with safe reduced speed (less than 250mm/s) *and safe monitored position. This* position monitoring shall be according to at least category 3 of ISO 13849, unless a risk assessment is performed and determines that a higher category is required.
3. The robot must sense and keep a safe distance from the human. The distance relates to the attended speed. The distance and speed monitoring shall be according to at least category 3 of ISO 13849, unless a risk assessment is performed and determines that another category is required.

Human–Robot Cooperation for Handling Tasks (cont.2)

If a robot's total power consumption can safely be limited to 80W as well as its static impact forces to 150N no additional sensor-based safety precautions are needed. Again, these conditions have to be secured by a risk assessment or security systems which comply with at least category 3 of ISO 13849. Currently, novel control algorithms, kinematic and actuator designs are being investigated to realize so-called intrinsically safe robots.

The described workcell complies with the ISO standard in such a way that the presence of the human is detected by activating both safety switches of the handle (first condition). The robot's built-in safe controller safely measures the end-effector's position and limits its velocity(second condition). Meanwhile most of the robot manufactures provide safe category 3 controllers. If the worker's presence in the workspace is not known (third condition, not applicable here) a safe sensor system has to detect safely the workers location according to category 3. Three-dimensional sensors meeting category 3 first appeared on the market in 2006, thus opening up a wide field of potential collaborative operations.

Safeguarding the Operator

- The standards state that the operator safeguards should:

1. Prevent the operator from being in the work envelop when the robot is executing a program, or
2. Prevent robot motion when an operator is present in the work space.

- In addition, the operator training should prepare the operators for thee hazards associated with the programmed robot tasks, so they can recognize them and respond appropriately.

Safeguarding the Programmer

- The standards state that a person programming robot operations or teaching location points should have the necessary training for the programming application, check that hazards do not exist, verify that all safeguards are in place and working, and leave thee work envelop before initiating the run mode.
- When the teach mode is used:

1. The robot system and other equipment in the work envelop must be under the control of the programmer
2. The robot system can operate at high speed under only special operational conditions, and
3. No robot motion can be initiated by remote interlocks or external signals.

- Finally, only the programmer is allowed in the robot work space when the robot is in the teach mode.

Safe Guarding Maintenance and Repair Personnel

- The standards address the maintenance of the robot in both the power-up and power-down modes. Rules are provided for the training of maintenance personnel, in addition, rules to cover entry of the work envelop and maintenance of o robot under power are listed.
- Since safety consciousness begins with the individual worker, the following guidelines should be emphasized to each worker:
- Rule 1: Respect the robot. Do not take the robot for granted or make an assumption about the next movement the arm will make.
- Rule 2: Know where the closest emergency stop button is at all times.
- Rule 3: Avoid locations in the robot work cell between the robot arm and fixed objects like metal posts or production machines (These types of locations are called pinch points).
- Rule 4: Know the robot. Pay attention to unusual noises and vibrations from the machinery.

TEXT AND REFERENCE BOOKS

- **Textbook:**

1. James A. Rehg: Introduction to Robotics in CIM Systems. Fifth Edition, Prentice-Hall. 2003.

- **Reference book:**

1. Mikell P. Groover: Automation, Production Systems, and Computer Integrated Manufacturing, Second Edition. 2004.
2. Mikell P. Groover, Mitchell Weiss, Roger N. Nagel, Nicholas G. Odrey: Industrial Robotics: Technology, Programming, and Applications, McGraw-Hill. 1986.
3. Farid M. L. Amirouche: Computer-Aided Design and Manufacturing. Prentice-Hall.
4. Richard K. Miller, Industrial Robot Handbook. Van Nostrand Reinhold, N.Y. (1987).