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DESIGN FOR ROBOTIC CELL SAFETY

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ABSTRACT

A robot usually works with other machines in a manufacturing cell. When considering safety, attention should be given not only to the individual machines and robots, but also to their interactions due to processing needs. This paper presents the six severity level design (SSLD) concept for safely designing a manufacturing cell. This design philosophy integrates guarding techniques with control actions, considers both production needs and safety concerns, and interfaces machine functions with process requirements. This philosophy has been implemented in an unmanned manufacturing cell that makes a family of parts. The designed system has the advantage of providing maximum protection to the operators while causing minimum interruption in production. Future research needs in the areas of sensor reliability, system integration, and training are also discussed.

Keywords: Robotic Safety, Manufacturing Cell, Safety Design

INTRODUCTION

A manufacturing cell is a collection of machines and robots that, performs a specific function, such as manufacturing a family of parts, and is the basic structure for a cellular manufacturing system[1-3]. Recently, there has been a great emphasis on how to design and control a manufacturing cell, but safety considerations have often been overlooked. The safety guarding in such a system can be classified into two levels--the individual machine level and the system level. At the individual machine level, safeguarding devices are used to prevent contact with dangerously moving part[4], to prevent human errors, and to protect humans from ejected objects. At the system level, consideration is given to the interactions between the machines in the cell and the manufacturing process performed in the cell. The safeguarding techniques for individual machines have been well defined. The robot is a relatively new machine designed for automating a manufacturing process, serving as a material-handling device or as a process-assisted (e.g., painting, welding, and drilling) device. It may be questioned if a robot can be treated as traditional machinery, but a review shows that most of the guarding principles for traditional machines are still applicable to industrial robots[5]. For robot guarding, there are many guidelines and standards available in literature[6-12]. Table 1 shows the definitions, descriptions, and application examples of various guarding techniques[4,13-16].

Although a robot usually has to work with other machines, there has been less attention paid to system level safety. Collins[17] mentioned the importance of space requirements for designing a robotic workstation to avoid pinch points. Linger[18] proposed the concept of the "production adapted" safety system, i.e., a "safety system based on high knowledge about the

process." He also presented a safety system that interfaces sensors, a control system, and a power/brake system to provide maximum protection to human operators. A safety system for automated production to maintain the highest level of safety with lowest loss of production has also been proposed[19]. Kilmer[20] proposed a safety sensor system to detect three levels of safety by region: perimeter penetration detection, intruder detection within the workstation, and intruder detection very near the robot. None of the mentioned literature has considered the interactions between a robot and the machines during the manufacturing process, however.

This paper presents the six severity level design (SSLD) for manufacturing cell safety. This design philosophy integrates guarding techniques with control actions, considers both production needs and safety concerns, and interfaces machine functions with process requirements.

SIX SEVERITY LEVELS DESIGN (SSLD)

The following principles were used when this design philosophy was formed:

- The design should be based on the knowledge of the manufacturing process[18].
- Safety measures should be provided for system failure, human mistake, and misuse of the safety devices[18,21].
- The control action should depend on the severity of the risk.
- The guarding technique should consider both individual machines and the interactions among the machines.
- Warning/alarming devices should be used first for personnel awareness.
- Guarding devices should be provided to isolate the hazard sources from the personnel. Control actions should be taken according to the level of severity of the danger.

Table 2 shows the six severity level design.. The column of warning signs/signals shows what type of warning devices can be used to call appropriate attention to intruding personnel and surrounding personnel. Warning signs and signals (both auditory and visual) are often used in a workplace as safety measures. The signs and signals must be simple and effective. Size, color, and location are the major considerations in placing them. Table 3 summarizes the principles for appropriately selecting a warning sign or signal[22-24].

The column of safeguarding devices in Table 2 shows the type of devices that can be used to isolate personnel from hazardous sources and to communicate with the system control device as necessary. The purpose of such a safeguarding device is to prevent contact between the source of the hazard and other objects. Safeguarding devices can be divided into three general categories with 12 individual guard types[25], as descrobed in Table 1.

The robot control action column in Table 2 shows the type of control action that can be taken to respond to different levels of severity. Robot control actions should be taken if there is a potential hazard to operators, to reduce the robot speed or to stop the robot. These actions should be activated only if the guarding devices and the warning signs and signals can not prevent the hazard source and the personnel form coming dangerouly close. To consider both safety and production, an appropriate robot control action should be taken according to the severity of the danger.

Severity Level 1 - Staying within the Perimeter of a General Work Area

In a manufacturing cell situation, the personnel is on the factory floor but still outside the cell. He or she should be aware of the cell operation. The major safety concern is to attract the person's attention and to prevent him or her from approaching the cell area. At this level, the use of warning signs are sufficient and no robot control action must be taken. The size of sign must be large enough, its color must be bright and different from the machine (or background) colors, and its location must be where people will see it when they pass.

Severity Level 2 - Approaching the Cell Area

As a person approaches the manufacturing cell area, although direct contact between the hazard source and the person is unlikely, a perimeter identification device (e.g., fencing with interlocks) should be installed to minimize unauthorized entry. A yellow warning light can also be installed to indicate that there are machines running nearby. No robot control action need be taken because the person is still at a distance from the robot working area.

Severity Level 3 - Entering the Cell Area

This is the level where the interaction between personnel and robot begins to occur. The personnel should be brought to maximum alertness, and the robot should take steps to reduce the risk level. As a person advances into the cell area, pressure mats can serve as a buffer between the person and the machines. The activated pressure mats can trigger a flashing yellow warning signal to attract the attention of personnel. Robot speed can also be reduced to reduce the energy released.

Severity Level 4 - Approaching the Working Area

The working area is defined as the robot working envelope plus the hazardous area for each machine. Photoelectric sensors (either a single sensor or a light curtain) can be used as the guarding devices. The warning light should become red to indicate the severity of the dangerous situation. A repetitive buzzer can be used not only as an additional warning to the personnel involved, but also to attract attention from other personnel in the same general area. The measures used at this level are to ensure that maximum attention has been drawn from the involved personnel, and to stop the intrusion with help from others if necessary. The robot's speed should be reduced to a minimum. The control actions do not completely stop production but minimize the energy released from the robot.

Severity Level 5 - Entering the Potential Danger Zone

This zone is defined as the area that the robot will be moving into and the area for the machine it will be working with for its next step. Both pressure mats and light curtain are activated at this level. Figure 1 shows the four zones under control. The system software keeps checking which zone the robot is working in (called immediate danger zone) and which zone the robot will move to (called potential danger zone). A red flashing light and a continuous buzzer can be used as the warning devices to indicate that the personnel must leave the potential danger zone before the manufacturing process can continue. The robot should freeze its motion if there is an intrusion in the Level 5 area; however, the control should be such that the process can continue at any time once the personnel leaves that area. At this level, all the power is still on, and the software is still in control.

Severity Level 6 - Entering Immediate Danger Zone

When a person is in the immediate danger zone, all possible actions should be taken to prevent contact between robot and personnel. In addition to the zone detection as described for Level 5, proximity sensors can be affixed to the robot arm as redundant sensoring devices to check if there is an object near the arm. Warning signs and signals should operate at maximum capacity (e.g., fast red flashes, and continuous buzzing) to indicate the immediate danger. The robot should be stopped immediately as the emergency stop button is activated. All the power is turned off in the system, and the software is no longer operational. A restart procedure must be followed before the system can resume its operation.

The proposed SSLD has been implemented in the unmanned manufacturing cell[26], which includes one robot, one CNC lathe, one CNC mill, three decouplers[27,28]. The safety devices include sensors attached to grippers, a light curtain, pressure mats, warning signals, buzzers, and a barrier with an interlock. A plane view drawing is shown in Figure 2. The whole cell is controlled by a IBM PC-compatible computer through a PCI 2000 input/output (I/O) board, an 8255A PPI, 8250 UART boards, and a designed circuit board (Figure 3).

DISCUSSION

A safe maintenance procedure is important to protect workers. A worker must often enter a robotic cell to perform maintainance, tool changing, and simple repair tasks. Some of the guarding devices and warning signs or signals can be deactivated for these purposes. For example, to change a tool for a machine in the potential danger zone, the buzzer can be turned off temporarily while the robot stops moving until the tool change is completed. It is preferable to turn off all the power before performing a maintenance job. If the robot must be moved, however, it should be controlled by a remote teach pendant at a slow speed. A set of guidelines for robot maintenance has been published by the National Institute for Occupational Safety and Health (NIOSH)[11].

It has been recommended in the available guidelines and standards that emergency stop buttons or deadman switches should be installed at various locations around the robotic workplace where an operator can use them as needed. The use of an emergency device usually causes the system to shut down, thus causing maximum interruption in production, and system operation must be resumed through a careful restart procedure. The implementation of the SSLD will minimize the use of such emergency devices to only when the control system malfunctions. The safety measures have been designed to function primarily in the control system when properly operating.

Sensor technology is a rapidly growing field, and the robot user needs to be aware of the currently available sensors and their characteristics in implementing a robotic safety system. There are still several problems that exist in applying sensors in a robotic cell. Most of the current sensors are still sensitive to both an object (e.g., raw material or machine) and a human. If a new sensor is developed that can detect a person while not detecting other objects, then personnel can be better protected in a robotic cell. Another problem is in the area of sensor reliability, fusion, and coordination. Sensor reliability has been a problem for a long time. Proper functioning of the sensors is critical for monitoring the safety of a robotic cell. When redundant or supplementary sensors are used in the system, however, their information merging (fusion) and coordination become a problem. How this information is used in interfacing with the manufacturing process is another critical issue.

Although they are not direct guarding methods, training and education supplement such methods by making employees more aware of robotic safety problems. For example, a person will not move close to a robot if he or she knows the robot has a dwell time during operation, even if the robot is stopped momentarily. Traditional training on factory safety discipline (e.g., a lockout procedure) is also important for enforcing safety guidelines.

CONCLUSION

Saftey should be the first priority when designing a manufacturing cell. A bandage approach (i.e., fixing the problem after it occurs) may result in tragedy. This paper has presented and demonstrated the SSLD to be used when a manufacturing cell is formed. This design concept not only provides a system with maximum protection for the operators but also provides one that results in minimum interruption of production.

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LIST OF TABLES

Table 1. Summary of Guarding Techniques

METHODS	DESCRIPTION	ADVANTAGES	DISADVANTAGE
1. Enclosures	isolation devices		
a. Fixed Barrier	barrier to enclose the hazardous part in an immovable shield	-simple -provides maximum protection -requires minimum maintenance	-interferes with visibility -requires other means of protection for maintenance personnel
b. Adjustable Barrier	barrier that is adjustable depending on the size of the stock	-flexible; can be adjusted to suit varying sizes of stock	-does not provide maximum protection -interferes with visibility -requires adjustment and frequent maintenance
c. Self-adjusting Barrier	barrier that has an opening that is only large enough for the different sizes of workpieces	-flexible; can be adjusted by machines automatically to suit varying sizes of stock	-does not provide maximum protection -interferes with visibility -requires frequent maintenance and adjustment

Table 1. Summary of Guarding Techniques (cont.)

METHODS	DESCRIPTION	ADVANTAGES	DISADVANTAGE
2. Interlocks	switching devices		
a.Barrier	protection barrier interlocked with machine controller	-removable -removing of the barrier stops the machine operation	-high initial cost -requires careful adjustment maintenance
b.Gates (1)Manual	gate that can be opened manually	-can be opened for maintenance purposes -opening of the gate stops the machine operation	-high initial cost
(2)Automatic	gate opened automatically by the machine cycle	-frees the operator from the need to open and close gate	-high initial cost -may catch operator's hands by automatically closing the gate
c.Sensing Systems (1)Photo-electric	consists of light sources and controls that are interlocked with the machine controller	-high visibility	-high initial cost -does not protect operators against mechanical failure
(2)Radio-frequency(RF) (Capacitance) Sensing	consists of RF source, and antenna to detect the intrusion into the capacitance field	-high visibility	-high initial cost -does not protect operators against mechanical failure -requires regular calibration and maintenance

Table 1. Summary of Guarding Techniques (cont.)

METHODS	DESCRIPTION	ADVANTAGES	DISADVANTAGE
3.Other Type			
a.Stroke Confiner	physical stop to limit the motor of a machine	-low cost -achieves worker protection without the addition of mechanical or electrical guards	-limited stock range
b.Pressure Sensing System	force/torque sensitive device used to prevent the machine from exerting excessive force/ torque	-protects both operator and the machine	-high initial cost -allows accidents to occur even when the machine stops
c.Two-Handed Controls	use two control buttons necessary to activate the machine	-prevents the operator from accidentally activating the machine	-limited to certain type of machines
d.Warning Devices	signs/signals to alert the person of dangerous situation	-easy to install -low cost	-less effective as a single method of safe-guarding

Table 2. Six Severity Level Design (SSLD)

Severity Level	Safe guarding Device	Warning visual	Warning Auditory	Robot Control Action
1. Staying within the perimeter of a general work area	---	Signs	---	None
2. Approaching the cell area	Fencing (rope) with gate	Yellow	---	None
3. Entering the cell area	Pressure mats	Yellow & flashing	---	Reduced speed (5)
4. Approaching the working area	Light curtains	Red	repetitive buzzer	Reduced speed (1)
5. Entering the potential danger zone	Pressure mats and light curtain	Red & flashing	continuous buzzer	Stop (no reset)
6. Entering immediate danger zone	Photo sensors	Red & max. frequency flashing	continuous buzzer	Stop (reset)

Table 3. Principles in Selecting Warning Signs and Signals[21-23]

A. Use visual signs when:

the message is complex, long, or will be referred to later.

the message deals with location in space.

the message does not call for immediate action.

the receiving location is too noisy for auditory signals.

the person receiving can remain in one place.

the person receiving is overburdened by the auditory system.

B. Use auditory signals when:

the message is simple, short, or will not be referred to later.

the message deals with events in time.

the message calls for immediate action.

the person receiving has to move around for the job.

the person receiving is overburdened by the visual system.

the receiving location is too bright or too dark where adaptation integrity is necessary.

the displayed information occurs randomly and must immediately capture the attention of the operator.

C. When using visual signs:

consider printing style, size, and location.

use sterotype or standard symbols.

select appropriate colors --

1. Red is used to alert that the system is inoperative.
2. Flashing red is used to denote an emergency condition that requires immediate action.
3. Yellow is used to indicate a marginal situation in which

caution is necessary or unexpected delay may be encountered.

4. Green is used to indicate all conditions are satisfactory.

5. White is used to indicate transient or alternative conditions.

6. Blue is used to indicate an advisory situation.

ensure luminance and sharp contrast with the background.

ensure that they are shaded or out of direct sunlight.

ensure that they are not subject to color detection confusion.

D. Auditory signals should:

have a signal level 15 db above the masked threshold (defined as the level required for 75% correct detection) for 100% detectability and for a rapid respons.

have a signal level less than 30 db above the masked threshold to minimize generated to the operator.

have a signal pitch between 150 and 1000 Hz.

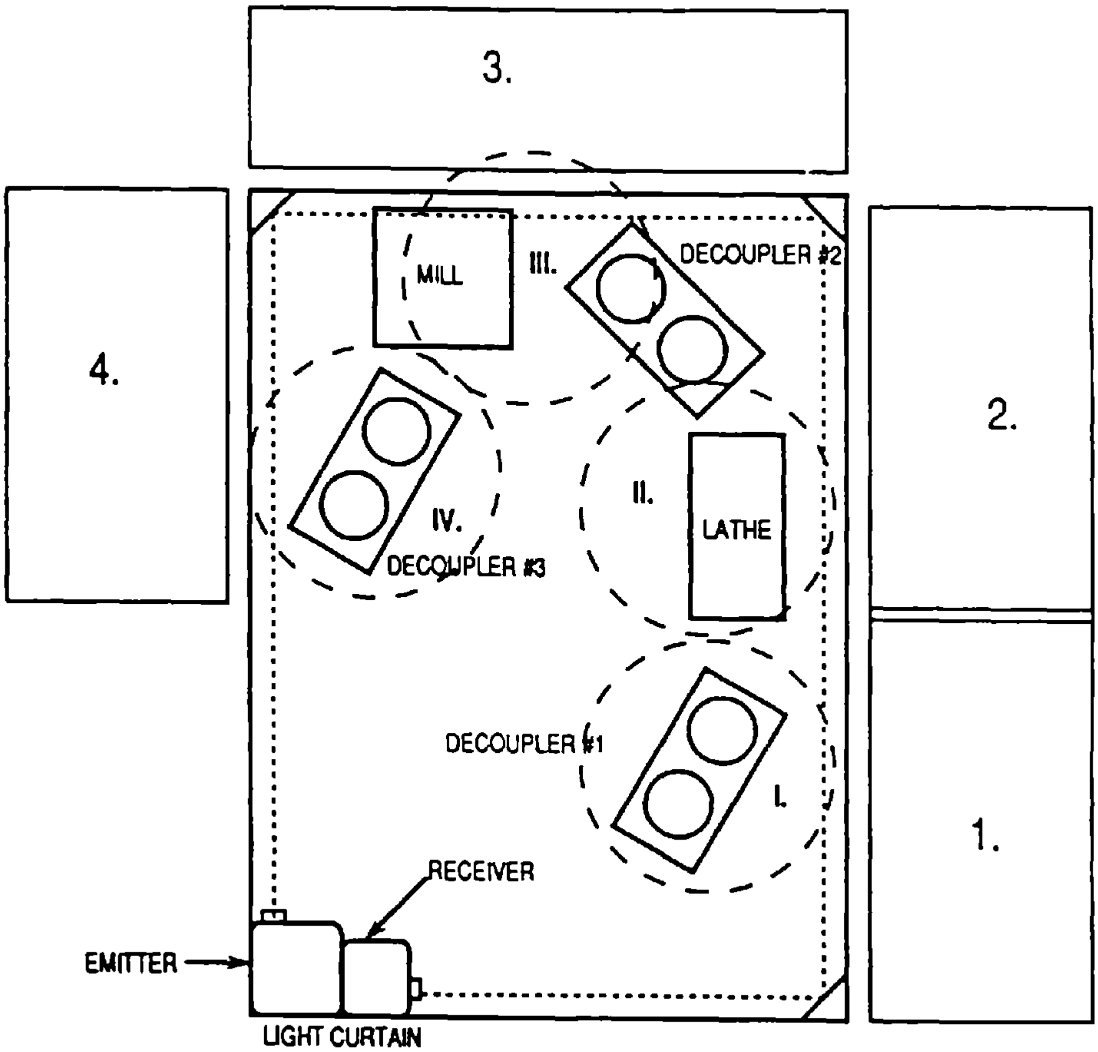
have a pulse spacing compressed to increase urgency.

cease only after the operator responds appropriately.

be consistent with others already in use in the plant.

not be confused with the noise generated from the machining process.

LIST OF FIGURES



1. Pressure mat #1
2. Pressure mat #2
3. Pressure mat #3
4. Pressure mat #4

I. The area surrounding decoupler #1
II. The area surrounding lathe machine
III. The area surrounding decoupler #2 and milling machine
IV. The area surrounding decoupler #3

Figure 1. Four Under-controlled Zones

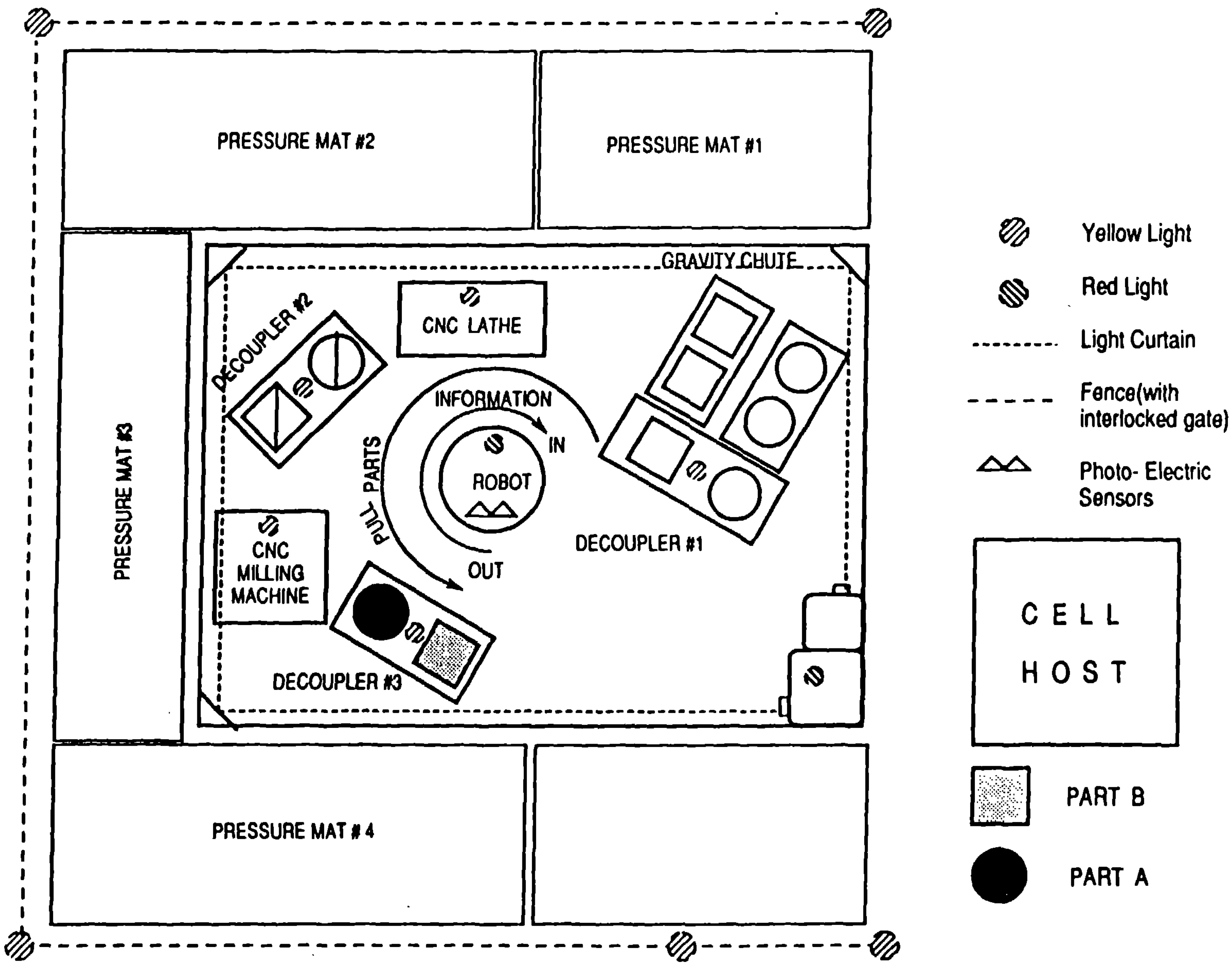


Figure 2. An Unmanned Manufacturing Cell with SSLD

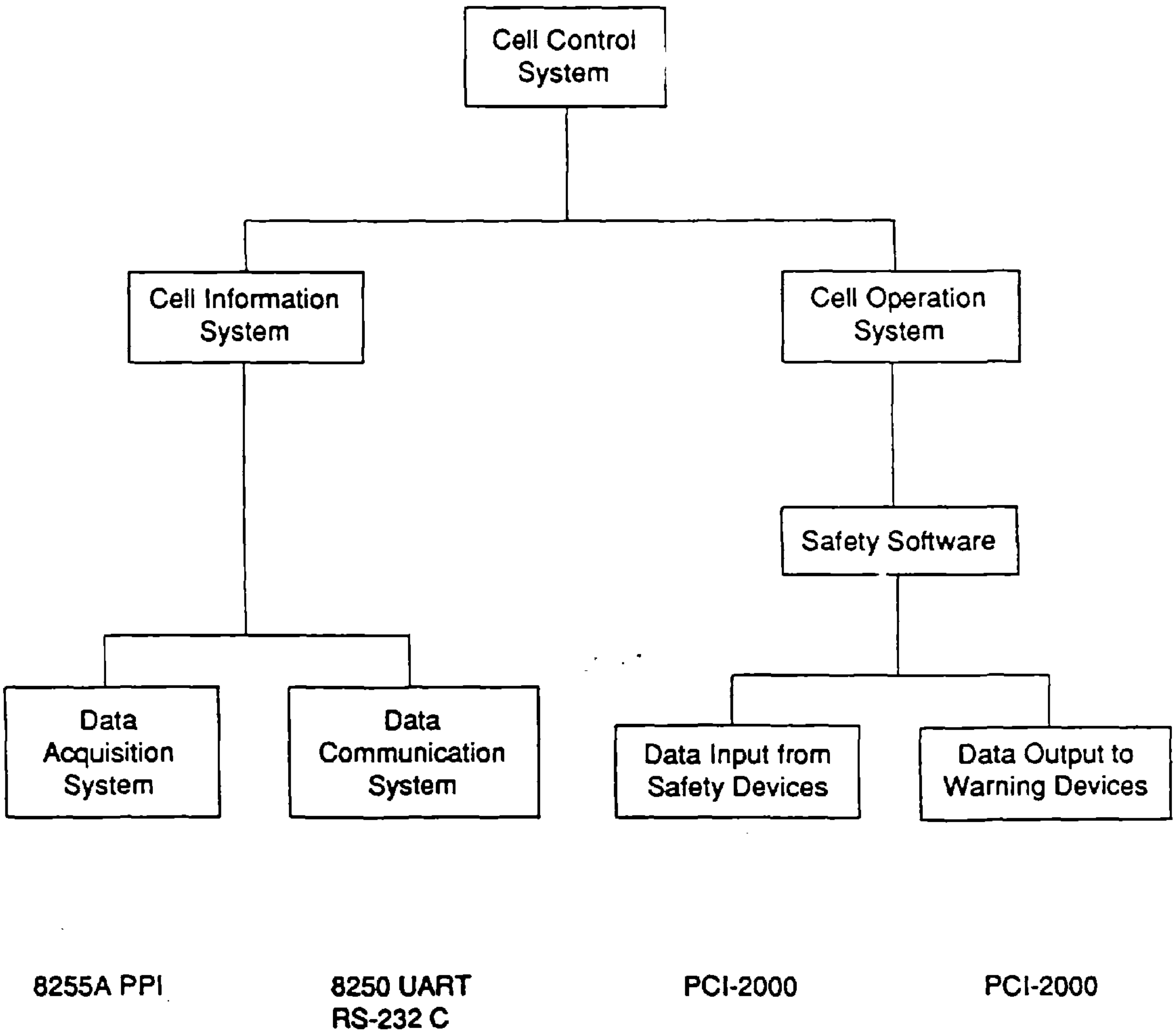


Figure 3. System Communication