EXPERIMENTAL EVALUATION of EMERGENCY STOP BUTTONS on HAND-HELD TEACH PENDANTS

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ABSTRACT

A teach pendant is a hand-held portable control and display device used for teaching and recording the movements of an industrial robot. There is no standard design for hand-held control pendants for robotic applications. A research project was undertaken by National Institute for Occupational Safety and Health (NIOSH) to evaluate the effect of the location and the diameter of the emergency stop button on the time required for a person to initiate an emergency stop during a simulated robotic task. A prototype teach pendant simulator was designed and constructed. The simulator pendant accommodated an emergency stop (E-stop) button of two different button diameters at ten different pendant locations. Using reach time as the dependent variable, statistically significant effects were found between the E-stop button diameter and button location.

INTRODUCTION

With the increased implementation of automation in manufacturing, the risk of injury to persons who program, operate, and maintain this type of automated equipment has also increased. To date, two robot-related fatalities have occurred in the United States (Etherton, 1988). In Japan, where industrial robots are more widely used, ten robot-related fatalities had occurred by the end of 1987 (Nagamachi, 1988). According to a survey by the Research Institute of Industrial Safety in Tokyo (Sugimoto, 1977), of the injuries involving robots, 33 percent involved programming; half of these were caused by erroneous robot movements and half were caused by faults in machines that interact with the robot. According to the Japanese survey and the NIOSH Technical Report "Safe Maintenance Guide for Robotic Workstations" (NIOSH, 1988), relatively few injuries occur during normal robot operation, while the greatest risk of injury exists when tasks such as programming, maintenance, or adjustment are performed inside the range of motion of the robot arm.

Teach pendants are hand-held portable control and display devices which are often used for teaching and recording the movements of industrial robots during such tasks as programming, maintenance, and adjustment. An analysis of the human/robot interface revealed that there was no standardized design of hand-held pendants used for robotic applications. A survey of current pendant designs (Parsons, 1987) revealed that emergency stop buttons are mounted at various locations such as the front, sides, and top of the pendant. Personal communication with pendant manufacturers indicate that numerous mounting locations have been considered for emergency stop devices, but no human factors experimentation has been available to determine the most appropriate location for minimizing reach time to initiate an emergency stop.

Recognizing the potential hazards created by this lack of standardization, the Robotic Industries Association (RIA) has prepared a draft Standard which presents human engineering guidelines for the design of teach pendants for industrial robots and robot systems - R15.02 (RIA, 1988). This proposed standard addresses the human factor concerns of safety, control design, location and arrangement for certain controls, visual displays, audio signals, and labeling of pendants. The draft RIA standard for pendants states that "the pendant shall have a readily accessible emergency stop function using hardware based components" and that "push-buttons or other devices on pendants that activate an emergency stop circuit shall be red and unobstructed." However, the draft consensus standard does not specify critical parameters such as button location or minimum diameter.

The important physical parameters of push-buttons are size, location, separation, shape, operating force, and displacement (Moore, 1975). This project specifically evaluated the relative significance of location and diameter of the emergency stop button by conducting a reach time experiment with the hand-held control pendant simulator. To avoid introducing additional variables into this experiment; 1) the operating force (or the spring constant) of the push button was designed to be equal for both the 1-inch and 1/2-inch diameter buttons at all ten locations, 2) the displacement of the emergency stop button when depressed was fixed at 3/16-inch and was constant at all ten locations, and 3) the height of the button above the surface of the pendant was fixed at 5/8-inch and was constant for all ten locations. An experimental study (Dalby and Price, 1978) showed that the shape of the button did not have a significant effect on reach time. Therefore, the shapes of the emergency stop buttons as well as the the weight and size of the teach pendant simulator were fixed.

To experimentally quantify the effect of diameter and location of emergency stop buttons a study was undertaken by the NIOSH's Division of Safety Research. This study examined human subject's hand reach time, or more specifically, the time required for a subject's hand to move from a standardized starting position to locate and depress an emergency stop button mounted on a hand-held control pendant. The question explored in this research effort was: In an emergency situation, when the operator response time is critical, what relative effect do the design parameters of diameter and location of emergency stop buttons have upon the time required for a person to initiate an emergency stop?

METHODOLOGY

Pendant Simulator

Design parameters for developing a simulator pendant were partially obtained from the RIA subcommittee responsible for developing the draft standard "Human Engineering Design Criteria for Hand-Held Robot Control Pendants." Additional input was obtained from personal discussions with control pendant manufacturers and users. The prototype pendant was designed to represent control pendants currently being used in industry. The simulator pendant accommodates an emergency stop button of 2 different target diameters at 10 different locations (See Figure 1). Based on personal communication and written comments from robot and pendant manufacturers and the Robotic Industries Association, ten locations and two convex mushroom-shaped buttons were chosen for study. One button diameter was 1/2-inch (1.22 cm.) and the other was 1-inch (2.54 cm.). Two button locations were on the left side surface, three on the top side surface, two on the right side surface, and three on the front surface of the simulator pendant. The dimensions and specifications of the prototype pendant were selected to represent average dimensions of a single-handed robot teach pendant (Levonski, 1983).

The simulator robot teach pendant's emergency stop button was hardwired to a digital timer with the capacity to record a reaction time to within one-thousandth of a second. A General Electric P-50 five-axis industrial robot was programmed to provide the robot error stimulus for the subject to initiate an emergency stop. Ten different programs were recorded in the P-50 robot memory. Each program performed the same task repeatedly, except that an erratic motion of the robot arm was randomly introduced at different stages in each program to simulate a hazardous condition which required the human subject to initiate an emergency stop.

Subjects

Twelve males in the age range of 21 to 30 were used as test subjects. Ten of the subjects were right-handed, but all twelve of the subjects preferred to hold the pendant in their left hand and activate the emergency stop button with their right hand. Subjects were screened to ensure that none had experience working in an industrial job involving robot programming or maintenance. Because the emergency stop button is rarely depressed, the reaction time proficiency was assumed to be similar for industrial and non-industrial persons.

Procedure

Each subject was told that the industrial robot had been programmed to simulate a workstation task. The robot had been installed for only thirty days and was subject to a large number of task malfunctions. Each test subject was instructed to use their three middle fingers to depress and hold the touch pad down while watching the robot cycle through a well-defined work task. They were instructed to release the touch pad when a malfunction in the robot task was observed and to immediately depress the emergency stop button. Each test subject was positioned behind a 4-foot-high plywood barrier outside of the range of the robot arm at all times.

When the stimulus of an erratic robot movement was observed, the subject released the touch pad and depressed the emergency stop button located on the pendant. The digital timer started when the touch pad was released and stopped when the emergency stop button was depressed. This timer recorded the time, in milliseconds, required for the test subject's hand to travel from the initial standardized touch pad starting point to the emergency stop button, thus obtaining the subject's reach time.

Data was collected for each subject for all button diameters and locations. Three replications of each simulated emergency stop were randomly introduced to each subject, where a replication represents the same combination of button diameter and location. Thus, a total of 60 reach times was recorded for each subject.

10 Locations X 2 Diameters X 3 Replications
= 60 Treatments

The order of treatments and the stimuli to initiate an emergency stop were presented to each subject randomly. To minimize learning effects during the experiment, each subject practiced twenty emergency stops before the project data collection began.

RESULTS

Overall, the fastest average reach times occurred for locations on the front surface of the simulator pendant. When depressing the 1-inch-diameter emergency stop button, the average reach times for locations eight, nine, and ten were .121 seconds, .113 seconds, and .110 seconds, respectively. Depressing the 1/2-inch-diameter button, the average reach times for locations eight, nine, and ten were .138 seconds, .120 seconds, and .127 seconds, respectively. The data revealed that in all locations the mean times for the 1-inch-diameter emergency stop button was quicker than the 1/2-inch diameter. Figure 1 shows the average reach time for both diameters and the difference between these reach times. Overall, the 1-inch-diameter button allowed subjects to depress the emergency stop button over seven percent faster than the one-half inch diameter button.

The slowest reach time for the 1/2-inch-diameter button occurred when the emergency stop button was at location 2 on the left side surface of the pendant (.169 seconds) and locations 4 and 5 on the top surface (both .167 seconds). The slowest average reach time for the 1-inch-diameter button occurred on the top surface (.160 seconds). See Table 1 for a summary of the average reach times of all twelve subjects.

TABLE 1
MEAN REACH TIME FOR VARIOUS
BUTTON DIAMETERS AND LOCATIONS

BUTTON LOCATION (See Figure 1)	1/2-INCH DIAMETER	1-INCH DIAMETER	DIFFERENCE (seconds)
1	.164	.147	.017
2	.169	.158	.011
3	.163	.156	.007
4	.167	.163	.004
5	.167	.161	.006
6	.144	.142	.002
7	.147	.138	.009
8	.138	.121	.017
9	.120	.113	.007
10	.127	.110	.017

TABLE 2

Significance of the Emergency Stop Button Location, Diameter, and Surface on Which the Button is Mounted

SOURCE	DEGREES OF FREEDOM	F VALUE	p VALUE
LEFT SURFACE (LOCATION 1*2)	1	2.60	.1090
TOP SURFACE (LOCATION 3*4*5)	2	0.57	.5687
RIGHT SURFACE (LOCATION 6*7)	1	0.01	.9398
FRONT SURFACE (LOCATION 8*9*10)	2	2.83	.0613
ALL SURFACES	3	68.19	.0001
BUTTON LOCATION	9	24.10	.0001
BUTTON DIAMETER	1	11.19	.0001

The initial statistical analysis examined each of the four surfaces independently to determine if there was a significant effect between reach times for different emergency stop button locations on the same surface. Table 2 shows that there was no significant difference ($p > .109$) between locations 1 and 2 on the left side surface of the pendant. In fact, the mean reach times for all twelve subjects only differed by .005 seconds. The analysis revealed that there was no statistically significant difference between locations 3, 4, and 5 ($p > .5687$) on the top side surface of the pendant or between locations 6 and 7 ($p > .9398$) on the right side of the pendant. It was also determined that there was no statistically significant difference ($p > .0613$) between locations 8, 9, and 10 on the front surface of the pendant. Therefore, the mean values of the reach times for the individual locations on each of the left, right, top, and front surfaces were combined to provide one mean reach time for each of these four surfaces for further analysis.

After combining the location values into an average reach time values for the four respective surfaces, the next step was to determine the effect of the surface on reach time. It was determined that there was a statistically significant effect ($p < 0.0001$) on reach time between surfaces. The analysis also identified a statistically significant difference ($p < 0.0001$) between button diameters.

DISCUSSION

The main finding of this research was the variation in subject reach time between: 1) the surface on which the button was mounted and 2) the diameter of the button. All subjects were able to reach and depress the emergency stop button more quickly when it was mounted on the front surface of the simulator pendant and was 1-inch in diameter. The apparent explanation is that when the emergency stop button was located on the front surface of the pendant simulator, the subject's hand moved primarily in a unilateral motion. In contrast, to depress the emergency stop buttons on the left, right, and top surfaces, the subject's hand was required to move in a bilateral motion. This change of direction, while the hand was moving, had a considerable influence on extending the reach time required for the subject to initiate an emergency stop.

RECOMMENDATIONS

To expand on the requirements of the RIA standard and to further reduce the risk of injury to robot technicians and other operators of hand-held control pendants, two recommendations are suggested based on the results of this research:

1. Design criteria for emergency stop buttons or devices should consider that certain locations of the button are substantially more accessible during an emergency. Specifically, emergency stop buttons or devices should be mounted on the same surface as the other control pendant keys. Data from this study indicate that depressing emergency stop buttons that only required unilateral hand movements (from the subject's starting hand position to depressing the emergency stop button) significantly reduced reach times.

2. Design criteria for an emergency stop button should consider that the diameter of the emergency stop button can greatly affect an individual's ability to locate and depress the button. According to the results of this experiment, reach time is quicker with a 1-inch-diameter button than a 1/2-inch-diameter button during an emergency. It is recommended that future studies examine several different button diameters to determine the optimal diameter. Until such a study is conducted, it appears that emergency stop buttons on teach pendants should be larger than one-half-inch in diameter.

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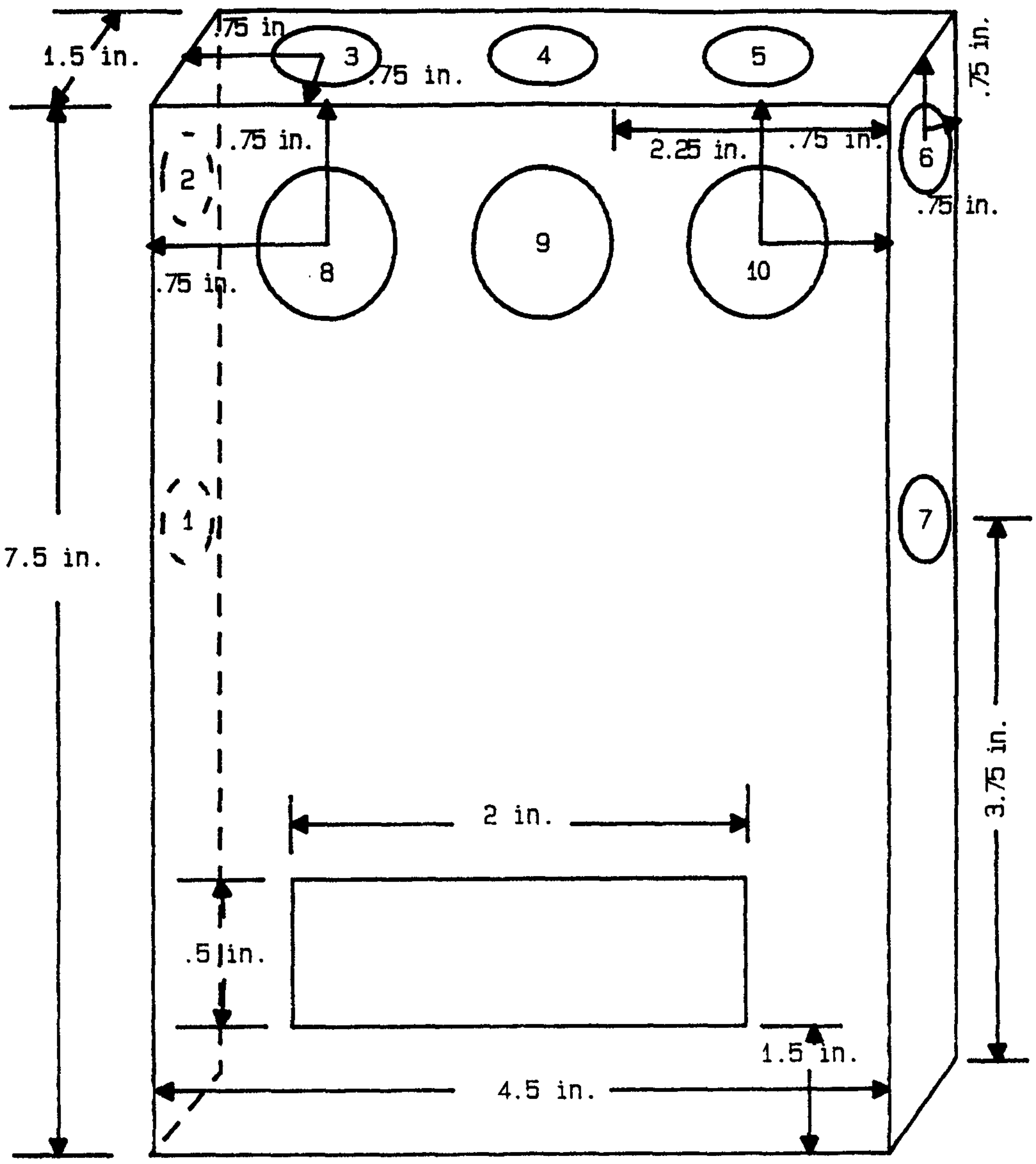

FIGURE 1 - FRONT VIEW OF PENDANT SIMULATOR ILLUSTRATING LOCATIONS 1-10.