*NIOSH Technical Report*

# SAFE MAINTENANCE GUIDELINES
# FOR
# ROBOTIC WORKSTATIONS

John R. Etherton

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
National Institute for Occupational Safety and Health
Division of Safety Research
Morgantown, West Virginia

March 1988

# DISCLAIMER

DHHS (NIOSH) Publication No. 88-108

# PREFACE

The Occupational Safety and Health Act of 1970 (Public Law 91-596) states that the purpose of Congress expressed in the Act is "to assure so far as possible every working man and woman in the Nation safe and healthful working conditions and to preserve our human resources...by," among other things, "providing for research in the field of occupational safety and health...and by developing innovative methods, techniques, and approaches for dealing with occupational safety and health problems." Later in the Act, the National Institute for Occupational Safety and Health (NIOSH) is charged with carrying out this policy and specifically to "conduct special research...relating to occupational safety and health as are necessary to explore new problems, including those created by new technology in occupational safety and health."

This guide is concerned with robotics technology. Its aim is to help someone who has been given a robotic safety responsibility to learn ways to prevent injuries during tasks which call for personnel to intervene in robot work zones. There are many reasons why personnel enter robot work zones (job set up, repair, programming, inspection). The injuries which have occurred happened most frequently when corrective maintenance was being done. This guide describes the hazards which exist when a worker is in a robot's working area and means to minimize or eliminate them. When the safety of a robotic system under development is in question, this guide can be an aid for developing training of personnel, task design, workspace design, simulation, maintenance data collection, equipment specification, and maintenance instructions. Where safety solutions have already been applied to robot work stations, this guide may be used to evaluate their effectiveness.

# ABSTRACT

This report contains guidelines for preventing injury due to unexpected or unintended robot motion to personnel whose job is to correct problems with the normal operation of robotized industrial systems. The tasks which these people do in the course of their workday include: diagnosing and correcting equipment failures, cleaning scrap, clearing jams, repairing broken components, programming, and job set up. Safety devices and procedures for controlling access to areas of robot motion hazard are discussed. By referring to these guidelines, topics for safety meetings with robot maintenance technicians can be developed. They also inform designers of robot systems about means to minimize or eliminate risks in the robot work zone. Developers of the robot safety plan for a workstation are told about how to identify the different tasks their plan will have to cover.

Corrective maintenance during production operations requires repeated human interventions into robot work zones. The factors which make these interventions difficult include the unexpected occurrence of problems and the uncertainties which may exist in diagnosing them. Analysis of robot related injuries demonstrate that these interventions have resulted in serious injuries and sometimes in fatalities. Although automated production, including robotics, can furnish the means for improving working conditions, the risks which exist during necessary intervention tasks warrant consideration.

Systematic approaches to selecting safeguards and setting safety procedures are presented. One of these, the Structured Analysis and Design Technique (SADT) methodology, is discussed as one way in which safety personnel, production personnel, and maintenance personnel can work together to achieve the safe robot maintenance goal. This box-and-arrow diagramming methodology is a tool for organizing an analysis to achieve the goal of maintenance intervention without injury.

Maintenance management topics on availability, maintainability, maintenance policy, and downtime data collection are discussed as they relate to robot safety. Maintainability is a quantitative measure of material performance, differing from maintenance which is a work activity. Examples of corrective maintenance activities for welding robots illustrate one approach to conducting a robot maintenance safety analysis. Examples of maintainability data demonstrate quantitative measurement of potential exposure to robot hazards.

# ACKNOWLEDGEMENTS

The development of this document was one of the objectives of a collaborative project between the National Institute for Occupational Safety and Health (NIOSH) and the Institut National de Recherche et de Sécurité (INRS) in France. The collaboration was in the form of a work/study year spent by the author at the Institut National de Recherche et de Sécurité, Centre de Recherche, Départment "Ergonomie - Sécurité", Service "Electronique - Sécurité des Systèmes", Avenue de Bourgogne, B.P. 27, 54501 Vandoeuvre, Cedex, France.

The author would like to thank J. P. Vautrin and D. Pagliero, the members of the Service Electronique - Sécurité des Systèmes and all those INRS personnel who assisted the author during his year of work/study at the INRS. The author is also grateful to the Conseil D'Administration of the INRS for their interest in this contribution to work injury prevention. My sincere thanks also go to the safety and working conditions personnel, workers, and management from French and U.S. industry who supported the development of examples used here. Finally, the support and comment provided by John Moran, Charles Reese, James McGlothlin and Tim Pizatella in completing the drafts and in maintaining communications from Morgantown, WV during the work/study is recognized by the author as a significant factor in the completion of this guide.

Reviews of this document were provided by Larry Reed, DSR/NIOSH; Austin Henschel, DSDTT/NIOSH; Harvey Meieran, H.B. Meieran Associates; Mansour Rahimi, University of Southern California; and the Motor Vehicle Manufacturers Association of the United States.

## CONTENTS

## CONTENTS *(Continued)*

## TABLES

## FIGURES

# PROTECTING WORKERS INSIDE ROBOT WORK ZONES

## 1.1 Who should read these guidelines?

These guidelines are intended to provide practical assistance to personnel who have responsibility for or participate in designing or ensuring the proper use of safety systems and procedures for a robotized production system. These guidelines are also intended to be instructive to personnel who have primary functions other than the safety of robotized systems. Safety engineers and specialists, maintenance supervisors, production supervisors, and designers of robotized systems are some of the people who can use these guidelines.

Safety conscious robot users recognize that when a technician enters the working area around a robot to correct a problem, he enters a region in which he is at risk of being seriously injured, perhaps fatally. Such injuries have occurred in a variety of unexpected ways: workers have been caught between a robot and a work table or struck during a high-speed movement of a robot. One worker was fatally crushed against a fixed post, while another was killed when a robot pushed him into the tooling of the machine the robot was feeding.

Such examples are not intended to provoke alarm, but they do illustrate the importance of anticipating potential dangers in the design, installation, operation, or maintenance of robotized work systems. And, by taking action to prevent serious injuries, other losses that accompany personnel injury can be avoided. These include lost production time, equipment damage, lower worker confidence in the performance of equipment, and engineering time spent redesigning safety systems.

## 1.2 Programmable motion control

This document offers guidelines for preventing injury due to unexpected or unintended robot motion and related hazards to personnel who work on robotized industrial systems. These personnel may be programmers, maintenance technicians, or robot system operators. The entry of a person into a robot's work zone is dangerous when the computer controlling the robot is still processing a program which contains initiating commands to actuators (motors). Once inside the robot's work zone, the person can simply get in the robot's way and be pushed, struck, or crushed.

Robots are useful in part because they move flexibly and automatically, but therein lies their hazard. They can be taught to move to any location within their limits of travel and to make that move over and over again. These motions can be used to perform a variety of industrial tasks such as moving portable tooling into position, moving workpieces to new locations, and assembling several workpieces.

Two kinds of circuits work together to produce robot motion: the drive circuit which powers (electrically, hydraulically, pneumatically) the mechanical actuators which actually move the robot; and the control circuit that determines the timing, distance, and rate of motion. The drive power circuits for actuators (motors, hydraulic cylinders) are turned on and off and regulated by commands from various parts of the control circuit (computer program, sensors and human actuated switches.)

### 1.3 Tasks inside a robot's workzone

Robot movement is used on many different applications and there are many different ways that people work on these applications. Although it is possible that personnel not normally assigned to a workstation could get dangerously close to a robot out of curiosity or to offer assistance, most injuries at robot workstations occur to personnel who are carrying out an assigned task. These tasks are for the purpose of

- programming the system to begin automatic operation;
- returning the system to automatic operation after a problem has occurred;
- permitting the system to continue operating as designed.

These tasks do not require continual human proximity to the robot. To do them, people temporarily work near the robot. The tasks include testing, fault elimination, diagnosing equipment failures, adjusting robot trajectory, cleaning scrap, clearing jams, repairing broken components, programming and job setup. All of these tasks need human hands and eyes to resolve unstructured problems within the robot workzone.

A recent study of working conditions with robotic automation in the automotive industry concluded that:

> *The automation of dangerous or disagreeable working tasks can contribute to an improvement in conditions at work stations. In order for this to be the case, it is important to take into account the necessity and the specifics of human interventions during the design of equipment, the organization of work, and training. To the contrary, not taking these maintenance operations into account could force the operators concerned to work under precarious safety conditions.[1]*

### 1.4 Injury reports

In the United States, Sweden, and Japan injuries to personnel and near-misses have already been reported. In all three countries, maintenance tasks have comprised a substantial portion of the number of robot-related injuries reported.

In a sample of 20 reports of robot-related injuries or near-misses in the U.S., it was found that 13 of these occurred during corrective maintenance [7]. These reports are the first attempt to systematically collect robot-related injury information in the U.S. and were voluntarily submitted by robot users to the Motor Vehicle Manufacturers Association.

Between 1979 and 1983 there were 36 reports of accidents to Swedish workers at robotic installations. These included 14 accidents during interventions into the work zone of the robot while the robot was performing normal operations, i.e., during automatic operation. During manual operation of the robot, such as repair and programming, 13 accidents occurred [8]. In these reported cases, 16 percent were head injuries. Gantry-type robots would be expected to have greater head injury risk because of the overhead location of most robot parts.

Fatalities also have occurred, although not frequently. Unpublished Japanese reports indicate five fatalities in that country. In 1984, a fatality involving an industrial robot was investigated by the National Institute for Occupational Safety and Health [9]. This fatality involved a worker doing corrective maintenance who was trapped between the back of a robot and a fixed post. So, it has unfortunately been shown that death can be a result of insufficient safety measures, either on the part of workstation equipment or on the part of the worker.

### 1.5 Future safety concerns

On first reading, the injury numbers may not seem large. But remember that the data have been collected voluntarily over a rather short period of time and also that widespread use of robots has not been the case until relatively recently. When we realize that more and more robots will be installed, three factors emerge to motivate safety planning:

*1. The population of personnel at risk is growing.* There has been a 25 to 35 percent growth per year in the number of robots which must be maintained. A decline in this rate of growth has occured, but the robot population continues to grow. At a 20 percent annual growth rate the 1985 population of 20,000 robots will become about 50,000 by 1990. In a study of occupations which will be affected by robotics in 1990, the U. S. Bureau of Labor Statistics foresees a growth of 2.8 percent among engineers and 1.9 percent growth among maintenance personnel.

*2. The potential hazards in tasks which people do at robotized systems evolve as the technology evolves.* First-generation robots are now beginning to be used in smaller companies, while robotic equipment being constructed and installed today reflects progress toward computer-integrated manufacturing (CIM). This represents workstations and tasks for personnel on two levels: individual robots and robotized systems. The consensus safety standards in the area of programmable automation, which have only very recently appeared (1986), do not provide sufficient guidance on robotized systems.

*3. Older robots with fewer safety features will continue to be used.* Smaller companies, less able to afford state-of-the-art technology, will seek to enhance their production with the installation of "discarded" robots. The reliability of these older robots may not be as great as with the newer ones and this may adversely affect safety.

# HAZARDS AND HAZARDOUS LOCATIONS

## 2.1 The robotized workstation

For the purpose of identifying where injuries can occur, the robotized workstation can be divided into two zones or volumes: the robot movement zone and the approach zone. These zones are illustrated in Figure 2-1.

The robot movement zone is defined by the points in space indicated in Figure 2-2. If technicians stand in this zone to do a task when power is available to the robot, they are exposed to crushing, shearing, and impact injury risks. Certain portions of this zone, such as the region around the end effector, are zones of increased risk.

Just outside the robot movement zone is the approach zone. The boundaries of this zone can be defined so that the limits within which protection is provided are known. In this zone personnel may be exposed to thrown objects, radiation, flash, electrical hazards, or mechanical hazards of associated equipment. Furthermore, personnel in the approach zone can potentially move into the work zone. Passage from the approach zone to the movement zone can be limited by the size of access openings through which personnel or working materials pass to reach the work envelope of the robot.

## 2.2 Causes of unexpected or unintended robot movement

Effective design of the workstation control system will minimize the chance that the robot and associated machines could move in a manner harmful to an operator who is inside the work envelope, and therefore satisfy the highest priority within the control logic. A powered robot motion is initiated by the closure of a power supply switch to an actuator (electric motor, hydraulic cylinder). This could be accomplished by any of the following:

- a planned step forward to an output condition in the control program
- a person switching the robot to automatic operation
- electromagnetic interference generating the voltage necessary for a logic switch at a microelectronic gate
- another control circuit inputting a switching signal
- a bug or error in the control software
- a hardware failure in the switching device
- automatic restart after a power interruption

Failure to stop when commanded is also a condition which may be evaluated as a potential hazard.

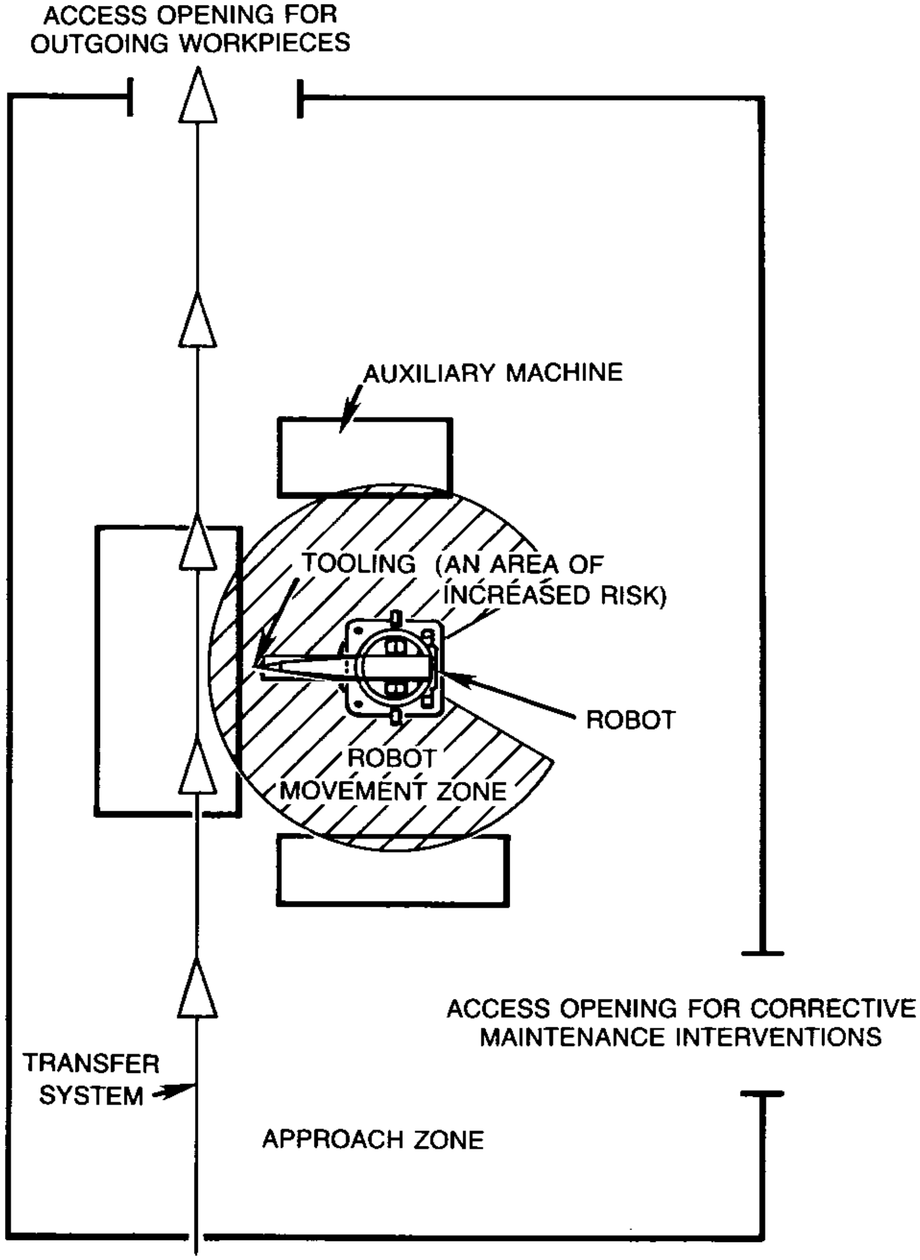


*Figure 2-1.* **The robot movement zone and the approach zone make up the danger zone of industrial robots.**

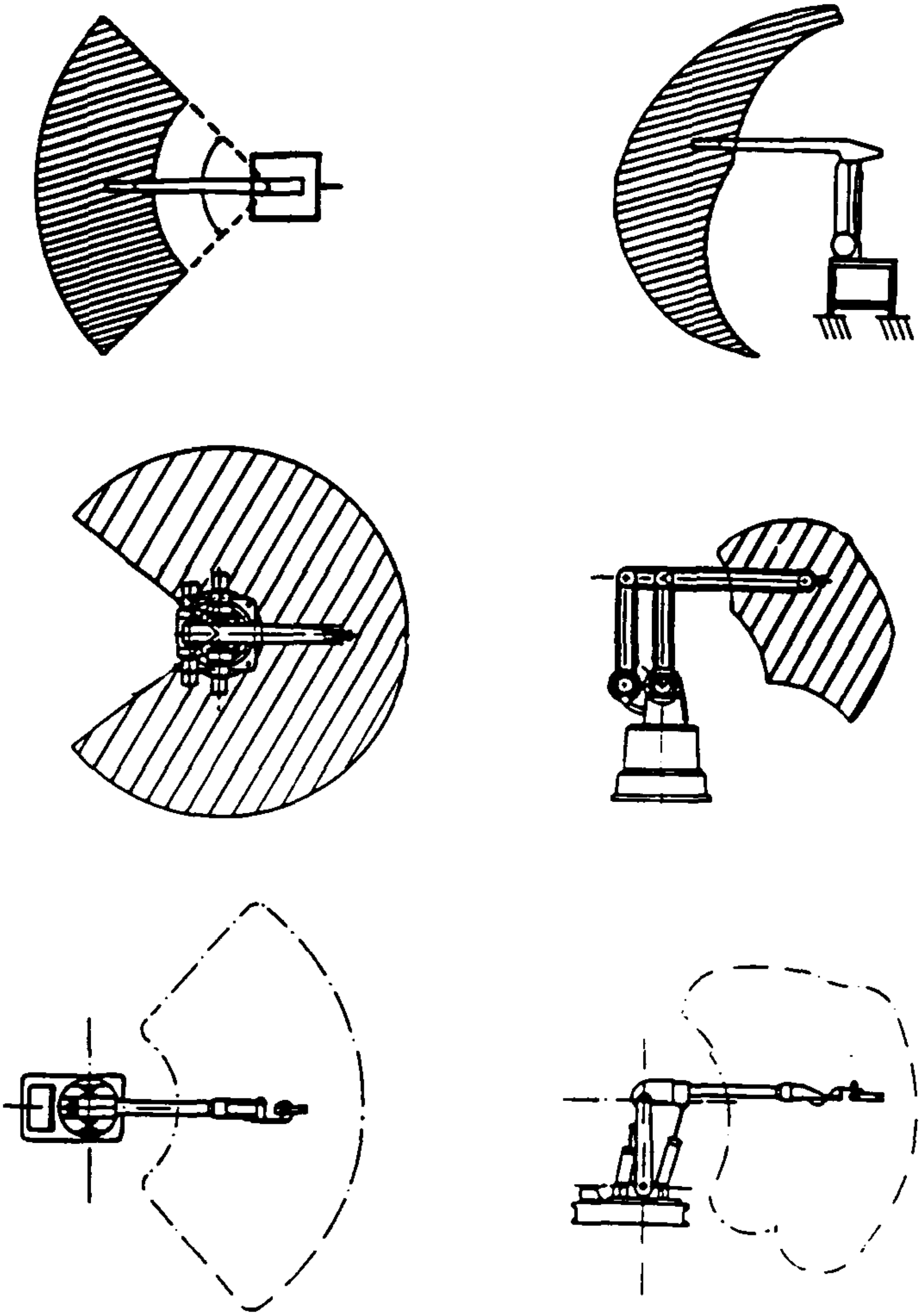


*Figure 2-2.* Robot work zones: the end effector indicates the extreme limits of the zone. [4]

Performance considerations for motion controls include:

- the failure of single elements of the start/stop control ought not lead to dangerous operation
- the effects of the environment ought not lead to dangerous start/stop action; this includes erroneous information coming from a sensor due to environmental interference, software logic changes induced by electrical interference, and switching signals induced by electrical interference
- measures taken to avoid errors of inadvertent use of start/stop controls; deadman switches could be helpful in this regard
- software testing to eliminate dangerous bugs in the program

Jones and Dawson report that from 1 to 5 percent of the downtime on the robotic systems they surveyed was due to erratic functioning of the robot [5]. Vautrin reports a survey in which 13 of 102 French robot users indicated experiences in which erratic robot movement could have caused injury [6]. In reports to the Motor Vehicle Manufacturing Association, 7 of 20 accident/near-miss incidents involved loss of robot motion control.

### 2.3 Results of unintended or unexpected motion

If a person is present when a motion initiating event occurs, the ensuing robot motion can lead to injury by

- impact
- puncture
- pinch point closure
- dragging a person over a sharp object
- pushing a person into another machine's point of operation

Personnel can be struck by

- any part of the robot itself
- a workpiece being handled by the robot
- robot tooling.

### 2.4 The hazards of tooling manipulated by the robot

Robots manipulate many kinds of end effectors (e.g., grippers, welding electrodes, grinding wheels, lasers, high pressure water jets). Problems with these end effectors are the cause of many maintenance interventions. End effectors can inflict dangerous cuts or burns or they may become dangerous due to robot movement which can cause puncture wounds. A workpiece which is being handled can become a source of danger should a gripper lose its hold and allow the workpiece to fall or become a projectile.

### 2.5 The hazards of other machines

A transfer system or a machine tool in the workstation can fail and become the reason for a maintenance intervention. While working to repair a problem on these systems personnel may be within the robot's reach.

### 2.6 Other hazards

Equipment which 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. A pinch point could be created if control cabinets are located too close to the robot. Also, cables on the floor present tripping hazards.

## PROTECTIVE DEVICES AND PROCEDURES

### 3.1 Protective devices

This section discusses the performance and use of some devices and guards which could be installed on robotized systems to provide protection during workzone interventions. Here, we describe what these devices ought to do, but not how they ought to do it. A general performance requirement of these devices is that they be capable of protecting the worker during temporary interventions at random times. In high-risk situations, effectiveness of safety devices can be assured by monitoring circuitry to detect and react to failure of the safety function. Protection can be provided directly by devices which function exclusively for safety or indirectly by elements in the control system which are switched to a safe condition during an entry into the work zone.

### 3.2 Presence sensing devices

Presence sensing devices use a sensing field or area to detect if someone is approaching the hazardous motion zone or if the robot is moving hazardously toward a person who is in the work envelope. Presence sensing examples are given in Table 3-1. These devices are effective only on systems which can be stopped quickly. All sources of danger are shut down when the device is activated. In case a person is approaching the hazard zone, the protective condition (stopped robot motion) will be effective only if it occurs prior to the moment that the person gets within the robot's reach. This means that effective detection will occur at a distance from the work zone perimeter such that continuing human motion will only encounter a stopped robot.

When these devices are being considered for use, it is a good idea to discuss their general principles of operation with qualified technical personnel. To be effective, the device will initiate a safety command (i.e., bring the robotic system to a safe energy state before a person reaches it) under variations in environmental conditions and direction of human approach to the danger zone. Safe control will be maintained as long as personnel are in the hazardous location. Advantages of effective presence sensing devices are that they permit quick access to the robot's workzone and they operate without depending on a human reaction. Combining several of the same sensor or sensors of different types could provide full coverage of monitored zones if a single sensor is subject to inaccurate detection.

Table 3-1 (a). Characteristics of safety sensors for robots

| Sensor type | Sensitivity to characteristics of personnel | Typical robot zone protected | Limitation of detection | Sensing mode | Region of measurement | Detection elements |
|---|---|---|---|---|---|---|
| Optical beam | The human body or part of the body interupts an optical plane. | Approach Zone | Not detected if not in the optical plane. | Active | Directed light beam (stationary or mobile). Wavelength: $10^{-2}$ cm to $10^{-6}$ cm | Photoelectric cells and reflectors or receivers mounted on fixed supports. |
| Ultrasonic | The human body reflects an ultrasonic impulse. | Movement Zone (partial) | The body has a variety of reflecting surfaces. | Active | Directed ultrasonic impulses. Frequency: 50 KHz to 60 KHz | Ultrasonic emitter and receiver mounted on the robot or near to it. |
| Capacitive | The human body alters the state of an oscillating electromagnetic field. | Movement Zone | The grounded condition of the body is one of the factors which can also alter the field. | Active | Partially directed three dimensional field in the radio spectrum. Frequency: $10^3$ to $2x10^5$ Hz | A conductor for generating the field (metal tubing or structure). |
| Infrared | The human body is a source of radiated heat | Movement Zone | Other sources of heat may be present. | Passive | Frequency: $3x10^{11}$ to $4x10^{14}$ Hz. Power: 0.1 W/cm$^2$ at 25°C | Sensing cells mounted overhead or in positions nearby. |
| Tactile | Contact with the human body or with a body part induces a force. | Movement Zone | Reaction occurs only after contact. | Passive | Static threshold: 2 - 10 mbar | A surface covering material containing force transducers. |

Table 3-1 (b). Characteristics of safety sensors for robots

| Sensor type | Sensitivity to characteristics of personnel | Typical robot zone protected | Limitation of detection | Sensing mode | Region of measurement | Detection elements |
|---|---|---|---|---|---|---|
| Pressure sensitive mats | Detection of the human body by its weight. | Movement Zone | May be stepped over. | Passive | 40 Kg / 200 cm$^2$ (Static threshold recommended by the INRS) | The sensing mats which contain the force transducer. |
| Vision | The human body reflects light. | Approach Zone | Recognition of the body pattern. | Passive | An array of pixels which respond to variations in the luminance in the visual spectrum: $3.95 \times 10^{14}$ to $7.9 \times 10^{14}$ Hz | Camera connected to a pattern recognition processor. |

For these methods of detection, the response time for safety is composed of:

- rate of sampling of the danger zone,
- verification time for the object detected,
- stop time of the robot after issuing the stop command.

### 3.3 Fixed barriers with interlocked gates

Fixed barriers with interlocked gates permit workzone entry only along paths which are monitored by the interlock. Machine structures and transfer line structures can be used as part of a barrier. To date there has not been an industrywide quantitative analysis of the relative effectiveness of the various kinds of safeguards. The data from plant records needed to carry out such an analysis could be difficult to obtain. Therefore, for psychological reasons, barriers are preferred. When the gate in a protective barrier is opened, an interlock will either (1) cut off the supply of hazardous energy into the work zone or (2) prevent automatic operation while allowing for manual operation to do troubleshooting or programming. This condition will be maintained as long as the open gate permits access to the work zone.

An effective barrier will

- prohibit access to hazardous areas,
- not be rigid if it is situated in proximity to the robot and if trapping points exist,
- protect against thrown workpieces or against the projection of materials being used (paint, glue, water jet...),
- not be easily bypassed by climbing over or crossing through,
- be fixed far enough from the robot so as to avoid unnecessary trapping points, and
- have inspection windows adequate for seeing critical areas.

An effective interlock will

- permit automatic operation only under the condition that the gate is closed,
- incorporate a blocking device to prevent opening until shutdown is achieved (if the process cannot be interrupted at random times), and
- require deliberate manual action to restart automatic operation after a gate has been closed.

Guardrails, chains, and similar awareness or warning devices provide protection only when the limit they imply is respected.

### 3.4 Visual indicators of energy level in the workstation

Safety can be enhanced if different colored warning lights are used to indicate when the system is in

- a full shutdown
- automatic control
- a partial shutdown

### 3.5 Emergency stops

An emergency stop is manually operated hardware (e.g., palm buttons, trip wires) which can be easily used when needed to quickly put the system into a safe state and maintain this state until a safe, intentional restart is accomplished.

Optimally, emergency stop devices are located where most likely needed. An emergency stop on the teach pendant accomplishes this for personnel using the teach pendant. Pressure-actuated pads mounted on surfaces in the work envelope are another alternative. A cable attached to a circuit-breaking switch provides many points along its length at which an emergency stop can be initiated. Convenience and ease of reach are important considerations in locating the emergency stop devices.

A periodic verification will ensure that the emergency stop works as intended. An effective emergency stop will be capable of interrupting the drive circuit even when energy to robot control circuits needs to be maintained.

In some factories it has been suggested that hitting an emergency stop leads to an extended period of time for restart due to the need to move the robot and other equipment to a home position. In other cases, this stop is used as a normal maintenance stop. Training which emphasizes immediate use of the emergency stop when needed will diminish workers' natural reluctance to use it due to time lost in restarting the system.

As a matter of practice, emergency stops are used infrequently. Jones and Dawson [5] report that of 2170 stops recorded at robotized workstations, there were only 11 cases in which the emergency stop was used while performing corrective maintenance.

### 3.6 Full system shutdown switch

This is a switch (or switches) intended as the normal way to remove power from the system. Verification that equipment does not remain energized through other circuits not controlled by this switch (or switches) is critically important. A lockout capability (key locked switch, padlock, or similar device) can prevent inadvertent switching by other persons while someone is in the work zone. Full system shutdown devices include valves for isolating hydraulic and air pressure sources. Readily available means for relieving or controlling stored energy can provide additional protection.

### 3.7 Safe intervention partial shutdown devices

A partial shutdown device limits energy to the robot, tooling, fixtures, and associated machines so that a low energy level sufficient to make a correction is available. When switched to this condition, automatic initiation of motion cannot occur. Manual initiation of motion from inside the workzone using a teach pendant is permitted.

A slow speed capability satisfies the need to move the robot for cleaning, clearing jams, and reprogramming. It reduces the energy in impacts and allows time to move out of trapping points. Training can emphasize, however, that trapping zones can injure whether they close slowly or quickly. A speed of 25 cm/sec has been recommended in the R15.06 safety standard for robots as a slow speed to use during interventions. However, this value is an estimate not based on any systematic research. Other slow speeds which have been suggested are 15 cm/s [30] and 30 cm/s [31].

### 3.8 Single function controls

The need will exist to operate single pieces of equipment in the workstation safely, such as transfer lines and machine tools, if this operation is to occur while someone is in the robot's work zone.

### 3.9 Key lock switches

Key locks on the switches which energize equipment can help to avoid one person inadvertently restarting a system while a second person is still in the workzone. This has proven fatal on computer controlled machinery.

### 3.10 Moveable interlocked barriers

These temporary devices consist of a removable barrier with an integral switch capable of deenergizing the electric, pneumatic, or hydraulic robot drive power sources. These are used where a robot is isolated and deenergized for maintenance while other equipment in the same system is run in automatic mode.

### 3.11 Devices for limiting the robot movement zone

Devices for defining and for changing the size of the robot movement zone include limit switches and fixed stops located near an axis of rotation or translation. Fixed posts intended to stop robot motion may create man-sized trapping areas, however. Guards can provide protection against pinch points at fixed stops.

### 3.12 Training and human factors

A human factors analysis will include consideration of safety supervision, working conditions, and training. Factors in such an analysis are illustrated in Table 3-2. In regard to working conditions, Damon and Decoster state:

> *It is probable that taking into account the necessity for easily making human interventions will allow an improvement in reliability and working conditions. The problem of work load for operators during breakdowns exists because workers must carry out a large number of interventions and handle large amounts of information under time constraints [16].*

|  |  |
|---|---|
| *Supervision* | If the personnel who supervise for safety are different from the personnel who supervise for production, conflicts of interest may be avoided. This is not to say, however, that production supervisors ought to be excluded from the safety program. It generally enhances a safety program to have production supervisors well trained in safety policies and enforcement. |
| *Training* | Identify unrecognized risks.<br>Make personnel aware of the various energy sources for the end effector, for the robot, for auxiliary machines, and for the transfer system. |
| *Controls* | Prevent the inadvertent use of automatic start switches.<br>Select a slow speed for programming. Conveniently locate emergency stops. |
| *Vision* | Use layouts which provide for visual verification of the nonpresence of a human in the work zone before restart. |
| *Communication* | Clear dialogue within the working group depends on understandable verbal and hand signals. |
| *A second person "Buddy System"* | A person ready to push the emergency stop provides added protection. |
| *Freeing a trapped person* | Train personnel in how to extricate fellow workers who may become caught. |

**Table 3-2.** Human factors considerations for safe robot maintenance

# SYSTEMATIC METHODS FOR INJURY PREVENTION ANALYSIS

## 4.1 Benefits of safety analyses

Before selecting which safety devices to use, deciding where they will be placed, and instituting safe procedures, conducting a systematic safety analysis will ensure that devices and procedures are appropriate for actual or anticipated tasks and hazards. There are several benefits to doing this. Such an analysis will help meet the ANSI R15.06 standard for safe use of robots and the OSHA 1910.212 general machine safety standard. It can also be used to justify purchasing decisions with upper management. Combinations of human errors and equipment failures which lead to injury can be identified and avoided. Also, it can help foresee ways that injury could occur due to incorrect procedures. For instance, a safety device which may be subject to frequent false alarms is likely to be disconnected or turned off with the result that no protection is provided. In the same way, a device which makes restarting after a problem has been corrected a time consuming process may not be used. Or, a safety device may interfere with the task to the extent that it will not be used.

Four methods useful in predicting potential injury situations and in planning appropriate protection against these situations are briefly introduced here. Sources for further information about these methods are given. These are not the only methods available and other methods may be equally effective. These methods are presented to acquaint maintenance personnel with orderly and thorough ways to plan for injury prevention. It is advisable for maintenance management and staff to work with qualified safety professionals when trying to use these methods. Before beginning, commit time for completing these analyses and carrying out safety actions. Teamwork among safety, maintenance, and production staff is critical to getting positive results from these methods.

Job Safety Analysis and Fault Tree Analysis are presented because they are generally accepted safety analysis methods. The Diagram for Controlling Hazardous Energy During Maintenance and Servicing is introduced because the question of having energy present during maintenance is a crucial hazard factor. The SADT method is introduced as one way to organize an analysis when personnel from various functional disciplines contribute information toward the design of protection systems for robot maintenance workers.

Various other methods can be used depending on how thorough the analysis is to be and the technical expertise available for the analysis. These include Failure Modes, Effects, and Criticality Analysis (FMECA) and sneak-circuit analysis. They are not discussed here because they would be performed by personnel not necessarily in the audience for which these guidelines are intended.

The objective of an analysis would be to identify design and procedural factors to

- reduce the number of hazards (and of the possibility of combined hazard),
- reduce the degree of hazard (amount of energy available),
- reduce the dimensions of the danger zone,
- reduce the period during which the risk exists or duration of work within the danger zone,
- improve the perception of risk,
- create possibilities for escape at times of risk,
- train and create awareness among workers for recognizing, controlling, and eventually eliminating risks [13].

### 4.2 Job Safety Analysis method

In each step of a task in the workzone, what hazards are present and is there a control in place against them?

**4.2.1 Characteristics of method** - This method identifies hazards faced by a technician in each step he takes to complete a task. It may also give some insight into the effects of mistakes in procedure and of measures which would minimize the effects of these errors. This method requires a review of each type of corrective maintenance that the technician carries out. It involves three steps: 1) break down the robot technician's job into the different tasks that are done, 2) identify all hazards of each task, and 3) develop solutions.

**4.2.2 Example** - Table 4-1 is a generalized example of an output from a Job Safety Analysis.

**4.2.3 Limitations** - Be aware of the variability in the way that tasks are performed.

**4.2.4 Reference** - *Supervisors Safety Manual*, National Safety Council, Fourth edition, 1976.

### 4.3 Fault Tree Analysis

What combinations of human actions and equipment conditions could lead to a robot related injury?

**4.3.1 Characteristics of the method** - This method begins with defining the unwanted injury event and proceeds by graphically constructing the sequences of events and conditions that would lead to that event. When failure rates and

| **Phase of the task** | **Hazards** | **Preventive measures** |
|---|---|---|
| *Diagnose fault* | *Proximity to moving robot necessary to identify problem* | *Automatic diagnostics such as force gauges on welding electrodes, strain gauges on cutting tools* |
| *Verify that energy that is supplied to work zone will be at safe level during intervention* | *Could be attempted while robot is in automatic operation* | *Ensure that interlocks engage before robot can be reached*<br>*Provide convenient selectors for switching from automatic to manual control* |
| *Verify that energy that is stored in the work zone is released safely* | *Robot is blocked and will move when block is removed* | *Control panel indicators and training to relieve stored energy* |
| *Perform corrective task* | *Movement of the robot is needed* | *Slow speed used*<br>*Locate controls, tool change positions, loading stations outside work zone* |
| | *Automatic operation is initiated* | *Accessible emergency stop; Verify interlocks* |
| *Restart* | *Personnel still in work zone* | *Key to lockout held by person in work zone* |

**Table 4-1.** Job Safety Analysis Example

human reliability values are available, the probabilities of the various sequences can be computed.

**4.3.2 Example** - A small part of a fault tree for robot safety is shown in Figure 4-1. It shows some of the logical sequences of events and conditions which can lead to robot related injury.

**4.3.3 Limitations** - The analysis is effective only to the extent that knowledge of the events that could lead to an injury are within the expertise of the individuals performing the fault tree analysis and are foreseen by them.

**4.3.4 Reference** - S. Malasky, *System Safety*, 2nd ed., Garland STPM Press, New York, 1981

### 4.4 Diagram for controlling hazardous energy during maintenance and servicing

How will energy be controlled during workzone interventions?

**4.4.1 Characteristics of the method** - A guide to steps that can be taken to provide protection during maintenance procedures is given in A Diagram for Controlling Hazardous Energy During Maintenance and Servicing [11]. It uses a diagram to show the necessary actions and conditions required to accomplish maintenance on energized and de-energized systems and to restart the systems. This guide was developed to cover all kinds of maintenance. It is general enough that it can be adapted to cover maintenance of programmable systems such as robots.

**4.4.2 Example** - An example of using this method on a robotized system would be for tasks such as reprogramming points when robot motion is necessary. In this case, the four conditions indicated in Figure 4-2 would apply.

**4.4.3 Limitations** - Factors that need to be known include 1) nonhazardous energy levels, 2) proximity to the robot necessary to accomplish the task, and 3) whether proven methods exist for performing the task with energy present.

**4.4.4 Reference** - *Guidelines for Controlling Hazardous Energy During Maintenance and Servicing*, NIOSH, Division of Safety Research, Morgantown, West Virginia, 1983.

### 4.5 The SADT method

How can hazard evaluation be organized when information from various personnel is required?

**4.5.1 Characteristics of the method** - The Structured Analysis and Design Technique (SADT) is a general problem-solving tool. It is introduced here to illustrate how personnel having various areas of expertise can work together in designing a robotic safety system. More detail is given on this method than on the methods previously discussed because this is a new approach to safety analysis. It is a simple method to understand but in practice it demands disciplined and coordinated team work. It allows results to be made

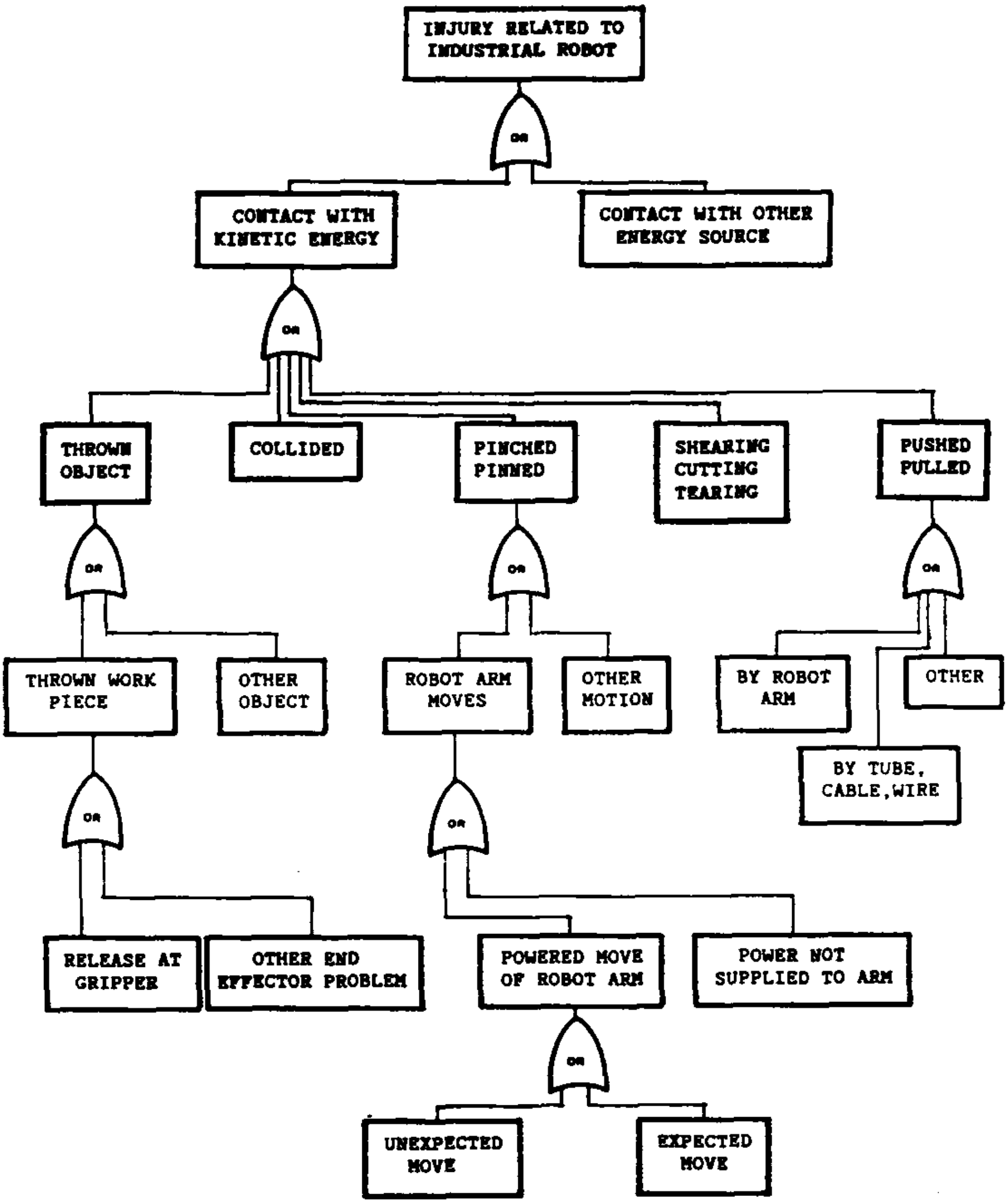
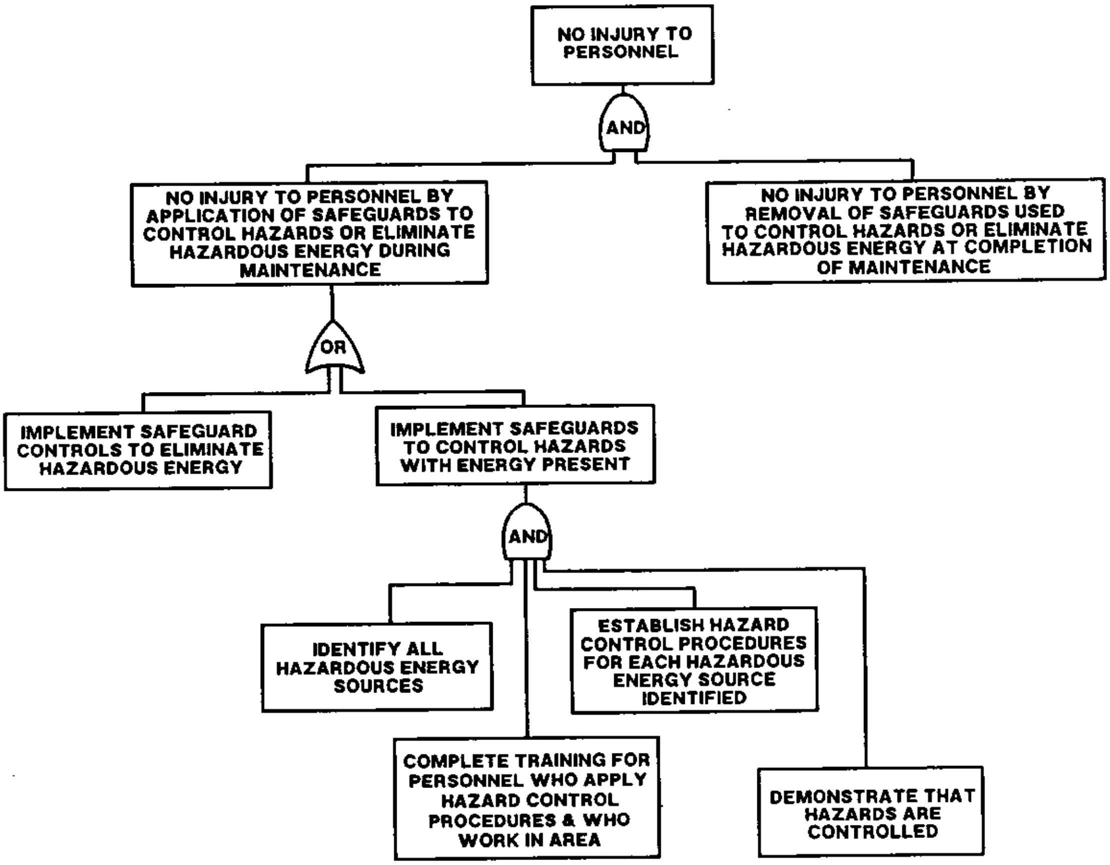


*Figure 4-1.* Fault tree for accidents related to industrial robots (after Sugimoto [10])

*Figure 4-2.* Conditions to be met to control hazards with energy present



evident which show clearly the quality of this team work. The training of such teams requires a significant commitment of time. The team members making up an SADT study group for robotic safety might include:

- production personnel (including robot programmers and operators)
- personnel assigned to equipment acquisition
- maintenance personnel
- safety personnel

SADT is applicable only when it has been decided that the problem in question is so complex that it needs an extremely thorough analysis prior to design. It can be used for robotic system hazard identification and control design analysis when input can be combined from personnel associated with the design, installation, operation, and maintenance of the robotized system. Information from these different areas of specialization which could be useful in an effort to safeguard personnel performing robot maintenance includes quality data, maintainability data, injury report data, safety device reliability data, and human factors data.

With SADT [14] the analysis of any problem is carried out according to a descending, modular, hierarchic, and structured logic (Figure 4-3). SADT models include both objects (documents, products, information, data) and activities (performed by men, machines, or programs). The complete SADT model of a problem shows these two aspects and the linkages existing between them. To present the analysis graphically, two symbols are used: activity blocks and connecting arrows. The activity block contains a description of an activity represented as an active verb. Naming an activity leads to precision of the analysis logic. Each one of the four sides of an activity block has a specific meaning (see Figure 4-4):

- Input: the data or tangible information which is to be acted upon,
- Output: the data or tangible information which is a result of the activity,
- Control: the constraints which regulate the activity, and
- Mechanisms: the means by which the activity is accomplished.

**4.5.2 Example** - Figure 4-5 shows one approach for linking information from five activities related to robot maintenance intervention.

**4.5.3 Limitations** - SADT imposes directed team work and organized discipline of thought and action. These factors are essential if the results of the analyses carried out under an SADT structure are to be understood and used by system designers. Successful results will also be limited by the expertise of users in applying the graphical rules of SADT.

**4.5.4 Reference** - Those interested in training in the use of SADT may wish to contact SofTech, Inc., 460 Totten Pond Rd., Waltham, MA 02154.

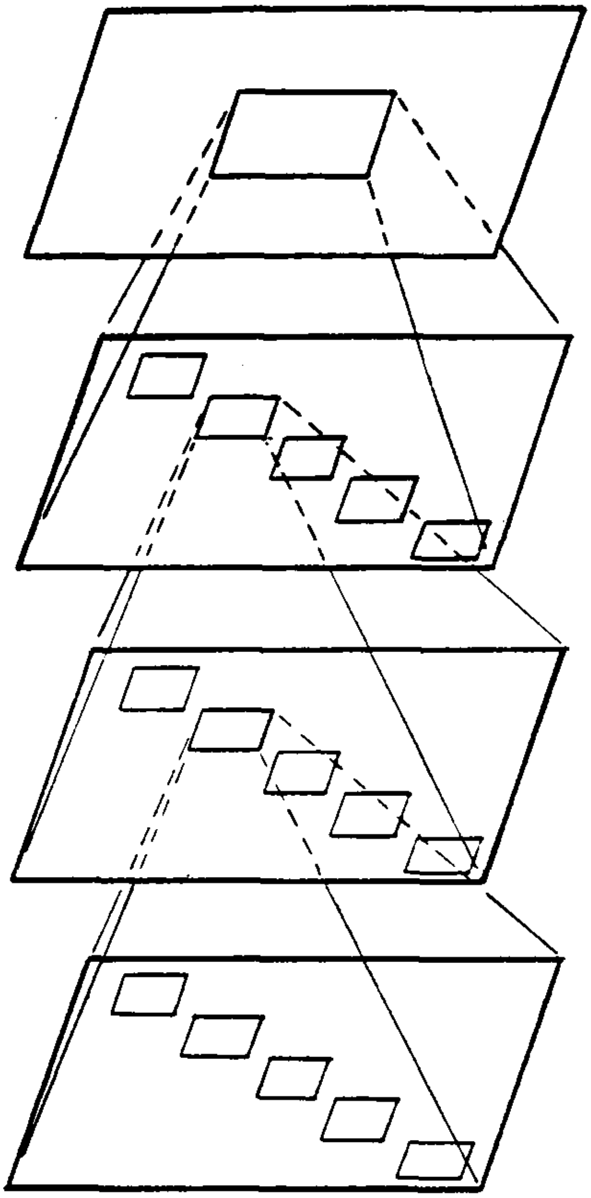


*Figure 4-3.* The SADT structure

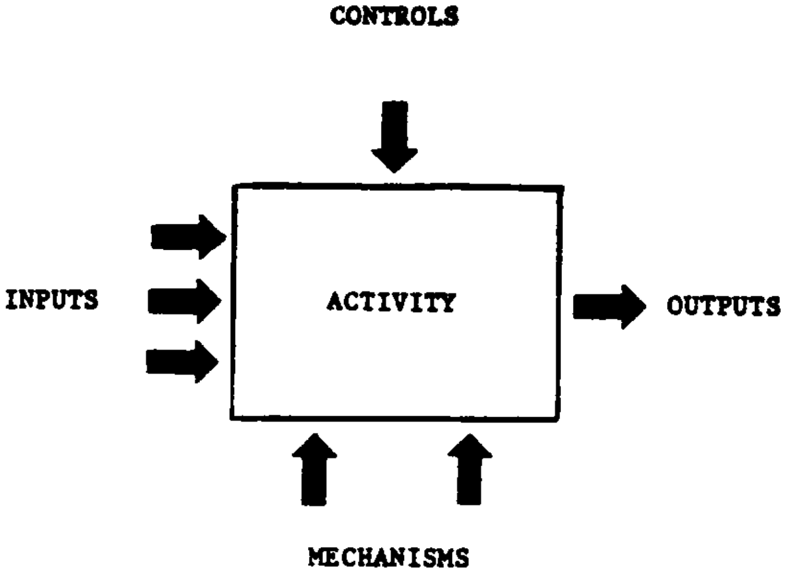


*Figure 4-4.* SADT symbols

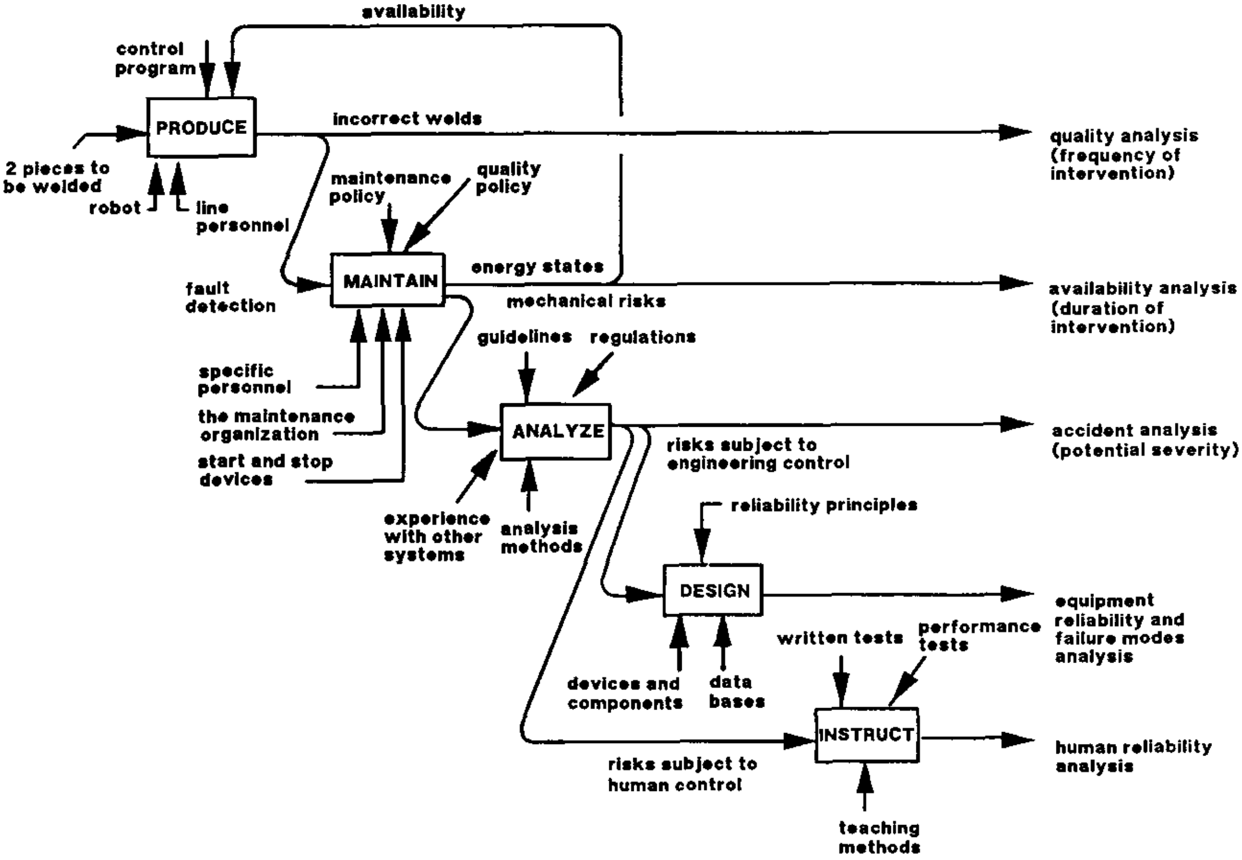


*Figure 4-5.* Example of a first level SADT diagram

## 4.6 Task observation grid

**4.6.1 Characteristics of the method** - A form for recording the characteristics of interventions and accompanying human actions was developed as a means of classifying observed safety conditions during work zone interventions (Table 4-2). This form can be used to assure that a safety analysis takes into account the many kinds of interventions which occur.

The categories in Table 4-2 are described in Table 4-3. For each type of intervention, the seven columns of Table 4-2 are filled in and their safety adequacy examined. Thus, all interventions can be planned for.

**4.6.2 Example** - Tasks in robot work zones were observed and grids filled out for two specific cases. Examples are shown in Tables 4-4 and 4-5. These two cases are not comparisons. Rather, they describe actual corrective actions in specific robot applications. The common factor in these cases is the necessity for human intervention into programmable work zones.

**4.6.3 Limitations** - The analyst's understanding of established procedures and safety devices used is crucial.

**4.6.4 Reference** - This format was developed by the author specifically for analyzing robotic system interventions.

## Table 4-2.

### LISTING OF HUMAN INTERVENTIONS FOR MAINTENANCE INTO A ROBOT WORK ZONE

| FUNDAMENTAL CAUSE FOR THE STOP | NATURE OF THE INTERVENTION | WAS THE STOP PROGRAMMED OR RANDOM | STOPPING MODE | PROTECTIVE DEVICES PUT OUT OF SERVICE | PROTECTIVE DEVICES IN SERVICE | MODE OF RESTART | VERIFICATION OF PROTECTIVE DEVICES |
|---|---|---|---|---|---|---|---|
| ROBOT: UNDER REPAIR, OUT OF POSITION | | | | | | | |
| TRANSFER SYSTEM OR ASSOCIATED MACHINERY: UNDER REPAIR, ADJUSTMENT | | | | | | | |
| TOOLING OR GRIPPER: UNDER REPAIR, ADJUSTMENT | | | | | | | |
| PROTECTIVE MONITORING DEVICE: UNDER REPAIR | | | | | | | |
| WORK PIECE: QUALITY | | | | | | | |
| CLEANING | | | | | | | |

| **Column Heading in Table 4-2** | **Definition** |
|---|---|
| *Fundamental cause for the stop* | The elements which were identified as having failed (broken tool, improper position of the work piece.) |
| *Nature of the intervention* | The intervention may be carried out as a diagnostic action, as action to identify the fundamental cause of failure, or to carry out a repair on a cause already identified. |
| *Was the stop programmed or random?* | The stop may have been anticipated (scheduled work stops) or unanticipated (random event). A factor to be taken into consideration in the planning of a safety system is the degree to which it is anticipated that intervention tasks will occur randomly. |
| *Stopping mode* | The switches or controls which were operated to achieve the stop. |
| *Protective devices put out of service* | In order to do the maintenance there may be some safety devices which are put out of commission. |
| *Protective devices in service* | While the maintenance action is underway what are the safety devices used? |
| *Mode of restart* | After the maintenance is complete what is the sequence of control operations which achieves a restart of the robotic system? |
| *Verification of protective devices* | After restart is achieved how is it verified that safety devices are operational? |

**Table 4-3.** Definition of categories in Table 4-2

## Table 4-4.

SITE #1:

## LISTING OF THE SAFETY PHASES OF HUMAN INTERVENTIONS INTO ROBOT WORK ZONES TO PERFORM MAINTENANCE

| FUNDAMENTAL CAUSE FOR THE STOP | NATURE OF THE INTERVENTION | WAS THIS A PLANNED OR AN UNPLANNED STOP | STOPPING METHOD | PROTECTORS IN OPERATION | METHOD FOR RESTARTING | VERIFICATION OF THE PROTECTOR |
|---|---|---|---|---|---|---|
| Tooling | Weak current | Unplanned | Sensor/ Normal sequence | E-Stop;<br>Line stopped;<br>Interlock | Close gate;<br>Step through several points with teach control; Normal sequence | **Panel lamp** |
| | Stuck electrode (seven times) | Unplanned | Same | Same<br>Second person | Step through several points with teach control;<br>Close gate; Normal sequence | **Panel lamp** |
| | Replace faulty electrode | Unplanned | Same | E-Stop;<br>Line stopped;<br>Interlock | Same | **Same** |
| | Change electrodes | Planned | Sequence at central control; Robot put into repair position at post | E-Stop;<br>Line stopped;<br>Interlock | Sequence at central control | **Same** |

## Table 4-5

SITE #2:

LISTING OF THE SAFETY PHASES OF HUMAN INTERVENTIONS INTO ROBOT WORK ZONES TO PERFORM MAINTENANCE

| FUNDAMENTAL CAUSE FOR THE STOP | NATURE OF THE INTERVENTION | WAS THIS A PLANNED OR AN UNPLANNED STOP | STOPPING METHOD | PROTECTORS IN OPERATION | METHOD FOR RESTARTING | VERIFICATION OF THE PROTECTOR |
|---|---|---|---|---|---|---|
| Transfer Line | Adjust stops on limit switches | Unplanned | Post in manual | Line stopped;<br>E-Stop;<br>Trip wire | Select auto mode;<br>Push start | Visual |
| Position of Tooling* | Verify that reprogrammed points in right positions | No stop - Pause waiting for other robots to finish cycle | Robot was in a waiting mode for next assembly | Emergency stop; Trip wire;<br>Second person | Next cycle begins as programmed | Visual |
| | Reposition points (5 times) | Unplanned | Post in manual/Step-by-step on robot | Emergency stop; Trip wire;<br>Line stopped | Select auto mode;<br>Push start button | Visual |
| Test Replacement Part | Exchange old part with test part | Unplanned | Post in manual | E-Stop;<br>Trip wire | Select auto mode;<br>Push start button | Visual |

# MAINTENANCE MANAGEMENT FOR ROBOTIC SAFETY

Maintenance managers responsible for robotized workstations are generally interested in having detailed hazard information on their workstations for two cost reasons. First, maintenance activities which lead to an injury may be followed by a long period of system downtime to determine the exact cause of the injury. If some of this time is charged against the maintenance group it could include the cost of idled workers and lost production on the robotized workstation and on workstations which it supplies. Secondly, some of the costs of safety devices and safe procedures development which are found inappropriate to the work being done could be charged against the maintenance group. The ANSI standard on robotic safety[1] requires maintenance safeguarding which corresponds directly to the type and level of hazards presented by robots and robot systems. The data used by maintenance management can aid in determining the hazard levels for maintenance tasks. This section explores three areas of robot maintenance management which relate to cost effective injury prevention. These are 1) quantitative analysis of maintainability and availability, 2) policy regarding corrective and preventive maintenance, and 3) computerized maintenance data collection.

## 5.1 Maintainability and availability

For robotics safety personnel to work cooperatively with robotics maintenance management requires awareness of the special meanings of two terms which are easily confused -- maintenance and maintainability. "Maintenance" is a descriptive term for the full range of human activities and organization by which equipment repair and servicing are carried out. "Maintainability", on the other hand, is a quantitative, performance measure for the ability of a particular equipment design to be repaired. Values for maintainability are determined when a maintainability objective has been defined for a system. This objective is sometimes expressed as the acceptable amount of downtime for the system.

One definition of maintainability is that it is a characteristic of design and installation that imparts to a system a great inherent ability to be maintained, in a way that lowers the required maintenance man-hours, skill levels, tools, test equipment, facilities, and logistics costs and thus achieves greater equipment availability [32]. For industrial robotics, this means that a system with a better maintainability value than another system will be available for production more of the time because to fix it takes less time, needs fewer skilled personnel, utilizes more effective tools, test equipment, and facilities, and is less costly. From a safety perspective, computed maintainability values are acceptable only when it is shown that the use of effective safety devices and procedures has been considered within the computation.

---

[1] *"Personnel that maintain and repair robot systems shall be safeguarded from injury due to unexpected or unintended motion. The means and degree of safeguarding, including any redundancies, shall correspond directly to the type and level of hazards presented by robots and robot systems and its dangers to personnel."* ANSI R15.06

Maintainability is expressed in several ways:

- by the Mean Time To Repair (MTTR); depending on the case, this value could deviate from the mean according to a lognormal, Weibull, or exponential distribution,
- by the duration of that repair which has a cumulative probability of completion of 0.9 (see Figure 5-1),
- by the availability of equipment, where

$$A = \frac{MTBF}{MTBF + MTTR}$$

A = Availability
MTBF = Mean Time Between Failure
MTTR = Mean Time To Repair

- by the value of the annual acceptable unavailability, where

$$U = 1 - A$$

U = Unavailability

Engelberger has indicated that a mean time between failure (MTBF) of 400 hours has been attained for robots specifically [3]. Other parts of a robotized workstation and the total workstation have different failure rates.

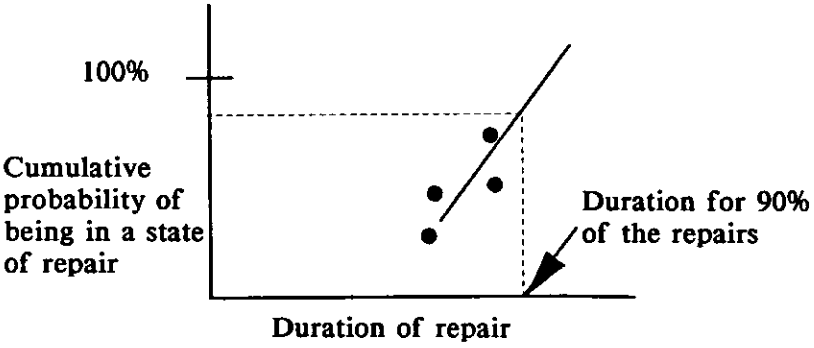


*Figure 5-1.* Maintainability expressed as the 90th percentile of repair durations.

### 5.2 Three examples of potential hazard exposure information from maintainability data

The time of exposure to hazards during corrective maintenance tasks on robotized systems is one factor to be considered when selecting safety devices and setting safety procedures. As will be seen in the following examples, data collected for maintainability analysis can indicate how often and for how long maintenance workers are potentially exposed to robot hazards.

### 5.2.1 Frequent and long duration potential exposures

A welding robot system had two lines with fifteen robots each. Downtime data were collected on the welding elements of the system over a period of three months (1634 working hours). Table 5-1 summarizes the data collected. For the sixteen different problems associated with the robot tooling, two tasks were done daily while four tasks lasted over 1/2 hour. The mean time to repair (MTTR) for welding equipment was 11 minutes. This is the time of potential exposure to hazards associated with welding equipment on these lines.

For the frequent tasks in this example, the safety analyst might pay particular attention to the ease of use of safeguards and look for standardized, safe procedures. For the long duration tasks, the necessity for having the robot under power merits evaluation.

### 5.2.2 Fault diagnostics reduce duration of potential exposure

Figure 5-2 shows the difference in time of potential exposure to maintenance risks (downtime) between a system without fault diagnostics and one with such diagnostics. Using fault diagnostics reduced maintenance time, and thereby potential hazard exposures, by 32 to 39 percent over previous times. The diagnostics in this case monitored for 1) exceeding the expected time duration of a mechanical operation, 2) inadmissible logic states, and 3) exceeding parameters (pressure, temperature) which could be detrimental to system components.

### 5.2.3 Short, frequent exposures

Figure 5-3 is a sample of downtime information from an automotive assembly plant. It shows that 75 percent of the downtime for maintenance interventions carried out during one production period lasted one minute or less. The safety consideration here would be that safety systems be installed which could not be easily bypassed (e.g., low fence, interlock easily jammed shut). Some workers bypass safety devices when an intervention is usually short and a stoppage seems unnecessary.

## 5.3 Maintenance policy

Figure 5-4 indicates different types of maintenance. Maintenance policy is the company's rule for when preventive maintenance is to be done and when nothing is to be done until corrective maintenance is needed. Preventive maintenance which can be done with power off to the robot is less hazardous than corrective maintenance which may have to be done with power on. The maintenance policy followed can affect potential hazard exposure. For example, a robot workstation might be used in a normal production mode to build up extra stock during scheduled maintenance periods (such as during a night shift dedicated to maintenance). This stockpiling allows the robot workstation to be shut down for corrective maintenance in times of normal production with no loss of output from the workstation. However, this is advisable only after the necessary preventive maintenance has been performed in the scheduled maintenance period. A maintenance policy of temporarily deferring inconsequential corrective maintenance and permitting the robot workstation to operate in a degraded mode until it can be completely deenergized would reduce exposure to hazardous energy.

| | | Production downtime (min) | Number of repairs | Minutes per repair |
|---|---|---|---|---|
| * | Broken tubing - cooling water leak | 1236 | 150 | 8.2 |
| * | Electrode stuck | 996 | 133 | 7.5 |
| | Welding fixture malfunction - cooling water leak | 805 | 27 | 29.3 |
| | Joint broken - cooling water leak | 670 | 25 | 26.3 |
| | Electrode element - cooling water leak | 432 | 69 | 6.3 |
| | Electrodes misaligned | 353 | 34 | 10.4 |
| | Leak in the pneumatic system | 210 | 27 | 7.8 |
| ** | Transformer power connection out of service | 195 | 2 | 97.5 |
| | Electrode holder out of service - loss of cooling water | 145 | 14 | 10.4 |
| ** | Power cable separated | 120 | 1 | 120.0 |
| | Hydraulic relay replacement | 115 | 9 | 12.8 |
| ** | Thyristor panel out of service | 100 | 3 | 33.3 |
| | Flux problem | 75 | 8 | 9.4 |
| ** | Secondary fuses melted | 60 | 1 | 60.0 |
| | Hydraulic relay malfunction | 40 | 7 | 5.7 |
| | Servo valve out of service | 35 | 2 | 17.5 |
| **Totals** | | **5587**<br>**(93 h 7 min)** | **512** | **MTTR**<br>**10.9** |

* denotes frequent tasks
** denotes long-duration tasks

**Table 5-1.** Repair experience for the tooling on a robotic line

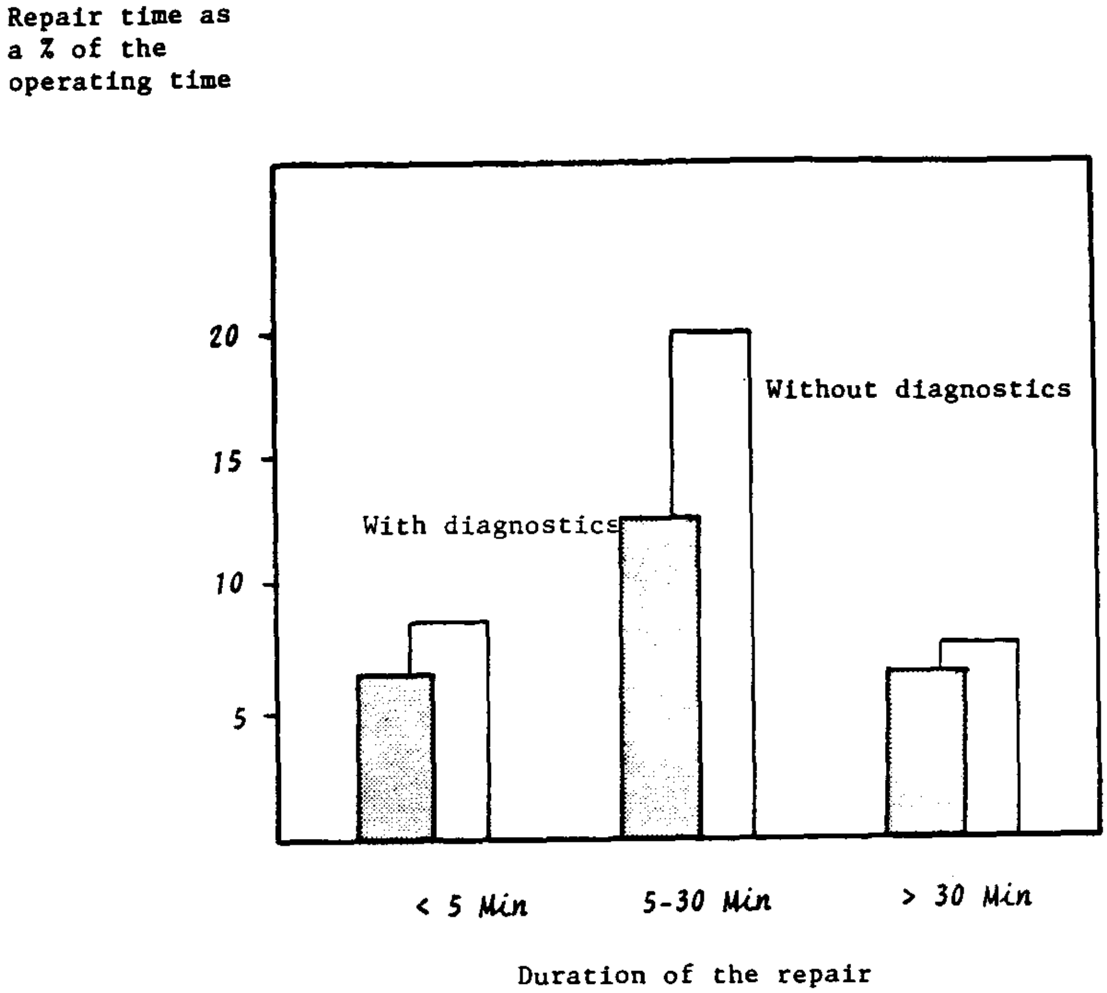


*Figure 5-2.* Repair exposure time with and without diagnostics

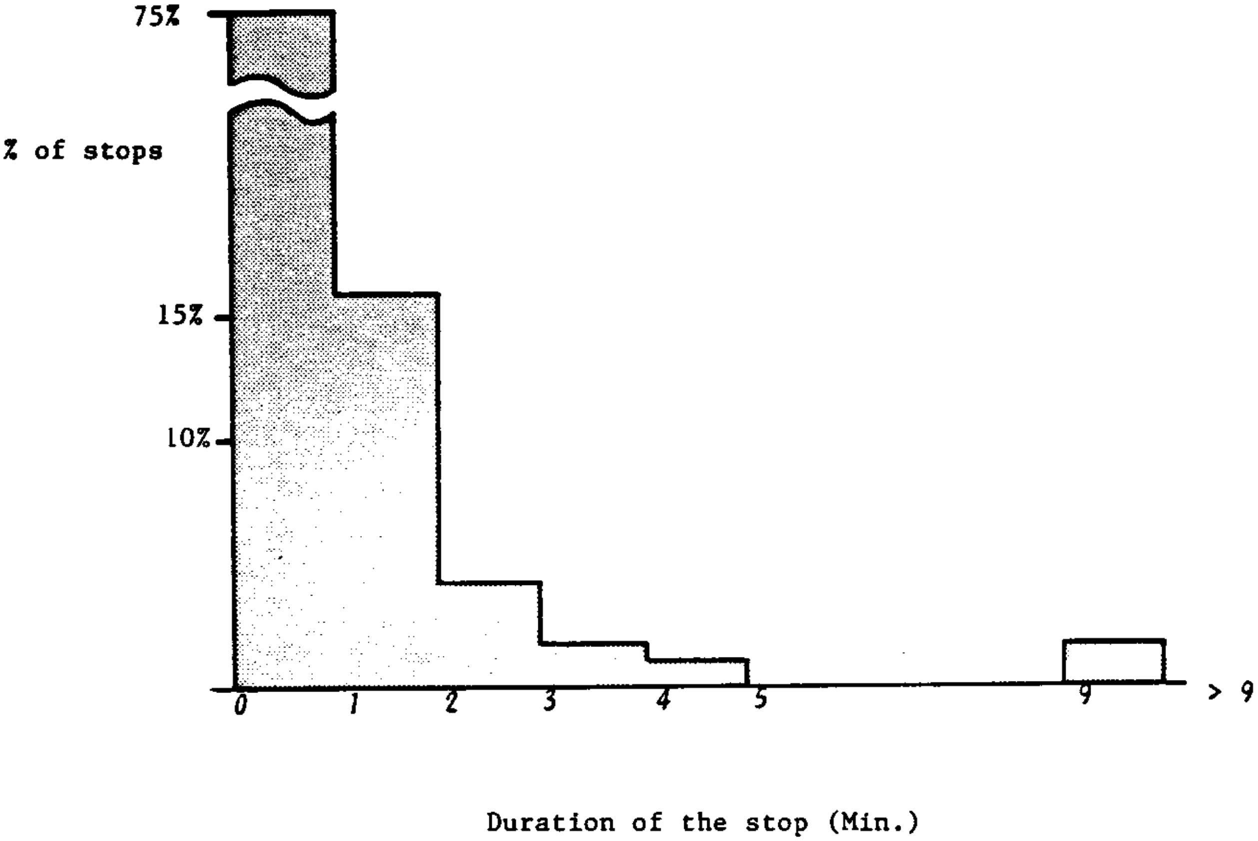


*Figure 5-3.* **Frequency among 31 causes for the stopping of a robotic system**

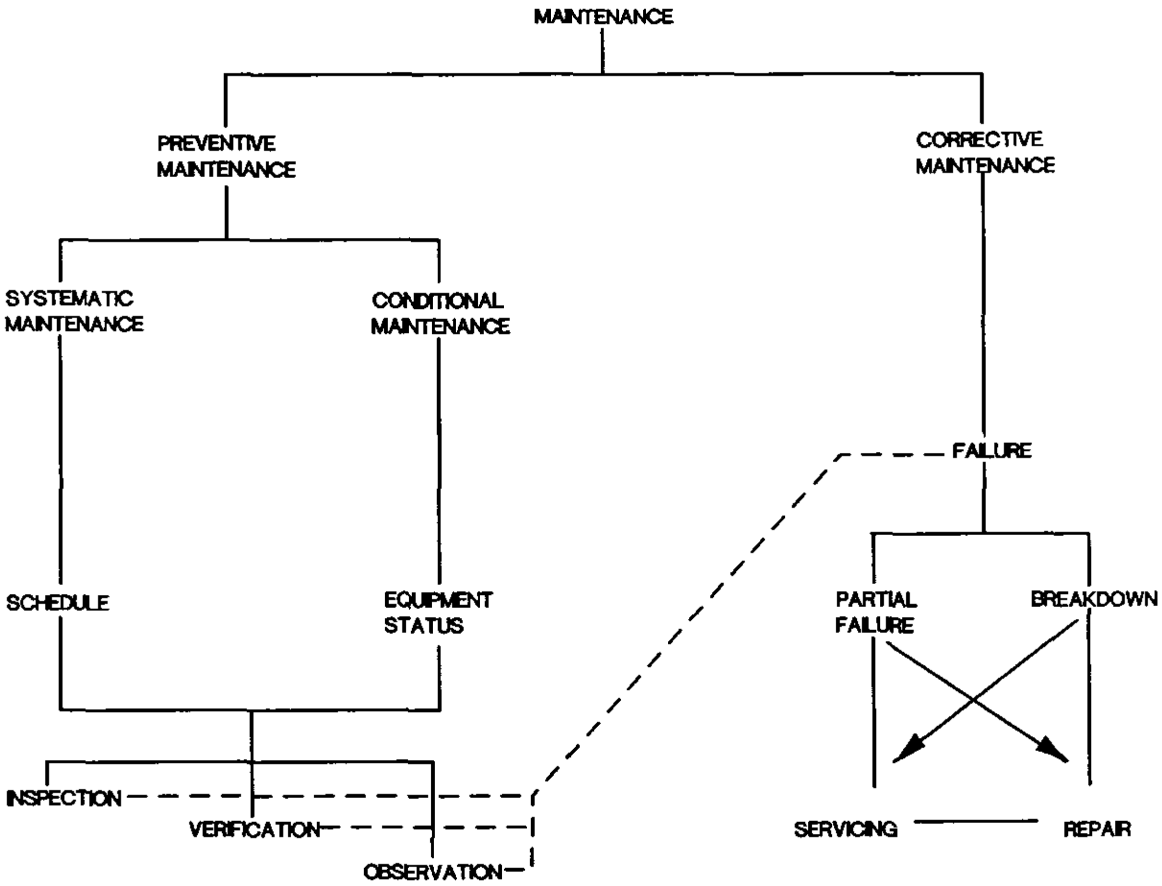


*Figure 5-4.* The different types of maintenance [19]

Jones and Dawson have reported information collected on robot system stop times for three companies with seemingly different robot maintenance policies (see Table 5-2). This data covers more than 20,000 hours of robotic production for 37 arc welding and spot welding robots [5].

| | Percentage of cases where each action is recorded | | |
|---|---|---|---|
| **Action taken** | **Company A** | **Company B** | **Company C** |
| Replacement of faulty equipment | 3.6% | 19.0% | 22.8% |
| Adjustment/cleaning | 7.0% | 16.4% | 50.3% |
| Resetting | 72.4% | 64.0% | 41.2% |
| Reprogramming | 8.1% | 8.9% | 7.6% |
| Routine maintenance | 2.0% | 5.7% | 22.3% |
| Unplanned maintenance | 67.4% | 21.0% | 11.1% |
| Fault diagnosis | 5.9% | 2.3% | 1.0% |
| Other | 6.6% | 1.6% | 6.3% |

**Table 5-2.** Action taken in recorded stop time incidents.

[Note: Columns do not add to 100 percent because more than one action could be taken during the same stop.]

From this table it can be seen that between the companies there is a wide divergence in the types of actions being taken during robot stops. In particular, if we look at the action called routine maintenance, we see that Company A has a policy of seldom stopping for routine maintenance (only 2 percent of actions taken during stops) whereas Company C stops quite a bit for routine maintenance actions (22.3 percent of all stops).

Table 5-3 compares four possible maintenance policies according to the information used and the type of organization in which they are found.

| TYPE OF MAINTENANCE | USE OF INFORMATION | ORGANIZATION |
|---|---|---|
| Preventive maintenance; systematic and conditional.<br>Systematic analysis, using sensors and the computer, of the reliability and the service life of problematic machines. | Many numerically controlled machines.<br>Many sensors and microprocessors.<br>Internal technical information network (bus). Computers dedicated to maintenance, frequently with a signal processing interface. | Close cooperation with production services so that the production personnel participate in the search for better methods of maintenance. An existing office for methods study, information processing, and reliability. |
| Systematic preventive maintenance.<br>Conditional maintenance by systematic visits and measurements made on certain equipment. | Many numerically controlled machines with sensors not tied into the maintenance information system.<br>Integrated maintenance management system on a computer dedicated to the maintenance service. | Quasi-contractual arrangements with the production service. The existence of an office for methods and new projects. A budget categorized according to equipment and work group. |
| Systematic preventive maintenance.<br>Experimental use of vibration analysis techniques etc. | Many applications developed on the information processing systems of the company but without these systems being integrated. Many manual input systems: inventory, etc. | The existence of job analyses. The overall budget for the service and its divisions is not detailed. |
| Corrective maintenance except for changes of lubricating oil and periodic greasing. | No information processing, or only the batch processing of data by the information processing service of the company: cost accounting, inventory management. | Maintenance service organized with little structure, often completely dependent upon the production service. |

**Table 5-3.** Four levels of maintenance management [21]

### 5.4 Maintenance intervention reporting

Several categories of data reporting have been suggested for evaluating maintenance [24-26]. Maintenance information which could be useful in a safety analysis includes:

- reference to the device being repaired, e.g., manufacturer, type, number within the series,
- the date (year, month, day), the cause and the nature of the intervention. If the cause is a failure, the time, the origin and the indication of the failure,
- the length of time in service for the smallest subunit identified as the device being repaired and for which such information is available,
- where in the system the failed parts are located: sub-assembly, component, etc.,
- defaults in the component being repaired or being exchanged, and the reason for the replacement,
- the category of maintenance (corrective, preventive,...),
- the job title of the repair person,
- the means available to conduct the repair within this category of repair,
- the date of taking the system out of service and putting it back into service, and
- the length of time during which the maintenance intervention took place on the system and on the sub-system.

The possibilities for collecting maintenance safety data on robotized installations are significant when the computer memory capacities at such installations are sufficiently large. Safety departments may find it beneficial to develop or use existing data bases as a way to collect injury prevention information.

## CONCLUSIONS

**Effectively designed safety systems for robotized workstations will accommodate the need for personnel to approach the robot from time to time.** An important aspect of robotized production which can not be neglected is that such production depends on the performance of randomly occurring human tasks near the robot. These random tasks may not be rare events. The purpose of the safety system is to protect a person who enters a zone which is normally a robot's work zone from potential hazards of unexpected robot motion. Therefore, tasks which require personnel to work near a robot while it is under power will only be done in a selected safe control condition.

**Because robotized systems may be quite complex, a systematic approach for analyzing robot maintenance safety is advised.** Before implementing proposed safety measures, it is prudent to evaluate their effectiveness in regard to the types of intervention anticipated for the workstation. After implementation, periodic reviews of the effectiveness of the safety measures for the interventions which are actually occurring can be made. Verification, not only of safety device performance in these situations, but also of worker understanding of proper safe equipment operation, is clearly warranted.

Diverse factors need to be considered in a systematic analysis for safe maintenance of robotic workstations. These factors might be evaluated by various, appropriately qualified persons. For example, a person qualified in machine control would be needed to assess whether a failure mode of a programmable control device could have as its result the dangerous movement of electrical, hydraulic, or pneumatic driven elements which still have power available during a maintenance task. Someone skilled in labor-management cooperation might be needed to determine how to gain acceptance of the use of new safety devices. Personnel involved in robotic system acquisition and improvement could advise on how the design of a robotic system could change as technology changes. Safety professionals would be able to provide information on choices between protective devices and procedures, safety regulations in force, and prudent safety engineering principles.

**Evaluation of maintenance policies and records will help in determining the degree of potential hazard exposures inside robot work zones.** Such evaluation is needed to understand the seriousness of the need for robot safety measures in comparison with the need for devoting resources to other areas of safety need in the evolving workplace. Evaluations which make use of maintenance records of worker exposure to robotic hazards can show the effectiveness of different hazard control equipment and procedures.

## BIBLIOGRAPHY

[1] Daniellou, F. "L'Impact des Technologies Nouvelles sur le Travail en Postes dans l'Industrie Automobile" [The Impact of New Technologies on Workstations in the Automobile Industry] Collection de Physiologie du Travail-Ergonomie du Conservatoire National des Arts et Métiers, Paris p. 146; p. 144.

[2] *Computerized Manufacturing Automation*, Office of Technology Assessment, OTA-CIT-236, Washington, DC, April 1984.

[3] Engelberger, J. "Robotics: 1989", Robotics Today, Dec. 1984, pp. 57-59.

[4] Cugy, A. *Les Robots: Spécifications Techniques* [Robots: Technical Specifications], Hermes Publishing, Paris, 1983.

[5] Jones, R. and Dawson, S. "People and Robots: Their Safety and Reliability" in *Robot Safety*, IFS (Publications) Ltd., Bedford, UK, 1985.

[6] Vautrin, J-P, Dei Svaldi, D. Manipulating Industrial Robots in France - Effects on Health, Safety and Working Conditions: Results of the INRS-CRAM Survey. **Journal of Occupational Accidents.** 8(1986), 1-12.

[7] Reports of robot safety incidents voluntarily supplied to the Motor Vehicle Manufacturers Association, Detroit, Michigan.

[8] Carlsson, J. "Robot Accidents in Sweden", National Board of Occupational Safety and Health, 5 - 171 84 Solna, Sweden.

[9] "Request for Assistance in Preventing the Injury of Workers by Robots" National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 85-103, Dec. 1984.

[10] Sugimoto, N., Kawaguchi, K. "Fault Tree Analysis of Hazards Created by Robots", Proceedings of 13th International Symposium on Industrial Robots, Chicago, April 1983.

[11] NIOSH. *Guidelines for Controlling Hazardous Energy During Maintenance and Servicing*, DHHS (NIOSH) Pub. No. 83-125. NIOSH, Division of Safety Research, Morgantown, West Virginia, 1983.

[12] Barrett, R., Bell, R., Hodson, P. Planning for Robot Installation and Maintenance - A Safety Framework. Health and Safety Executive, Her Majesty's Stationery Office, London (Undated).

[13] Nicolaisen, P. "Sicherheitsprobleme beim Einsatz von Industrierobotern" [Safety Problems Related to Industrial Robots], **Modernes Unfallverhutüng**, West Germany, no. 25, pp. 39 - 42, (INRS translation 16 - 82).

[14] Ross, D. "Application and Extensions of SADT", **Computer**, April 1985, pp. 25 - 34.

[15] Meagher, J., Derby, S., Graham, J. "Robot Safety/Collision Avoidance". **Professional Safety**, Dec. 1983, pp 14 -16.

[16] "Propos Raisonnables sur l"Automatisation de l"Industrie" [Proposals for Industrial Automation], see article by Damon and Decoster, Centre de Recherche en Gestion de l'Ecole Polytechnique, Paris, February 1984.

[17] Guyot, G. "Maintenabilité des appareils électroniques", [Maintainability of Electronic Equipment]. *Technique de l'Ingénieur*, Fiche E - 437, 1978.

[18] Rojon, A.,Ralko, J.P. "Analyse de la Disponibilité d'un Système Automatisé" [Availability Analysis of an Automated System]. Proceedings of 4th International Colloquium on Reliability and Maintainability, Vol. 2, Perros Guirec, France, May 1984, p 464 - 468.

[19] "Vocabulaire de Maintenance et de Gestion des Biens Durables", [Vocabulary for Maintenance and Management of Equipment]. Association Française de Normalisation, NFX 60-010, Paris, June 1984.

[20] Matull, E., "Unterstützung der Instandhaltung hochautomatisierter verketteter Anlagen durch Fehlerdiagnose-Systeme" [Maintenance of Large Automated Installations: Fault Diagnostics Considerations]. **Zeitschrift Fuer Wirtschaftliche Fertigung**, 77(1), 1982, pp. 25-27.

[21] Gabriel, M., Pimor, Y. *Maintenance Assistée par Ordinateur*, [Computer Aided Maintenance]. Masson, Paris, 1985.

[22] Martineau, G. "Maintenance et Paradoxes de l'Evolution Technique" [Maintenance and its Contradictions for Evolving Technology], **Enjeux**, No. 52, November 1984, pp. 51 - 54.

[23] Dolle, F., Moalla, M., Rodrigues, P. "Concevoir des Systèmes Automatisés" [Designing Automated Systems]. **Le Nouvel Automatisme**, March 1983, pp. 33 - 38.

[24] Marcovici, M. "L'Evaluation de la Fiabilité Opérationnelle des Equipements" [Evaluating the Operational Reliability of Equipment], in the training workbook for the Analysis of the Reliability and Safety of Industrial Systems, CAST, INSA 20, Avenue Albert-Einstein, 69621 Villeurbanne, pp. X.11 - X.30.

[25] Martineau, G., Dupoux, B., Euvrard, A. "Comment prévoir la disponbilité des moyens de production" [How to Predict the Availability of Production Equipment], Proceedings of 4th International Colloquium on Reliability and Maintainability , Vol. 2, Perros Guirec, France, May 1984, pp. 484 - 488.

[26] Jones, R.,Khodabandehloo, K. "The Use of Event Tree Analysis for Robot Hazard Analysis", Centre for Robotics and Automated Systems, Imperial College of Science and Technology, London, July 1984.

[27] IGL - "Introduction SADT" [Introduction to SADT]. REF.6 - SADT, Paris, July 1982.

[28] "Intégration de la Sécurité dans la Conception des Machines et Appareils" [The Integration of Safety into the Design of Machines and Devices]. Edition INRS Ed 623, Paris, April 1983. pp. 23 - 4.

[29] "L'Impact des Technologies Nouvelles sur le Travail dans l'Industrie Automobile" [The Impact of New Technology on Work in the Automobile Industry], Fondation Europenne pour l'Amélioration des Conditions de Travail, Dublin, Ireland, 1984. p. 5

[30] National Safety Council, *Robots*, Data Sheet 1-717-85, Chicago, 1985.

[31] Nagamachi, M., "Human Factors in Industrial Robots and Robot Safety Management in Japan", **Applied Ergonomics**, March, 1986.

[32] Kapur, K. "Reliability and Maintainability" in *Handbook of Industrial Engineering*, G. Salvendy, editor, John Wiley and Sons, New York, 1982, p. 8.5.25.

## ADDITIONAL REFERENCES

Altamuro, V. "Working Safety with the Iron Collar Worker", **National Safety News**, July 1983, pp. 38 - 40.

Bachert, R., Evers, K., Crawford, B., Santucci, P. "Man-Machine Simulation Using SADT/SAINT Techniques", Proceedings of Human Factors Association of Canada Annual Meeting, October 1981. (NTIS Doc AD/A 144 530).

Backstrom, T., Harms-Ringdahl, L. "A Statistical Study of Control Systems and Accidents at Work", **Journal of Occupational Accidents**, 6 (1984) pp. 201 - 210.

Bernard, J. "Le Microprocesseur bien sûr, mais..." [The Microprocessor of Course, But...]. **Revue Industries et Techniques**, No. 441, 31 December 1980, pp. 204 - 208.

Conner, M. "Structured Analysis and Design Technique - Introduction". **IEEE Engineering Management Conference Record**, 1980.

Dolle, F., Rodrigues, P. "Simulateurs pour la Conception et l'Exploitation des Systémes de Production Automatisés" [Simulators for the Design and Use of Automated Production Systems], **RGE**, January 1985, pp. 34 - 38.

Fink, D. *Electronics Engineers Handbook*, McGraw Hill, New York, 1975.

Harms-Ringdahl, L. "Production Disturbances - A Safety Problem in Automatic Machines", Proceedings of Conference on Analysis, Design, and Evaluation of Man-Machine Systems, Varese, Italy, Sept. 1985.

Kloeckner, E. "Etude sur les Ratios en Maintenance" [A Review of Quantitative Relationships in Maintenance]. **Achats et Entretien**, No. 369, December 1984. pp. 27 - 36.

Kneppert, M.,Pagliero, D.,Vautrin, J-P. "Sécurité en Robotique" [Robotic Safety], **Enjeux** No. 58, May 1985.

Laprie, J.,Costes, A.,Landrault, C. "Parametric Analysis of 2-Unit Redundant Computer Systems with Corrective and Preventive Maintenance", **IEEE Transactions on Reliability**, Vol. E-30, No. 2, June 1981. pp. 139-144.

Lissandre, M., Rigal, G. SADT - SPECIF: Des Moyens de Modèlisation des Systèmes Automatisés de Production [SADT - SPECIF: Methods for Modeling Automated Production Systems], IGL, 39/41 Rue de la Chaussée d'Antin - 75009 Paris.

"Occupational Fatality Associated with a Robot". **Morbidity and Mortality Weekly Report**, U.S. Dept. of Health and Human Services, Public Health Service, March 22, 1985, pp. 145-146.

Parsons, H. "Robotics and the Health of Workers" in *Occupational Safety and Health in Robotics and Automation*, N. Noro, editor, Taylor and Francis, London, 1987.

"Prévention des accidents au cours des travaux d'entretien et des travaux neufs dans les usines" [Accident Prevention During Maintenance and New Installation Work in Factories]. Ed. INRS No. R 118, April 1975.

*RIA Robotics Glossary*, Robotic Industries Association, Dearborn, Michigan, 1984.

Stowe, W. "Robots - Safe or Hazardous". **Professional Safety**, Dec. 1983, pp 32 - 35.

"Techniques de Sécurité Appliquées aux Robots Industriels" [Safety Techniques Applicable to Industrial Robotics]. **Cahiers de notes documentaires**, No. 112, 3me trimestre, INRS, Paris, 1983.

Traversa, A. "Exemple de recherche d'optimum "Fiabilité - Maintenabilité" au stade de projet d'un système mécanique" [An Example of Reliability and Maintainability Optimization on a Mechanical System Project]. **Mécanique**, No. 301 - 302, January - February 1975, pp 37-40.

Vogrig, R., Morel, G., Dei-Svaldi, D., and Vautrin, J-P., "Contribution à l'analyze de la sécurité d'un système automatisé par SADT [Contribution to the safety analysis of an automated system using the Structured Analysis and Design Technique (SADT)], **Cahiers de notes documentaires**, no. 123, 2$^{e}$ trimestre, INRS, Paris, 1986.

Wisniewski, G. "Robot Training in the Automotive Industry," Proceedings of the Conference on Robotic Safety, Motor Vehicle Manufacturers Association of America, Inc. and Oakland University, Rochester, Michigan, 1983.

# GLOSSARY

**Active maintenance time** - the time during which one or several persons work on a piece of equipment in order to carry out maintenance.

**Approach zone of industrial robots** - the zone surrounding the movement zone. See Figure 2-1.

**Availability** - the ability of an item (under combined aspects of its reliability, maintainability, and maintenance support) to perform its required function at a stated instant of time or over a stated period of time.

**Availability time** - from the point of view of the user, the time during which a functional device is available.

**Conditional maintenance** - preventive maintenance which depends upon a type of predetermined event (autodiagnostic, information from a sensor, measurement of wear, etc.) which reveals a state of reduced function of the equipment. These predetermined events can require random maintenance actions.

**Corrective maintenance** - maintenance carried out after the appearance of a failure and intended to put the device into a condition in which it can fulfill its required function.

**Danger zone of industrial robots** - the danger zone of a robot consists of two parts: the zone of movement and the zone of approach. The danger zone depends upon the end effector but does not take into account the robot application.

**Detection** - the action of identifying by means of close monitoring, continuous or not, the appearance of a failure or the existence of a failing element.

**Diagnostics** - the identification of the probable cause of the failure with the aid of a reasoning logic based on all of the information resulting from an inspection, quality control, or a test.

**Failure isolation** - the action carried out in order to define precisely the element(s) by which the failure presents itself.

**Industrial robot** - materials handling mechanism capable of automatic position control, reprogrammability, and multiple use, which can be used to orient materials, workpieces, tools, or specialized devices in the course of making varied movements and programmed to execute a variety of tasks.

**Inspection** - monitoring activity which is carried out as part of a defined mission. This activity is not necessarily limited to comparisons with preestablished data.

**Maintainability** - under the given conditions of use for which it was designed, the capability of a piece of equipment to be maintained or re-established in a state in which it can accomplish its required function, when maintenance is carried out under given conditions using prescribed procedures and means.

**Maintenance** - the combination of technical actions and corresponding administrative actions undertaken to maintain or reestablish a piece of equipment in the state necessary to fulfill its required function. (It is often possible to accomplish maintenance actions on an operational system which will allow the system to operate in a state of degraded operation).

**Maintenance and servicing** - The tasks necessary to keep a machine, process, or system in a state of repair or efficiency. This activity includes inspection, servicing, repair, troubleshooting, set up, clearing jams, and other related activities. These activities are not considered to commence on a new system until it becomes operational.

**Mean time to repair (MTTR)** - total time for corrective maintenance divided by the total number of corrective maintenance actions during a given period of time. The MTTR can also be defined as the arithmetic mean of the times required to carry out maintenance actions.

**Movement zone of industrial robots** - this is the space accessible by combined movements of robot components, under all possibilities of displacement and along all axes. See Figure 2-1.

**Preventive maintenance** - maintenance conducted at predetermined intervals or corresponding to prescribed criteria and intended to reduce the probability of failure or degradation of performance of the device.

**Quality control** - verification of conformity to pre-established criteria.

**Repair** - specific and limited intervention for corrective maintenance after a failure.

**Robot configurations** - installation of a robot according to intended use; e.g., at a fixed work station, on a machine, on a vertical slide, on an overhead gantry, or on a mobile linear base.

**SADT** - signifies Structured Analysis and Design Technique. This is a tool for graphic representation and a method of analysis which has as its objective the simplification of problem solving on complex systems. It uses the principle of subdividing a problem into its subparts and structuring them from most to least complex.

**Systematic maintenance** - preventive maintenance carried out on a schedule established according to time period or number of units in use.

☆U. S. GOVERNMENT PRINTING OFFICE: 1983/543-159/605