A MODEL OF HUMAN REACTION TIME TO DANGEROUS ROBOT ARM MOVEMENTS

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ABSTRACT

An increasing number of studies indicate that robots are the most hazardous equipment in industry. The very virtue that makes them attractive for industrial work, the programmable arm, is the cause of accidents since the arm motion is often difficult to perceive. The present paper presents a model of human reaction time and emergency behavior. The total reaction time is the sum of three elements: perception, decision making and motor response. Each of these three elements are modeled using concepts such as perceptual discriminability and single detection theory. Finally the results of an experiment is presented where the human reaction time is modeled as a function of robot arm speed.

INTRODUCTION

Although it is widely recognized that there are serious safety hazards with industrial robots, only limited statistics have been published so far. It is therefore difficult to evaluate the safety of robot workplaces in any detail. 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 robot years. This may be compared to industrial presses, previously the most hazardous industrial machines with one accident per 50 years. Later studies seem generally to be in support of this finding (Sugimoto and Kawaguchi, 1983; Carlsson, 1984).

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. Particularly for operators who program and maintain the robot it may then be important to limit the speed of the robot arm movement. Several organizations have developed standards that regulate the maximum speed of arm movement. The Robot Industries Association recently published a standard ANSI R15.06, which postulates that "All robots shall have a slow speed. The maximum slow speed of any part of the robot shall not exceed 25cm (10in) per second. The same speed has been endorsed by the International Standards Organization. Other standards are more conservative. The Underwriters Laboratory suggests that the teaching speed of the robot arm shall automatically be restricted to six in/sec (Winrich, 1986). The same speed (14 cm/sec) is endorsed by the Japan Industrial Safety and Health Association (1985). The latter recommendation seems to be the only one 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 the subject as if the wrong button had been pushed. The time between the start of the robot movement and when the subject pushed the stop button averaged .53 sec. Assuming a teaching speed of 14 cm/sec and the reaction time of 1.42 sec (0.53 sec plus two standard deviations) the robot arm would move 19.8 cm. It was suggested that, to optimize human vision of its operation, a workers face might be between 20 and 30 cm from the robot while teaching it. Hence, the 14 cm/sec maximum teaching speed could keep the robot from striking any operator, given that he/she tried to stop it. The 25 cm/sec limit set by ANSI and ISO is clearly arbitrary. Obviously, the choice of appropriate arm speed deserves more research. It is one of the most critical design aspects of robots and has great safety implications. The purpose of the present study was 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 (Helander and Karwan, 1987).

A MODEL OF HUMAN REACTION TIME AND EMERGENCY BEHAVIOR

The model to be developed is conceptually similar to the Model Human Processor (Card, Moran and Newell, 1983). The information processing is divided into three stages: the perceptual time, the decision making time, and the motor response time. This division is somewhat arbitrary, since one may well formalize the information processing using additional stages, such as stimulus detection, brain recognition and so forth. However, depending upon the approach taken to experimentally verify or measure the components it may be practical to group such components into larger units. In the current approach, the perceptual system must detect that the robot is moving and recognize this movement as potentially dangerous. The decision making is necessary to decide whether to push the emergency stop on the teach pendant. Finally, moving the hand to the emergency stop would be accomplished by commands from the motor processor. Accordingly, the total time (T) for complete interaction time may be written as:

$$T = T_p + T_d + T_m \quad (1)$$

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.

Consider time zero to be the beginning of an unexpected and potentially dangerous signal. 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 $T_p + T_d + T_m$ were greater or equal then 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. If the decision is made that there is a signal, then there will also be a motor response. If the decision is made that there is no signal, then there is no motor response. Therefore, if $T_p + T_d \leq T_i$, but the decision is "no signal" (no hazard), then injury will also occur. Assuming a signal is present, we can compute the probability p for the overall risk using these two mutually exclusive cases:

$$p\ (\text{risk}) = p\ (\text{late response}) + p\ (\text{wrong decision}) \quad (2)$$

From a safety prevention point of view one must avoid both of these events. Circumstantial environmental factors determine the outcome, and it does not seem reasonable to model or predict the type of accident.

To obtain an empirically justifiable model whose predictive strength could be tested in research, 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 potential dangerous robot movement is denoted by T_p. The perceptual processing time T_p varies inversely with stimulus intensity and typically lies in the range of 50-200 msec. (Card, et al., 1983). This range can easily be extended in extreme situations. Here the stimulus intensity is a function of several 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 model.

Define λ. Let δ be a minimum threshold of discriminability (below which there is no reasonable expectation of perception). We can then hypothesize a relationship between T_p and λ as shown in figure 1.

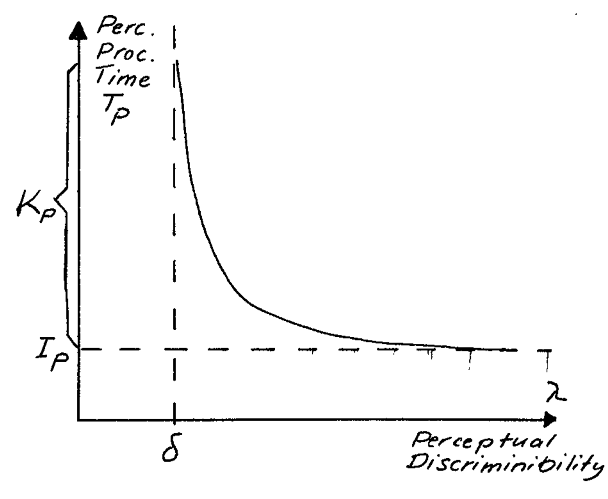

Figure 1. T_p as a function of λ

I_p represents a asymptote for the minimal perceptual processor time (e.g. 50 msec) and $I_p + K_p$ an upper limit on T_p at the threshold w (e.g. 300 msec). Then the following equation can be used to approximate the curve:

$$T_p = I_p + K_p e^{-(\lambda-\delta)} \qquad (3)$$

The concern is now how to relate g (perceptual discriminability) to the numerous independent variables. Let g_i denote an important component of perceptual discriminability. For example: g_v, g_s, g_{pt} and g_{vc} could denote parameters relating to velocity, size, primary task and visual contrast.

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

$$\lambda = \sum_{i=1}^{n} w_i \lambda_i \qquad (4)$$

where $\lambda_i = f(i)$; $i = 1,\ldots,n$

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

$$\lambda_v = a_v^2 + b_v + c \qquad (5)$$

with unknown coefficients a, b, and c.

The most difficult component to fit would be the effect of the primary task. We propose 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.

Motor Processor Time (T_m)

The hand movement to an emergency stop button can be modeled using Fitts' law (Welford, 1968).

$$T_m = I_m \log_2 (D/S + 0.5) \qquad (6)$$

where
- S = stop button size
- D = distance of hand to stop button
- I_m = constant, about 70-120 msec

Decision Making Time (T_d)

We can model the decision making time as the choice between only two alternatives: hit the stop button or do not. With only two alternatives we propose that the theory of signal detection (TSD) be used. 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), that is safe robot movement, was present.
SN- Distribution of intensity given that a signal (S), that is unsafe robot movement, was present as well as noise (N).

The decision situation is shown in Figure 2, where the four shaded areas represented the probabilities of four outcomes:

Hit- Operator responds "signal" when SN is true. That is, the operator presses the stop button in response to a real threat.
Miss- Operator responds "noise" when SN is true. That is, the operator fails to detect the unsafe movement. As a consequence the operator may be "hit" by the robot arm.
False Alarm- Operator responds "signal" when N is true. That is, the operator thinks there is an unsafe robot movement, when in fact it is safe. The operator thereby hits the stop button in error.
Correct Accept- Operator responds "noise" when N is true. That is, the operator does not hit the stop in response to a safe robot movement. This is a correct decision.

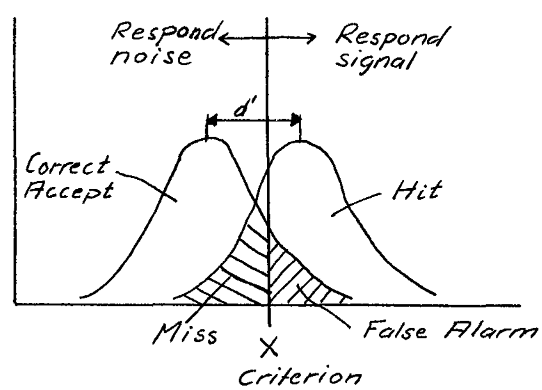

Figure 2. Decision variables and outcomes in TSD.

The location of the criterion x, the borderline between signal and noise, depends on the costs and payoffs associated with the outcomes. The actual criterion would be expected to follow an optimum criterion β which is a function of the rate of unsafe movements p', and the costs and payoffs:

a = value of not stopping safe robot arm (correct acceptance).
b = cost of not stopping dangerous movement (miss).
c = cost of stopping safe robot movement (false alarm).
d = value of stopping dangerous robot arm movement (correct rejection).

Using these terms, b is given by

$$\beta = \frac{(1-p')}{p'}\frac{(a-c)}{(d-b)} = \frac{(1-p')}{p'}g \qquad (7)$$

where g represents the relative costs of decisions on safe movements to the decisions on dangerous movements. How well the operator follows β in choosing x can be modeled considering the operators conservatism. In fact, several studies indicate that human signal detectors tend to choose less extreme values of x than this normative theory would predict. A suitable model for this conservatism is given as

$$x = m\beta + (1-m) \qquad (8)$$

where m represents the conservatism ranging between m=0 for extreme conservatism and m=1 for no conservatism.

The cost-payoff ratio g can be changed by management by instructions and feedback to the operators, whereas changing the sensitivity d' must involve perceptual factors such as conspicuity or skill. In our context misses resulting in accidents can occur if the operator perceives a high penalty to starting up the robot after the button is activated. If pressure exists to "keep the line moving" then an inappropriately high criterion value may be employed.

The operator sensitivity in respect to decisional manipulations of costs/payoff is denoted by d'. In our context d' should be a function of all 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:

$$d' = a\lambda + \mathbf{b} \qquad (9)$$

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 cognitive part of the information processing may often be difficult to distinguish in experiments. Although we conceptually distinguish between these entities, it may be impractical to observe and measure them experimentally as separate 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 a movement that is difficult to perceive would imply a small d'.

PILOT EXPERIMENT

An experiment was conducted in which four robot arm speeds (15, 25, 35 and 45 cm/s) were calculated. Subjects were instructed to hit an emergency button in case the robot arm moved beyond an expected target position. For each trial, subjects were exposed to between 20 and 30 repeated linear movements of the robot arm from a start position toward the target position and back again. Three of these, randomly inserted in the control program, were movements beyond the target position. These three movements were the data collection for which subjects reaction time were collected.

Nine male test subjects in the age of 20-60 years participated in the experiments. Prior to the trials, the subject practiced using the palm button on two overrun conditions at 25 cm/sec.

RESULTS

A linear relationship was found between the robot arm speed and the distance the robot moved before it was stopped by the emergency button, see Figure 3.

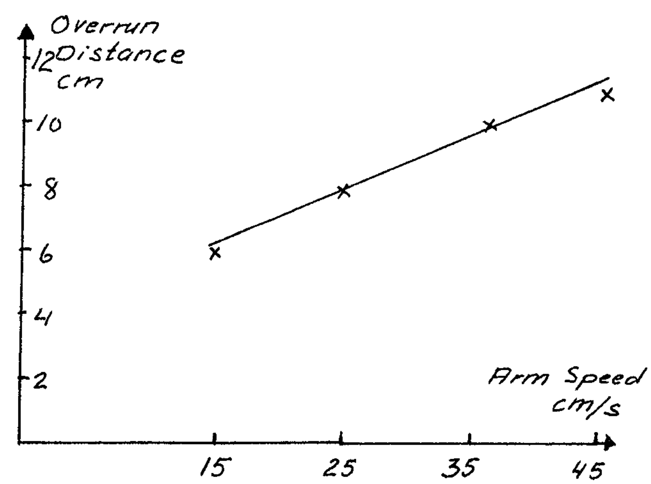

Figure 3.

As can be seen, at a robot speed of 45 cm/s, the mean overrun distance was 10.9 cm and at 15 cm/s it was 6 cm. The corresponding reaction times were approximately 250 and 400 ms respectively. Obviously, the movements beyond the target position was easier to perceive at the faster distance than at the slower distance. Going from 15 to 25 cm/sec increased the overrun distance by about 1.5 cm. This negligable increase was obtained because the reaction time decreased from 400 msec to 310 ms.

The safety interpretation of these results is difficult. Some overrun is inevitable before a person can actuate stop controls, and the hazard increases with the speed of the robot arm. At present time, we need more research involving analysis of maximum robot reach, human visual requirements in programming and troubleshooting and a better understanding of the theoretical framework outlined above can be applied to this problem.

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