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ROBOTICS SAFETY: EXCLUSION GUARDING FOR INDUSTRIAL OPERATIONS

J.E. HAMILTON and P.A. HANCOCK

Department of Safety Science and Human Factors Department, Institute of Safety and Systems Management, University of Southern California, Los Angeles, CA 90089-0021 (U.S.A.)

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ABSTRACT

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From early concept to present reality, this paper catalogs the development of reprogrammable, multifunctional, industrial manipulators: Robots. A summary of published studies concerning the safety aspects of the large scale application of robots by industry outside the United States is presented. From this and our own survey observations, a proposal for performance guidelines in the guarding of industrial robots is presented.

INTRODUCTION

The word "robot" first entered the English language in 1923 when Czech playwright Karel Capek's *R.U.R.* (Rossum's Universal Robots) was translated and introduced to the English speaking world the Czech word for "worker". In the play Rossum and his nephew build humanoid "Robots" to relieve men of their drudgery. Initially, Rossum's robots are a boon to society, heralding an era of prosperity and abundance. The robots are both stronger and more intelligent than human beings, yet diligent and most subservient. All manner of men rely on, and benefit from, robot labor. Just when the reliance is complete, the robots rise up and annihilate human civilization.

In 1942, Issac Asimov penned *The Three Laws of Robotics*, thereby naming the science. Asimov's laws are still lofty design standards. They state:

1. A robot must not harm a human being, nor through inaction allow one to come to harm.
2. A robot must always obey human beings, unless that is in conflict with the First law.

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3. A robot must protect itself from harm, unless that is in conflict with the First or Second laws (Asimov, 1950).

Those interested in robots are fond of citing these logical and humanitarian laws as an underlying ethic which they share. However, in practice this is not always the case. Modern designers and manufacturers build large, quick, practical, and potentially dangerous machines. The task of mishap avoidance is left to local management. Unfortunately the topic may not be addressed until after disaster has struck.

The first patent for a robot was issued to G.C. Devol in 1961 under the title *Programmed Article Transfer.* That same year, Devol and Engleberger at Unimation, Inc. put the first industrial robot to work in a die casting operation (Engleberger, 1980).

In 1969, Kawasaki Heavy Industries of Japan was licensed to build and distribute the Unimation point-to-point design in the Far East. Japanese industry recognized the production potential of robots and put them to work at a variety of tasks before the rest of the manufacturing world had even given robots serious consideration. From 1975 to 1982 the number of Japanese companies employing robots nearly doubled each year, and trebled in 1981 (Ministry of Labor, 1983).

The rapid expansion of this new technology has not been without incident. A 1983 study of accidents involving industrial robots, published by the Japanese Ministry of Labor, disclosed that in the period 1978 to mid-1982 there were 48 recorded mishaps involving human workers and robots. Of these, two resulted in the death of the worker. Two produced lost-time injuries, seven resulted in minor injuries, and 37 were recorded as near misses. The extremely high ratio of incident to fatality is particularly noteworthy. In most common occupational situations, an incident to fatality ratio greater than 300:1 is exhibited (National Safety Council, 1981).

CLASSIFICATION

The Robot Industries Association (RIA), formerly Robot Institute of America was founded in 1974 and after eight years reached consensus on the definition of a robot as: "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks".

This definition intends to exclude prosthetics, exoskeletal lifting devices, teleclenic or remote manipulators, and various locomotive devices. It is possible in many specific applications to interface a computer with any of the above to perform a required task with precise repetition. However, the resulting special purpose automation lacks multi-functional adaptability. All successful commercially produced industrial robots share the following characteristics: gripper, articulated joint, arm, power and speed commensurate to the task, programming controls, memory, accuracy and reliability.

Robots are often classified according to the type of control scheme employed. Limited sequence, or *pick and place* machines use a system of mechanical stops, limit switches, or plugboards and relays to establish the end points of desired travel. The drive system is either on or off, and no incremental control is applied.

Playback robots with point-to-point control systems are programmed by positioning the robot gripper to the desired location using manual control of the drive system. The operator uses a *teach pendant* to jog the gripper to the desired location, then presses a record button to commit the coordinates to memory.

A *continuous path* control system is the most versatile. To program, the operator holds the end effector of the robot and moves it through the desired sequence at the required speed. The control program records position signals on cue from a time standard. This allows robots to be effective in the more fine grained applications, such as welding and spray painting. The machine will then replicate the skilled motions of the programmer exactly; to tolerances even the programmer himself would be unable to maintain.

CURRENT POPULATION AND PROJECTIONS

As with any population in flux, it is difficult to determine the exact number of robots employed in the world today. Ostberg (1984) has estimated that less than 50,000 robots existed as of July 1984, with less than 8,000 presently in use in the United States. Nearly all of these units are owned by the automobile manufacturers and other large corporations. Although American business has been slow to accept the benefits of packaged automation, this attitude is changing rapidly in the push for increased productivity in the present decade.

General Motors (GM) started using robots in die casting, welding, and painting operations as early as 1961. In 1980, GM owned only 300 robots. Demonstrated increases in productivity and quality have prompted GM to project a total of 20,000 robots operating in General Motors plants by 1990. This is a five-fold increase over the current estimated GM population of 3400 (Mittlestadt, 1984).

The same concepts that guaranteed the success of assembly lines apply to the installation and operation of robots in the production, packaging, or distribution of manufactured goods. Nearly any task requiring repetitive motion, regardless of the environmental stresses, is a candidate for robotic application. Returns on investment in excess of 60% for a manufacturing cell (one robot tending two or more machines) have been commonly projected. Payback periods are calculated to be from one to three years, depending on the number of shifts per day that the robot is in operation.

Adaptability to new circumstances endows the robot with intrinsic value. Used robots are traded in an after market, which enhances propagation.

Financing is readily available. The cost benefits cited above are not limited to large corporations employing vast numbers of robots. A small company using only two or three robots for two shifts a day can enjoy similar savings. Together these factors indicate that in the immediate future, a real and dramatic increase will occur in the robotics industry as small and medium size companies begin to install these machines for the first time.

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HAZARD ASSESSMENT

In 1983, as an example, the California legislature exempted all injuries resulting from worker contact with *power presses* from the exclusive remedy of workers compensation. The rationale, in part, was that the hazards associated with power presses are fully recognized and controllable. Even under the nebulous definition of Assembly Bill 684, hazards presented by the point of operation or die area are obvious. The motion of forming machines is reciprocal: the parts of the die come together, the material is formed, the parts of the die move apart, and the formed material is extricated.

Types of injuries sustained from forming machines are limited by the geometry and size of the die opening. The most common injuries are amputation or crushing of phalanges, hands, and arms (National Safety Council, 1981). The machine has only one degree of freedom, i.e. it operates in one plane. The *point of operation* (POO) is well defined. Thus, the unknown variable is time. Not knowing *when* a malfunction or misoperation will cause the machine to cycle is the problem which makes guarding of power presses necessary. The Occupational Safety and Health Administration's 29 CFR 1910, General Industry Standards, and Title 8, California Administrative Code require the employer to guard the point of operation sufficiently to exclude the employee's body parts from the point of operation.

In contrast, robot units present several unknown parameters. These machines operate in three planes. The volume described by movement of the robot arm on three axes, at maximum extension, is the robot's point of operation. Types of injuries caused by robots are more diverse than other machines. Robots can strike, crush, or thrust to any location inside the point of operation. Tools or parts held by the end effector can be launched on varied trajectories well outside the point of operation. Sources of a robot malfunction can be the drive system, the control system, or the control program software. This increases the number of possible sites of error generation and magnifies the effect of a control error. Carlson et al. (1979) surveyed twenty-one local chapters of the Swedish Metal Workers Union. These chapters represented the operators of approximately half of all the robots employed in Sweden at the time. The complied questionnaire data indicated that one accident occurred per every 40 robots operating during calender year 1977. Backstrom and Harms-Ringdahl (1983) established a good correlation between these worker-reported figures and official Swedish government occupational injury statistics, attesting to the validity of the original reports.

A Japanese study of robot operators completed in 1977 indicates that 4% had suffered a lost time accident, 8% had been involved in a robotic accident, and 42% reported near misses (Ostberg, 1984). From the experience of both Sweden and Japan, the world's leaders in the use of packaged automation, the best estimate of accident frequency rate is one accident per 40 robots per year. The rate for power presses is one accident per 50 presses per year. This seems to indicate that both the frequency and severity of accidents involving industrial robots can be potentially worse than that experienced with power presses.

In January, 1985, the authors designed a survey to determine the current incidence and severity rates of accidents involving robots and union workers in the United States. This survey is yet to be completed. However, preliminary indications closely parallel the results of studies conducted in Japan and Sweden. Two fatalities have been recorded in this country, with incidence ratios similar to those mentioned previously.

Lauck (1984), Chairman of the Safety Standards (R15.06) Committee of RIA and a member of the General Motors Robotics Council has stated the "need to rethink our approaches to safe-guarding as it applies to those who will be required to teach, service, and work side-by-side with robots". In analyzing GM robot/employee injury experience, Lauck stated that the injured employee was either (a) not authorized to be in the robot area, (b) not aware of all the ramifications of the robot operating program or (c) not alert to adjacent robots and equipment. Lauck stressed that training the employee to stay out of the way is the key to robot accident prevention.

However, of the 18 near-accidents studied by Sugimoto and Kawaguchi (1983), 44.4% were the result of erroneous motions of the machinery. These errors in movement were not related to the tasks being performed by the human inside the point of operation. Since the operator did not control or precipitate these unintended robot movements, the level of operator training and experience would be ineffective in preventing similar occurrences.

Lauck's stated view is manifest throughout the RIA's proposed ANSI standard for robotic safety which was drafted in 1984. This is the first of several proposed standards to be published by RIA, although no empirical data is cited to support the need for, or adequacy of, the proposed safeguarding measures. This document effectively catalogs hazard control equipment and devices which have been applied to robot systems, but leaves the onus of collision avoidance on operating personnel rather than on the engineering and design of the machine.

ROBOTS AND HUMAN EXPOSURES

Exposure to hazards associated with the industrial robot system can be classed into four groups by the circumstances causing the exposure; casual, required maintenance, programming (teaching), and integrated production operations.

Casual exposures are those generated by the unique appearance and capabilities of these machines. Executives bring in stockholders and customers to aquaint them with the latest innovations. Workers come from other departments to make their own assessments. It is natural for people to observe, touch, and thereby accept new objects, particularly if the robots are of anthropomorphic design. Persons unfamiliar with the operating cycle may mistake a programmed dwell for a stopped condition and enter the point of operation.

Robots, in common with other machines, are not self-sufficient. They must be tended by human operators for any condition other than normal operating circumstances. This exposure includes preventative and repair maintenance, and adjustment of feed, process step, and position indicating devices.

Programming exposures are inherent in the design of nearly all continuous path controlled robots available today. The programming procedure requires the "teacher" to enter the operating envelope, grasp the end effector, and perform the desired operation. As the arm of the robot is led through various manipulations the microprocessor records spatial relationships and velocities, creating the program for perfect replication of the craftsman's art.

The advent of integrated production operations (i.e., robot and human worker in side-by-side indexed assembly applications) was first envisioned by General Motors Corporation. GM contracted Unimation to develop a man-sized robot capable of handling auto parts weighing up to 2.3 kg. GM's analysis indicated that this would include approximately 90% of the individual parts used in automobile assembly. The evident intent of the Programmable Universal Machine for Assembly (PUMA) development effort is to achieve interchangeability between constituents of the labor force. The humans on the assembly line would be productively employed, yet available to stop, signal, or adjust for robot misfunction. Should a reduced number of human employees report for a work shift, additional PUMA's could be rolled into place and loaded with the proper task program for that work station.

GUIDANCE

The diversity of robot size, design, and operational requirements is a frequently cited problem in attempts to determine the extent and type of guarding necessary for a particular installation. This may result in confusion, inconsistency in guarding design throughout a plant, or inadequacy of guarding design and administrative safeguards. In addition, any adopted guidelines should specify performance criteria rather than compliance requirements. The former fosters innovative design, while the latter discourages it.

Patrick and Mertz (1970), in studying impact injuries on the human body and cadavers concluded that the human head "is the most important body part to protect", and that force applied so as to result in hypertension of the head and neck is the most likely to produce injury. This study estimates the skull fracture threshold at 912 kg-force when delivered anterior-to-posterior in 4 ms to the forehead of a cadaver skull. The force was applied by contact with a 6.35 cm diameter flat and padded impactor. The threshold will vary directly with the thickness and compressibility of the padding. The extent of guarding necessary for a particular robot installation should be predicted on the robot's capabilities. Those packaged automation units capable of delivering the equivalent force necessary to produce serious injury in critical human body parts should be fully exclusion guarded. Those units not developing sufficient momentum at the most unfavourable conditions of velocity, load, and arm extension could be exempted from full exclusion guarding of the *restricted operating envelope.* By definition, those areas where mechanical stops have been installed in the drive system to limit travel are known as restricted. All areas which the drive system may enter are referred to as the restricted operating envelope.

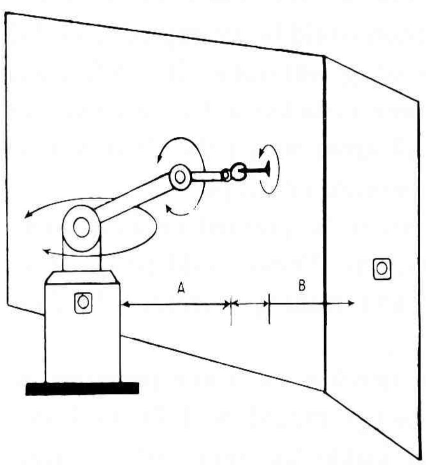
A necessary exception to this criterion would be pointed or sharp-edged end effector tooling or payload configurations. These could prove lethal even when propelled with minimal force and should, therefore, be fully exclusion guarded.

Robots of sufficient size and power to develop the force necessary to produce serious bodily injury to human beings should be fully exclusion guarded. Persons should not be permitted inside the point of operation of such a robot when power is applied. The following performance guidelines would establish a Robot Operating Volume Exclusion System (ROVES) for each powered unit:

1. The restricted point of operation should be fully enclosed. Materials of construction should be substantial enough to prevent inadvertent personnel entry into the exclusion volume.
2. The enclosure should be capable of containing (with a reasonable deformation ratio) the intended load when launched at the maximum velocity attainable in drive system failure; i.e., full power applied in one direction with zero-powered resistance in the opposing direction.
3. Minimum lateral dimensions of the enclosure should include an allowance beyond the maximum extended reach (arm + end effector + load) as a safe haven to which the operator may retreat in the event power is inadvertently applied to the robot (Fig. 1).
4. Sensors monitoring the means of access should be inter-locked via logic

circuits to depower the robot prior to personnel entry. Reset should be outside of the enclosure but in line of sight of the means of access. Logic ciruits should require a reverse sequence to enable reset.

5. *Emergency stop* switches should be provided inside the enclosure, on the housing of the unit and in the haven area. *Emergency stop* should interrupt drive power and be connected via logic circuits requiring a reverse sequence to enable reset (Fig. 1).
6. Programming schemes should not require the operator to either enter the point of operation or be in physical contact with the machine *when power is available to the drive mechanism.* The concept of Zero Mechanical State, (ZMS) as defined in American National Standard Z241.1 — 1975, should be applied to robot installations in every instance when approach by a human being inside the point of operation is necessary.
7. Cables providing electrical control and feedback signals between system components should be shielded to preclude the introduction of induced false signal voltages.



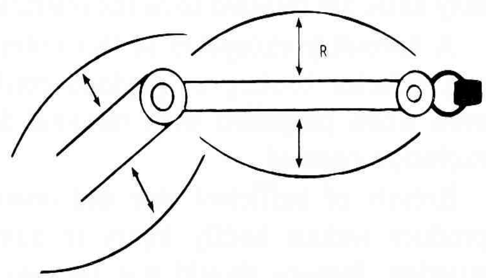


Fig. 1. To determine minimum enclosure dimensions, an allowance (B) should be added to the maximum extended reach (A).

Fig. 2. Proximity sensing radius (R) should equal ten times the stopping distance required for the manipulator plus design load.

All industrial robots, irrespective of size, should be provided with a proximity sensing system. The sensing system acts as a fail-safe to prevent the robot from colliding with a human being. The proximity sensing system should be designed on the premise that the imminent collision is the result of a robot system error.

1. The proximity sensing system should act to depower or brake the robot arm using other than normal control and power system operating devices.
2. The proximity sensing system should be capable of sensing an intrusion

at a distance (R) equal to 10 times the stopping distance of a fully loaded arm (Fig. 2). This provides a margin to account for the velocity of the human being on a closing vector (50%), and the effects of environmental factors on daily instrument calibration and response of the sensing devices (50%).

CONCLUSIONS

We have a rare opportunity to realize enormous benefits from the application of robotic innovations in the industrial setting. The proven economic feasibility and adaptability of packaged automation units ensures rapid and diverse proliferation throughout the manufacturing base.

However, the less pleasant aspects of world-wide application of these devices should not remain unheeded. Evidence suggests that robots are currently among the most dangerous machinery operating in industry. While this is due in part to their novelty, positive design and installation engineering efforts are necessary to prevent future tragedies which transgress Asimov's initial principle. Industrial robots should be provided with sensing devices to stop the robot's motion prior to a collision with a human being. Robots with sufficient power and speed to inflict serious or fatal injury on human beings should be exclusion-guarded to preclude human entry into the point of operation when drive power is applied. As part of that effort, this work advocates full exclusion guarding of the robot entity, utilizing the concept of a Robot Operating Volume Exclusion System (ROVES).

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