A Safety and Collision Avoidance System for Industrial Robots

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Abstract—**As more and more robots are installed in the industrial sector, the statistical likelihood for accidents involving robots increases unless careful design and implementation of safety features occurs. Some worker deaths related to robot accidents have been reported in Japan. Most workers and users of robots have embarked on a safety program depending on personnel training, preventative maintenance, and perimeter barriers and/or interlocks. Most of these necessary methods still do not address the issue of personnel required to be close to a robot during teaching, maintenance, and troubleshooting. The results of a research project underway at Rensselaer Polytechnic Institute to develop a computer controlled sensor system that will monitor the working envelope of a robot are discussed. If an dangerous situation occurs, this system will cause the robot to take corrective action to avoid personnel injury or damage to the robot or equipment.**

INTRODUCTION

THE INTRODUCTION of new automation into the manufacturing environment has historically caused worker injury. Equipment design, employee training programs, safety regulations, etc., eventually evolve to reduce the injury rate. Recent years have seen increased legislation to protect personnel in their workplace.

One new form of automation is being introduced into our factories at an increasing rate. This is the industrial robot. Three of four worker deaths have been reported for accidents involving robots [1], [2]. There are expert predictions that the U.S. robot vendors could have sales of $2 billion in 1990 [3]. The number of personnel interacting with these robots will necessarily increase as these robots must be installed, tested, taught, maintained, serviced, and repaired. Anyone who has ever tried to program a robot to perform a complicated or precision tasks knows that close interaction with the robot is often required. The increased number of robots installed, coupled with more sophisticated applications, could lead to some potentially unsafe and dangerous situations. Even intrinsically safe robots have failure modes. For instance, could the robot controller be susceptible to radio-frequency interference (RFI) noise when maintenance people have the robot paused and the controller panels open [5]? Could the controller be operating in too hot an area but the overtemperature circuits not react? Ironically, increased robot reliability and intelligence may actually accentuate the problem by creating a false sense of security for workers.

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The present state of robotic safety evolves around the triad of

1) perimeter warnings and interlocks,
2) personnel training programs,
3) preventative maintenance.

These three items are necessary for protecting workers, observers, and intruders from injuries caused by a robot, but are the three items both necessary and sufficient? A fourth item should be added. This would be a system that would use various sensors and a computer independent of the robot system to monitor the entire working envelope of the robot and take corrective action if unsafe conditions occur. Sugimoto amd Kawaguchi's extensive robot safety study in Japan concludes that, "Only when robots themselves are able to detect the approach of humans and perform appropriate actions to avoid accidents will safety in the human robot work place be assured" [2].

Rensselaer Polytechnic Institute (RPI) is currently engaged in a research effort to investigate a stand-alone safety system that will monitor the area a robot can reach and take corrective action if predefined parameters are violated. This could serve as an additional layer of protection for many unsafe conditions that could occur in various robotic installations. This paper discusses the results of this research effort. Sections II and III discuss general considerations for robot safety and classification of robot safety systems. Sections IV and V discuss the RPI robot safety system as currently implemented. Section IV and VII present conclusions and directions for future research.

GENERAL CONSIDERATIONS FOR ROBOT SAFETY

A typical on-line robot system will have evolved through a series of sequences, each presenting a different set of circumstances and safety hazards. A typical sequence may include

1) robot installation, setup, and check out,
2) integration of the robot into robotic work station and interface testing,
3) programming of the robot,
4) system testing and bringing the system on-line,
5) operational mode,
6) maintenance, service, and restarting the system.

For any system, the robot will have been installed, setup, and checked out. Various gain adjustments and active testing will be performed to verify proper installation. The robot is then programmed and integrated into a larger manufacturing system. The integration will usually consist of linking various sensor and interlock inputs and interrupts to the robot, establishing links to various other computers or controllers and interfacing various outputs from the robot. Once the total robotic system has been debugged, the system is classified operational. Preventative maintenace and various other service tasks will still need to be performed on the robot and peripherial equipment. Such a system will need a restart sequence after a problem interrupts the normal operation.

In designing a safety system to help protect workers, robot and equipment, one should address as many of the aforementioned situations as possible. The safety system itself, to be practical, must be able, to a reasonable degree, to fit the following criteria for any given application:

- inexpensive,
- fail safe,
- reliable,
- highly immune to false triggers,
- nonfragile,
- capable of an industrial environment,
- immune to RFI and power spikes,
- easy to install,
- hard to bypass,
- fairly simple to program.

Algorithms must be user friendly, allowing sensor violation parameters and teaching methods to be utilized quickly and effectively. The modification of the safety system program should not add unreasonably extra effort after a modification of robot sequences.

Classification of Robot Safety Systems

To facilitate discussions of robot safety, zones or levels of protection have been previously designated by Kilmer, National Bureau of Standards [4]. These levels (see Fig. 1), slightly expanded, are defined as

level 1 workstation perimeter penetration,
level 2 A: area within the workstation but outside the reach of the robot,
B: area within the workstation within the reach of the robot,
level 3 a small volume surrounding the robot arm which moves with the arm.

Level 1 protection is commonly attained by the use of wire fencing which not only keeps out unauthorized personnel, but also protects personnel from flying projectiles if the robot should lose its grip on an object or a part should break in pieces. Other level 1 safety devices which have been used or studied include pressure-sensitive mats [4], photoelectric fences, and camera surveillance. Standard safety devices such as warning lights, warning signs, and audio alarms which sound during a robot move may also be considered as level 1 safety.

Safety at levels 2 and 3 has been much more difficult to implement and is the subject of this current research. Kilmer [4] has reported on the work at the National Bureau of Standards using ultrasonic transceivers on a robotic arm for safety purposes. A more passive type of level 2 safety is the use of a deadman switch on the teach pendant, which is incorporated into several commercial systems.

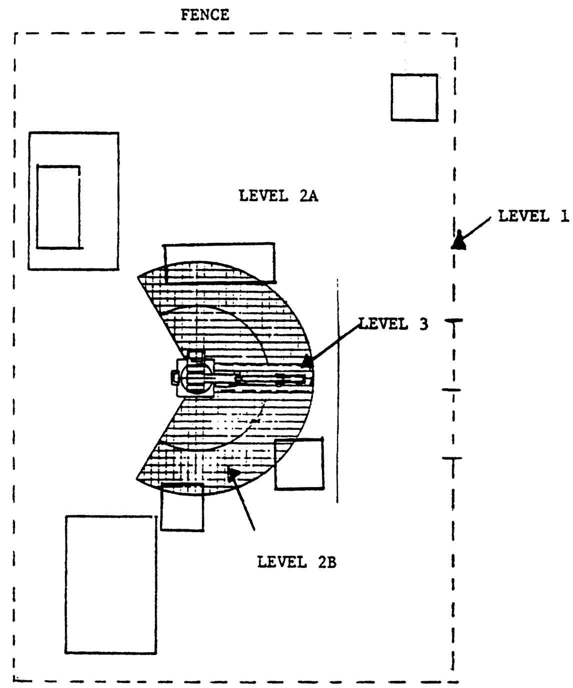

Fig. 1. Robotic work station.

A second classification scheme relates to how the sensor or sensors are used to improve safety. The two broad categories under investigation are

a) generic (robot sequence independent),
b) mapping (robot sequence dependent).

A generic sensor or system is one which is largely independent of the robot sequence. Thus the same sensor setup can be used on different robot installations and for different tasks within an installation, with little modification. The threshold levels utilized by the "unsafe condition" algorithms in the safety computer would be set for each task or combinations of tasks. Most level 1 safety technology is generic. In levels 2 and 3, generic sensing usually means monitoring distances, veloci ties, and parameters derived from returned signal characteristics, then comparing to some predetermined thresholds. An example is a sensor which monitors velocities and shuts down the arm if any velocity in the work volume exceeds the threshold.

The converse of generic systems are sequence-dependent systems, which are best implemented by a mapping approach. In mapping, a teaching sequence is performed, during which the safety system records information (i.e., distances or velocities) about the task being performed. During operation, the sensing system compares current information to the stored map information, and can signal a shutdown if the deviation is too great.

Generic sensing is attractive because of its generality, ease of application, and the absence of a teaching step. However, certain situations and some sensor technologies are not suitable for a generic approach. Also, the overall design of a generic system may be more complex, because of the generality involved, than that of a mapped system. This research had addressed both generic and mapped application of safety sensors.

Overview of the RPI Safety System

As stated earlier, the purpose of this research was to investigate and develop a safety system for providing protection within the robot work envelope (levels 2 and 3). This level of safety requires active real-time monitoring of sensory data. A number of sensing technologies were reviewed (Table I) on the basis of sensing characteristics (range, ability to detect humans, etc.), durability, and cost.

TABLE I
CANDIDATE SENSORS

Photoelectric Proximity
Inductive Proximity
Capacitive Proximity
Infrared-Passive
Infrared-Active
Ultrasonic-Motion
Ultrasonic-Rangefinding
Microwave-Motion
Microwave-Presence
Camera Surveillance

From this list, four technologies emerged as having superior properties for robot safety:

1) ultrasonics
2) microwave
3) infrared
4) capacitance.

For each technology, representative sensing units have been obtained and tested. Commercially available units have been used where possible to help reduce the cost and to use proven circuitry. However, in many cases it was necessary to modify or redesign the commercial circuitry to enhance our application and to allow computer control of sensitivity and other sensor functions.

After individual testing and circuit redesign was completed, the systems were interfaced to a safety computer. The present system development will allow the use of various numbers of each of the four sensor types, the number and configuration being tailored to the particular robotic application. The software is modular in form, allowing for the management of different combinations of sensors, and different work cell configurations.

To ensure the integrity and effectiveness of the safety system, it is essential that the safety computer be constructed of high-reliability components and incorporate self-checking diagnostics. It is also recommended that the safety computer be a separate entity from the robot control computer [7], [12].

Once the safety system has detected a violation, there are a number of possible responses, ranging from an alarm to robot shutdown. The exact manner of applying this graduated response was not addressed by this current research, as the emphasis was on *reliably detecting* violations. A reasonable sequence would be to activate an alarm when the intruder first enters the outer perimeter; then slow the robot if he enters the outer workspace, but not in the immediate area of the robot; and finally completely halt the robot if the intruder is in danger of imminent collision. In any case, it is necessary that false alarms be minimized or the safety system will be turned off or otherwise circumvented.

Safety System Components

Ultrasound

Ultrasound sensing is based on producing a high-frequency (above 20 kHz) sound wave, transmitting this sound wave, and then measuring the time interval until a reflection is detected back at the source. Thus it is necessary both to produce and detect ultrasound signals. The distance to the reflecting object is linearly related to the observed time delay by the speed of sound. Ultrasound sensing is used in intrusion detectors, for focus control in a popular instant camera, and for industrial gauging and ranging.

The National Bureau of Standards safety study [4] used ultrasound sensors mounted on the center post and boom of a Stanford-type manipulator to achieve generic, level 2 safety for the manipulator. This approach is valid when the sensors can be mounted so that all reflecting surfaces remain beyond the minimum distance of concern. This constraint becomes difficult to meet in many applications, because the robot is closely surrounded by other (possibly moving) equipment. This research has concentrated on the use of ultrasound sensors near the end effector in both generic and mapping modes.

Two types of ultrasound sensors were obtained for testing: electrostatic units and piezoelectric units. The electrostatic unit is used in the instant camera, has a range of 0.9–35 ft, requires a 300-V supply (undesirable in some industrial applications), and costs less than $50. This cost includes the analog control electronics. The piezoelectric units use a lower supply voltage but are somewhat more expensive. Both units require additional circuitry in order to interface to the safety computer. Fig. 7(c) shows the ultrasound sensors mounted on the wrist of a T3 robot.

The ultrasound sensors performed quite well in both generic and mapped modes. The safety computer controls the sequence of ultrasonic sensor firings allowing for the optimizing of sensor resources depending on conditions (i.e., the direction of robot travel). A few problems are the subject of ongoing research. The first deals with the relatively narrow detection beam (10°–30°) of the ultrasound sensors. Narrow beams are desirable for ranging, but for many safety applications a wider field of coverage is desired. Horns and diffraction grating have been investigated to produce a more divergent beam. Concentric spreading horns produced satisfactory divergence, but more investigation is required on methods of attachment.

A second problem concerns the relatively low repetition rate of the electrostatic transducers (10–20 Hz), caused by mechanical transients and circuit reset which must occur between pulses. Separation of the one-unit transceivers into separate transmitters and receivers can help this problem. A slow recovery cycle can also cause problems with high-speed robots which may move 5 in in 0.1 s. This may be overcome by using multiple sensors with overlapping coverage.

Finally, occasional false triggers occur, apparently caused by multiple echoes or ultrasonic noise induced in the environment by vibrations, etc. Different methods to eliminate false returns are under investigation including "chirped" signals, use of highly ramped gain in return signal processing, and possible omnidirectional monitoring of coincidental environment noise. It may be desirable to take special measures such as using sound absorbing materials or surface coatings at certain locations within the robot motion envelope. Another solution is to use multiple sensors of different frequencies and to require multiple triggers before flagging a violation.

Microwave

Two types of microwave sensors are commercially available: presence sensing and velocity sensing. The microwave presence sensing uses an amplitude modulated signal and at the present time is more expensive ($2000 or more per unit) than the velocity sensors which are commonly used for control of automatic doors and intrusion detection. These velocity sensing units are based on the Doppler principle that when a wave is reflected from a moving object, the frequency of the reflected wave is increased (or decreased) by an amount proportional to the object's speed.

The velocity sensing microwave units which were obtained for testing produced an output pulse train proportional to the Doppler frequency shift. By measuring this frequency it was possible to determine the approximate velocities of objects in the sensor's detection area, which is large enough to cover the working area of the T3 robot (Fig. 2). It is possible to isolate a microwave detection area from outside interference by use of the proper wire mesh shielding.

The microwave sensor was investigated for both the generic mode and mapping mode. In the generic mode, the sensor is used to monitor the robot workspace and flag a violation if some velocity threshold in the robot area is exceeded. This condition could be caused by an out-of-control robot or by an intruder, but either case warrants some corrective action.

In theory, it should be possible to mask out the velocity components due to the robot by the mapping method, and this aspect was heavily investigated as part of this research. Although some success was obtained with mapping, there are three complicating factors. First, the microwave unit does not accurately measure very low velocities. The Doppler shift frequency is very low, and the pulse train output is erratic. This can be overcome to an extent by simply disregarding small velocities. The second problem is that the sensor measures velocity components directly toward (or away) from the sensor, but not those tangential or lateral to the sensor. Thus an intruder walking laterally across the sensing area might not be detected. Orthogonally mounted microwave units of different frequency can be used to resolve this problem.

The third problem is that the reflected signal is directly proportional to the area of the reflecting object, inversely proportional to the distance from the sensor and effected also by the reflective characteristics of the surface material. Thus

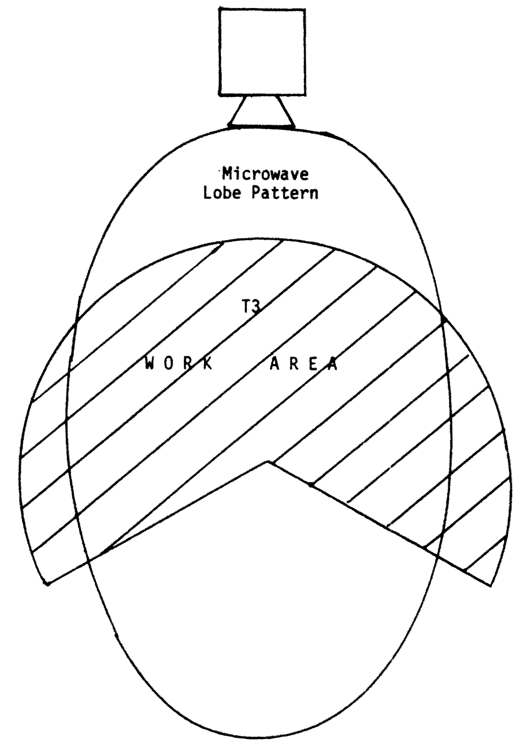

Fig. 2. Microwave lobe pattern.

in certain circumstances a human intruder might be masked by the signal reflected by a large robot such as the T3.

Infrared

The basis for the infrared sensor use is that all objects emit black body radiation if their temperature is above absolute zero. Humans emit radiation maximized in a well-defined spectral range (approximately 8–14 μ), so infrared sensors have been developed that are tuned to this wavelength. These commercially available sensors are designed to detect intruders in an office or home environment. The intruder, moving in the surveilance zone, brings with him a temperature variation. This infrared radiation of about 10 μm is within the design range of these devices. Various types of these units were purchased in order to test them and to modify their circuit designs for computer interfacing.

In the pyroelectric sensor device, the change in temperature creates a change in polarization of the electrical charge. Thus a temperature change will produce a current as a sensor output. This type of sensor device has a fast response and acts as a receiver to all human "transmitters." However, a simple pyroelectric device will also change its output reading for a slow but steady room temperature rise, and a false trigger may occur.

The combination of two pyroelectric devices, often referred as a dual detector, helps to solve the background sensitivity problem. Two similar but oppositely wired devices are aimed out onto the same general work area, as are the fingers in Fig. 3. The first half is designed to produce a positive current when a temperature rise occurs, while the second half is to produce a negative current for a temperature rise. If the background temperature does change, the net effect of the pair is a zero

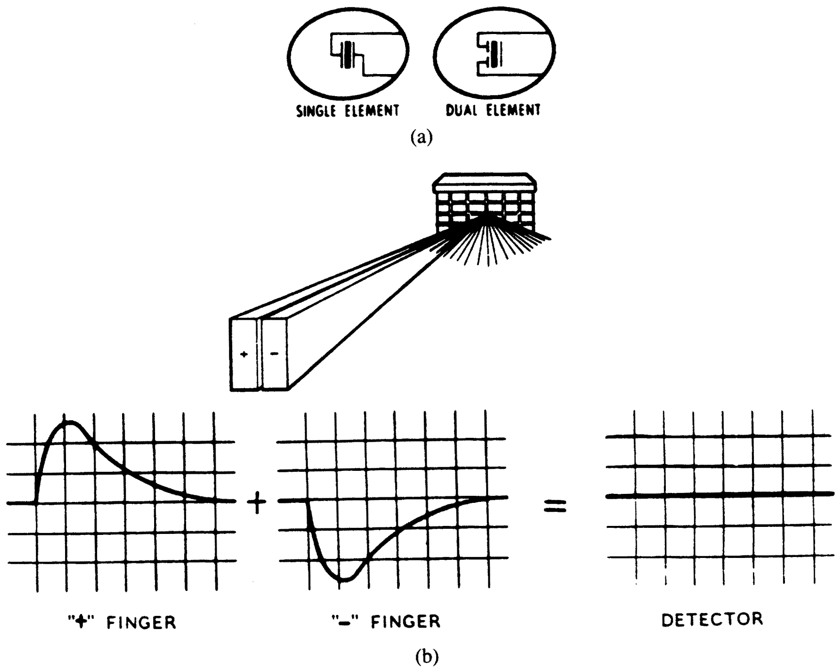

Fig. 3. Environmental disturbance rejection characteristic of dual element pyroelectric detector. (a) One pair of detection zones (fingers): one positive finger and one negative finger. (b) Fingers combined to form detector.

current output. However, an intruder, while in motion, will enter one of the zone's finger first and produce either a positive or negative current change. Fig. 4 shows the positioning of the infrared detectors in the robot workspace.

Test results on the dual detectors for human intruders were very favorable in laboratory conditions, but other background considerations also were investigated. Standard lightbulbs produce radiation in the "human" range, leaving the sensors flooded with infrared signals. The motion of the robot itself was found to cause trouble. The Cincinnati Milacron T3 industrial robot produced radiation above, below, and in the human range while performing various tasks, so a threshold setting on the sensors signal processing would not work.

It was found necessary to use the infrared sensors in a mapping procedure. This would mask out the repeatable performance of the robot. Cyclic measurements were very repeatable, so an adaptive value mapping technique was used. The system was then dependably able to detect human intrusions. The adaptive value process takes sample readings during the first cycle for its reference values. The second cycle's readings are compared, and if they do not deviate more than a threshold level, the cycle is considered trouble-free. The second cycle's values are substituted for the first cycles's values, becoming the new references. Thus slow temperature fluctuations will be ignored as long as the background changes are less than the threshold values.

The multiple fingers of the detection device can also be selectively masked out to keep a trouble source from constantly flooding the detection zone. The parabolic mirror or lens for that finger can be physically masked to "turn off" that pair of fingers.

Capacitance

The capacitive sensor is currently used in the factory environment in order to protect the worker from injury with such machines as presses and stamping machines. Upon entry of the protection zone a relay is triggered in the device which is in turn used to control the motion of the machine. The device must cause the machine to stop only. OSHA will not permit such devices to restart these machines.

Three commercial capacitance of RF presencing devices were available at the time of this research. The range of detection was one concern, since many commercial uses detect inches only. The robot working environments are often many feet. It is desirable to detect the intrusion several feet away since the robot, when at runaway speed, may reach 200 in/s. The unavailability of schematic diagrams from the manufacturer also forced the researchers to eliminate one type of unit.

The capacitance sensing device is designed to protect the worker from injury caused by interaction with a moving machine. By determining the changes in the capacitance between the sensor device and the ground, signals are generated which can be used to control machinery. The sensing unit usually consists of a control unit, an antenna as the sensor, a coupler and the connecting cable.

The control unit contains the power and comparative circuitry and relays. The antenna can be constructed from copper, galvanized steel, or other conductive metals. The antenna shape is configured for the particular application. It is connected to the control unit with a coaxial cable. The antenna and ground act like two plates of a capacitor. The area of the "plates" and their dielectric constants have a direct effect on the capacitance. The comparative circuitry acts as an impedance bridge. With the fluctuation of the surrounding field of the antenna, one arm of the bridge is thrown from its balance condition and one where current flows through a galvanometer. As part of the device setup, the bridge is nulled to take into account the particular environment present. In the available commercial devices, any changes from this null will trigger the signal for the relay. Depending on the application, the

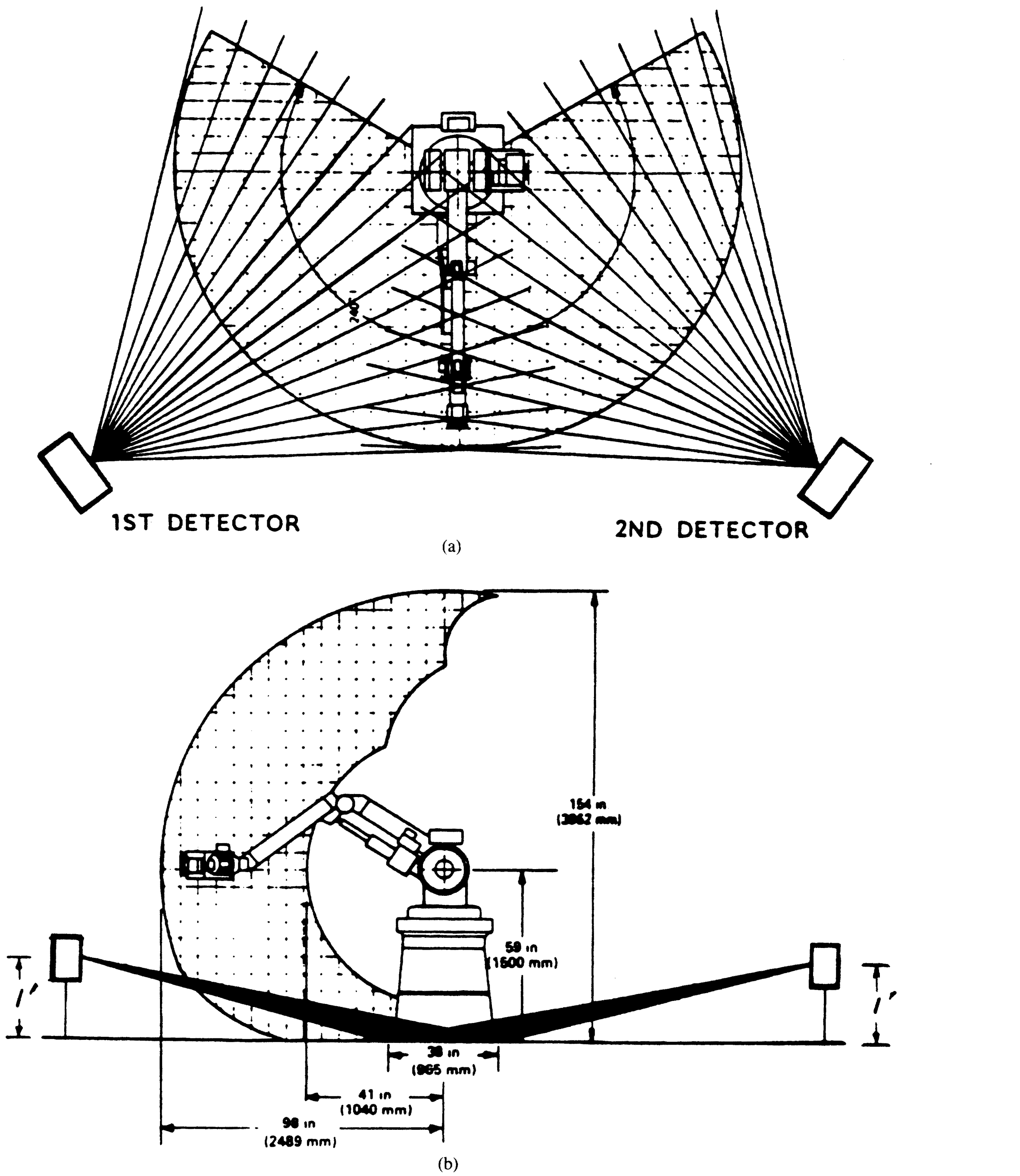

Fig. 4. Infrared sensor system using two pyroelectric detectors. (a) Top view. (b) Side view.

relay can be used to sound alarms, cutoff power, or apply a brake.

In applying the capacitive sensor to diverse robotic applications, the usually well-defined area of a static machine becomes one with many problems. For the antenna to be most effective, it should be placed close to the end effector of the robot and possibly on the sides of the arm (Fig. 7(d)). This motion is quite different from the design's original purpose. The motion will take the antenna from its null position, possibly causing a false trigger. The motion of a runaway robot can be quite large, so the process of deciding whether or not to trigger must be made quickly.

A number of environmental factors have a known effect on the capacitive sensor. With a change of humidity or temperature the balance in the bridge circuitry will be thrown off, possibly giving a false trigger. Since an air capacitor is being used as one arm of the bridge, any variation in temperature or humidity will change the dielectric constant of the air, and thus the capacitance. The individual components of the bridge may also change if the control unit is allowed to face the environment.

The capacitive units all tended to drift with time. Even with no motion, drift will eventually cause a false trigger. For a mapping scheme to work, a constant nulling circuit was designed, and efforts continue to reduce further the effects of drift. Circuits have been developed to distinguish the characteristic response of a human from that of the robot itself, and considerable research continues in that area.

Integration of Sensors Via the Safety Computer

All of the individual sensing systems described are available in commercial packages that operate in the threshold-alarm (generic) mode, particularly for intrusion detection. While such self-contained units can be used to a limited degree in a robot safety system (primarily at level 1), it is our contention that an integrated system under the control of a central microcomputer is superior for the following reasons:

1) allows more sophisticated processing of signals than simple threshold detection,
2) can combine information from several sensors to make a collision avoidance decision,
3) allows tailoring of the system to the particular application.

The development of the safety computer is proceeding in two steps: 1) development of the interface hardware and control software on a microcomputer development system, and 2) development of a stand-alone target system suitable for industrial application.

The National Semiconductor 6608 Development System, which was used in this project, features an 8086-based single board computer, serial and parallel interfaces, a programmable interval timer, an analog card, floppy disk drives, and the CP/M86 operating system (Fig. 5). This unit was chosen because the 8086 is widely used in industrial control applications. Furthermore, the CP/M86 operating system provides helpful software development tools, such as an editor, a file system, compilers and an assembler. Most of the software was written in Pascal.

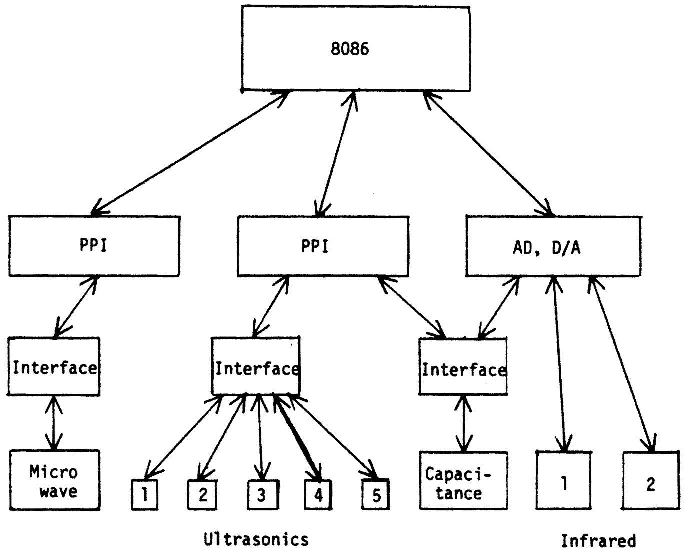

Fig. 5. Safety computer hardware configuration.

The control software was structured into four menu-selected modes (Fig. 6): 1) system configuration mode, 2) generic mode, 3) teach mode, 4) run mode. In the system configuration mode, the user tailors the sensor system for a particular application by selecting the sensors to be used, and by initializing control parameters for each sensor system. This mode can also be used to display stored data tables for mapped sensors.

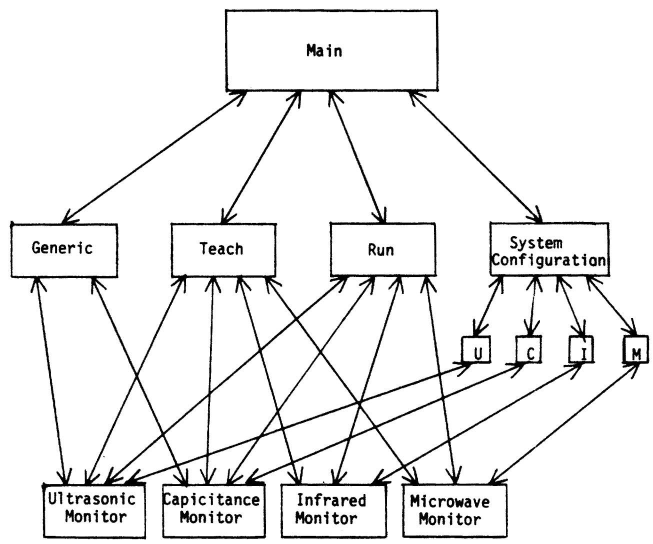

Fig. 6. Software block diagram.

In the generic mode only sensors which are selected for generic operation are activated. This mode is an appropriate operational mode for robot teach operations, during which new tasks are programmed with the use of a teach pendant. As part of the teaching process, new data should be collected for the mapped sensors, and this is handled by the teach mode software. Finally, Run mode activates both generic and mapped sensors to achieve a fully operation safety system.

Some Results and Observations

The individual sensors were tested and interfaced to the microcomputer between January 1982 and March 1983. The integration of the system was completed by August 1983, and efforts since that time have been focused on testing and improving the individual components and the overall system. Several conclusions have been reached as a result of this testing.

It becomes obvious very early in the project that the commercial sensor packages are far from optimal for the task of robot safety. In all cases, the sensor control electronics had to be modified to improve sensing performance, and/or to allow for computer interfacing. It is hoped that, as demand for robot safety increases, optimized sensor packages will be commercially available. Along this same line, it will be necessary to improve the physical packaging of the sensors to withstand industrial environments (One component of this project is to study environmental limitations on sensor performance.) A second conclusion is that no single sensor or combination of sensors can be expected to cover all robot safety and collision avoidance situations. By investigating the most promising sensor technologies, we hope that we can provide general guidelines which will help in configuring the safety system for a particular situation.

The idea of generic safety sensing, independent of robot tasks, is attractive because of its generality, but with the

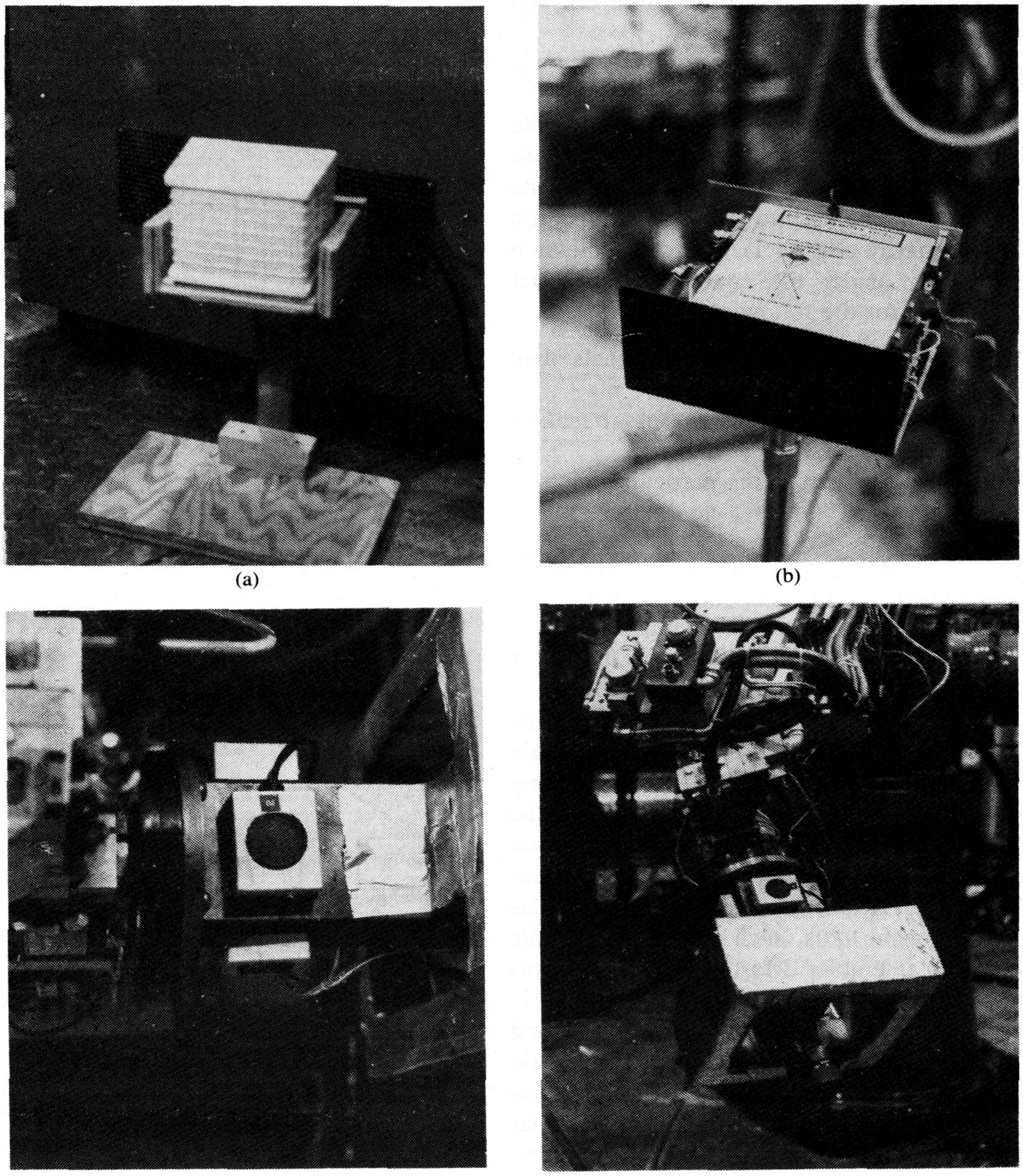

Fig. 7. (a) Infrared sensor. (b) Microwave sensor. (c) Ultrasound sensors mounted on wrist of T3 robot. (d) Antenna for capacitance sensor mounted on T3 robot.

current sensor systems, it is very difficult to achieve. The development of an inexpensive sensing system which can reliably differentiate between animate and inanimate objects would be a major step forward. For many current robot applications which involve simple repeated motions, the mapping approach produces a simple reliable safety system by masking out the constant background factors. As robot applications become more sophisticated, with interrupt sequences and adaptive sequencing, the mapping technique becomes unwieldy. It seems likely that a combination of generic and mapped features will continue to be present in robot safety systems.

The final conclusion from this research is that human factors will continue to be one of the major challenges for robot safety. The robot safety engineer must balance out the technical characteristics of the system against the human factors, as for example, in determining what level of false alarms can be tolerated, balanced against the consequences of not detecting a safety violation.

Directions for Futher Safety Research and Development

This robot safety research project has been attempting to address the various difficult and somewhat contradictory problems that exist in developing a system that would have acceptance on the factory floor. Any independent robot safety system must be introduced into the industrial environment in such a way as not to add an additional layer of "false security" to personnel. Additional personnel training, etc., will be required to facilitate the implementation. A great deal of work remains to be done before such a system could be introduced on the factory floor.

Investigation is underway for various methods of handling interrupted sequences and relative move sequences. Techniques need to be redefined for teaching the safety system worst case parameter variations that will be encountered due to peripheral equipment movement, e.g., conveyor belts. Software developed must be capable of being initialized by semitrained factory floor personnel. Sensor violation parameter insertions, methods of safety system teaching and program modification must be straightforward.

As at many industrial sites and universities, off-line programming capabilities exist at Rensselaer Polytechnic Institute for defining data points on a graphics terminal by moving a robot image through a simulated workspace. These points can be automatically down-loaded to the robot controller and then used to sequence the robot. With detailed descriptions of the workspace, software programs could be written that would generate the safety system program at the some time the graphics simulation generates the robot program.

Much research still needs to be done on robotic safety. It is recommended that research in this area is important and timely for the manufacturing community.

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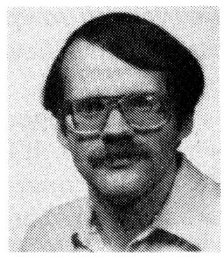

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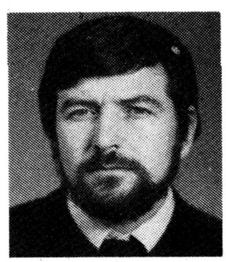
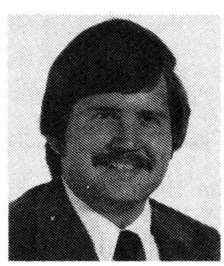
From 1972 to 1976, he was employed as a Product Design Engineer at the Delco-Remy Division of General Motors Corporation. From 1981 to 1985, he was an Assistant Professor in the Department of Electrical, Computer, and Systems Engineering at Rensselaer Polytechnic Institute. He is currently an Associate Professor of Computer Science at the University of Louisville, Louisville, KY. His research interests include robotics, artificial intelligence and distributed computing.

Dr. Graham is a member of ACM, and a Registered Professional Engineer in the State of Indiana.



John F. Meagher received the B.S. degree from Rensselaer Polytechnic Institute (RPI), Troy, NY, and the M.S. degree from the Florida Institute of Technology, Melbourne, in 1965 and 1972, respectively, both in physics.

He worked at the NASA Langley Research Center, IBM, and Gruman Aerospace Corporation. He is presently a Senior Project Manager at the Center for Manufacturing Productivity and Technology Transfer at RPI and Associate Director of the Computer Integrated Manufacturing Program.



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