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HUMAN MOTOR REACTIONS TO DANGEROUS MOTIONS IN ROBOT OPERATIONS
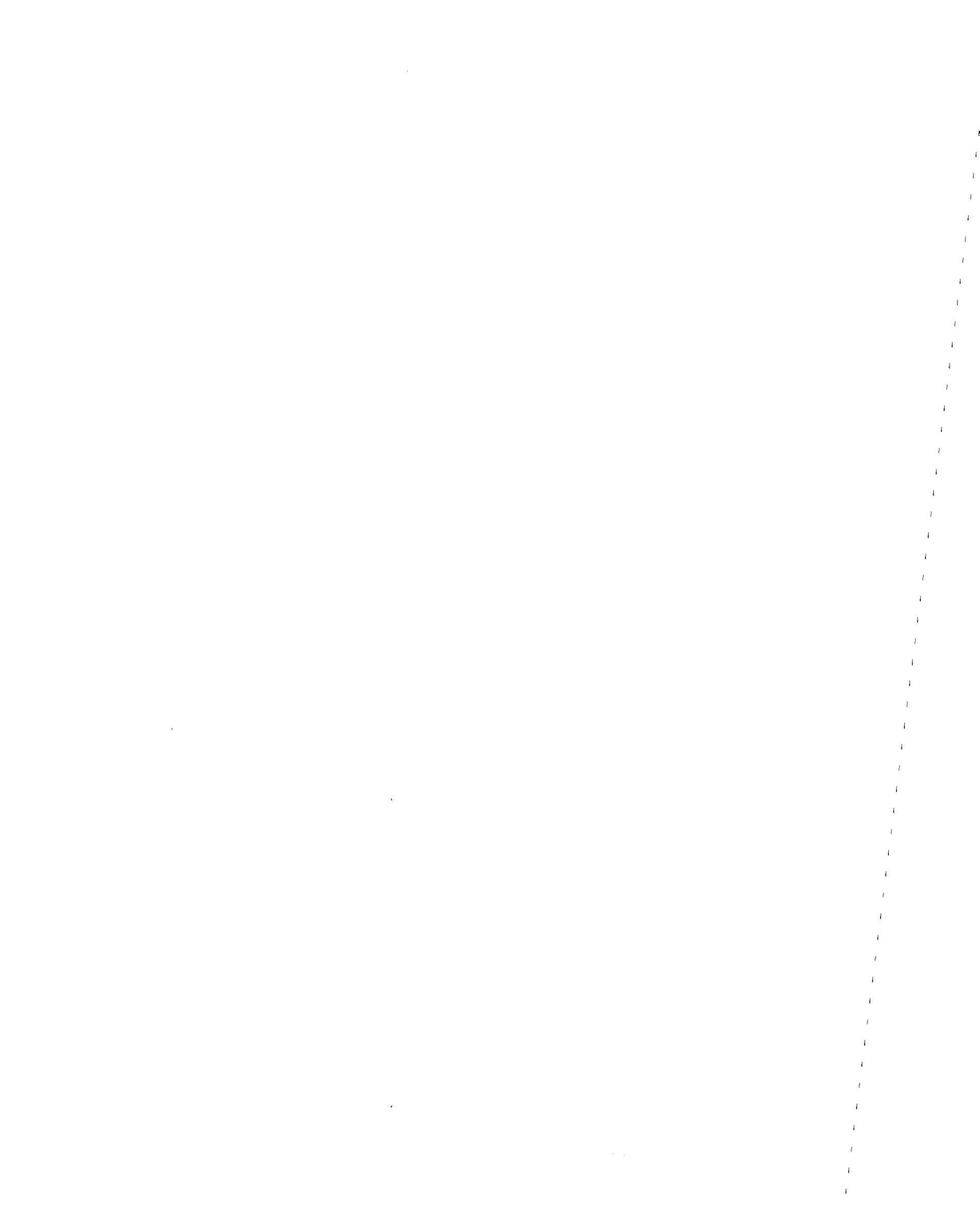
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16. Abstract (Limit: 200 words)

In order to increase the safety factor for human workers who must work in conjunction with robots, a study was performed to analyze a robotic operation at a factory and to use this analysis to propose a model containing factors which contribute to potential safety problems, such as being struck by a robot element or tooling or being caught in a pinch point. The study was also designed to develop a mathematical model relating robot speed and human reaction time to risk of injury by the robot. The site of the visit was a manufacturing company using an arc welding robot. Later two additional robots were added to the work force. Two were hydraulic and one an electromechanical version of the other two. They were to perform arc welding of steel frames for cabinets for computers. There were about 30 welds per frame. The productivity rate using these robots increased three to four times compared to manual welding. In the robot workplace there were three different types of jobs: the robot operator, the millwright and the electrician. Factors which influenced the robotic safety included speed of robot arm movement, design of the teach pendant, and movement pattern of the robot. The current workplace lacked safety devices such as safety gates, floor mats, or lock out procedures. A painting of the robot movement envelope on the floor had faded over the time.

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INTRODUCTION

The use of industrial robots in the workplace has increased significantly over the last few years. Although only limited statistics have been published on robot accidents, it is widely recognized that there are serious safety hazards with industrial robots (Tsuchiya, 1985). It is therefore difficult to evaluate the safety of robot workplaces in any detail. However, even with the general lack of accident statistics, several researchers have attempted to identify specific robot hazards. One study in Sweden investigated fifteen accidents occurring with 270 robots over a period of 2.5 years (Carlsson, Harms-Ringdahl, and Kjellen, 1979). A common cause was "pushing the wrong controls." The accident rate was estimated to be one accident per 45 robots years. This may be compared to industrial presses, previously the most hazardous industrial machines with an accident rate of one accident per 50 machine years. A study in Japan analyzed eighteen near accidents caused by industrial robots (Sugimoto, and Kawaguchi, 1983). Summarizing the results of their own investigation and the Swedish study, the authors stated that:

Most manufacturing companies are aware of the dangers of robots.

The accident rate of robots is significantly higher than for other machines. A majority of accidents occur during teaching, testing, and maintenance.

A later Swedish study (Carlsson, 1984) analyzed 36 accidents that occurred when the injured person physically contacted the robot. Twenty-eight of these accidents involved the use of "manual manipulators", which were mainly used to move material. The results of this study may therefore have limited applicability to robots. Fourteen of the accidents occurred while the operator was adjusting the flow of material

to the robot. It was assumed that in most cases the injured person had been working inside the robot's work envelope. Thirteen of the accidents occurred during programming, maintenance and start-up of the robot. These results partially support previous opinions that programming and maintenance are the most hazardous tasks.

Perceptibility of Robot Arm Movements

Robots are machines capable of complex movement patterns, and it may often be difficult for operators to both perceive and understand what is going on. It is particularly confusing when the robot arm stops as a natural sequence of the program. Sugimoto and Kawaguchi (1983) pointed out that there are so many different stop conditions that operators have difficulty in distinguishing between them, see Table 1.

Table 1. Causes for robot stoppage (Sugimoto and Kawaguchi, 1983)

- Emergency halt induced by emergency control

- Temporary halt induced by pause control

- Malfunction halt due to machine failure

- Condition halt induced by software

- Halt due to work termination

Emergency and temporary halts may be induced by the robot operator. Malfunction halts are due to machine failure, and condition halt is induced by software. Even for the experienced operator, it is difficult to understand why the robot has stopped and when it is safe to approach the robot.

To anticipate safety hazards, the robot operator should be able to perceive and react to robot arm movements in time to stop the arm before an accident or an injury can occur. It is therefore important that the speed of the robot arm movement is not so high that the operator has difficulties in perceiving the arm. Nagamachi reported the results of several experiments which investigated the perceptibility of robot arm movement as a function of speed (Nagamachi, 1984; Nagamachi and Anayama, 1983; and Nagamachi, 1986). In the first experiment, a robot arm moved at different speeds from 10 cm/sec to 50 cm/sec (4 in/sec to 20 in/sec). Subjects found that it was possible to make "work corrections" as long as the robot did not move faster than 20 cm/sec.

In a second experiment, the robot dropped a component part under the mechanical arm. Subjects were then asked to estimate the hazard in picking it up while the robot made a brief pause. Five robot pauses were investigated: 0, 1, 2, 3, and 4 seconds, and the robot moved at one of five speeds varying from 14 to 46 cm/sec (5.5 in/sec to 18.1 in/sec). The three- and four-second pauses were judged as completely safe regardless of arm speed. Nagamachi commented that in real life even the longer pauses would have been unsafe. The test subjects therefore misjudged the situation and the robot should have been turned off. According to Nagamachi, there is hence a high possibility of unsafe acts occurring even with long wait times.

In a third experiment, subjects were told to place themselves at the closest safe distance from the robot arm, while the robot arm approached at speeds varying between 14 cm/sec and 46 cm/sec (5.5 in/sec and 18.1 in/sec). For the lowest speed, the median distance was 1.3 cm and for the highest speed, 19.5 cm. Again, with the slower speed, operators had difficulties in assessing the real hazards and positioned themselves too close to the robot.

We have not been able to find any other experiments in the literature dealing with perceptibility of robot arm movement and appropriate robot arm speed. It should be

pointed out that although Nagamachi's findings are valuable, the results of the experiments are difficult to interpret. These experiments were performed in a university laboratory using students as test subjects. There are some disadvantages in this approach and Nagamachi obviously had difficulties in interpreting the results. For example, in the second experiment, Nagamachi concluded that the subjects had misjudged the situation and the robot should have been turned off. It seems likely that the motivational setting of the experiment encouraged subjects to respond that the three- or four-second pauses were safe. In a real-world environment, their judgment might have been different. One must therefore carefully examine the validity of the experimental situation. It would seem that important data could be gathered in an actual work situation with robot operators. Such an experiment could be performed in an unobtrusive manner and serve as a complement to the experiment proposed below.

The difficulties in perceiving robot arm movements were pointed out several years ago by Engelberger (1980) who observed that the size of the robot affects the perception of the movement. A small size robot gives a better sense of visual control than a larger robot, since it is easier to get a visual overview of the robot and the work environment. Obviously, not all robots are unsafe. For example, a Seiko robot used for assembly of watches handles only small objects and is not much of a threat. In contrast, a Cincinnati Milicron T3 robot is very large in size and poses much more of a threat of injury.

Standards and Guidelines for Robot Arm Speed

In order to make it easier for the operator to perceive the robot arm movement and take evasive action in time, it is important to limit the speed of the robot arm movement. Several organizations have been developing standards to regulate the maximum speed of robot arm movement. The Robotic Industries Association (1986) recently published an American National Safety Standard for industrial robots and industrial robot systems. This standard postulates that "all robots shall have a slow speed. The maximum slow speed of any part of the robot shall not exceed 25 cm (10 in) per second. The robot shall be designed and constructed so that in the event that any single, reasonably foreseeable malfunction, the speed of any individual axis shall not exceed 25 cm (10 in) per second."The same speed has been endorsed by the International Standards Organization which proposes a maximum speed of the robot arm movement of 25 cm/sec or less at the mounting flange interface. Other standards have been more conservative. The Underwriters Laboratory (U.L) has published a draft standard for industrial robots which is currently used by U.L. when a robot manufacturer contracts with U.L. for testing. This standards proposes that: "when in the teach mode, where it may be necessary for the operator to approach a robot, the maximum speed of the robot arm shall be automatically restricted to 6 inches/sec. A reliable means shall be provided to automatically limit the speed of the robot arm to 6 in/sec when in the teach mode. "This standard was based on industry experience and foreign recommendations (Winrich, 1986).

The Japanese safety guidelines state that the robot speed should "drop automatically when the operating condition has been switched over to teaching". In the interpretations of these guidelines the Japan Industrial Safety and Health Association (1985) say "it is recommendable that an industrial robot in the teaching operator mode

be automatically set to a linear velocity of not more than 14 cm/sec. . ., and that the velocity should not exceed 50 cm/sec even if the operator has changed the teaching speed (pp. 18)." It adds (p. 28) that in an actual teaching operation, the 14 cm/sec automatically selected "is changed over to a speed suitable for the job under the control of the worker. From the viewpoint of safe, therefore, the proposal is considered fully applicable. This proposal, however, persists upper as a limit value (sic) and may be lower dependant upon the job to be done."(The reader is left with some perplexity as to what is indeed required.)

According to this same publication, the 14 cm/sec (5.5 in/sec) was derived through a human factors experiment (Sugimoto, et al., 1984). In this study, subjects pressed a teach pendant button to make the robot rise but instead it moved toward him as though he had mistakenly pressed the button for "advance" rather than "up". The subject then had to release the button to halt the robot. Experimental subjects included seven male students, three females and one "aged". The time interval between the point when the robot began to move and the point when the subject released the button to stop it averaged .53 sec. Assuming a teaching speed of 14 cm/sec and a reaction time of 1.42 sec (0.53 sec + two standard deviations) it would move 19.8 cm. It was suggested that, to optimize human vision of its operation, a worker's face might be between 20 and 30 mm from the robot while teaching it. Hence, the 14 cm/sec maximum teaching speed could keep the robot from striking virtually any operator, given that he/she tried to stop it.

The 25 cm/sec (10 in/sec) limit set by RIA and ISO is clearly arbitrary. This has been recognized both by members of the RIA R1502 Committee on Human Interfaces to Robotic Systems, and the U.S. Technical Advisory Group to ISO/TC184/SC2.

Obviously, the choice of appropriate robot arm speed deserves research. It is one of the most critical design aspects of robots and has great safety implications.

The purpose of the present study was two-fold:

(1) to analyze a robotic operation at a factory and to use this analysis to propose a model containing factors which contribute to the potential safety problems such as being struck by a robot element or tooling or being caught in a pinch point.

(2) to develop a mathematical model relating robot speed and human reaction time to risk of injury by the robot. This model may be used as a theoretical framework to determine a recommended safe range of operating speeds.

We will first describe the evaluation of the robot work places and then the proposed mathematical model.

EVALUATION OF A ROBOT WORKPLACE

In order to obtain some information on the dangers of using robots, a manufacturing company was visited, and the robot operation was analyzed. The idea of using an arc welding robot was conceived by this company by the end of 1978, and a Cincinnati Milacron T3 hydraulic robot was aquired in December 1979. Later, two more robots were delivered, one identical to the first robot and one T3-746 robot which is an electromechanical version of the same robot. These robots are used exclusively for arc welding of steel frames for cabinets for computers. The large number of welds makes this a suitable application for robot welding. It has been estimated that under ideal conditions, the productivity rate could increase 3 to 4 times compared to manual welding. There are presently two robot operators. The principal investigator of this report spent six workdays at interviewing the operators and observing the work.

Task Description

The frames for the computer cabinets are approximately 3 x 5 feet and composed of tubular pieces of steel which are welded together. The pieces of steel are supplied to the working area on rolling carts. The pieces are then put into a hydraulic jig on a rotating table and tightened hydraulically. This makes the pieces fit well together. Therefore there is no reason to reprogram the location of the welds from one frame to another. The table is then rotated into the work area for welding, see Figure 1 and 2. There are approximately 30 welds on each frame. After welding is finished, the table is rotated back to the original position where the finished frame is lifted out and put on a transportation cart.
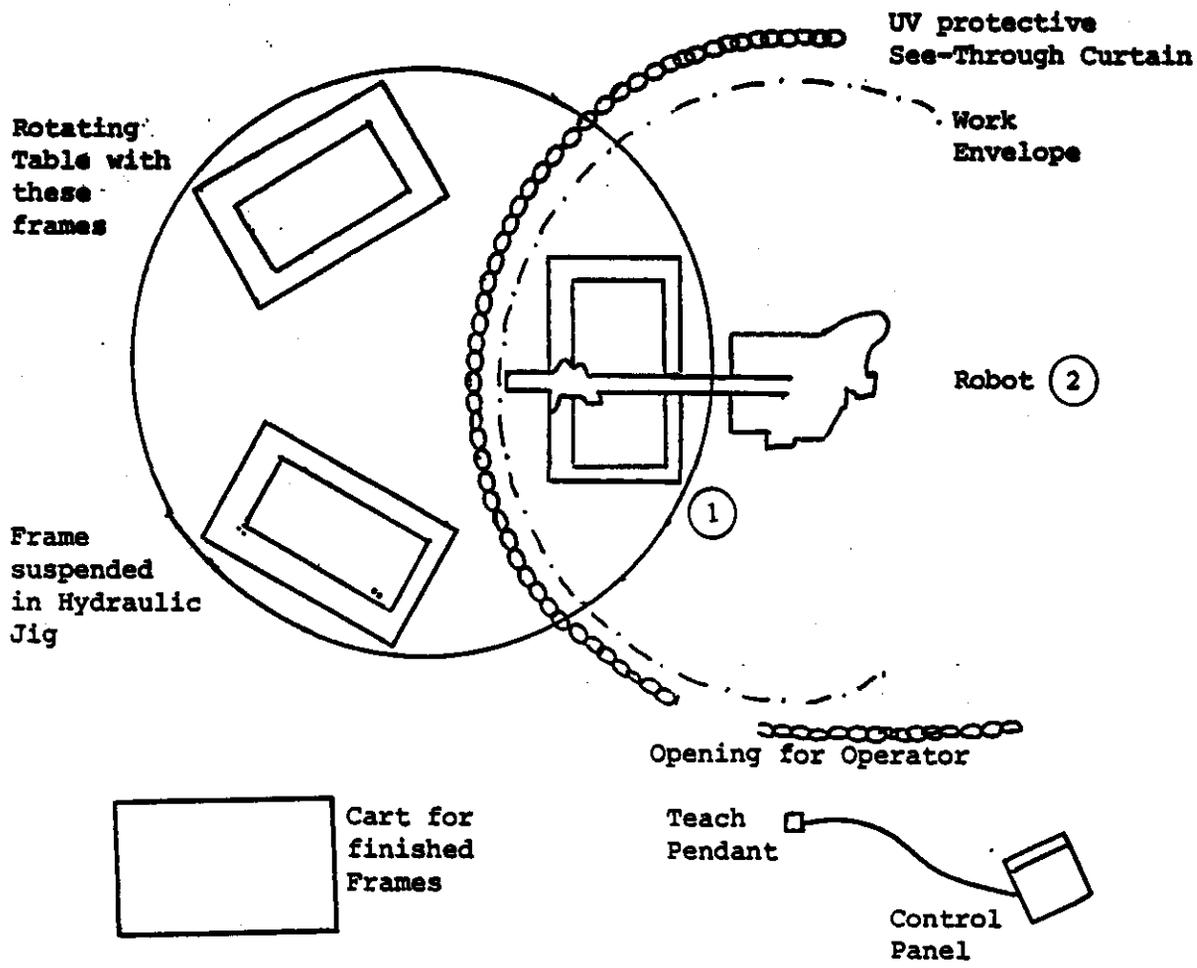
Figure 1. Robot Work Area. (1) Operator location for cleaning welding tip. (2) Operator location for readjusting welding parameters. For reprogramming welding points, the operator stands about 10-20 inches away from the welding nozzle at the end of the robot arm.
An overview of the work area is shown in Figure 2.

Figure 2.   Overview of work area. (A) The Cincinnati Milicron T3 robot is behind the yellow UV protective curtain in the upper right corner. (B) Robot behind curtain.

Description of the T^3 Robot

The Operating Control Panel has a display, several pushbutton controls with indirect lights, and key switches, see Figure 3.
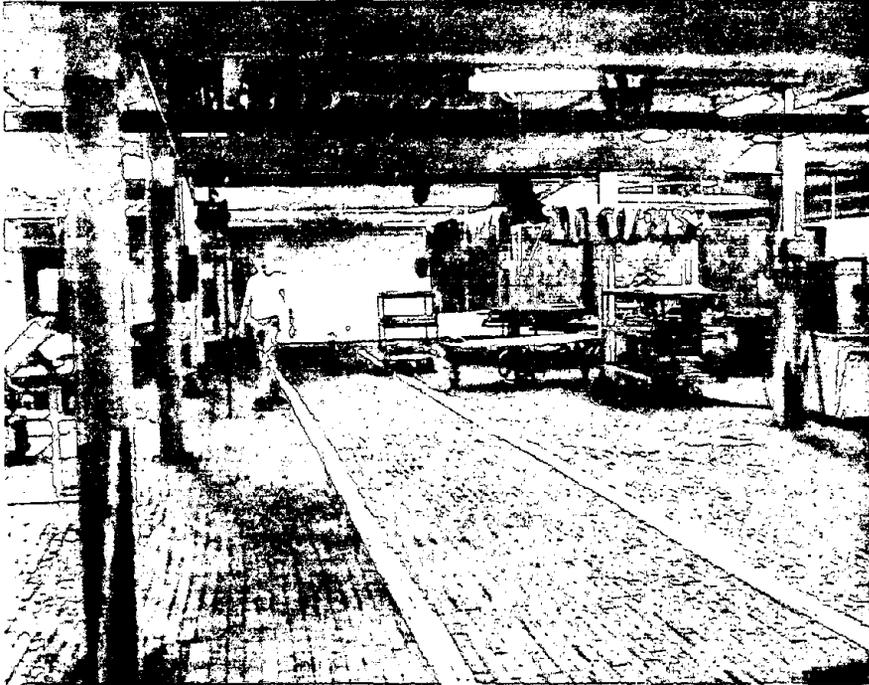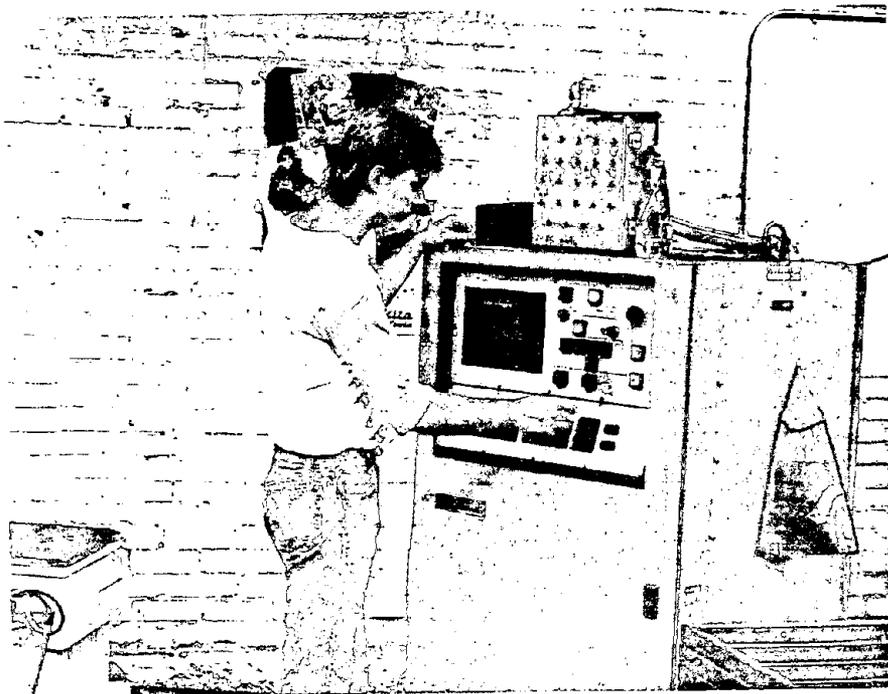


```
VF = X.X      HYD — XXX        DISPLAY 00.001


ERROR
DATA ENTRY


HOME
V(X)  = XX.XX · IN/S         X   XXX.XX   IN
TO(X) = XX.XX                Y   XXX.XX   IN
      = XX.XX                Z   XXX.XX   IN
                            D   XXX.XX,  DG
TEACH COORD = X             E   XXX.XX   DG
T1A = D (XX) T2B = D (XX)   R · XXX.XX   DG
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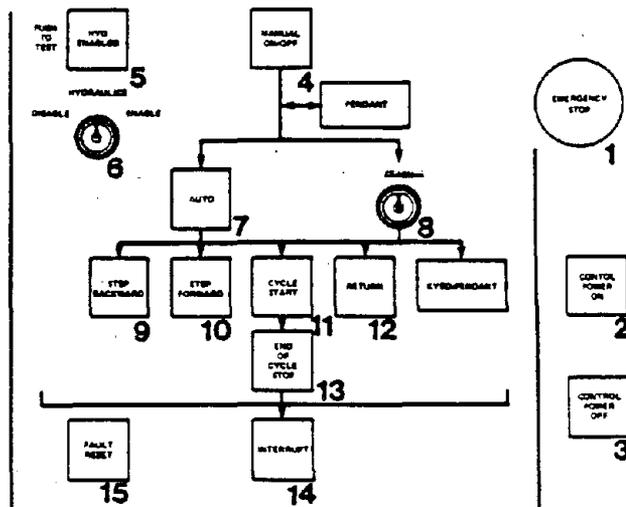
Figure 3   Operations Control Panel with Display and
Controls (A). Detail Layout of Panel (B).

The T^3 robot can move in three planes: X, Y, and Z. In and out motion is along the X axis, left and right motion along the Y axis, and up and down along the Z axis.

A hand-held pendant is used to teach the robot. The controls on the pendant are used for moving the robot into required positions, teaching of task sequence points, and entering the associated functions at those points.

Figure 4 shows, for comparison, the design of the teach pendants for the T^3 model and the T^3-746 model, both of which are used for similar tasks in this workplace. Obviously these teach pendants are very dissimilar in layout, and operation. Robot operators commented that this was confusing.

Figure 4.   Design of Teach Pendants for Cincinnati Milacron T^3
Control Pendant (A) and T^3 Model 746 (B)

Robot Interaction Tasks

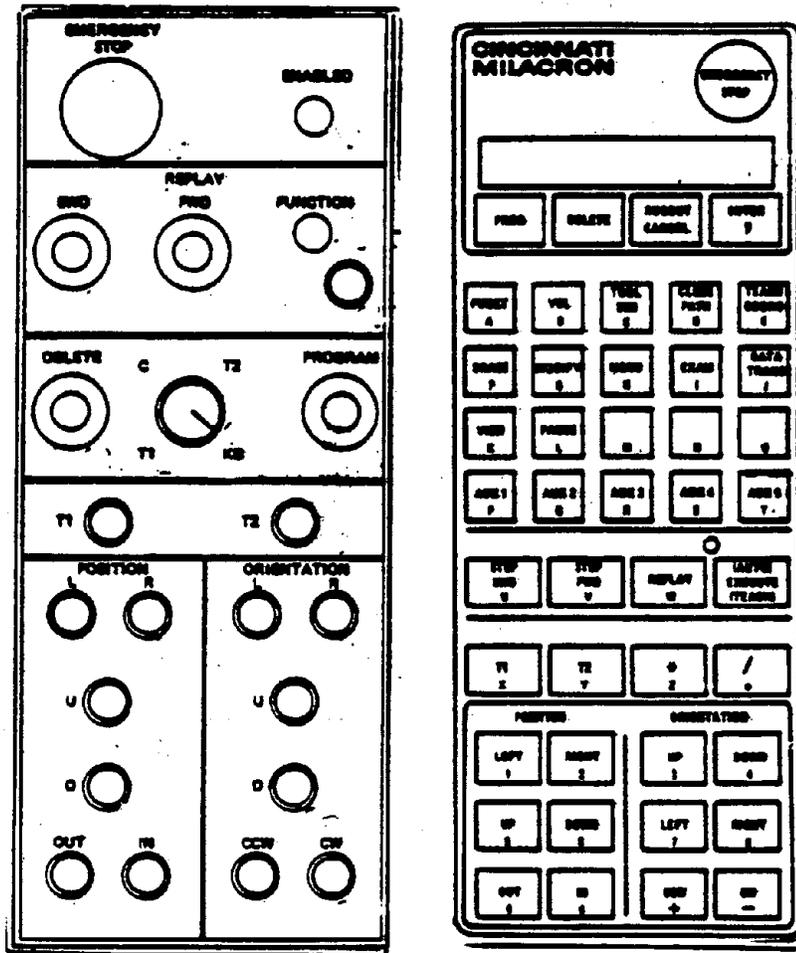There are three different types of jobs in the robot workplace: the robot operator, the millwright and the electrician. The robot operators are much more exposed to safety hazards than the millwright and the electrician. The latter rarely perform work at the robot workplaces; they are mostly called upon for preventive maintenance that occurs at a frequency of once per month or once per quarter. Hence, the two robot operators are the sole individuals who are frequently exposed to robot safety hazards.

Table 2 shows a list of tasks and task frequencies. This information was obtained by interviewing the supervisor, the robot operator, and the electrician. The frequency information in Table 2 and the rating of the tasks indicate three frequent tasks which involve close interaction with the robot. These tasks are: start up (if alignment of axes is involved), cleaning/welding tip, and (re)programming. The two potentially most dangerous tasks, cleaning welding tip and re(programming) are shown in Figure 5. A detailed task analysis is given in Tables 3, 4 and 5, which analyzes operator input (control action), display feedback, robot movement, operator location and potential safety problems. The information was obtained through an "observational interview."The robot was shut down and then started up. The operators explained each step in the task sequence, the display formation and how to use the controls. This procedure was repeated six times for each task, thereby obtaining a cross-validation of the task analysis.

Table 2. Frequency of Robot Interactive Tasks

Operator = Op, Electrician = El, Millwright = MW

| Task	Performed by	Frequency	Close to Robot Arm
Start up	Op	Daily	Yes
Clean welding tip	Op	30 per day	Yes
Replace wire	Op	2 per week	Yes
Reprogramming Welding Points	Op	Weekly	Yes
Programing new job	Op	2 per year	Yes
Replace hydraulic hoses	Op	2 per year	Yes
Adjust welding parameters	Op	Weekly	Yes
Examine all hydraulic lines	Op	Monthly	Yes
Shut off	Op	Daily	No
Clean work arm	Op	Daily	No
Enter hour motor reading	Op	Daily	No
Load parts in jig	Op	15 per day	No
Inspect welding quality	Op	15 per day	No
Lift welded frame	Op	15 per day	No
Check oil levels	Op	Weekly	No
Change fluid filter	MW	Quarterly	No
Check for leaks, loose mountings	MW	Quarterly	No
Obtain oil sample for analysis	MW	Semiannually	No
Lubricate motor, check bolts	MW	Quarterly	No
Clean air filter and fans	El	Monthly	No
Inspect wiring, relays, contacts	El	Quarterly	No
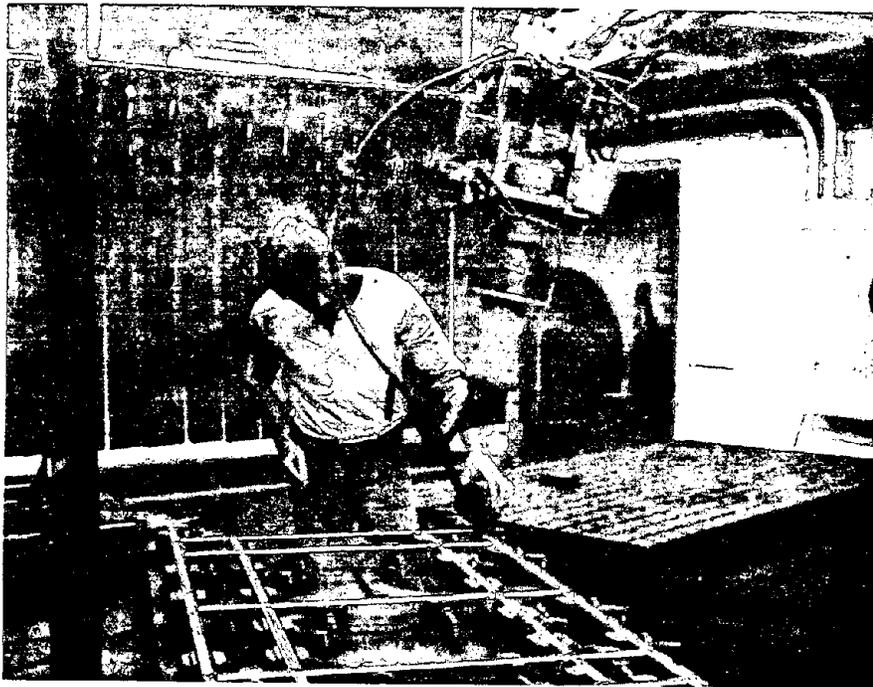
Figure 5   (A) Cleaning the Welding tip. (B) Typical posture for reprogramming the location of welding spots.

Table 3. Start Up

Subtask	Operator Input	Display Feedback	Robot Movement	Operator Location	Safety Problems
Start Robot	Turn key to Enable	Ready Systems Info	Home Position	Control panel	-
	Press "manual on"	No change	-	Control panel	-
	-	Aligned 1 2 3 4 5 6 x x x x	-	-	-
Let run for 10 minutes to heat oil	-	Look at temperature guage Check oil level	-	Control panel	-
Select robot operator	Press key for job	-	-	Control panel	-
Align axis	Press "out" on Teach Pendant Press "right" on Teach Pendant	1 2 3 4 5 6 x x x x x 1 2 3 4 5 6 x x x x x x	Moves out Moves right	Near robot to observe alignment mark	Yes
Select Mode	Press "auto"	Hyd-on !Error W-0115 Aligned 1 2 3 4 5 6 x x x x x x	-	Control Panel	-
Bypass error code	Press "enter"	VF=1.0 Hyd-on at 0.001 (home position)	Slight movement due to actuation of hydraulic lines	Control Panel	-
Start Robot	Press "cycle start"	VF=1.0 Hyd-on at 6.001	To work start position.	Control Panel	-

Table 4. Teach Mode

Subtask	Operator Input	Display Feedback	Robot Movement	Operator Location	Safety Problems
Select Mode	Put control panel key in teach lock. Turn key.	Hyd-on! Error W-0115 Aligned 1 2 3 4 5 6 x x x x x x	-	Control Panel	-
Bypass Error code	Press "Enter"	VF=1.0 Hyd-on Display 0.001 Home V(1)=17.6 in/m TD(1)=4.00 x=28.28 in y=0.00 in z=-35.72 in D=179.88 Dg E=0.00 Dg R=0.00 Dg Teach Coord = TIA=N- T2A=N-	-	Control Panel	-
Find point to program	Press "FWD" to Cycle Start	VF=1.0 Hyd-on Display 0.009 Cycle Start V(8)=800.2 in/m TD=27.71 Teach Coord=R TIA=N- T2A=N- x =67.36 in y=0.64 in z=-0.01 in D=116.42 Dg E=0.74 Dg R=0.00 Dg	Moves to Cycle Start Teach Pendant	Close to robot arm	Yes
a) using teach pendant	Press "FWD" until point is found	VF=1.0 Hyd-on Display 6.007 NOP V(8)=800.2 in/m TD=21.71 Teach Coord = R TIA=N- T2A=N+ x=61.98 y=30.81 in z=014.93 in D=129.36 Dg E=67.44 Dg R=49.60 Dg	Moves to point 6.007 Pendant	Close to robot arm with Teach	Yes

Subtask	Operator Input	Display Feedback	Robot Movement	Operator Location	Safety problems
b) using menu on display	Key "Menu"	VF=1.0 Hyd-on Display 0.009 Menu: Copy Go To Distance Mirror Floppy	Control Panel	-	-
	Key G, 6007	VF=1.0 Hyd-on Display 6.007 NOP V(8)=800.2 in/m TD=21.71 Teach Coord=R T1A=N- T2A=N+ x=61.98 in y=30.81 in z=-14.93 in D=129.36 Dg E=67.44 Dg R=49.60 Dg	Moves to point 6.007	Control Panel	-
a) change coordinate e.g. z-co-ordinate	Press "Delete" on Teach Pendant Move z-coordinate with TP keys Press "Program"	Same as above except change in coordinate values	Moves to programmed point	Standing at task with pendant in hand	Yes
b) change speed	Press "Delete" on TP	Veloc. in/min 1 = 17.1 2 = 18.1 3 = 18.5 4 = 16.2 5 = 170.0 6 = 225.2 7 = 550.0 8 = 800.2 9 = no more F = Vel. Factor	-	At Control Panel	

Subtask	Operator Input	Display Feedback	Robot Movement	Operator Location	Safety Problems
	Press # for velocity, e.g., 2 Press "Enter" Press "Program"	VF = 1.0 Hyd-on Display 6.007 NOP x=61.98 in V(2) = 18.1 y=30.81 in TD = 21.71 z=-1493 in Teach Coord=R D=129.36 Dg T1A=N1 T2A=N+ E=67.44 Dg R=49.60 Dg	-	At Teach Pendant	Yes
c) change Tool dimension	Only if different end-effector is used				
d) change function	Press "Delete" on TP Press "function" on Keyboard	VF=1.0 Hyd-on From 6.007 Function *NOP *Disable *Delay *Velocity *Output *DAC Tool *Adjust *Wait *Perform *Search *External	-	At Control Panel	

	Choose e.g.
	NOP
	
	Press "Enter"
	Press "Program"
	Etc.
		VF=1.0 Hyd-on Display
		NOP
		
		V(2):18.1 x=61.98 in
		TD=21.71 y=30.31 in
		Teach Coord = R z=-14.93 in
		T1A=N- T2A=N+ D=129.36 Dg
		    E=67.44 Dg
		    R=49.60 Dg
			-	At Control Panel	

Table 5. Clean Tip to Control Buildup of Welding Splatter

Subtask	Operator Input	Display Feedback	Robot Movement	Operator Location	Safety Problems
	Press "Interrupt" Put nozzle in can of "tip dip"	VF=1.0 Hyd-On Display 6.007 NOP V(2)=18.1 RD=21.71 Teach Coord=R x=61.98 in y=30.31 in z=-14.93 in D=129.36 Dg E=67.44 Dg R=49.60 Dg	Robot stops	Robot arm in outer perimeter	The operator location minimizes risk but cannot reach emergency stop button

Safety Considerations

As we briefly mentioned previously, there are several factors that influence robotic safety for this task including: speed of robot arm movement, design of the teach pendant, and movement pattern of the robot.

The two robot operators were interviewed with respect to possible problems with safety hazards. Most of the concerns seemed to concentrate on welding hazards and less on the moving robot arm.

Arc Welding

There is a transparent yellow curtain hanging around the robot installation. This is supposed to protect operators from UV radiation. However, one operator complained about dry eyes due to an accumulative effect of what he perceived was exposure to UV radiation throughout the day. After work, his eyes often felt very dry. There was also some problem with welding splatter which seems to affect the arms more than the face. We did not try to verify these complaints, since they are beyond the scope of this report

Robot Movement

The operators acknowledged that there may be safety hazards with the moving arm. However, there had been no accidents reported, although there had been a close call during programming. This involved a power disruption when the robot arm suddenly moved downwards.

There are three basic speeds that are used for programming robot movements. The lowest speed 0.7 cm/sec (0.3 in/sec), is used for welding. The intermediate speed, 7-9 cm/sec (~3 in/sec) is used to move the arm from a twisted position. Use of higher speed could impose excessive strain on the joints. The highest speed, 23-38 cm/sec (9-15 in/sec) is used for travel between welds.

The operators use a teaching velocity of 0.7 cm/sec (0.3 in/sec), but a velocity factor may be used to alter the speed. For example, a velocity factor of 3 would change the speed of the robot arm from 0.7 cm/sec to 2.1 cm/sec. This velocity factor may be de-activated if the machine reaches a speed that may damage the robot.

The operators complained about the different design of the teach pendants for the servo-electric and hydraulic robots. Although both robots are Cincinnati Milicron T3 robots, the designs of the operator consols and the teach pendants are different, see Figure 4. Even more disturbing may be the fact that the movement patterns of the robots are different. The 3-roll wrist of the T3-746 makes the movement patterns very different to the basic T3 model.

It may therefore be appropriate to extend the research questions from speed of robot arm to include pattern of movements and how robots are programmed to move. Helander (1986) pointed out that a "graceful" movement pattern may be easier to predict than a movement along the basic coodinates. This could be an issue for both manufacturers and programmers.

Finally, the operators pointed out that the teach pendant for the T3-746 has keys without touch feedback. It is therefore difficult to know if individual keys have been activated.

Ergonomic Problems

Safety is a systems problem and each workstation deserves analysis of broader issues than those traditionally labeled as safety. Table 6 gives an overview of both positive and negative ergonomics aspects of the workplace and are commented upon below.

The most positive aspect about this workplace was that operators had been selected and given adequate training for the job. The operators were well informed

Table 6. Positive and Negative Ergonomics Aspects of the Workplace

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Positive Aspects

- Operators selected for the task and well-trained

- Good housekeeping

- Rotating table allows working outside robot envelope

- Welding curtain reduces splatter and intrusion

Negative Aspects

- Lack of safety devices

- Non-uniform design of teach pendants

- Different motion patterns for robots

- Ambient illumination level too low

- Slipping hazard due to oily floor

- Manual lifting of 80-pound frames

- No touch feedback on teach pendant

---

about the technical aspects of the robot as well as safety issues. Furthermore, the workplace was well organized and the housekeeping was mostly good. There are, however, several negative aspects, some relating to the design of the robot and some to the design of the workplace.

We have already mentioned the confusion that may arise from different design of teach pendants and moving patterns. This may be particularly confusing to an operator who has been trained on one of the robots and is later asked to operate the other robot. There is a tendency for operators to revert to the originally trained pattern, so-called negative transfer of training. This is particularly common in stressful situations when the operator has little time to plan his/her control actions and must make quick decisions.

One of the most alarming aspects of this workplace is the lack of safety devices, such as safety gates, floor mats, lock-out procedures, etc. The operators do not seem to think that these are necessary. In fact, safety devices are considered a nuisance considering the required frequent cleaning of the welding nozzle. The only safety measure taken was to paint the projection of the robot movement envelope on the floor. However, the paint had worn and it was not possible to see the contours of the movement envelope. Also, the ambient illumination level was approximately 100-200 lux, which we consider too low for this type of operation.

The welded frames are lifted from the welding jig to a push cart. Since the frames weigh about 80 lbs and are difficult to handle, there are some concerns about the possibility of back injuries. There is a need to aid the lifting of the 80-pound finished frames. Presently this lifting is performed while twisting the body to the side, which is particularly hazardous. It should be possible to position carts or obtain lifting aids to make these lifts easier.

Finally, reports of robot accidents seem to indicate that many of the accidents occur during the performance of unusual or non-frequent tasks. It is therefore difficult to

present a complete analysis of all the safety aspects. This report has concentrated on the obvious safety hazards, such that are implied by the design of equipment and tasks. It is more difficult to analyze the organizational or procedural hazards in an industrial environment. These have as their basis the interaction between employees and management, which are difficult to observe both for the cursory observer and the employee himself. Many of the safety hazards can be avoided by prescribing rules that would make infrequent (and dangerous) events even less frequent. We have not addressed these issues here.

A MODEL OF HUMAN REACTION TIME AND EMERGENCY BEHAVIOR

The model to be developed below is conceptually similar to the Model Human Processor (Card, Moran, and Newell, 1983). The Model Human Processor is divided into three interacting subsystems: (1) the perceptual system, (2) the cognitive system, and (3) the motor system. The division of information processing into three stages is somewhat arbitrary. One may well formalize the information processing using additional stages, such as stimulus detection, neural transmit time, brain recognition time and decision making time. The most appropriate subdivision depends on the purpose of the model. For our present objective, that of modelling human emergency reactions to a moving robot arm, it may be practical to group stimulus detection, neural transmit time, and brain recognition time into one unit, referred to as the perceptual processor. The cognitive processor corresponds to the decision making time component and the motor processor will correspond to the motor response time component of the reaction time. However, depending on the approach taken to experimentally verify or measure either of these components, it may be practical to either consider the sum of all of these components (the reaction) or only the individual parts.

In the current approach, the perceptual system must detect that the robot is moving and recognize this movement as potentially dangerous. The cognitive processor must decide whether it is necessary to push an emergency stop button on the teach pendant. Finally, moving the hand to the emergency stop will be accomplished by commands from the motor processor.

The Total time (T) for completion of the reaction time may be written as the sum of perceptual processor time (T_P), decision (cognitive processor) time (T_D), and motor processor time (T_M). Thus total time equals:

$$T = T_P + T_D + T_M \qquad\qquad (1)$$

We propose that a curve fitting multiple regression technique be used to estimate T_P, the theory of signal detection be used to model T_D, and that Fitts' law be used to estimate T_M. Each component of the model will be expanded below. We first estimate the overall probability of risk employing the simplified model presented above.

Consider time zero to be the beginning of an unexpected and potentially dangerous signal (or robot movement). Let the velocity of the robot movement relative to the human operator be denoted by v and the distance to the operator be denoted by d. If an appropriate response is not taken in time, then injury (or physical contact) can occur in $T_I = v/d$ time units.

To avoid injury (or physical contact) the operator must complete a proper response before time T_I. If $T = T_P + T_D + T_M \geq T_I$ then the response is too late. Written another way, regardless of the decision made, if $T_P + T_D \geq T_I - T_M$ then injury results. Note that if the decision is made than there is signal (threat) that there will also be motor response. If the decision is that there is no signal, then there is no motor response. Therefore, if $T_P + T_D \leq T_I - T_M$ but the decision is that 'no signal' is present, then injury will also occur. Assuming a signal is present, we can compute the overall risk using the two mutually exclusive cases outlined above:
Assuming that

$$p(Risk) = p(A) + p(B), \qquad\qquad (2)$$

$p(A) = \text{probability of late response} = p(T_P + T_D \geq T_I - T_M)$

$p(B) = \text{probability of wrong decision} = p(T_P + T_D \leq T_I - T_M)$

As we indicated above, the risk could involve a wide spectrum of events from physical injury to a harmless touch by the robot. From a safety prevention point of view one must avoid any of these events. Circumstantial environmental factors determine the outcome, and it does not seem reasonable to model or predict the type of accident, nor could such a model be experimentally verified due to ethical considerations.

To obtain an empirically justifiable model whose predictive strength could be tested in future research projects, each component of the Risk equation (2) must be fully developed. Below we propose equations for experimental validation of T_P, T_D and T_M.

Perceptual Processor Time T_P

The time to detect, transmit and recognize a potentially dangerous robot movement is denoted by T_P. Perceptual processing time T_P varies inversely with stimulus intensity and typically lies in the range of 50-200 msec. (Card et al., 1983). The range can easily be extended in extreme situations. Here, the stimulus intensity is a function of many parameters including: robot velocity, angular velocity, size of robot arm, visual contrast of robot arm, direction of robot arm movement, and the primary task of the operator. We will first combine these parameters into what we define to be 'perceptual discriminability' and later expand the resultant model.

Define λ to be a measure of perceptual discriminability. Also let S be a minimum threshold of discriminability (below which no reasonable expectation of perception is possible, e.g. when the operator has his/her back turned to robot). We can then hypothesize a relationship between T_P and λ to be as shown in Figure 6.
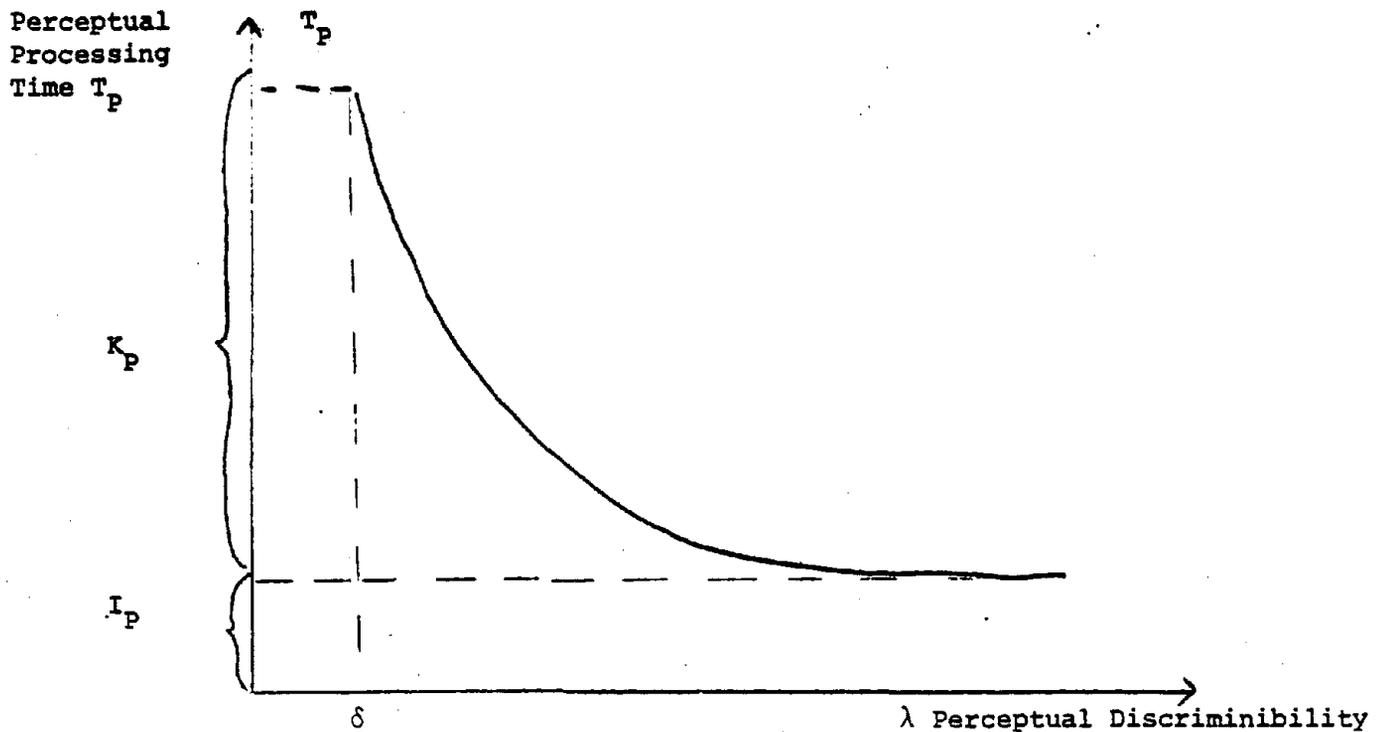
Perceptual
Processing
Time T_P

Figure 6. T_P as a Function of λ

Ip represents an asymptote for the minimal perceptual processor time (greater than neural transmit time). For example, Ip may be 50 msecs. Let Ip + Kp be an upper limit on Tp at a threshold δ (e.g. 300 msec.). Then the following model can be used to approximate the curve:

$$Tp = Ip + Kpe^{-(\lambda-\delta)} \tag{3}$$

As $\lambda \to \delta$ Tp $\to$ Ip + Kp. As $\lambda \to \infty$, Tp $\to$ Ip.

Using the above model, there is a one-to-one relationship between Tp and λ with an inverse relationship present. The real concern is thus how to relate λ (perceptual discriminability) to the numerous parameters of concern. We now propose to expand the model by representing λ as a function of these parameters.

Let λ_i denote an important parameter or component of perceptual discriminability. For example; λ_v, λ_s, λ_{PT}, λ_c could denote parameters relating to relative velocity (v), size (s), primary task (pt), and visual contrast (vc). Now λ can be written as a function of λ_i, i=1,...,n.

$$\lambda = f(\lambda_v, \lambda_s, \lambda_{pt}, \lambda_{vC}...)$$

The proper functional form of λ needs to be determined by a statistical fit of model coefficients. Our approach is to logically model each component and then find an appropriately weighted sum to approximate λ:

$$\lambda = \sum_{i=1}^{n} w_i \lambda_i \tag{4}$$

where $\lambda_i = g(i)$; i=1,...,n.

For example, discriminability due to velocity may be expected to be of the form:

$$\lambda_v = av^2 + bv + c \tag{5}$$

with unknown coefficients a, b and c.

The relationship with size of the robot arm should also be one in which discriminability may increase more than linearly with size.

Note that by replacing a, b and c by a/w_v, b/w_v and c/w_v, the weights in equation (4) become unnecessary.

The most difficult component to fit would be the effect of the primary task. We propose below to conduct a number of experiments with significantly different primary tasks (few demands to highly demanding) while varying velocities and other parameters to study this effect. Some experimental suggestions are given in a later section of this report.

An example of the model, including the usual error term, $\varepsilon_p \sim N(0, \delta^2)$ could look as follows for a given primary task:

$$T_P = I_P + K_P \, e^{-\lambda} + \varepsilon_p \qquad (6)$$

$$\text{where } \lambda = a_v\lambda_v^2 + b_v\lambda_v + a_s\lambda_s^2 + b_s\lambda_s + a_c\lambda_c^2 + b_c\lambda_c + c \qquad (7)$$

Motor Processor Time T_M

Our model of the motor processing time could be a simple one assuming an appropriately designed teach pendant. The hand movement to an emergency stop button can be modeled using Welford's (1968) variant of Fitt's law:

$$T_M = I_M \log_2 (D/S + .5) \qquad (8)$$

where S = target (button size)

D = distance of hand to target

I_M = a constant typically ranging from 70-120 msec.

In the proposed experiments, using the above model with a simple movement to a stop button will help us to separate T_M from total time $T = T_P + T_D + T_M$. This will allow us to fit the more difficult components which are functions of numerous parameters (eg. T_P).

Decision Making (Cognitive Processor) Time T_D

Most of the complicating factors regarding reaction time have been incorporated earlier in our model of the perceptual processor. T_P includes the time to detect, transmit and recognize a potentially dangerous robot movement. Given the earlier development of T_D, we can model cognitive processing time as the decision making time to choose between only two alternatives: hit the stop button or do not. (Other decisions, e.g. "run", are certainly possible for an untrained operator and could easily be incorporated by extending our model). With only two alternatives, and the most relevant factors already being considered in T_D, we will equate T_D to a constant I_D which denotes individual differences.

Recall that the second term of our expression for risk is the probability that a decision is made in time $(T_P + T_D \leq T_I)$ but that the decision was 'no signal' when one was indeed present. Below, we review the relevant concepts from the Theory of Signal Detection (TSD) to develop a model for determining this probability (Drury, Karwan and Vanderwarker, 1986).

TSD is a normative theory showing how an operator would choose and adjust a criterion for responding to "signal" (equivalent to dangerous robot movement) or "noise" (equivalent to safe robot movement). TSD models the operator as making a choice of

whether the current stimulus intensity (x) could best be characterized as coming from one of two distributions:

N -- distribution of intensity given that only noise (N), safe robot movement, was present.

SN -- distribution of intensity given that a signal (S), unsafe robot movement, was present as well as noise (N).

The decision situation is as shown in Figure 7, where the four shaded areas represent the probabilities of the four outcomes:

Hit -- Operator responds "signal" when SN is true

Miss -- Operator responds "noise" when SN is true

False Alarm -- Operator responds "signal" when N is true

Correct Accept -- Operator responds "noise" when N is true.

The practical implications of these situations are the following:

For a "hit", the operator responds to the signal so that he/she can press the stop button in time to prevent the accident.

For a "miss", the operator fails to detect the unsafe movement. As a consequence the operator may be "hit" by the robot arm.

For a "false alarm", the operator thinks that there is an unsafe robot movement, when in fact it is safe. The operator thereby hits the stop button in error.

Finally for a "correct accept" the operator does not take any action in response to a safe robot movement. He/she does not hit the stop button, which is a correct decision.
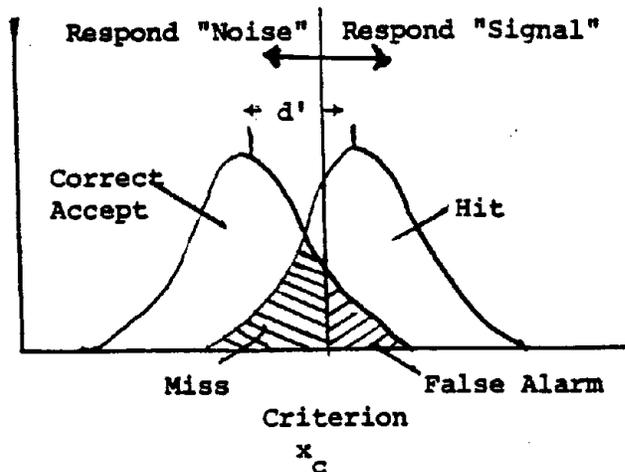
Figure 7. Decision Variables and Outcomes in TSD.

Choice of the value of the x which marks the criterion or cut-off between the "signal" and "noise" responses is made according to both the prior probability of a signal and the costs and payoffs associated with the outcomes. The actual criterion, x_c, would be expected to follow the optimum criterion β where the value of β is found as a function of the rate of unsafe movements, p', and the costs and payoffs:

a = value of not stopping safe robot movement (correct

acceptance)

b = cost of not stopping dangerous robot movement (miss)

c = cost of stopping safe robot movement (false alarm)

d = value of stopping dangerous robot movement (correct

rejection)

Using these terms, β is given by

$$\beta = \left(\frac{1-p'}{p'} \right) \left(\frac{a-c}{d-b} \right) = \frac{1-p'}{p'} \quad g \tag{9}$$

where g is $(a-c)/(d-b)$ and represents the relative cost of the decisions on safe movements to the decisions on dangerous movements. How well the operator follows in choosing x_C can be modelled by considering the observer's conservatism. It has been found in a number of studies that human signal detectors tend to choose less extreme values of x_C than the normative theory would predict (Drury, 1978). At $\beta = 1$, inspectors choose $x_C = 1$ but for $\beta < 1$ they choose $x_C > \beta$ and for $\beta > 1$ they choose $x_C < \beta$. A suitable model of this conservatism is given as:

$$x_C = m\beta + (1-m) \tag{10}$$

where m represents the conservatism, ranging between $m = 0$ for extreme conservatism and $m = 1$ for no conservatism. Another way of conceptualizing m is as the inspector's degree of sensitivity to the costs and probability changes demanded in Equation (9).

TSD is not just concerned with the choice of criterion but also with the ability of discriminating between signal and noise. In general, the ability to discriminate is defined as the area under the Receiver Operating Characteristic (ROC) curve which plots probability of Hit against probability False Alarm. For the special case of signal and noise distributions being normal and of equal variance, then the ability to discriminate can be defined as the difference in means of these two distributions, measured in terms of their common standard deviation. This leads to the following computational formula:

discriminability $= d' = z(p_1) + z(p_2)$

where $p_1 = p$ (correct acceptance) $=$

$1 - p$ (False alarm)

$p_2 = p$ (correct rejection) $= p(\text{hit})$,

and $z(p_1)$, $z(p_2)$ are their corresponding normal deviates.

Here a <u>hit</u> denotes stopping a dangerous robot signal. A <u>miss</u> indicates that the operator could be 'hit' by the robot arm.

For the criterion x_C, the computational formula is:

$$x_C = \frac{f[z(p_2)]}{f[z(p_I)]}$$

where $f[z(p_I)]$ is the normal ordinate corresponding to p_I and similarly for p_2. From the definition of the normal ordinate, this reduces to:

$$x_C = \exp\left[\frac{z(p_1)^2}{2} - \frac{z(p_2)^2}{2}\right] \tag{11}$$

If we know the discriminability of an operator, d', then we can work backwards to find the operator's overall performance (p_I, p_2) in terms of their normal deviates using Equations (9), (I0) and (11)

$$z(p1) = \frac{d'}{2} + \frac{1}{d'} \operatorname{Log_c}\left[m\ (\frac{1-p'}{p'})g + 1-m\right] \tag{12}$$

and

$$z(p2) = \frac{d'}{2} + \frac{1}{d'} \operatorname{Log_c}\left[m\ (\frac{1-p'}{p'})g + 1-m\right] \tag{13}$$

Note that the rate of the signal (alternatively the low probability of dangerous robot movement) appears explicitly in both equations (12) and (13).

A great advantage of TSD is that from empirical measures of p_1 and p_2, both of which co-vary, it is possible to calculate two other measures, d' and x_C which are

independent. Here d' is a measure of discriminability uninfluenced by the particular costs, payoffs and prior probabilities while x_c is a measure of criterion independent of the operators ability to discriminate between signal and noise.

The cost/payoff ratio g can be changed by management. Changing g involves instructions and feedback to the operators whereas changing d' must involve changes such as to conspicuity (lighting) or skill (training).

In our context, misses resulting in accidents can occur if an operator perceives a high penalty to starting up the robot after a stop button is activated. If pressure exists to 'keep the line moving', then an inappropriately high criterion value, may be employed.

The operators sensitivity irrespective of decisional manipulations of cost/payoff factor δ, is denoted by d'. In our context d' should be a function if all of the parameters we incorporated in modeling perceptual discriminability. Our hypothesis is that d' may be well represented by a simple function of λ (perceptual discriminability). Given a good statistical fit to the many parameters comprising λ and data collected on correct responses and hits, one would first try to fit d' as a linear function of λ:

$$d' = a\lambda + b$$

Being able to predict d' as a function of perceptual discriminability would allow us to predict the probability of a missed signal resulting in injury.

It should be observed that these fairly theoretical models have the main purpose of supplying a frame of reference for laboratory experimentation. The perceptual and the cognitive (decision making) part of the information processing may often be difficult to distinguish in experiments. Although we understand conceptually that these entities exist, it may be impractical to observe and measure them experimentally as seperate units. As we have noted above, it may then be possible to incorporate the perceptual

elements in d'. An easily perceived arm movement would imply a large d' and an arm movement that is difficult to perceive would imply a small d'. It is then difficult to distinguish between the noise and signal plus noise distributions.

EXPERIMENTS TO DETERMINE MODEL COEFFICIENTS

In this section, we briefly outline the types of experiments required to determine the appropriateness of the model developed earlier. This section is not meant as a proposal of a detailed experimental design. It is included to demonstrate how the previous model could be validated. A full proposal would need to address methodological and statistical issues in better detail. We propose that the model be validated with three experiments: a motor processor experiment, a perceptual experiment, and a decision making experiment.

Motor Processor Experiment

The model of reaction times, as previously discussed, assumes a simple movement to a stop button on an appropriately designed teach pendant. Subjects in our laboratory would first perform such a repetitive stopping task to calibrate Fitt's law for motor processing time:

$$T_M = I_M \log_2(D/S+.5) + \varepsilon_M \tag{14}$$

where I_M is a constant to be determined,

D is the distance of movement

S is the size of the stop button.

and $\varepsilon_M \sim N(0, \sigma^2)$ is an error term.

The value of T_M can be used in the following experiments to determine the more complicated functions for T_P and T_D.

Perceptual Processor Experiment

The major factors influencing reaction time have been incorporated in the expression for perceptual processing time, T_P. The decision making time, T_D, and the motor time, T_M would be treated as constants in this experiment.

$$T_P = T - T_M - T_D$$

Here we would vary the primary task, so that the operator would have as the primary task either to operate the teach pendant or perform a data entry task on a terminal located close to the robot, in which case observing the robot would be a secondary task. These two taks are typical for the types of interactions that operators have with robots. The parameters governing perceptual discriminability would also be varied. Factors to be incorporated in this experiment would include relative velocity of the robot arm, size and color of items held (e.g. colored foam squares which could approach but not actually reach the operator), angle of approach, etc. Nonlinear regression techniques could then be employed to fit the response time model for T_P as outlined above.

Decision Making

The experiment to determine the risk involved in making the wrong decision (recall our model using the Theory of Signal Detection) would be complex. Signals could not be sent frequently or else they would soon fail to be 'unexpected' events. Careful calibration of the random generation of signals would be required in lengthy experimental sessions. Different types of signals (velocity, arm size, etc.) would be factors in the experiment as well as frequency of signals. One would need to assume that a missed signal was the result of the wrong decision if average reaction time, or

some measure of $T_P + T_D + T_M$, was less than the time required to stop the signal (recall d/v, given a fit of $\overset{\bullet}{T}$ including an error term, one could calculate the probability that $T > d/v$). The fraction of hits and misses due to a wrong decision would be an estimate for the probability of hits and misses used to determine d' in our TSD model. d' could then be fit to the measure of perceptual discriminability λ as proposed in the model development.

REFERENCES

Card, S.K., Moran, T.P., and Newell, A. (1983). The Psychology of Human-Computer Interaction. Hillsdale, N.J.: Lawrence Erlbaum.

Carlsson, J., Harms-Ringdahl, L., Kjellen, U., (1979). Industrial robots and accidents at work. Stockholm: Royal Institute of Technology.

Drury, C.G., (1978). Integrating human factors models into statistical quality control. Human Factors, 20, 561-572.

Drury, C.G., Karwan, M.H., and Vanderwarker, D.R. (1986). The two-inspector problem. IIE Transaction, June 1986, 174-181.

Engelberger, J.F., (1980) Robots in practice. New York, NY: American Management Association.

Helander, M.G., (in press). Ergonomic principles in design of jobs and workplaces. In Dorf, R.C., and Nof, S.Y., (Eds.) Encyclopedia of Robotics. New York, NY: Wiley.

International Standards Association, (1986). Documentation N59 of ISO/TC184/SC2/WG3. New York, NY: American National Standards Institute.

Japan Industrial Safety and Health Association, (1985). An interpretation of the technical guidance on safety standards in the use, etc., of industrial robots. Tokyo, Japan: Author.

Nagamachi, M., (1984). Industrial robot safety management in Japanese enterprises. Unpublished paper. Hiroshima, Japan: Hiroshima University, Department of Industrial Engineering.

Nagamachi, M., (1983). An ergonomic study of industrial robots (1) - The experiments of unsafe behavior in robot manipulations (in Japanese). Japanese Journal of Ergonomics, 19, 259-264.

Nagamachi, M., (1986). Human factors of industrial robots and robot safety management in Japan. Applied Ergonomics, 17, 9-18.

Robotic Industries Association (1986). American Safety Standard for Industrial Robots and Industrial Robot Systems. Dearborn, MI: Author.

Sugimoto, N., and Kawaguchi, K., (1983). Fault tree analysis of hazard created by robots. Proceedings of Robots 7. 9:13-28. Dearborn, MI: Society of Manufacturing Engineers.

Sugimoto, N., et al. (1984). quoted in: An interpretation of the technical guidance on safety standards in the use. etc., of industrial robots. (1985). Tokyo, Japan: Japan Industrial Safety and Health Association.

Tsuchiya, K., (1985). Summary report on the 5th University conference on occupational health and safety in automation and robotics. Kitakyusha, Japan: University of Occupational and Environmental Health.

Winrich, M., (1986). Personal communication. Underwriters Laboratory.