Daniel PODGÓRSKI
Central Institute for Labour Protection
Warsaw

Tomasz WAŃSKI
Stanisław KACZANOWSKI
Industrial Research Institute for Automation and Measurements
Warsaw

ON SAFETY IN POLISH ROBOTICS APPLICATIONS

The paper is deevoted to some specific problem arisen from robotics applications in industry, namely a question about a safe co-operation between a staff and a robot. Some solutions obtained in this field are desctibed and the direction for future research in Poland is sketched.

INTRODUCTION

Robotics in Poland has been developing for about fifteen years. Scientific institutions sponsored with funds from the Polish Government have given a great contribution in research and design for this development. An overview of some more significant research and design results attained in robotics in Poland is presented in the first part of this paper.

Taking into consideration the importance of safety problems when introducing robots into industry, some relevant research safety in robotics applications was also undertaken as projects of the government programs. The following research institutes are the most active in this domain: the Industrial Research Institute for Automation and Measurements (PIAP) and the Central Institute for Labour Protection (CIOP).

Safety problems related to industrial robot applications can be divided into two main groups:

- consideration of safety issues in the design of industrial robots — mechanical design of the robot arm, design of the robot control system hardware and software,
- installation of safety systems in robot workplaces for detecting human presence inside or nearby the robot dangerous movements zone.

Since both these types of problems are equally important to achieve the appropriate safety level on robot workplaces, research works on safety in robotics applications in Poland were performed in these two directions at almost the same time. Results reached in the design of safe industrial robots are described in the second part of this paper, and results obtained in the field of safety in developed systems are presented in the third part.

Finally, an outline of prospective goals for future research in those two main areas of safety in robotics applications is also presented.

DEVELOPMENT OF ROBOTICS IN POLAND — AN OVERVIEW

Robotics understood as a branch of science and technology has been developing in Poland since the mid 70's. The important moment in robotics development came in 1977, when the licence for manufacturing the IRb robots was purchased from the Swedish company ASEA. These robots have been manufactured up to 1988 with the same trade name, and since 1989 — have been called the IRp's. The type designation has been changed due to intrinsic changes introduced as well into the robot manipulator as into the robot control system.

Besides the IRb robots several other types of robots of original Polish design have been manufactured. These pneumatically, hydraulic and electrically driven robots are used mostly for workpiece manipulation (i.e. pick-and-place tasks), spray painting and spot welding. At present about 100 robots a year are manufactured in Poland.

Polish industry employs about 500 robots altogether. Most of them have been manufactured in Poland. The most popular foreign robot manufacturers are: UNIMATION, CLOOS and COMAU. The main application areas are: arc and spot welding and machine-tool servicing. It should be emphasized that several quite complicated robot applications, such as: plasma spraying, polishing, machine part regeneration with aluminium padding, sintering details from iron powder and assembly of small electrotechnical equipment have been designed in Poland without any foreign aid.

Several specific robot parts or equipment used in robot applications have been developed in Poland. The most important achievements in this field are: electric drives with DC and AC motors, harmonic drives, automatic gripper change equipment, various types of sensors, industrial vision systems, welding equipment especially designed for robot technology and rotating holders for welded workpieces.

Other important results of research were also obtained in the development of robot testing and evaluation methods and the design of specialized testers as well as maintenance and diagnostic equipment.

Many Polish research institutes and technical universities have undertaken specific problems in robotics. The most important results obtained in this field include the following:

- mathematical modelling and computer simulation of robot kinematics and dynamics including various physical phenomena (development of methods and algorithms for time-optimal robot trajectories, development of automatic generation of robot dynamics equation matrix including drive system softness, arm elasticity, mechanical friction and backlash),
- development of an integrated package of computer programs for static and dynamic robot manipulator modelling applicable in various types of robots,
- application of a new robot control algorithm based on the idea of "feedforward" (i.e. prediction and neutralization of expected effects) used to velocity or position signals — the great qualitative progress in the design of robot axis controllers,
- a new programming language oriented on workpiece manipulation tasks aided with computer simulation for visual control of robot movements trajectory in three-dimensional graphics,
- special methods and programs for multi-criterion optimization oriented for the design of mechanical robot manipulator parts and optimal models for robot drives,
- application of vision systems for robot control (development of algorithms useful for static and dymanics analysis for on-line robot trajectory control in three-dimensional graphics).

And finally it is of a great importance that a new original construction of an underwater operating robot for ship hull conservation tasks has also been developed and tested.

SAFETY ASPECTS OF INDUSTRIAL ROBOT DESIGN

A general idea of the robot fail-safe design

It is generally accepted that introduction of robots into industry can improve working conditions by elimination of workers from dangerous and monotonous jobs. But robots create new hazards and some of these hazards are the result of inappropriate design of the robot itself. It is particularly important to make the robots as reliable as possible because a great number of accidents at robot workplaces were caused by robot malfunctions during programming or testing. Moreover, a great number of accidents was also caused by erroneous action of robot operators, which in turn was due to an inadequate design of the robot control elements.

The basic approach to achieve the acceptable level of robot safety is a fail-safe design. The fail-safe design can be based on many well-known general rules, however in the case of robots it is necessary to analyse hazards caused by each type of potential robot failure in order to determine the most efficient precautions. The typical examples of quite efficient fail-safe design methods is redundancy technique and application of additional safety measuring devices.

These measuring devices should be understood as additional subsystems, devices or sensors incorporated in the robot control unit and the robot manipulator in order to monitor independently the operation of the robot system. In the case of detecting any robot failure or its improper working conditions by any of these measuring devices, the robot movements should be stopped, which means that the robot should achieve the state of safety.

A new control system for the IRp-6/60 industrial robots

A modification of the control system for the IRb robots manufactured under the ASEA licence was made by the Industrial Research Institute for Automation and Measurements in the mid 80's. The new construction of this system is now called IRp and it is able to perform two types of trajectory control: point-to-point (PTP) and continuous path (CP) — (Jabłoński et al., 1986).

The new control unit enables simultaneous control of up to 6 robot axes and up to 3 external drives with DC motors for external equipment (including robot track motion). It also enables monitoring of analog and digital external signals and the control of a number of bistable-driven external devices. It is possible to incorporate the robot control unit into a flexible manufacturing system by using a set of additional built-in modules.

The control unit hardware is based on the Polish digital automation system with a 16-bit central processing unit. The hardware is modular and consists of various electronic PCB panels. Software of the IRp controller has also a modular structure and it makes the development of the software possible and relatively easy.

Each drive system for a robot axis (as well as for external motors) consists of axis position controller and power controller panels. An axis position controller is based on 8-bit processor. This enables a great qualitative development of control unit and realization of a number of new robot functional features, which are as follows:

- PTP and CP trajectory control with direct velocity declaration in milimeters per second,
- tool centre point (TCP) trajectory programming in various systems of coordinates namely: joint oriented, cartesian, or cylindrical,
- tool centre point trajectory programming with either linear or circular interpolation,
- adaptive control with the use of various external sensors (proximity, tactile, etc.),
- preparation of application programs library with the use of magnetic tapes and discs,
- possibility for off-line programming.

The application program is prepared by means of a hand-held teach pendant. This microprocessor-based module is equipped with an alfanumeric display (2 rows 24 characters each), a set of fixed keys and a set of soft-keys (the current function of these keys is shown on the display just above them). The pendant communicates with control unit by means of a standard RS232-C interface. These technical solutions enable interactive programming — the operator is informed about program instructions parameters and the robot status on the alphanumeric display.

Teach pendant enables edition of application programs: insertion and deletion of instructions, change of numerical parameters, etc. The multistep robot velocity correction during automatic execution of application program is also possible by means of a teach pendant.

The pendant is equipped with a joystick for manual control of robot movements during programming. The joystick has three degrees of freedom: left-right inclination, forward-backward inclination and knob rotation. Movements of external axes can also be controlled by this joystick.

The present state of safety of the IRp-6/60 robots

The well-known safety hazards associated with robots have forced the designers to insert additional circuits and apply some specific technical solutions in the IRp control unit to increase its reliability and safety, namely:

- hold-to-run control on the teach pendant,
- watch-dog within the teach pendant,
- watch-dogs in axis position controllers,
- circuits for on-line signal bus checking,
- brakes on manipulator axes.

A hold-to-run switch prevents an unintentional robot movement caused by incidental pushing the joystick by the robot programmer or by droping the pendant to the floor. Electrical signals from joystick induce robot movements only when this switch is pressed.

In the case when the program of the pendant internal microprocessor stops or runs improperly, the watch-dog device in the pendant forces the program to return to its regular routine.

Watch-dogs in robot axis position controllers cause an emergency stop of the robot movements when there is detected that the program of any of these controllers runs improperly.

The robot control unit is equipped with a special control panel to monitor several internal parameters. Some part of its hardware is used by the central processor unit to check signal buses by means of control data transmission just to stop the robot when any failures or distrubances are detected.

Electrically driven brakes on robot manipulator axes disable the robot movement in the case of emergency stop or switching off the power supply.

The solutions described above have a direct impact on safety in robotics applications. But there are also other technical means which have indirect influence on safety. These means include the following:

- dialog programming with help of the teach pendant,
- multi-action start system for the application program,
- possibility of connecting the external stop devices,
- reduction of the robot speed in the case when the pendant is taken out from its normal place in the control cabinet.

A multi-action start system also prevents from accidential running of an application program. It makes impossible to start a program execution by using a single button only. A user should push two distinct buttons at least, and moreover, in a prescribed sequence.

The solutions above described reduce the possibility of hazards and accidents in robot workstations. These are the basic means of safety for operators and programmers who are mostly exposed to hazards at robot workplaces.

Research on further improvements in safety of the IRp robot applications

At present work on increasing the safety level of the IRp robots is continued in PIAP. The purpose of this work is to establish a set of technical and organizational means for increasing the safety of this robot applications by preparation of appropriate design rules (as well for hardware as for software), methods of supervising various subsystems within the robot control system, new proposed robot functional features (e.g. safety stop function and emergency withdrawal function), recommendations concerning robot workstation organization, operator training programs, etc.

Within these works the following main subjects should be worked out: identification of hazards at robotic workplaces (specifically the analysis of workplaces in Polish industry), methodology for estimation of the safety level of a robot or a robot workplace, development of the robot structure with regard to the best avilable safety level from technical and economical point of view.

Several technical means have been proposed in this field. The most important ones deal with self-test system incorporated in the control unit and the safety performance of drive and measurement system. The idea of the self-test system structure is shown in Figure 1.

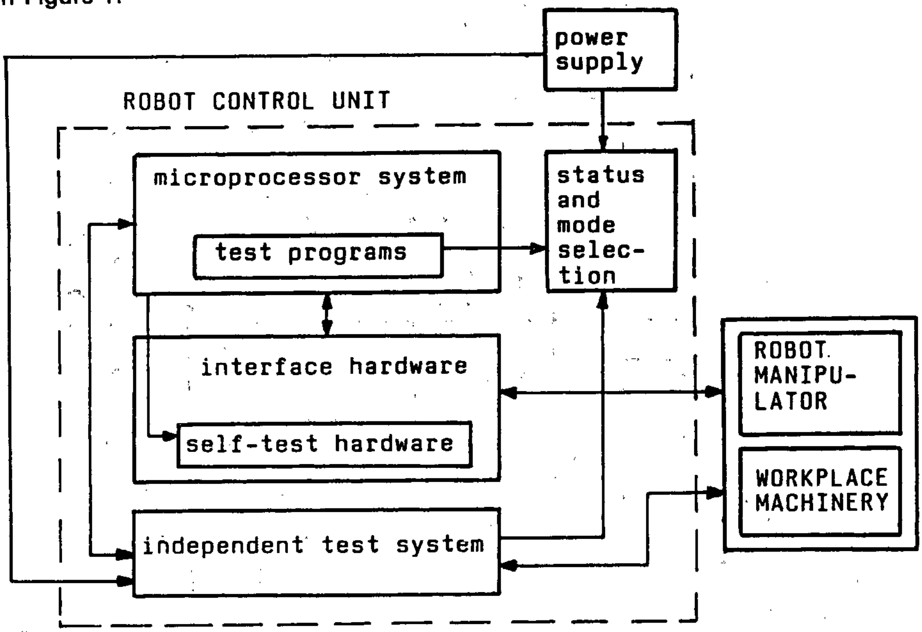

Fig. 1. The structure of the robot self-test system.

The problem of reliability of drive system is essential for robot construction and applications. Almost every failure in this system may cause the most dangerous situation — a rapid, unpredictable robot arm movement. The best prevention, beside the carefull design and manufacturing of this system, is the use of redundancy technique. The idea of implementation of redundancy in the design of robot drive system is illustrated in Figure 2.

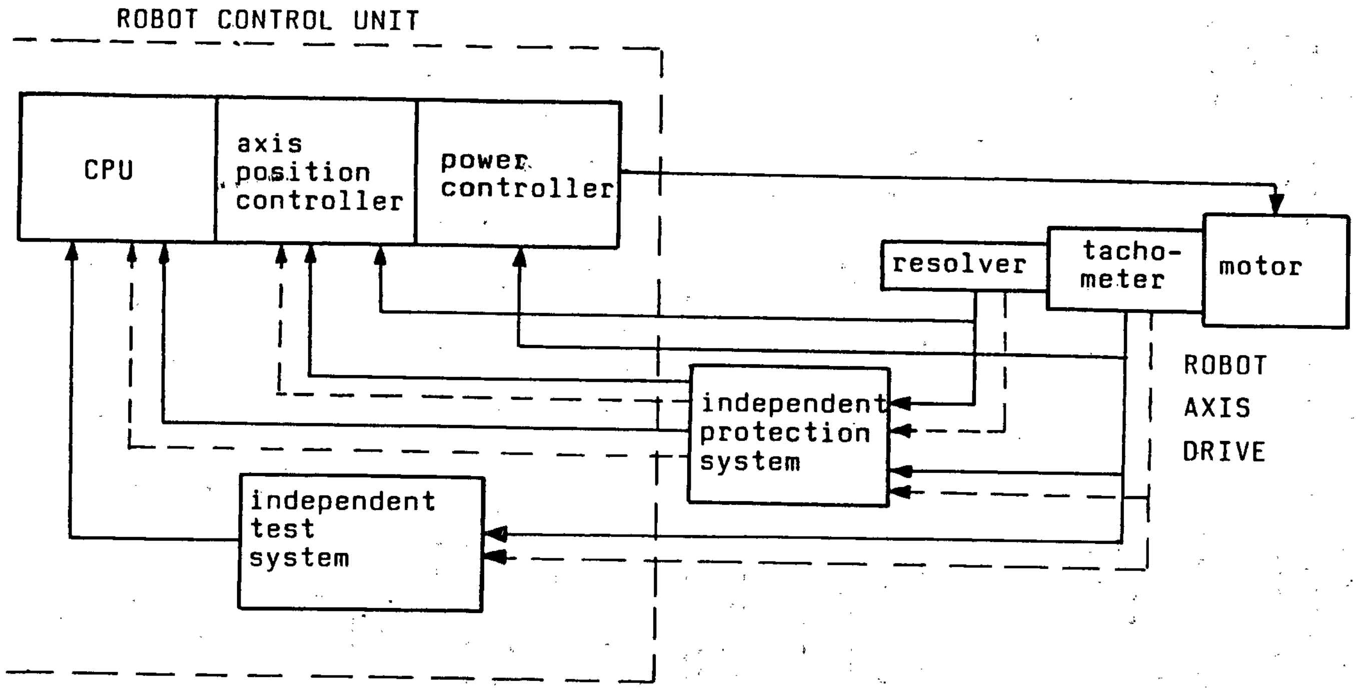

Fig. 2. The idea of redundancy technique application in the design of the robot drive system (redundant signals are sketched with dashed lines).

The results of research works will be applied in construction of new robot types. Some of them will be introduced in the IRp-6 robot design and they include:

- development of the start-stop system with external commands (e.g. external generation of "safety stop" signal) in automatic and manual operation modes,
- a robot environment monitoring system (power supplies, peripheral machinery, gate interlocks, etc.),
- self-test (performed in each robot start-up routine and during normal operation),
- several velocity ranges for manual robot movements control with the joystick,
- emergency withdrawal function.

The first two solutions can be easily implemented by expanding the bistable input/output system and introducing some changes into software. The start-up test should be constructed so it examines as many mutual interdependences between factors describing internal and external robot conditions as possible, taking additionally into account the situation of its performance. Namely, the start-up test running in a manual operation mode (usually applied in a teaching phase) has no limited duration, and thus it can concern all interdependences. On the other hand the start-up test for an automatic operation mode (usually used in a normal robot operation) should be as fast as possible. Therefore the start-up test for an automatic operation mode is frequently prepared as a set of separate routines performed sequentially, each one in another moment of an application program execution.

The possibility of changing joystick range can make the programming process easier especially when high positioning accuracy level is necessary. It can also decrease the hazard level caused by incidental programmer's errors.

The new emergency robot withdrawal function has been proposed by Wański (1983). The purpose of this function is to take automatically back the robot arm from the dangerous position to the place defined as the "safe position". The withdrawal can be activated by the operator, external safety sensor or by a special sensor (e.g. a gripper temperature sensor or a robot arm load sensor) in the case when the robot arm is in a condition which can result in its damage. This function is mainly for protection of robot's arm, so it is of lower priority compared with any other safety stop command.

The idea and examples of robot end-effector trajectory during emergency withdrawal are shown in Figure 3.

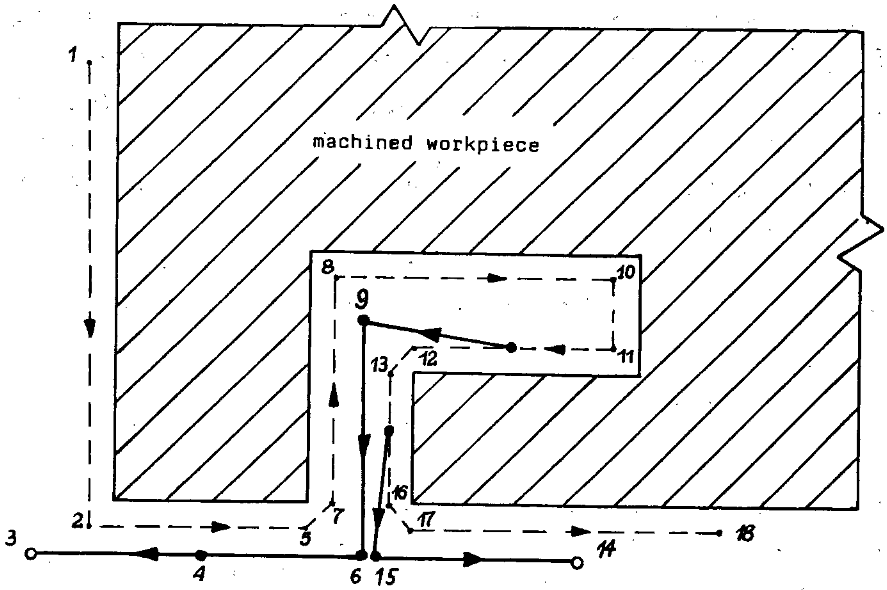

Fig. 3. Examples of robot end-effector trajectories during normal program execution (dashed line) and during emergency withdrawal (continuous line), points 3 and 14 — end safe positions.

During preparation of the application program some additional intermediate or end safe positions are introduced into the robot control unit memory. These positions are ignored during normal execution of this program. After activation of withdrawal signal the application program starts its backward execution. Since that the normal trajectory points are omitted and the instructions with emergency positions are executed only until the end safe position is reached.

The emergency withdrawal function consists in a new organization of hardware and software resources existing in the control system for prevention of hazards and accidents and elimination of possible destructive results.

The above described solutions constitute a complex set of measuring devices that will be introduced to increase the level of intrinsic safety of the IRp robots.

DEVELOPMENT OF SAFETY SYSTEMS FOR ROBOT WORKPLACES

Safety system sensors

One of the ways to prevent a personnel from interacting with industrial robots is to equip robot workstations with safety systems detecting human presence nearby the robots. These safety systems can be divided into three groups according to their coverage level of the physical regions around the robot (Kilmer, 1985).

The 1st level safety systems have the most widespread insight into robot worksplaces. These systems provide perimeter detection of persons crossing a workstation boundary by means of interlocked physical barriers, light curtains or floor safety mats. Since these types of safety systems do not protect the personnel during the robot programming or during robot maintenance when close interaction with robots is required, it is very important to perform research in development and application of the 2nd level safety systems which would be able to detect human presence within and around the robot movements zone, and of the 3rd level systems which would be able to detect human presence nearby the contact surface of the robot arm.

There are many various kinds of sensors which can be applied in the design of the safety systems of the 2nd and the 3rd level. The most popular kinds of sensors are passive and active infrared sensors, capacitance sensors and ultrasonic sensors. A proper selection of the most suitable sensor type to obtain the safety system with the best technical parameters is very important. Costs of the safety system design and manufacturing depend also on the selection of the sensor type. Particularly the necessity to provide the most reliable detection of human presence and the sensor immunity to false triggers should be taken into consideration during the safety system development.

Therefore the examination and assessment of the sensor operational reliability in the robot workstation environment should be the first phase of the safety system development process.

The first research work in Poland on the safety system for the 2nd and 3rd level was carried out in PIAP at the beginning of the 80's. The system developed has consisted of active infrared sensors mounted on the robot arm. Laboratory tests on the active infrared safety system operation used various kinds of obstacles (including a mannequin of human adult size). Their results proved appropriate system effectiveness in detecting this objects in safe distances from the robot arm — (Wydżga, 1981).

A study on the application of ultrasonic safety sensors

Further research work in Poland in the area of safety robotic systems development was undertaken in CIOP. It focused mainly on the possibility of ultrasonic sensors application for robotic safety purposes.

In order to evaluate the ultrasonic sensors usefulness in robot safety systems design, a laboratory model of safety system was developed during the 1st phase of a study performed in CIOP (Podgórski, 1989). A block diagram of this model is shown in Figure 4.

The safety system model incorporates ultrasonic sensors which can be attached to various places of the IRp-6 robot arm. Each sensor consists of two piezoelectric transducers: a transmitter and a receiver. Transmitters emit short ultrasonic pulses at the rate adjusted from 10 to 50 times a second, and receivers detect echo pulses reflected from objects placed in detection zones.

The operation of the safety system model is controlled by the computer software divided into three main procedures. The first one is running during teaching the robot and it determines the presence of any objects in the sensor detection zones when the system performance is independent of the robot task (generic model). When the robot operator is outside the robot workstation and the robot is switched to automatic mode, the second procedure is performed and the currently measured distances between the sensor and reflecting objects are stored in the computer memory during the first automatic cycle of the robot program. During execution of the next cycles of the robot program the third procedure is running and the data obtained currently from the ultrasonic sensors are compared on fly with previously determined values stored in computer memory (mapping model).

Ultrasonic sensors detection capability will to be investigated in both generic and mapping modes experimentally with the use of obstacles of various shapes and dimensions and made of different materials.

Two types of piezoelectric transducers were employed for ultrasonic sensors design: the MPU-1 working at 40 kHz and the RU-200 working at 200 kHz. The former are manufactured in Poland by UNITRA-CERAD and the latter is produced by Siemens AG in FRG. The comparison of shapes and dimensions of detection zones for both types of ultrasonic sensors is shown in Figure 5. Points of the detection zones boundaries were determined by the position of a sphere of 15 cm diameter covered with a wig of natural slight curly hair. This obstacle was simulating a human head. It was chosen because the head is the human body part most sensitive to injuries, and human hair have relatively low ultrasonic radiation reflectivity coefficient.

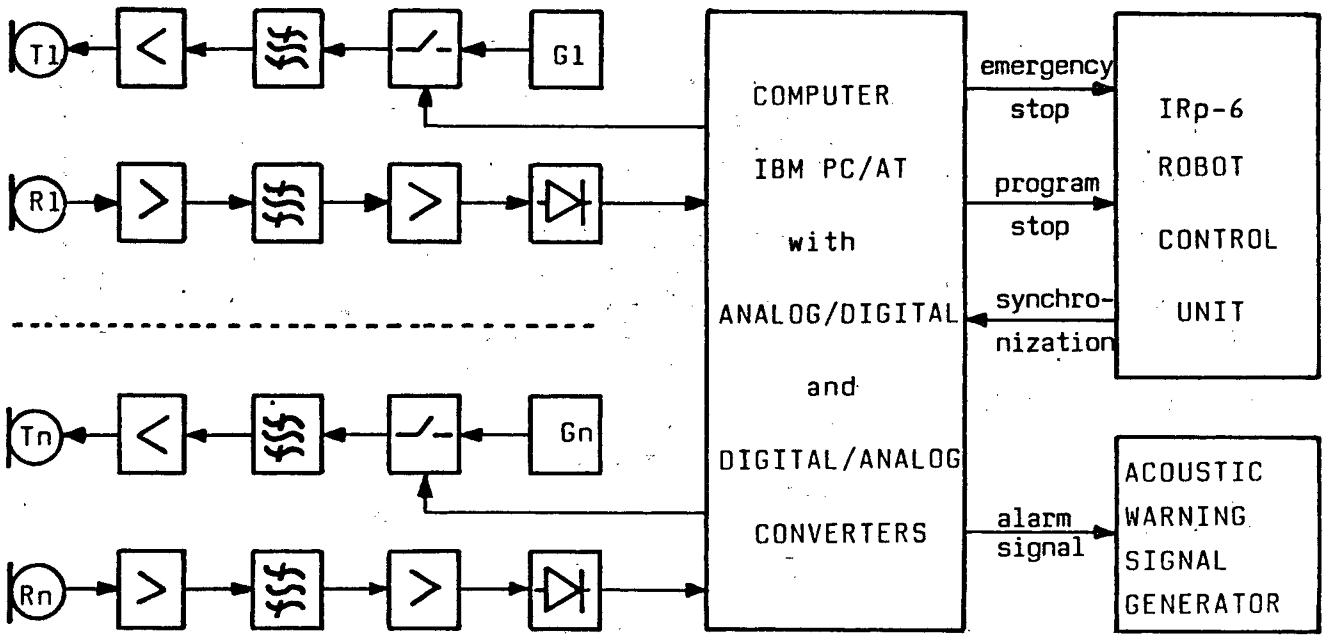

Fig. 4. Block diagram of the safety system model.

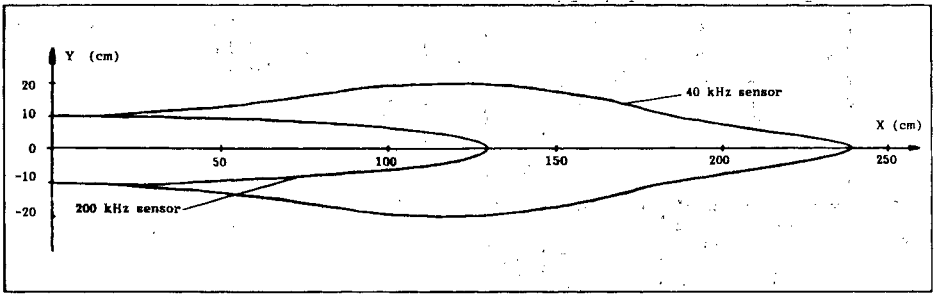

Fig. 5. Comparison of detection zones of 40 kHz and 200 kHz ultrasonic sensors.

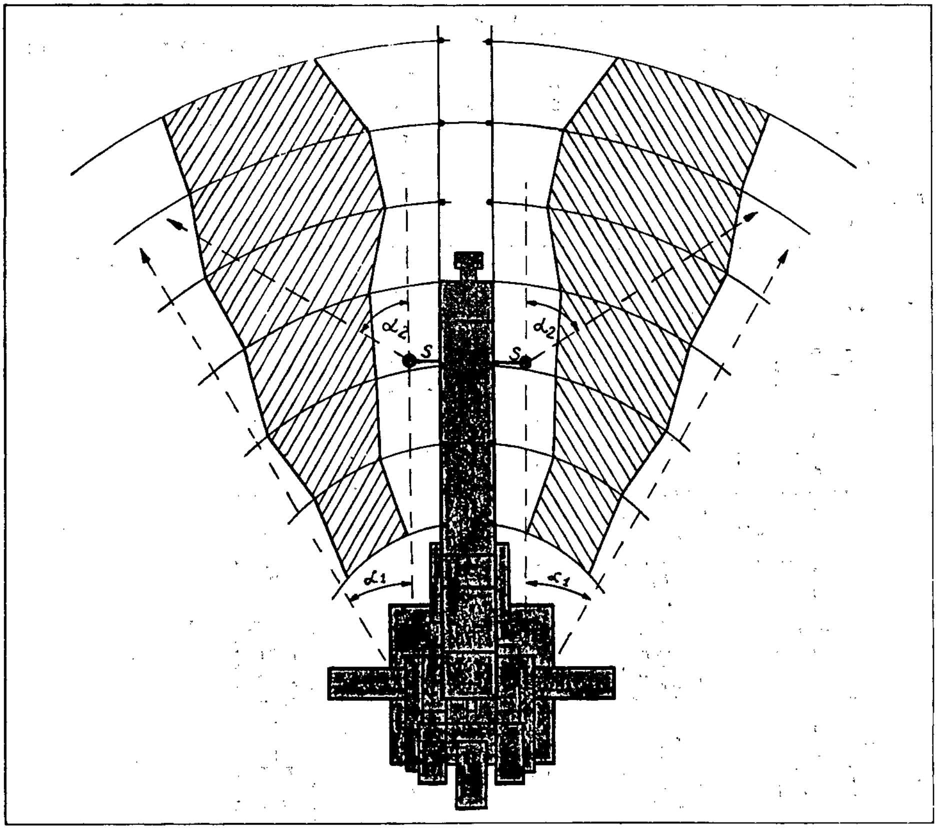

Fig. 6. Distances between a mannequin and the robot arm stopped by ultrasonic sensors (S) measured for various robot speed and for optimum sensors arrangement (α_1=30°, α_2=60°) — see the text for detailed description.

The detection zone for the 40 kHz sensor (see Figure 5) is about two times longer than the detection zone for the 200 kHz sensor. Similar proportion was also found by comparing detection ranges measured for these sensors with obstacles of other shapes and dimensions. This is mainly caused by greater attenuation of acoustic energy in air for higher frequencies (the attenuation increases approximately proportional to the 2nd power of frequency).

Though detection ranges for 200 kHz ultrasonic sensors are smaller, these sensors are used in applications. Their application in safety system can be motivated by their better immunity to false triggers caused by external noise sources in industrial environment. Measurements of ultrasonic background noise associated with various manufacturing operations were performed by Bass and Bolen (1985). The results obtained show that ultrasonic sensors for robotic applications with an adequate signal to noise ratio should have the working frequency above 100 kHz. Operations with laser etching and high-velocity fluid or air spraying are the exceptions where ultrasonic noise can disturb sensors with working frequency even up to several hundred kHz.

Since the attenuation of ultrasonic radiation in air depends on temperature and humidity, the influence of these climatic factors on detection ranges of ultrasonic sensors was measured in a microclimatic chamber. The results of these measurements show that the detection ranges decrease when temperature or humidity increases.

In normal climatic conditions occuring on most robot workstations in industry (temperature: 15°-25°C, humidity: 40-60%) changes in detection ranges of ultrasonic sensors do not exceed several percent. But when the safety system is used in more fluctuating climatic conditions, the changes in detection ranges can reach even thirty percent and the influence of temperature and humidity on safety system performance should be predicted and eliminated by compensation of echo signal amplification in receiving channel for each sensor individually.

Series of measurements of distances between a mannequin of human adult size and the robot arm stopped by the safety system were performed to determine the appropriate arrangement of the ultrasonic sensors on the robot arm. Combinations of the following factors were applied during these measurements:

- robot arm movement speed (from 0.3 m/s to 1.5 m/s measured for the end-effector in maximum arm extension),
- repetition frequency of pulses emitted by the ultrasonic sensors (from 10 to 50 Hz),
- distance between the mannequin and the robot base main axis (from 40 to 160 cm),
- distance between places of attaching the sensors and the robot base main axis

(from 0 to 90 cm),

- angles between the sensor detection zones and the surface of the robot arm (from 15° to 60°).

The arrangement of four ultrasonic sensors on the robot arm determined as the result of these measurements is shown in Figure 6. The outer and inner borders of the lined areas consist of points relevant to distances between the robot arm and the mannequin measured after stopping the robot for the minimum and maximum speed of its arm respectively.

The measurements performed also revealed that the adequte ultrasonic pulse repetition rate should be about 20-30 times per second. When the repetition rate was lower, in some cases the robot was stopped too late and its arm struck the mannequin.

Results of examinations of ultrasonic sensors performed in the first phase of the CIOP study show that these sensors have suitable detection capabilities in static and dynamic conditions, so they can be applied in the generic safety systems. But further research is still required to evaluate of this sensors feasibility for mapping robotic safety system design.

GOALS FOR FUTURE RESEARCH

Safety consideration is still important trend of industrial robot design problems in Poland. It can be expected that intrinsic safety will have to be built into various robot hardware subsystems in the future. Further qualitative evolution of robot intrinsic safety will also be the result of application of artificial intelligence methods for robot software design. Therefore redundancy and self-diagnostic techniques will be more widely applied in future robot constructions. This is particularly important for mobile robots and for robots with vision sensing systems. Therefore, intensive research should be performed to obtain significant improvements in this field.

Further development of safety systems for detecting human bodies in robot workplaces yields further evaluation of ultrasonic sensors feasibility for these systems. Hardware and software of the safety system model should be modified to obtain the appriopriate compensation of temperature and humidity influence and to attain better synchronization with robot control unit. This will make a good position to perform tests on the safety system operation when the mapping mode will be applied. Problems of reliability of sensors and safety system controller will also be solved by application of fail-safe design methods.

ACKNOWLEDGMENTS

The research works presented in this chapter were granted by the State Office for the Promotion of Progress in Science and Technology Development, Central Programs of Research and Development: "Industrial Robots" (project No. 100), and "Protection of Man in the Working Environment" (project No. 121/IV).

REFERENCES

Bass, H. E. and Bolen, L. N., 1985, Ultrasonic Background Noise in Industrial Environments, *Journal of Acoustical Society of America,* vol. 78, No. 6, pp. 2013-2016.

Jabłoński, P., Pachuta, M., and Wański, T., 1986, The New Control System for the IRb-6 and IRb-60 Robots. In *Proceedings of the United Nations Economic Commission for Europe Conference "Industrial Robotics"*, Brno, February 24-28.

Kilmer, R. D., 1985, Safety Sensor Systems. In *Robot Safety,* M. C. Bonney and Y. F. Yong (eds.), (IFS Publications Ltd, UK, Springer Verlag, Berlin), pp. 223-235.

Podgórski, D., 1989, *Electronic Safety System for Protecting Workers at Robot Workstations* (Central Institute for Labour Protection, Warsaw) — unpublished report in Polish.

Wanski, T., 1983, Emergency Withdrawal — a New Robot Function. *Pomiary, Automatyka, Kontrola,* No. 7, pp. 243-245.

Wydżga, S., 1981, *The Device Protecting Industrial Robot from Injuring the Human* (Industrial Research Institute for Automation and Measurements, Warsaw) — unpublished report in Polish.