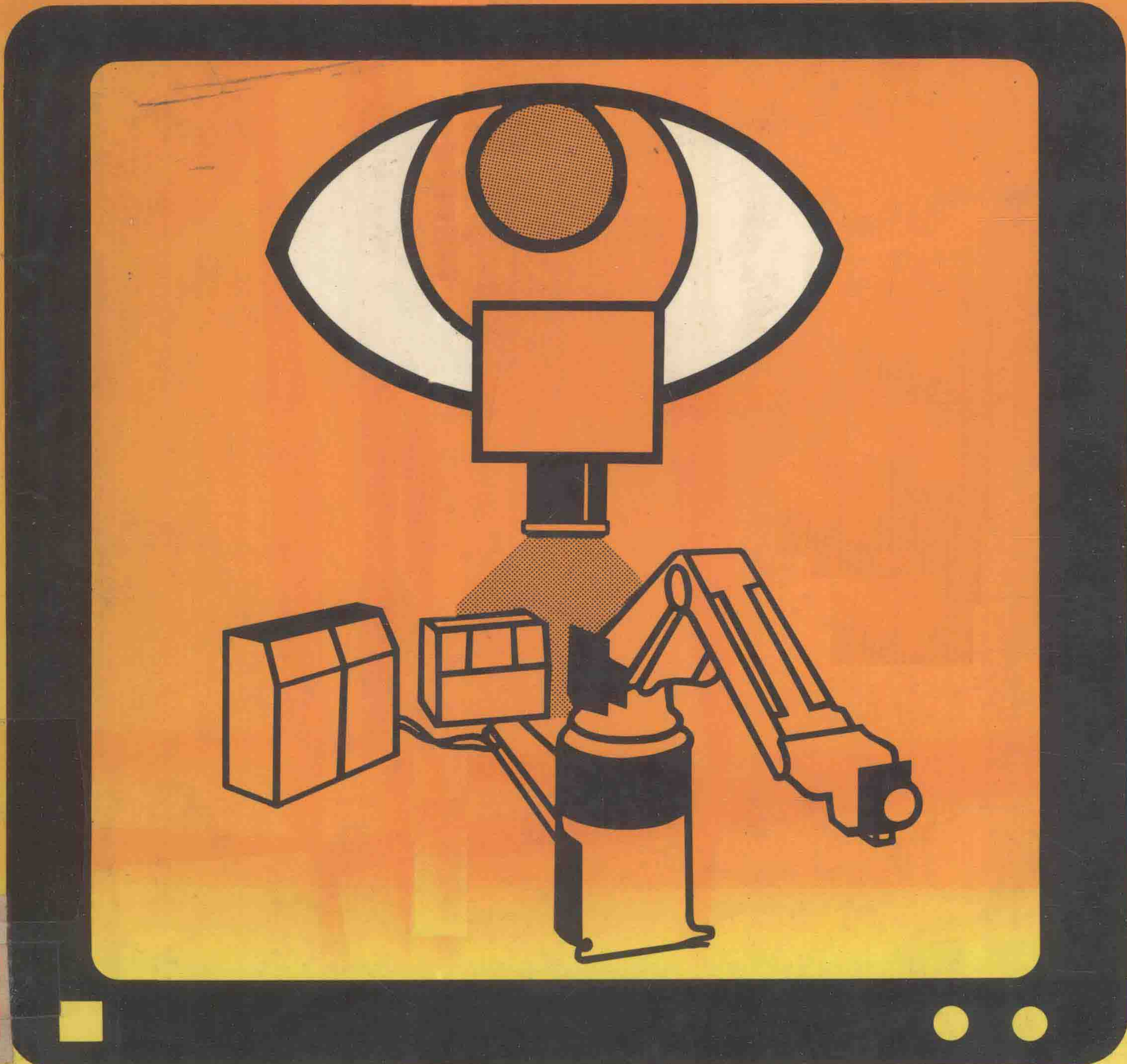
Proceedings of the
1st International Conference on

Robot Vision and Sensory Controls

April 1–3, 1981. Stratford-upon-Avon, UK.



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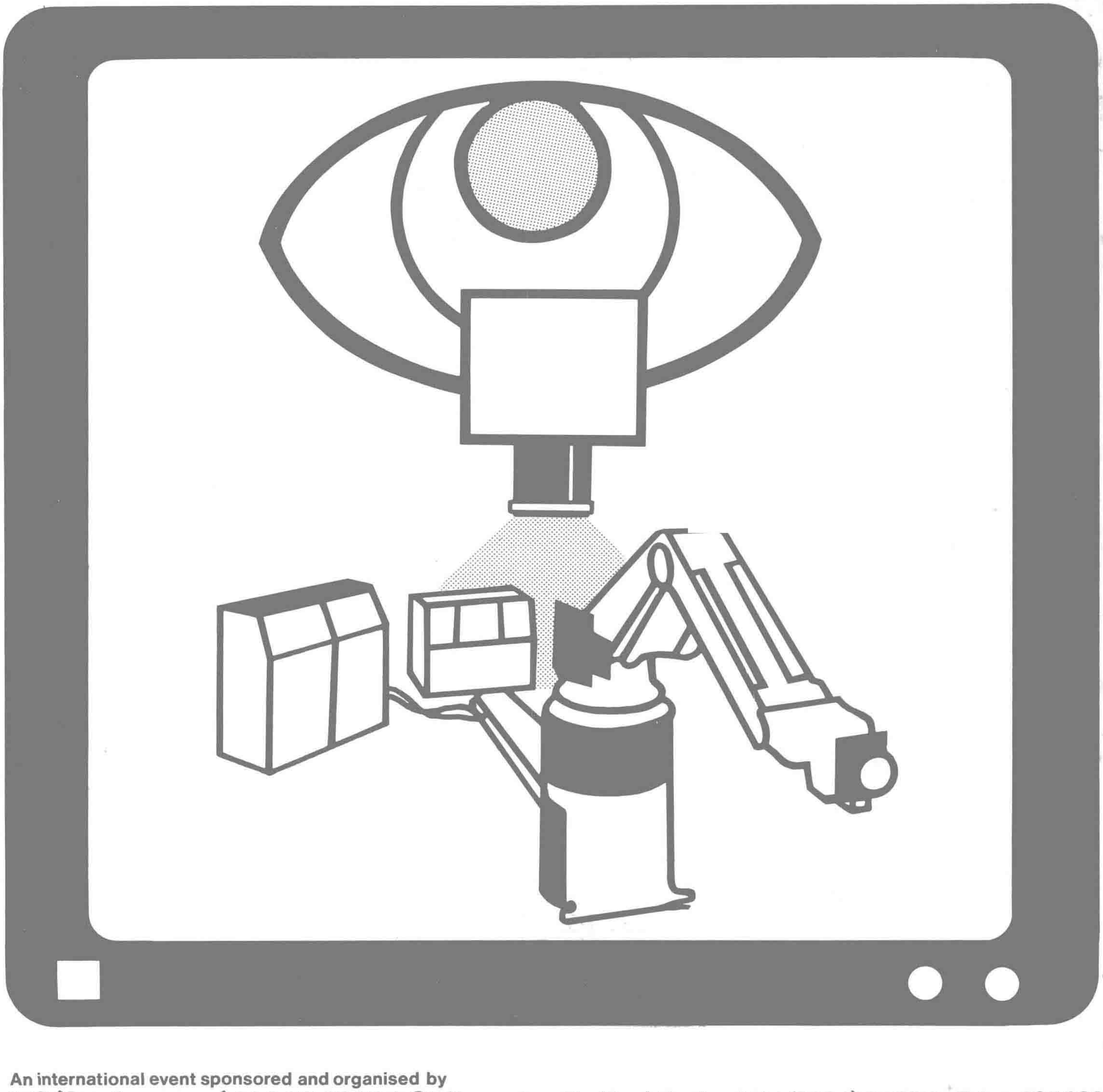

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The 1st International Conference on Robot Vision and Sensory Controls

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ASSESSMENT OF ROBOTIC SENSORS

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ABSTRACT

Exploratory robotic sensing must be advanced in two main directions:

(1) Improving the performance of (a) existing visual sensors (by upgrading TV cameras, by controlling the illumination, by advancing the capabilities of machine vision and hardware/software vision modules, and by developing special machine-vision functional chips); (b) range sensors (by attacking the problems of correspondence, missing data, occlusion, and speed, by generating efficient processing methods, and by developing inexpensive units for proximity sensing); and (c) touch and force/torque sensors (by developing a high-resolution, compliant, two-dimensional transducer array and integrating it with local microprocessors).

(2) Applying existing sensors other than the ones above to robotics (including acoustic sensors, temperature sensors, and other high-technology sensors), especially where transducers must be positioned and oriented precisely, and extending the capabilities of such sensors to image sensing for robotic tasks.

INTRODUCTION

A. Human and Robotic Sensing

A robot is an autonomous machine performing certain human-like tasks. Replacing a human by a robot is justifiable where human operation is:

* Undesired, because it is harmful, hazardous, strenuous, unpleasant, or dull;

* Uneconomical, because the cost of employing people is higher than the cost of using robots;

* Inferior, because its repeatability and accuracy are lower than those of the robot.

To perform human-like operations, a robot, like a human, must do two kinds of sensing:

(1) Internal robotic sensing, which monitors the state of the robot's system (kinesthetic, joint loads, internal temperature, etc.).

(2) External robotic sensing, which monitors the state of the robot's environment (determining the presence, identity, position, and orientation of objects, inspecting their surfaces and interiors, tracking them, etc.).

Internal robotic sensing is similar to internal human sensing, except that the latter is much more complex physically and includes emotional sensing. External robotic sensing is both similar and dissimilar to external human sensing. The similarity is that both robot and man use artificial sensors (instruments) to measure physical properties in their environments and that both may or may not carry these sensors on their bodies. The dissimilarity is that external robotic sensing is done directly, whereas external human sensing is done via natural human sensing (vision, hearing, touch, taste, or smell). While robotic sensing has the advantage of being interfaced directly, natural human sensing has the advantage of being more perceptual.

B. Sensing Steps

We define sensing (regardless of whether it is human or robotic, internal or external) in a broad way (i.e., as perception): Sensing is the translation of relevant physical properties of surface and volume elements into the information required for a given application. The physical properties are electric, magnetic, optical (e.g., surface reflectance and volume transmittance at different wavelengths of the incident radiation), mechanical (e.g., presence/absence, range, position, velocity, acceleration, stress, and pressure), temperature, and so forth. The information required for inspection of products, for example, may consist of dimensions, weights, defects labeling, "reject-accept" decisions, and the like.

Sensing is performed in two basic steps:

(1) Transducing--converting the physical properties into a signal (e.g., electrical).

(2) Processing--transforming the signal into the required information.

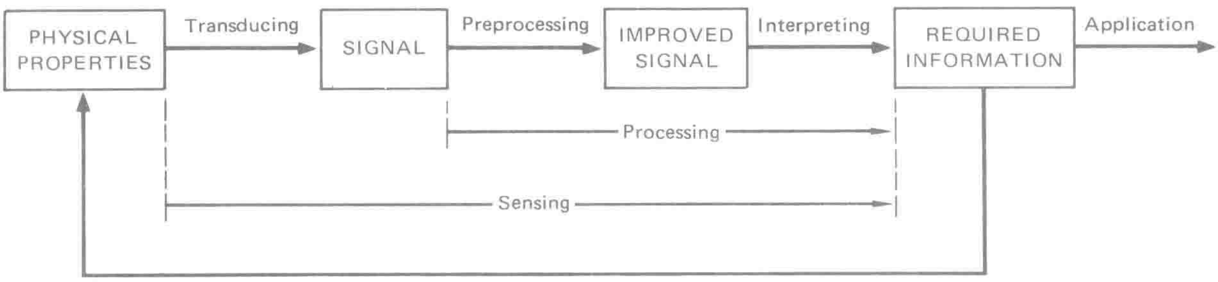
Step (2) may consist of two substeps:

(2a) Preprocessing--improving the signal by noise reduction, averaging, filtering, data compaction, and the like.

(2b) Interpreting--analyzing the preprocessed signal and extracting the required information.

If the extracted information is not sufficient, that information may be used to modify and repeat Steps (1) and (2) until the resulting information is acceptable.

A summary of the above discussion is shown in the following block diagram:



For example, suppose that we wish to employ an industrial robot in arc welding of two plates oriented at 90 degrees to each other (a fillet joint). The physical properties we need to sense include the position and orientation of the arc-welding torch relative to the two plates as a function of time. Alternative transducers may be used, such as a magnetic probe (transducing eddy currents in the plates), or a solid-state TV camera (transducing the line of intersection between a projected plane of light and the two plates). In this example processing the eddy currents may be simpler and faster than processing the image of the intersection line. If, however, there is a variable gap between the two plates due to poor fitup, then visual sensing is preferred because additional processing of its data can provide the three-dimensional variation of the gap. Other physical properties we may wish to sense for this task include:

* The shapes of the molten puddle and the resulting joint weld, especially if the joint is partially filled in multipass welding, using a TV camera

* The spatial distribution of temperature around the weld, using a two-dimensional noncontact high temperature sensor (e.g., a pyroelectric vidicon TV camera, combined with suitable infrared optics and spectral filtering)

* The homogeneity of the weld interior, using an x-ray sensor or an acoustic sensor.

Knowing these properties will enable us to properly control the welding parameters (the position and orientation of the torch as a function of time as well as the line feed and the arc voltage or current) in order to achieve high quality welds.

C. Classifications of Robotic Sensors

In addition to internal sensing versus external sensing, there are several ways to classify robotic sensing:

* Noncontact versus contact sensing.

* Sensed physical properties, such as images (visual, x-ray, infrared, temperature, etc.), proximity, range, touch, force/torque, and spectral signatures.

* Physical dimensionality of the sensed targets (1 to 3 dimensions).

* Dimensionality of image representation, such as a single point, a linear image, and an a real image.

* Passive versus active sensing, such as visual sensing using ambient light versus controlled illumination.

* Nondisturbing versus disturbing sensing.

* Temporal versus frequency versus spatial sensing.

Robotic sensors are surveyed in [1-3].

CAPABILITIES AND FUTURE IMPROVEMENTS OF ROBOTIC SENSORS

In this paper we will use the distinction between noncontact and contact sensors [2]. Basically, a noncontact sensor measures the response of a target to some form of electromagnetic radiation (visible light, x-ray, infrared, radar, acoustic, electric, magnetic, neutron, and so forth). A contact sensor, on the other hand, measures the response to some form of physical contact (e.g., sensing touch, force/torque, pressure, position, temperature, electrical and magnetic quantities, and so forth).

Let us now examine the capabilities and limitations of existing noncontact and contact sensors, and point out where improvements are needed and likely to take place in the near future.

A. Noncontact Sensor Improvements

1. Visual Sensors. We begin with visual sensors, which we consider to be the most important human as well as robotic sensors in general. Visual sensing transducers are usually TV cameras that scan a scene and convert a raster of reflected light intensity values into analog electrical signals. The signals are generated by opto-electrical devices, such as vidicons and solid-state linear or area arrays, preprocessed in hardware, and fed serially at a rate of 60 or 30 frames per second into a computer. The computer analyzes the data and extracts the required information, such as the presence, identity, stable state, position, and orientation of an object to be manipulated; part integrity and completeness of assembly under inspection; and the like. Computer vision is a large field and no attempt is made here to survey it. See [4-18] for detailed information on computer vision in general and robotic vision in particular.

In the following sections we outline visual-sensor features that need improvements.

a. Solid-State TV Cameras. The following improvements in existing capabilities of solid-state TV cameras, without substantial cost increase, are needed:

Chip

* Higher resolution (e.g., 512 X 512 or 1024 X 1024 pixels) with higher dimensional density (e.g., less than 1/2 mil between neighboring centers) and precision.

* Improved quality of pixels--fewer defective elements, higher and more uniform sensitivity, a wider dynamic range of intensity, and antiblooming.

* Color discrimination, preferably red, green, and blue.

Lens Design

* Lower distortion and lower astigmatism at low cost.

* Better focusing in the infrared region.

Adaptability of Camera Parameters. For any rectangular window within the image of the field of view, we should be able to obtain automatic and adaptable

* Lens opening

* Focus

* Binary or tertiary thresholding.

Front-End. The front-end of a TV camera (lens, chip, and minimum circuitry) should be characterized by better features than now exist. These features include:

* Ruggedness

* Minimum size and weight

* Fast tilt and pan movements

* Fast zoom (if used).

Where the target is not accessible to the front-end of the TV camera, use of fiber optics could be satisfactory (they should have low optical signal loss, high mechanical flexibility, etc.).

b. Controlled Illumination. Robots should be able to control the illumination of the targets they view to improve the signal/noise ratio under various operational constraints and to simplify the extraction of spectral and geometrical features of the targets. Specifically, these goals can be achieved by controlling illumination parameters, such as the

* Pattern (e.g., a scanning beam, a plane [10,13], multiple planes, etc.)

* Wavelength (visible and infrared)

* Source (e.g., incandescent, fluorescent, flash, and laser)

and by properly sensing and analyzing the resulting images.

c. Hardware/Software Vision Modules. Development of hardware/software modules, such as SRI's Vision Module [12], should achieve extended capabilities, including:

* Cost-effective, rugged, and easily trained modules for factory-floor applications.

* A library of basic subroutines for binary and gray scale data.

* Direct interface to a robot path control.

* Common application programs for material-handling, inspection, and assembly tasks.

d. Special Machine-Vision Functional Chips. In recent years metal-oxide semiconductor (MOS) and charged-coupled devices (CCD) chips have been developed to execute special computer-vision functions at a high rate (e.g., 10MHz) by Hughes and the University of Southern California [19, 20], Westinghouse and the University of Maryland [21, 22], and others [23]. These functions include edge detection (e.g., by using the Sobel operator [19]), correlation, masking, and convolution operations. This development should continue to improve the chip performance and be extended to include other computer-vision algorithms.

2. Range Sensors. A range sensor measures the distances from a reference point (usually on the sensor itself) to a raster of points in the scene. Humans can estimate range values based on visual data by perceptual processes that include stereopsis as well as comparison of image sizes and projective views of world-object models. Some animals (e.g., the bat and the dolphin) can estimate range values by use of active range sensing in which a sonic wave is transmitted and the elapsed time for the return echo is determined approximately.

Range sensors that can be applied to robots are still confined to laboratories. Three basic optical range-sensing schemes are classified according to the method of illumination (passive or active) and the method of range computation (triangulation or time of flight of light):

(1) Stereo [4, 24]--passive illumination (ambient light); triangulation

(2) Projector/Camera [10, 13, 25, 26]--active illumination (e.g., a projected light plane); triangulation

(3) Laser-scanner/photomultiplier [27, 28]--active illumination (a laser beam): time of flight of light.

Sensing range with a stereo pair of TV cameras (or one camera in two locations) entails the problem of determining corresponding points in the two images of the scene [4]. Although solutions to this problem have been proposed by several researchers (e.g. [24]), there is still need for a reliable and fast method to perform the correspondence computation.

Range sensing based on triangulation has the drawback of missing data for points not seen from both positions (of the cameras in the stereo scheme or the projector and the camera in the projector/camera scheme). This drawback may be reduced, but not eliminated, by using additional TV cameras (or camera front-ends). The use of additional cameras may also provide a partial solution to the general problem of occlusion, including self-occlusion, in machine vision. Instead of a projector/camera scheme we now have a single projector with multiple TV cameras or camera front-ends, viewing the target from different angles. Such a solution will also entail additional computer processing. Justification of the additional hardware and software will depend on the importance of the additional information this scheme provides.

The main drawback of the laser-scanner/photomultiplier scheme is that it is too slow, especially if the target is dark [28]. This drawback may be resolved by increasing the laser power, increasing the photomultiplier-receiver area, and improving other sensor parameters. Each of these solutions may, in turn, introduce new problems (e.g., safety, size, and cost problems).

Acoustic rangefinders, like the one used in the Polaroid cameras, yield only a single range value (minimal or average). To obtain a range image, they must be scanned and spurious echo signals must be disregarded. In addition, for high spatial resolution new techniques are needed to overcome the absorption of the energy of a high-frequency acoustic wave by its medium.

Range sensing in general has hardly been utilized in performing robotic tasks, such as object recognition and inspection, manipulation, and navigation. More research is needed in this area for such applications. Simultaneously, research and development effort is also needed to improve range-sensor capabilities (higher speed, higher resolution, higher accuracy, wider range, smaller size, and so forth) and to reduce the cost of such range sensors.

3. <u>Proximity Sensors</u>. A proximity sensor senses and indicates the presence of an object within a fixed space near the sensor. Different commercially available proximity sensors [29] are suitable for different applications. For example, eddy-current sensors can be used to precisely maintain a constant distance from a steel plate. A common robotic proximity sensor consists of a light-emitting-diode (LED) transmitter and a photodiode receiver [2]. The main drawback of this sensor stems from the dependency of the received signal on the reflectance and orientation of the intruding object. This drawback can be overcome by replacing proximity sensors by inexpensive range sensors, which are yet to be developed.

B. <u>Contact Sensor Improvements</u>

1. <u>Touch Sensors</u>. A touch sensor senses and indicates a physical contact between the object carrying the sensor and another object. A simple touch sensor is a microswitch. Basically, touch sensors are used to stop the motion of a robot when its end-effector makes contact with an object. Such "move till touch" control is applicable to a variety of tasks, including:

* Reaching a target (e.g., to perform spot welding)
* Preventing collision damage
* Self-training of certain robot trajectories
* Centering of the robot grippers on an object without moving it
* Measurement of object dimensions, using a robot with high resolution joint encoders
* Object recognition.

Existing touch sensors are excellent for tasks in which the information about a single-point contact is sufficient. They are inadequate for tasks requiring multiple-point contact, i.e., if it is not known a priori where contact will be made. An example of such a task is object recognition where visual sensing is impractical (e.g., in unavoidable darkness, such as undersea [30]). Use of area touch sensors [31-34] to recognize objects on the basis of touch patterns is presently difficult because these sensors have insufficient compliance and coarse spatial resolution. Coarse resolution, in turn, is caused by the bulkiness and high cost of existing touch transducers. To overcome these limitations, there is need for research and development of a high-resolution compliant array of touch transducers. In addition, these transducers should be multiplexed and their signals processed by an in-situ microprocessor to eliminate the use of too many interface wires. Loading the microprocessor with appropriate programs, we may thus obtain a "smart" touch sensor capable of determining the identity, position, and orientation of three-dimensional objects under variable conditions.

2. <u>Force Sensors</u>. A force sensor measures the three components of force and three components of torque acting between two objects. In particular, a robot-wrist force sensor [2, 35, 36, 37] measures the components of force and torque between the last link of the robot and its end-effector by transducing the deflection of the sensor's compliant sections, which results from the applied force and torque.

Existing force sensors employ different transducers (e.g., piezoelectric, used by Kistel in Switzerland). The best transducers for robots are semiconductor strain gauges cemented onto the compliant sections [2, 36]. Future improvements should result in reduction of size, weight, and cost, and increase in accuracy, resolution, and dynamic range of force sensors.

As with touch sensing, there is a need to extend force sensing from a single point to an array of points of high spatial resolution (e.g., 1 mm). Such an array force sensor could be used to determine the identity, state, centroid, and orientation of an object resting on the sensor where visual sensors are inappropriate. Mounted on the grippers of a robot, two such array force sensors can be used to verify that the proper object is held at the proper gripping locations with the proper force and that no slippage has occurred. As with touch sensors, a local microprocessor should analyze the sensed data to eliminate the interface wiring and to relieve the higher-level computer from force/torque data processing.

C. <u>Other Robotic Noncontact and Contact Sensors</u>

In addition to the sensors described above, there are other noncontact and contact sensors that exist today but have not been utilized in robotics.

1. <u>Acoustic Sensors</u>. An acoustic sensor senses acoustic waves in gas (noncontact sensing), liquid, or solid (contact sensing), and interprets them. The level of sophistication of sensor interpretation varies a great deal among existing acoustic sensors, from a primitive detection of the presence of acoustic waves to frequency analysis ("signature") of acoustic waves to recognition of isolated words in a continuous speech. Although animals utilize natural acoustic sensing for detection of events, communication, and other functions, and although man has utilized artificial acoustic sensing to augment similar functions, artificial acoustic sensing has hardly been applied to robotics. This situation will probably change as the application of robots increases. For example, in addition to man-robot voice communication, acoustic sensing can be utilized by robots to assist in controlling arc welding, to stop the motion of a robot when a loud crash is sensed, to predict a mechanical breakage about to happen, to implicitly or explicitly inspect objects for internal defects, and so forth. Research is needed to develop methods and software for successful use of acoustic sensing in such applications.

2. <u>Temperature Sensors</u>. Temperature sensing, both contact and noncontact, also has hardly been performed by robots. Such performance may be useful where robots operate autonomously, where human presence is undesired (e.g., an environment of extreme temperature), or where temperature images are required.

There is a need to increase the accuracy of hot temperature sensors (e.g., for measuring the temperature of molten steel) and to improve their area imaging capability. A significant progress in sensing temperature images has been achieved in recent years by improving the capabilities of pyroelectric TV cameras.

CONCLUSIONS

To perform some of the tasks presently done by man, a robot must be able to sense its internal state and its environment. A robot sensor, consisting of a transducer (which may or may not be mounted on the body of the robot) and a processor, converts certain physical properties into the information required to perform a given task.

Only rudimentary sensors (e.g., a microswitch) are currently applied to robots on factory floors. We believe that some laboratory sensors, especially visual sensors, and computer control will soon be incorporated into industrial robots in factories. Two main issues, however, are yet to be resolved before these second-generation, "intelligent" robots are in widespread use:

* Meeting production requirements of reliability, speed, and cost

* Allaying some management fear of the economic, social, and political implications entailed in this new technology.

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