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# DISPLAYS FOR SUPERVISORY CONTROL OF MANIPULATORS*

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## Abstract

The problem of displaying information generated by sensors attached to the terminal device of a remotely controlled manipulator is considered. The sensors under consideration are proximity, force-torque, tactile and slippage sensors. The paper describes and evaluates several examples that have been implemented in the JPL teleoperator project using audio and graphic displays of information generated by four proximity sensors attached to a manipulator end effector. Design schemes are also discussed related to the display of information generated by a six-dimensional force-torque sensor, a multipoint proportional tactile sensor, and a directional slippage sensor. The paper concludes with a discussion of future integrated displays of visual (TV) and handbased sensor information.

## I. Introduction

Space missions planned for the shuttle era will involve an extensive use of various manipulators with associated tools to perform a variety of science and engineering tasks in space. Payload handling in the shuttle, satellite servicing or retrieval in earth orbit, assembly of large area structures in space such as antennas, solar power stations and space processing systems, unmanned in situ exploration of lunar and planetary terrains and materials or sample analysis in sealed space laboratories will require the extension and augmentation of man's manipulative capabilities by employing remotely operated manipulator systems with or without special purpose tools. Remote manipulation implies operating conditions which impose various information and control communication constraints.

A major challenge in the development of remotely controlled manipulator systems is the acquisition and use of sensor information which supplements the visual information for control. Non-visual information related to manipulator control can be obtained from proximity, tactile, slippage and force-torque sensors attached to the terminal device or arm mechanism. Proximity sensors provide information on short (few centimeters) distances in known direction between terminal device and objects. Tactile sensors provide information on the distribution and amount of contact area pressure between terminal device and objects. Slippage sensors provide information on the slip and possibly also on the direction of slip of an object on the inner surface of the mechanical "fingers". Force-torque sensors mounted between the terminal device and last wrist joint provide information on the amount of force and/or torque exerted by the terminal device on objects along three orthogonal directions referenced to the terminal device.

This paper considers the problem of displaying information generated by proximity, force-torque, tactile and slippage sensors attached to the terminal device of a remotely controlled manipulator. The sensor information displayed to the operator serves several purposes depending on the modes available to the operator for manipulator control. In a manual control mode, the sensor information displays are elements in the continuum of a real-time control loop in the sense that they guide the operator's control inputs by providing continuous information feedback to the operator on the appropriate "external error state" of the manipulator. In a computer control mode, the sensor information displays are discrete elements outside the real-time control loop. They provide information to the operator prior to the selection and initialization of an appropriate control algorithm, and inform the operator about the performance of the control algorithm selected for the task at hand. Supervisory control by definition implies the availability and use of both computer and manual control modes for remote manipulator control.

The basic challenge in displaying sensor information to the operator is twofold: a) selection or design of a proper type of display, and, b) selection or design of a proper format for a given type of display so that the display presents all necessary information in a timely manner and in a form easily perceivable by the operator. Since the use of direct or indirect (TV) visual information is inevitable in remote manipulator control, a fundamental topic is the integration or integrated display of visual and non-visual sensor information.

Section II of the paper is devoted to some general considerations on various display concepts. Section III summarizes our work on audio and graphic displays of proximity sensor information, and compares the two types of displays in terms of actual control performance data. Graphic display of force-torque sensor data is discussed in Section IV. Graphic display of tactile and slippage sensor information is treated in Section V. Implementation concepts for integrating visual and non-visual sensor information are briefly discussed in Section VI.

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## II. Display Concepts

A wide variety of display types are available and can be used in teleoperator systems. Displays can employ a single bulb, the operators sense of touch, analog and digital meters, bar displays, audio tones, and black and white or color TV. The displays may either be presented separately or integrated into an overall workspace display. Each of these is appropriate to some sensor data types or teleoperator applications and inappropriate to others. They are considered here in the context of supervisory control of manipulators with data developed from hand mounted sensors.

The simplest display listed above is the single bulb or LED display. It can indicate task completion, initiation or completion of some event, or the simultaneous existence of some set of conditions, e.g., a hand is at the proper orientation and distance from a particular object. Unless the data to be presented is binary in form this type of display is limited. Blinking the display allows some relief from the basic binary nature of the display.

Individual bar displays where the bar length is an understood function of the sensor output provide improved resolution and ease of interpretation but are inflexible in an application where it is desirable to show the sensor data first in one orientation and then another. A display would be required for each orientation in this case. The display can, however, be interpreted quickly. Analog meters provide somewhat greater resolution but are less quickly interpreted. Digital meters, on the other hand, provide considerably increased resolution and accuracy but require even more time for interpretation.

The use of audio tones in remote manipulator control has been explored for proximity sensors to some extent and shown to be effective in improving performance as measured by time to task completion, efficient use of resources, or task accuracy (Ref. 1). The primary scheme employed is to display the outputs from various sensors as frequency or amplitude changes. Coded tone messages, e.g., Morse code or the code modulation schemes used in fire stations could also be employed. While coded tones can transmit a much wider range of messages they also are slow. Tone displays also compete with background noise and thus the data can be lost. However, they do make use of a human perception channel that is always open, is omnidirectional, and does not depend on the operator's focus of attention. In common practice (Ref. 2) use of audio presentation of relevant information is recommended if: a) The message is simple. b) The message is short. c) The message will not be referred to later. d) The message deals with events in time. e) The message calls for immediate action. f) The visual system of the person is overburdened. These conditions define both the advantages and the limitations of displaying sensor information by audio means.

In an effort to overcome some of the limitations inherent to audio displays, graphic displays are being investigated. These displays offer adequate resolution for an operator to monitor or control a manipulator, are easy to change so that the sensor data can be seen in different perspectives, and are fast enough to keep up with the process and do not add more than a few hundredths of a second time delay. TV displays can be constructed using vector, line, or other scanning mechanisms. Line TV displays have been employed here for compatibility with other displays and because of the potential for integration of the sensor data into the operator's stereo or mono scene display. Color display of sensor data while also practical has not yet been investigated. It offers a means of providing scale change data to the operator.

## III. Proximity Sensor Displays and Performance Evaluation

Proximity sensors which measure the distance between the hand and an object along a vector fixed to the hand, have been shown to be effective with tone displays as shown in Ref. 1. It was also shown that four tones were less effective than two due to the complexity of interpreting the data in that particular experiment.

For completeness, some performance data related to the combined use of visual and proximity sensor audio information are quoted in Table 1. In the performance experiment a parallel finger hand was equipped with four proximity sensors, with two sensors on each finger in a configuration as shown in Figure 1. The proximity sensors are described in Ref. 3.

In the control experiments, the signals of each proximity sensor are presented to the operator as a distinct audio tone. The tones are distinct in both pitch and source (loud speaker) location. The pitch of the tone generated through the voltage output of the proximity sensor indicates the distance between the sensor head and the objects. Each audio display of the four sensors covers a different pitch range. The maximum sensed distance is about 8-10 cm. The control is performed from a remote control station fully isolated from the task scene. The operator in the remote control station can utilize both mono and stereo TV displays, and listen to the audio tones of the four loudspeakers displaying the proximity sensor signals. The four loudspeakers are arranged in a two by two meters vertical quadrangle around the operator. In this way, the operator can easily identify the sensor source of the individual signal.

The vantage point of the stereo TV cameras is from the shoulder of the slave arm and about 0.5 m above it. The vantage point of the mono camera is from the side, varying between 50 to 90 degrees relative to the field of view of the stereo cameras. Neither the stereo nor the mono view can provide a complete visual feedback to the operator under the described setup. In particular, the visual feedback is highly degraded and obscured when the hand moves near solid objects.

The main point of the remote control experiments is to test whether the operator can integrate the information content of the proximity sensor signals presented by audio tones with an incomplete visual feedback and find control strategies to perform remote manipulator tasks which are very difficult or near impossible under the existing visual feedback arrangements. The information content of the proximity sensor signals can provide clues to the operator to solve two basic problems: overcome the lack of depth information apparent in the TV displays, and locate objects or parts of the work scene invisible in the TV displays.

Figure 2 shows two typical task arrangements for proximity control performance tests. The two tasks were:

> Task 1: Move from standby position to the rectangular block at "A", pick it up, and place it on top of another rectangular block located at "B", and align the two blocks. The two blocks are of equal size.
>
> Task 2: Move from standby position and pick up a partially obscured irregular object (a rock).

The performance data shown in Table 1 are related to Task 1 above. The data clearly show the validity of the following conclusions: 1) Proximity sensor information can replace or supplement part of the visual information required for control. 2) Control tasks which cannot be performed using visual information alone can be performed using a combination of proximity sensor audio tones and visual information. 3) Control performance is sensibly influenced by the location of the proximity sensors on the terminal device. 4) Number of independent proximity sensor signals significantly affects operator's control performance. This last conclusion is one of the main motivations for investigating graphic/TV techniques to display proximity and other sensor information to the operator.

As seen in Table 1, when the operator had to deal with signals from four proximity sensors the performance time increased by 30-40% as compared to the performance time related to the use of only two proximity sensors. It shows that signal detection and processing capabilities of man are very limited, and can be saturated very easily. Man is essentially a single-channel signal detector and processor at a given instant. It is interesting to note that the information content of four proximity sensor signals was considerably more complete for the control task than the information content of only two proximity sensors. Consequently, one could have expected a faster and more error free operator performance. It was not so, however, since the human operator had to derive the "completeness" of information by a mental integration process correlating different motions with different sensor signals.

The TV graphics offers an alternative means to display the proximity sensor data in an easily interpreted (geometric) form. It is the form in which the data is normally perceived. Given greater computational capabilities and dedicated special purpose displays the data could be even presented in stereo, rather than in mono as done here.

Two different graphic display representations have been tried. The first, see Figure 3, shows a line drawing of the hand in broad lines. The sensor data is represented by the four narrow lines. The two forward sensors are numbered 1 and 2; and the two down sensors are numbered 3 and 4. The letters "P" give the origin, and the length of the narrow line show the separation between the sensor and the object. For objects beyond the sensor's range the line length is bounded. In the case where the object is too close, the sensor output is on the inside of the bell shaped multivalued response curve and, since no discrimination is possible, a false value is shown. The location of the sensors is shown in the left part of Figure 3, and also in Figure 1. In Figure 3, none of the sensors "see" an object and all the proximity sensor outputs are shown as full length.

Figure 4 shows an actual task scene together with graphic display of proximity sensor signals as the operator uses the graphic display combined with stereo TV display in the remote control station. Since the mechanical hand partly obscures the blocks in front and below the hand, the operator has to rely on the graphic display of proximity sensor data to determine the hand's geometrical relation to the nearby blocks. As seen in the upper right part of Figure 4, this determination can be done easily and accurately from the graphic display.

The ability of this display concept to show geometric relationships can be seen from a comparison of Figure 5a with Figure 5b; Figure 5a with Figure 5c; and Figure 5b with Figure 5c. In each pair the first figure shows the scene being sensed, and the second shows the sensor/display response.

The second display representation tried is shown in Figure 6. There the preceding display has been put in a different perspective. It is this representation which was used in the performance tests summarized in Table 2.

The performance data shown in Table 2 are related to the following simple task: Move the terminal device from the standby position to a block on the table and stop it at a predefined distance in front of the block with a predefined elevation above the table. In the first set of experiments the audio tones used were generated by two (one out and one down) of the four proximity sensors in the form described previously. In this first set of experiments the predefined stop distance and elevation were set for 2.7 inches. In the second set of experiments the operator used graphic information display of proximity sensor signals in a form as shown in Figure 6. In the second set of experiments the stop distance and elevation were set for 2.4 inches. In each set ten experiments were performed. The actual arm motion involved about 20 inches travel in each case. From time to time the block was slightly repositioned in order to prevent the operator's motion from the standby position to the desired stopping conditions from becoming a "habit". The TV visual field was arranged so that the stopping conditions could only partly be assessed visually, and even this partial visual assessment could only be a rough estimate. The overall experimental set-up was identical to that described previously.

Table 2 shows that graphic display improves task performance accuracy by a factor of nearly three as compared to task performance accuracy when audio displays are used. This accuracy improvement can be attributed to two factors: a) The eye can more easily compare absolute measurements from a multichannel signal than can the ear. b) The geometrical pattern context of the sensor signals is immediately apparent to the eye. In addition to accuracy improvements, task performance time with audio display was 14.7 sec. with 5.3 sec. standard deviation, but task performance time with graphic display has been reduced to 13.3 sec. with 4.0 sec. standard deviation. Further performance time improvements can be obtained with graphic display through an improved system integration in the control station. It is noted, however, that a selective and interpretive preprocessing of the sensor signals before the generation of the audio tones would reduce the mental load for the operator to interpret the complexity of the tones. This procedure would also lead to improved task performance.

For both display representation types (as shown in Figures 3 and 6, respectively) equivalent data processing was employed. The data from each sensor was converted into digital form by a 8 bit high speed (5 μs conversion) A/D converter. An IMSAI microprocessor, see Figure 3, which employs the Intel 8080 microprocessor chip, corrected the sensor data for nonlinearities, and computed the displayed scene. The display used has alpha-numeric and graphic capabilities. In the latter mode a standard TV frame can be subdivided into a 48 x 128 matrix of points. Each sensor's output was represented as a bar 0 to 12 or 0 to 31 points long. While this allows rapid interpretation of the data it provides only low accuracy. Although the scene is displayed at standard TV rates, the changes were updated only every 10-30 ms depending on the display representation and various timing parameters. The software for this processing requires only about 800 words of 8 bits each. The coding was performed in assembly language.

## IV. Force Sensor Display

A force/torque sensor has been mounted at the wrist of the JPL CURV arm as shown in Figure 7. The sensor is described in detail in Ref. 4. Its mechanism has been developed by Vicarm Inc., while its electronics has been developed at JPL. The primary use of the sensor will be in supervisory control where the control computations are performed by an Interdata model 70 computer. To provide the operator with additional data by which to monitor the control process a force display is being developed. To relieve the Interdata from the display computations and to simplify the software development a distributed processing scheme will be employed. Here, since the sensor signals are already digitized for the Interdata, no separate A/D conversions will be made. Instead a special buffer has been developed which allows the IMSAI microprocessor to "listen" in on the CURV Interdata bus to acquire the sensor data. Preliminary force sensor display representations are shown in Figure 8. In the left part of Figure 8 the force sensor outputs in hand reference frame up (U), down (D), forward (F), backwards (B), right (R), and left (L) are shown nested in a hand schematic. In the right part of Figure 8 the proximity sensor data representation has been included also. In both cases the force sensor data is shown in each of its three orthogonal components. A similar representation is being considered for a torque display.

The dynamic range of the sensor is more than two orders of magnitude: from 2 oz. to 800 oz. force and from 3 in. oz. to 1840 in. oz. torque. It is expected that force-torque control tasks can be subdivided into three regions: low (2-40 oz.), medium (40-120 oz.) and upper (120-800 oz.) dynamic regions. In order to obtain adequate display resolution in all three regions, the use of appropriate scale changes is considered matching the range of each dynamic region. A further consideration is the display of the force and torque vectors in addition to their three orthogonal components. The vector displays would aid the integrated perception of the full dynamical changes acting at the terminal device.

The display of force or torque data is made more difficult by the fact that it is not fundamentally geometric perceived. With force or torque the point of application relative to the sensor and the grasping implement must be considered in addition to the force or torque sensed at the wrist base of the hand. Thus, the development of useful force-torque data displays is a demanding and non-trivial task. The problems of force-torque sensor information display have also been recognized elsewhere (Ref. 5).

## V. Tactile and Slippage Sensor Displays

Figure 9 shows the breadboard of a multipoint proportional tactile sensor with a visual display based on an arrangement of light bulbs. Each bulb corresponds to a sensitive spot on the sensitive surface. The sensitive surface is built of two nets of electrodes separated by conductive rubber. The two nets of electrodes form a 4 x 8 matrix pattern. The sensitive surface will cover the inner and outer surfaces of the mechanical "fingers". The sensor will sense the amount of normal force (pressure) acting at a given point ("spot") on the finger.

The light bulbs used in the breadboard display provide only a very rough indication of the amount of pressure sensed at a given spot. The development of a graphic color display is under consideration where colors would be used to indicate the amount of pressure sensed at a given point on a finger. An alternative display concept would utilize only black and white frame. The frame would show the geometrical contours of each part of the finger equipped with the artificial skin. The sensitive spots would be indicated by a square net inside of the geometrical contours, each square corresponding to one sensitive spot. The amount of pressure sensed at a spot would be indicated by a number inside the square scaled to the measurable pressure range. Since the dynamical range of the sensing device under consideration is quite wide (more than two orders of magnitude), the combination of colors with numbers could also be explored to indicate pressure intensity at a given spot. For instance, a more refined extension of a color isoclinal display format could be that a given color indicates a certain pressure range and the number coded in that color indicates the level of pressure within that pressure range. In this case, the numbers could be restricted to a few, for instance from 1 to 9, since yellow 9 could be equivalent for instance to 9 oz. pressure, green 9 to 19 oz., red 9 to 29 oz., and so on. Figure 10 shows the sketch of a tactile sensor graphic display concept. In References 6 to 8 alternative schemes and techniques are described for tactile sensing displays.

Sensing the slip of an object on the surface of the finger due to insufficient grasp force (that is, sensing a tangential force acting on the surface of the mechanical finger) can be accomplished by direct and indirect means. An indirect sensing concept can be based on monitoring changes in the area distribution of pressure patterns sensed by a multipoint tactile sensor. An appropriate pattern recognition scheme could even indicate the mean direction of slip relative to the contact surface. The display of slip can easily be incorporated into the graphic display format of tactile sensing by using an arrow referenced to the contact surface. The orientation of arrow would indicate the direction of slip.

If the sensing of slip is accomplished by direct means (that is, by using a slippage sensor), the information display can be based on the rotating bar or rotating arrow concept shown in a graphic display screen. The length of the bar or arrow could indicate the rate of slip since direct sensing of slip can also provide information on the slip rate. Several slip sensor concepts are currently under implementation at JPL. Figure 11 shows an LED display of a directional slip sensor breadboard model under development at JPL. The display indicates sixteen directions in equal angular increments on a full circle.

## VI. Integrated Displays

Integrated display of information generated by sensors attached to the terminal device of a remotely controlled manipulator can be considered in two stages. In the first stage the concern and task are the integration of proximity, force-torque, tactile and slippage sensor information within a given graphic display frame. In the second stage, the problem and goal are the integration of graphic display of the above quoted multisensor information with and/or within the picture of a TV display frame. Since not all sensor information may occur simultaneously in all cases, the integration scheme can be based on a "call" concept controlled by the operator.

The design of integrated display formats is under development at the JPL teleoperator program. Preliminary format concepts are shown in Fig. 12. Consideration is also given to the human factors relevant to the design and integration of audio and graphic displays for sensor information which is basically non-visual in nature. The development of various visual and non-visual displays is to be followed by a program of evaluating the utility of the displays in the performance of remote manipulation within the context of a supervisory control system, employing several test persons.

## VII. Conclusion

The display of information generated by non-visual sensors attached to the terminal device of a remotely controlled manipulator is a relatively new area of research and development. In fact, even the development of the relevant sensors is a relatively new endeavor. Preliminary experiments at JPL have shown the utility and limitations of a few audio and visual display schemes employed for proximity sensors. In particular, it has been shown that appropriate graphic displays can substantially increase control performance in accuracy and time. However, considerable work is ahead before the development of visual and non-visual displays of non-visual sensor information for manipulator control will reach a high level of maturity.

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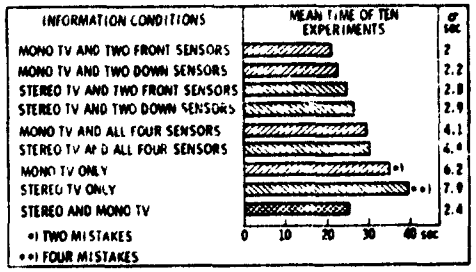

TABLE 1 Performance data for combined use of visual and proximity sensor audio information

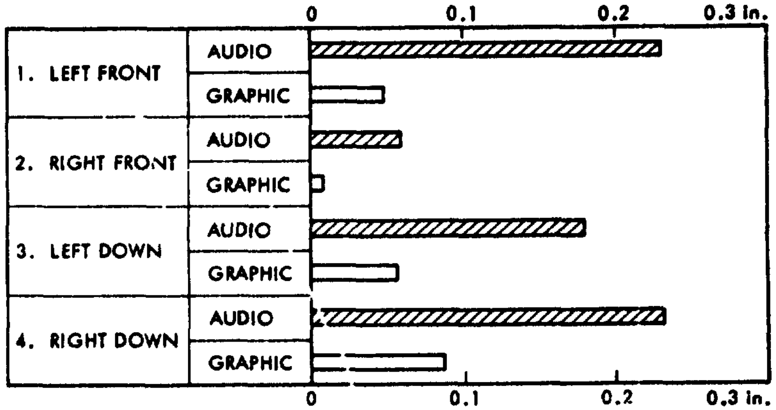

TABLE 2 Performance data for comparing utility of audio display versus graphic display of proximity sensor data. (Bars show difference between requested and actual positioning accuracy for ten experiments.)

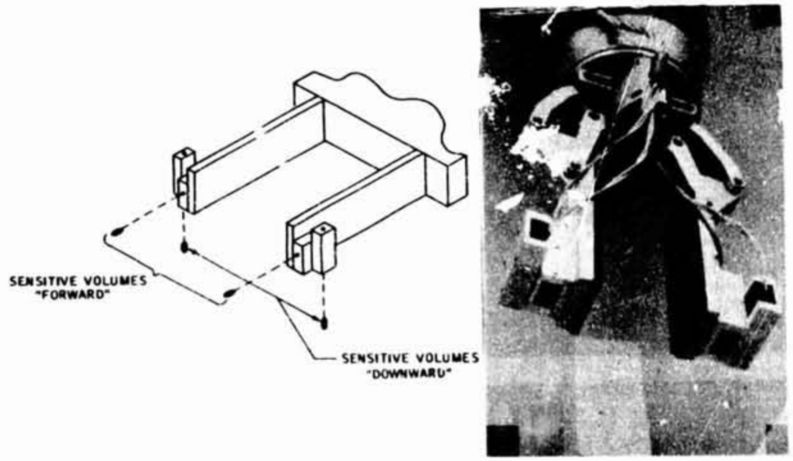

FIGURE 1 Four proximity sensors on parallel jaw terminal device.

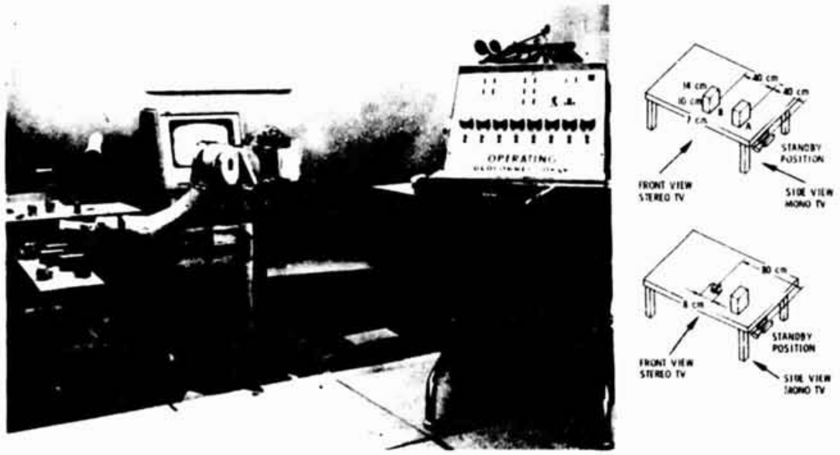

FIGURE 2 Task arrangements for proximity control performance tests.

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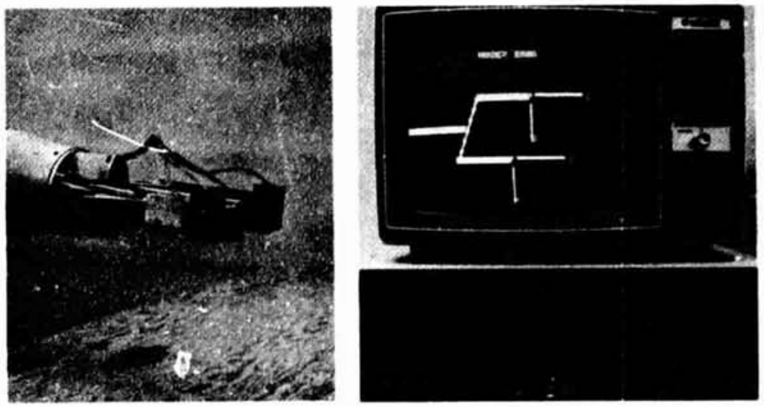

FIGURE 3 Graphic display of information from four proximity sensors

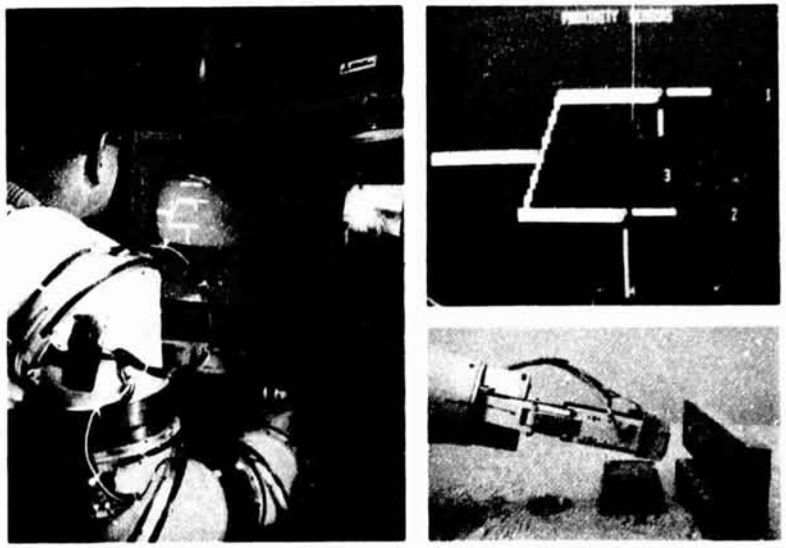

FIGURE 4 Operator working with graphic display of proximity sensor information.

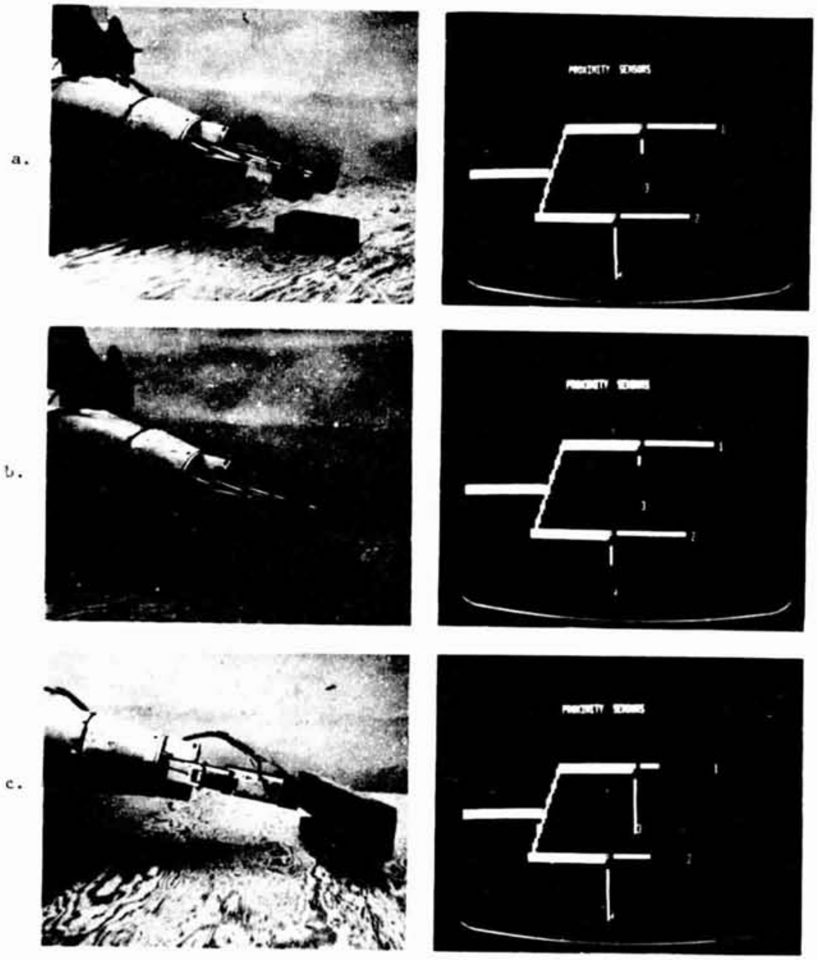

FIGURE 5 Different proximity scenes on graphic display.

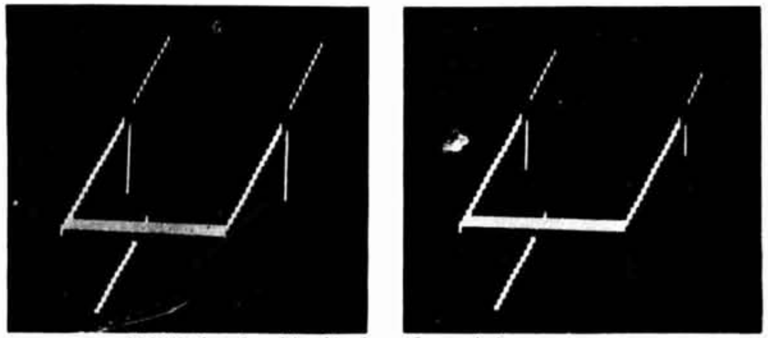

FIGURE 6 Graphic display of proximity sensors information in left-forward perspective.

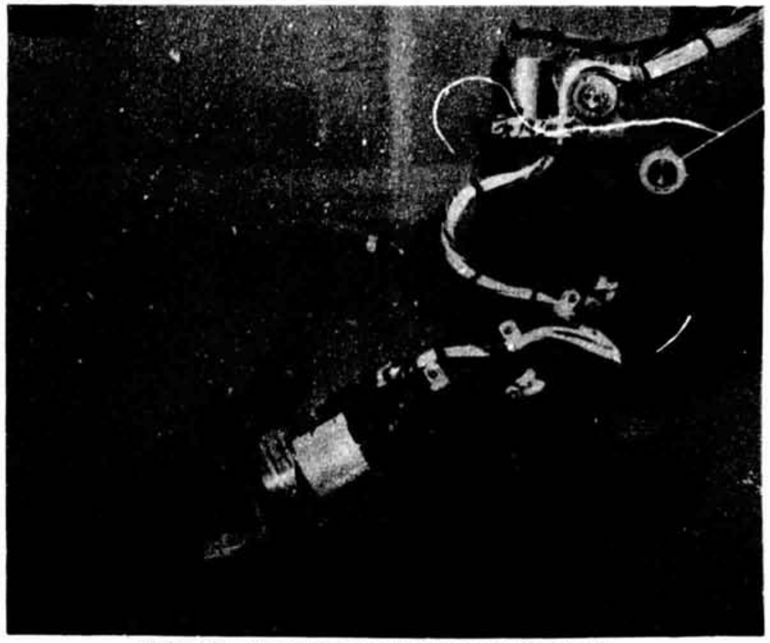

FIGURE 7 Force-torque sensor on JPL CURV arm.

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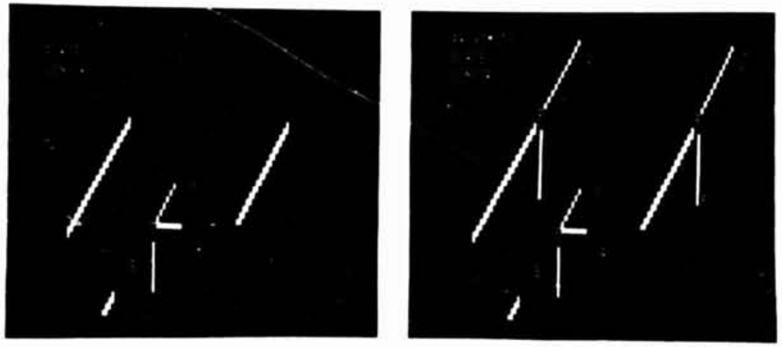

FIGURE 8 Preliminary formats for graphic display of force-torque sensor information alone and combined with proximity sensor information.

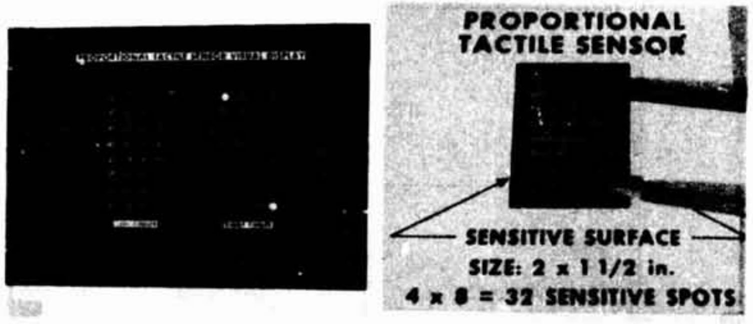

FIGURE 9 Tactile sensor breadboard with visual display.

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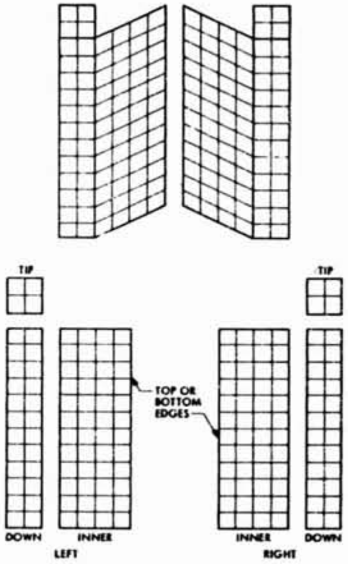

FIGURE 10 Tactile sensor graphic display concept.

FIGURE 11 Directional slip sensor breadboard display.

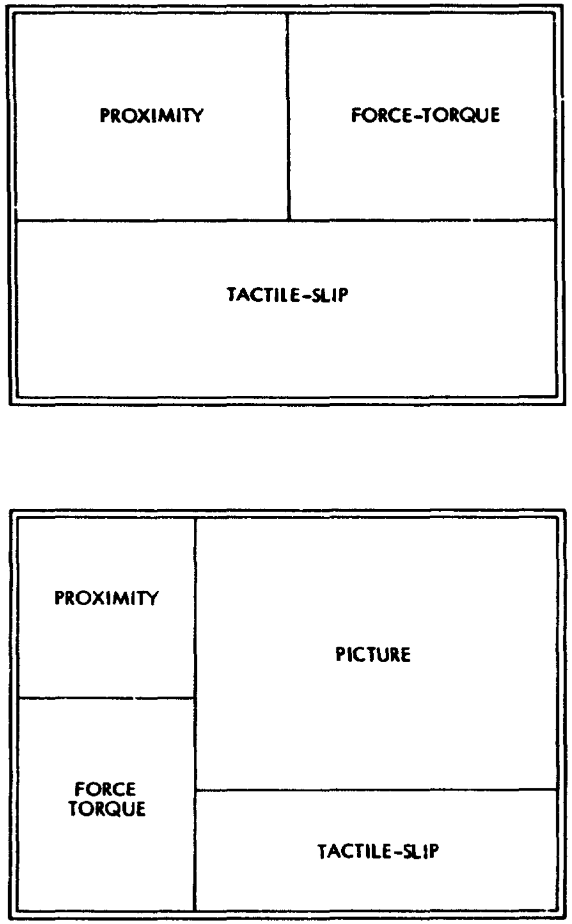

FIGURE 12 Integrated display concepts.