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EVENT-DRIVEN DISPLAYS FOR MANIPULATOR CONTROL *)

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SUMMARY

This paper considers the problem of constructing event-related information displays from multidimensional data generated by proximity, force-torque and tactile sensors integrated with the terminal device of a remotely controlled manipulator. Event-driven displays are constructed by using appropriate algorithms acting on sensory data in real time. The purpose of event-driven information displays is to lessen the operator's workload and to improve control performance. The paper describes and discusses several event-driven display examples that have been implemented in the JPL teleoperator project, including a brief outline of the data handling system which drives the graphics display in real time. One application shows the integration of a set of four proximity sensors with a JSC four-claw end effector for the shuttle manipulator training facility of JSC. The paper concludes with a discussion of future plans to integrate event-driven displays with visual (TV) information.

I. INTRODUCTION

The objective of this paper is to show and discuss display techniques aimed at reducing the dimensionality of proximity, force-torque and tactile sensor data, and conveying the sensory information to the operator of a remote manipulator in terms of significant events related to the control task. An event-driven display is a display which shows whether or not some desired state of the teleoperator effectors/sensors has been achieved. It may or may not show the details of the state itself, rather it displays the occurrence of the event. Hence, event-driven displays compress and explicitly indicate sensory data in terms of control goals or subgoals which require specific control decisions and actions.

The general problem of displaying information generated by proximity, force-torque, tactile and slippage sensors integrated with the terminal device of a mechanical arm has been treated in a previous paper (see Reference 1).

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The information generated by these sensors is basically non-visual: short (few centimeters) distances in given direction between terminal device and object; amount of force and/or torque exerted by the terminal device on objects along three orthogonal axes referenced to the terminal device; distribution and amount of contact area pressure between terminal device and object; or slip of an object in some direction on the inner surface of mechanical "fingers". Hence, the general problem and objective of displaying this type of information to the operator of a remote manipulator are to make non-visible events visible or, alternatively, to make non-visible events easily perceivable by using some appropriate means (e.g., audio tones).

The information generated by proximity, force-torque, tactile and slippage sensors has two specific features: it is multidimensional, and it requires quick (sometimes split-second) decision or control response. It is noted that, in general, the required decision or control response is also multidimensional. The use of multidimensional data with quick response requirements in a real time manual or computer control environment is a demanding perceptual and cognitive workload for the operator of a remote manipulator. It is a major source of errors, and can result in a general degradation of control performance. The purpose of event-driven sensory information displays is to lessen the operator's workload and to improve overall control performance of remote manipulators.

The concept of sensory information "events" is discussed in Section II. The general features of "event-driven displays" are briefly discussed in Section III. Section IV describes several event-driven display examples that have been implemented in the JPL teleoperator project. These include two uses of four proximity sensors and a single use of a six-dimensional force-torque sensor integrated with manipulator end effectors employing both audio and graphic display techniques. One application shows a set of four proximity sensors integrated with a JSC four-claw end effector to be used at the JSC Manipulator Development Facility. A simple touch sensor example is also described. The concluding Section V summarizes the results and outlines future plans to integrate event-driven displays with visual (TV) information. A brief description of the data handling system which drives the graphics displays in real time is presented in the Appendix.

II. SENSORY INFORMATION "EVENTS"

Proximity, force-torque and touch sensor data are inherently multidimensional. A six-dimensional force-torque sensor outputs the time trajectories of three orthogonal force and three orthogonal torque components normally referenced to a hand coordinate frame. The hand coordinate frame itself is a variable (i.e., has time trajectories) relative to a fixed "base" reference frame. A multipoint proportional touch sensor measures the area distribution and amount of contact pressure over a fixed surface. A single proximity sensor measures short (few centimeters) distances in a given direction relative to a hand coordinate frame. Several proximity sensors in a given emplacement geometry on the hand can measure several or all six position and orientation variables of the hand relative to objects.

A sensor-referenced or sensor-guided manipulator control task contains a goal or a set of subgoals. The control goal or subgoals are expressed as a combination of various sensory data. The simultaneous occurrence of time trajectories of various sensory data at a single point or within a given subvolume of a multidimensional data space can be called a sensory information "event". Hence, sensory information "event" is the projection or mapping of the control goal or subgoals into a multidimensional data space.

Figure 1 gives simple illustrations for the concept of sensory information "event". Equal length of two proximity sensor beams can be an "event" in the sense that it may signify, e.g., the roll, yaw or pitch alignment of a mechanical hand relative to an object. Equal magnitude of two orthogonal force components can be an "event" in the sense that it may signify, e.g., the push or pull of an object by a mechanical hand in a given direction. Or, for instance, half contact coverage of a touch-sensitive area on a mechanical finger can be an "event" in the sense that it may signify, e.g., that there is sufficient contact between hand and object for successful grasp.

The operator's attention in both manual and computer control is normally focused at the control goals or subgoals, that is, at the sensory information "events". Typically, when such "events" occur, some control action must be taken. It is to the operator's advantage to have these sensory "events" displayed in easily perceivable and unmistakably unique forms. In the absence of such "event" displays, the operator must determine the occurrence of the "event" by following and evaluating a multidimensional set of data in real time. This is not only a demanding task and heavy workload for the operator, but also a common source of errors.

III. DISPLAY OF "EVENTS"

Event-driven displays can be implemented by developing and/or employing appropriate real-time algorithms which (a) coordinate and evaluate sensor data in terms of predefined "events" and, (b) drive some appropriate information display in real time. Manipulator control tasks can be subdivided into a multitude of sensory "events", and each event may have a variety of characteristic parameters. Thus, the development of fairly general purpose event-driven displays requires that the logic/parametric structure of the algorithms be flexible in the sense that changing control goals or subgoals can be accommodated by simple call-changes in the algorithms in a given control/operation environment.

The actual event display can be implemented by alternative means, the selection of which depends on the application environment. For event displays, both audio and visual display techniques are suitable. An important consideration for selecting or designing event displays is the "warning effect" the display can or shall impose on the operator. By definition, the occurrence of a sensory event should call the operator's attention to some appropriate control decision or control action, without disturbing his normal visual attention directed toward the overall control task. Note that the control can require split-second decisions. Another important consideration is related to the selection of the content of the display format. How much and what kind of detailed information the operator should be exposed to in addition to the "event information" within the same general frame of information? Too much information can be disturbing. Too little information can defy the purpose. The display of uncorrelated data, or the display of correlated data in uncorrelated form, may impose heavy cognitive load on the operator.

Properly designed event-driven displays are expected to have a number of benefits: (a) simplify on-line control decisions; (b) reduce errors caused by human factors; (c) reduce perceptual/cognitive workload on human operator in a real-time control environment; (d) improve overall control performance in control situations which many times require split-second type control decisions.

IV. EXAMPLES

A. Event-Driven Proximity Displays

Event-driven displays have been constructed for proximity sensors on two arms in the JPL teleoperator project, and also for a proximity sensor system developed at JPL and integrated with the four-claw end effector of JSC to be used at their shuttle manipulator training facility.

1. JPL Teleoperator Arms

Both the JPL/CURV and JPL/Ames arms are equipped with four proximity sensors, and the event-driven display developed recently is applicable to both sensor systems. Although the sensor hardware is quite different on the two arms, the sensor display drive software is common except for the routines that get the data. Similarly, the event logic is common. The details of the computer hardware and software are described in the Appendix.

The general format of graphics display of four proximity sensors data is shown in Figure 2. The display shows a view of the "bone" of a parallel jaw hand and four beams emanating from the hand, two from each jaw. The beam lengths are proportional to the sensitive length of the sensor beams. Each beam length is bound to 10 cm (4 in.).

Figure 3 summarizes the proximity events together with the event logic and event parameters that have been implemented. In the present implementation the parameter D is fixed at 5 cm. D is always defined parallel to and halfway in between the two beams which measure roll and yaw alignments, respectively, and relative to the line connecting the two fingertips. The tolerance, T, can be set by switch inputs on the computer's front panel. Values from 0.5 to 7.5 cm are allowed. Any combination of the four event logic equations may be selected to control the event success blinker. The success may be defined as X alignment with a tolerance, say, of 1 cm (corresponding to about 5 degrees when the hand is fully open). Or, the success may be defined as Y range of 5 cm together with X alignment to within 0.5 cm tolerance (corresponding to about 2.5 degrees when the hand is fully open). This latter "success case" would be useful in moving the hand over a table to a wall while holding an object vertical. With this event logic, the hand roll angle would be small as the range measurement is made on both sensors and the object would be held with the hand 5 cm above the table. The final approach to the wall would be reached with the hand perpendicular to the wall.

The event indicator blinker has initially been placed in the top left hand corner of the monitor screen. Though all four sensor beams are shown on the monitor, the operator does not have to evaluate the four beams quantitatively in terms of a predefined event. This is done for him by the display drive logic automatically and in real time. He can take a more qualitative look at the four beams to determine, e.g., why the success blinker is "off"; that is, what to do in order to get the success blinker "on".

Figure 4 shows two uses of the event-driven proximity display. The first pair of photographs (Figure 4A) shows the hand above a table and skewed to a block. The task is to achieve alignment with the table and the block. The display shows the operator how to bring the hand perpendicular to the block while maintaining the hand level at 5 cm above the table. The second pair of photographs (Figure 4B) shows that this has occurred and the event blinker has come on. The third pair of photographs (Figure 4C) shows a different alignment problem. Here, it is desired to bring the hand in level over the plate on the table. There are no forward references. Following the required corrections as indicated by the display, the desired level state is achieved, and the event blinker comes on as shown in the fourth pair of photographs (Figure 4D).

While the two uses of the event-driven display shown in Figure 4 are simple, they do demonstrate the usefulness of the concept. As more complex tasks are performed and analyzed, a detailed examination of the benefits can be made. Future improvements in implementation are also planned to enable a broader variety of events to be defined. Ranges, alignment angles and tolerances could be individually defined rather than being commonly constrained as at present.

2. JSC Four-Claw End Effector

A proximity sensor has been developed for and integrated with a four-claw end effector of JSC. The purpose of this sensor system is to aid the operator to find the proper final depth positioning and pitch and yaw alignments of the four-claw end effector on a 16-m long manipulator relative to the grapple fixture of a large payload. The overall control is visually guided.

The sensor system, together with the grasp envelope and measurement definitions are shown in Figure 5. The use of the sensor system is presently restricted to the verification of a "successful grasp state" before grasp action is initiated. The "successful grasp state" is defined by the dimensions of the grasp envelope (see Figure 5) and by the dynamics of grasp.

When a "successful grasp state" has been reached, the data processing electronics automatically turns on a simple "success display" (a buzzer or a green light, or both), indicating to the operator that he is ready to grasp.

The data processing required to drive the "success display" has two modes: analog and digital. The analog drive logic implementation is quite simple as indicated in Figure 6. In fact, with this simple analog implementation the full capabilities of the sensor system cannot be utilized to account for all physically possible combinations of depth, pitch and yaw error states which, due to the dimensions of the end effector's grasp envelope, still would allow successful grasp. To achieve a full utilization of the sensor system capabilities versus all allowable depth, pitch and yaw error combinations, "success algorithms" have been developed and implemented using an Intel 80/20-4 single-board microcomputer together with an Intel single-board A/D converter.

For the purpose of experimentation, several "success algorithms" have been implemented in the digital computer to drive the displays. The algorithms are simple, and account for all (or for almost all) allowable error states combinations for successful grasp. Algorithms have also been implemented which utilize the outputs of any three out of the four sensors to indicate the "success states". This is useful if one sensor eventually fails, or if one sensor eventually misses the top (reference) surface of the grapple fixture due to allowable lateral alignment errors. (Note that the four-sensor configuration is redundant to define and compute depth, pitch and yaw errors. A triangular configuration of three sensors would be sufficient for that purpose.)

For the sake of brevity, only one "success algorithm" is shown in this paper, summarized in Figure 7. It is called "conic algorithm" since it condenses the individually allowable pitch and yaw errors into a simple allowable cone angle error condition. (See Condition 2 in Figure 7.) Three kinds of "success definitions" have been developed, each with three sets of "success parameters". All nine variations have been implemented for "all four" and for "three-out-of-four" sensors. All together 18 algorithms are stored in EPROM in the microcomputer. Any one of the 18 algorithms are easily callable by dialing the appropriate number between 1 and 18 on a BCD switch integrated with the microcomputer.

Very successful operational ground tests have been conducted with the sensor and simple display system at JSC using the 16-m long arm of the JSC Manipulator Development Facility in realistic large payload handling experiments. Fig. 8 shows a floor set-up scene (direct visual contact with target) for capturing a moving target. All together 112 test runs have been performed by 4 operators. The final result is that, when the "success display" (tone or green light) was on, the operators got a capture every time. There were no operator mistakes under sensor-indicated grasping conditions, and the sensors never indicated wrong conditions for grasping. Three of the four operators favored the buzzer for "success display". The utility of the display increased with task difficulty. The display was required to aid the operator to successfully complete the most difficult tasks without error.

The simple success display (tone or green light) does not show the details of the three-dimensional (depth, pitch and yaw) error states. Advanced graphics display concepts have been developed and implemented recently using the JPL teleoperator breadboard system to experiment with various formats. The advanced formats have been designed to convey to the operator not only the "success" information but also the details of the three (depth, pitch and yaw) errors so that the operator will know from the sensors "what to do" in order to get to the "success" state or to fine-control the grasp. Fig. 9 shows an advanced "success display" concept implemented in color graphics. Success is indicated here by all error bars turning green. The unsuccessful error combinations are indicated by all error bars turning red. The length of the error bars is proportional to the respective errors under both "green" or "red" conditions.

B. Event-Driven Force-Torque Display

Fig. 10 shows a six-dimensional force-torque sensor integrated with the JPL/CURV arm. The sensor mechanism has been built by Vicarm Inc. The sensor electronics and data handling have been developed at JPL. More details of this sensor system can be found in Ref. 2. Fig. 10 also shows a graphics display format: each force and torque component is displayed both numerically and graphically. The length of the bars is proportional to the value of the respective force or torque components. The bars originate from the center vertical line on the screen. To the left from this center line the force-torque field is negative, to the right it is positive. The force-torque components are referenced to a hand-based coordinate frame. The force-torque distribution seen on the graphics display of Fig. 10 actually shows the forces and torques felt at the hand base while the hand is pushing the object as indicated on the same figure. As seen, a simple push scene can generate a rather complex force-torque relation felt at the hand base.

The application of event-driven displays to force-torque sensor data will significantly enhance the use of that data type under manual or computer aided control. The events marked can show complex relationships between forces and torques alone or in combination. Further, when the desired force-torque events are not existing, the display format can be changed to show the operator what has to be done to reach the desired state. A simple example can best illustrate the concept.

Consider the task of sliding a block in a groove across a table by pushing it. (See Fig. 11) The applied forces must be in the direction of the groove if the block is to be moved efficiently and safely. Fig. 11 also shows an appropriate "event-driven" display. When the forces are applied correctly, the operator will know it by the event indicator. If not, the operator will see the force errors and be able to apply the needed corrections. Practical application and demonstration are needed before the benefits of this display concept can be fully documented.

An interesting use of even-driven displays is to signal the operator to switch displays. Say, for example, it is necessary to move a manipulator to an object and then move the manipulator into contact with the object without knowing the exact position of the object beforehand, or having specially positioned TV's showing all the necessary views.

With event-driven displays, the task could be performed as follows: using a proximity event display set in a position sensing mode, the operator moves the manipulator rapidly towards the object. When signalled that the manipulator is near the object, the operator slows its motion and switches the display to a force/torque even mode. When contact has been achieved, the operator is again signalled before the forces reach an unacceptable level. Thus, event-driven displays used in combination hold great promise for even greater benefits in that tasks can be performed more rapidly, more reliably and with lower expenditure of resources.

C. Event-Driven Touch Display

The touch sensor unit being used here has two 4 by 8 matrices of points that can sense applied pressures. These matrices, or perhaps some with higher point density, can be mounted on the inside of mechanical fingers (jaws) and used to sense contact areas or the location of points of contact between finger and object. Similar units could be mounted on other surfaces to sense other contact forces or patterns of contact areas. At each point of the sensor matrix the pressures applied locally are sensed by measuring the conductivity of a pressure sensitive plastic. The measurement concept and the actual sensing elements are shown in Fig. 12.

Fig. 12 also shows the basic touch sensor displays. The numeric representation of the sensor output gives a more quantitative impression of the applied forces distribution and is particularly useful for diagnostic work. The color or B/W shades displays are more graphic and are easier to understand at a glance although less information is presented.

A particular event-driven touch sensor display is planned to be implemented to further enhance the control context of data presented to the operator. The display concept (shown in Fig. 13) is aimed to give a quantitative indication to the operator when the contact area increases by predefined amount. While the pressures applied will still be shown as dark or light shades of a color, the color itself will be changed to reflect the total applied pressure over a given area. The matrix displayed may be red, if less than half the sensitive points have made contact; orange, if between 1/2 and 3/4 have; or green, if more than 3/4 have. Thus, a green condition will signify a safe grasp.

V. CONCLUSIONS

1) Performance tests conducted at JSC with a three-dimensional proximity sensor system and "go-no go" display have shown the basic utility of a simple event-driven display which conveys critical control information to the operator based on real-time algorithmic evaluation of multidimensional data.

2) In general, event-driven displays enhance the control context of sensory information since events can be defined with respect to critical control decisions or control actions.

3) Preliminary experiments strongly indicate the need of integrating visual and non-visual sensory information within a single perception format. This may require the development of TV monitors with sensory information overlayed to or cut into the camera information.

4) Extensive experimentation is needed with a multitude of event-driven display formats in order to develop a reliable rating of the different formats. The experimentation will by necessity encounter questions in human factors engineering. Presently it is not clear what kind of *objective* measures would be suitable to meet the challenges in the performance evaluation of event-related human factors.

ACKNOWLEDGEMENT

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APPENDIX

1. Computer System

A single computer system is used for software development and display driving. Its principal elements are shown in Fig. 14. The signals to be displayed can come from any of five sources: JPL/AMES arm proximity sensors, JPL/CURV arm proximity and force-torque sensors, touch sensors, or the JSC four-claw proximity sensors. (These last signals come through an Intel 80/20 processor.) The display computer processes these signals into the desired display format so that they may be seen in color or in B/W, with or without alpha-numeric text.

The display computer is an S100 bus based system and employes a Z80 based processor operating with a 4 MHZ clock. The computer communicates to the outside world through a 7 channel 8 bit A/D converter, 2 serial ports, 8 bit parallel ports, a dual floppy disk, and, of course, a graphics color/BW TV display. The operator interface is through an ADM-3A terminal, a TTY and the dual disk.

The graphics display is performed by DMA on a memory map. That is, the display driver circuitry timing operates independently from the main program and shares the memory storing to the screen image. Various display parameters are under program control: display on/off, point density, B/W or color, etc. The graphics densities employed are: 64 by 64 color and 128 by 128 B/W for the touch sensor; 128 by 128 B/W for the proximity sensors on the JPL/CURV and Ames arms and for the force-torque sensor on the JPL/CURV arm; and 64 by 64 color for the JSC four claw proximity sensors.

The signals from the JPL/Ames arm proximity sensor electronics are sent to the display computer on 4 analog lines. The A/D conversion is done inside the display computer by an 8 bit successive approximation converter. Each conversion takes about 5 μs.

The signals from both sensors (proximity and force-torque) on the JPL/CURV arm are converted to 12 bit digital words in the CURV vehicle electronics and then stored in a buffer memory associated with the Interdata M70 minicomputer which performs control and supervisory functions. The data is transferred in parallel to the display computer as two 8 bit words. The data to be transferred is specified by the address sent to the buffer memory from the display computer.

The signals from the touch sensor are converted to 12 bit digital words by the touch sensor electronics. The point of the sensor matrix to be sampled is under control of the display computer. An address is sent to the touch sensor electronics, the point is sampled, and the data is sent to the display computer as two 8 bit words. Due to the handshaking signals which are under software control, the whole process takes about 100 μs.

The signals from the JSC four-claw proximity sensors are processed by the Intel SBC 80/20-4 computer. Only the pitch, yaw, and range error signals and the "event" signal are passed over to the display computer. These signals are encoded into three 8 bit parallel words. The two computers run asynchronously since the TV graphics display process is much slower than the event indication bulb and tone process (about 16 times per second versus about 100 times per second.)

2. Software System

The software for the display programs has been written in assembly language to maximize the signal processing and display formatting rate. This has been an effective approach since the processing and formatting are logically and mathematically simple. Typically, the symbolic language version of a program takes 10-15K bytes to store, and the machine language version 1-2K bytes.

The programs have been written in a structured subroutine format. The top level is a sequence of calls to subroutines. The first calls are to routines which initialize constants and set up the displays. These are followed by the main program loop which calls routines: to see if the display program should be exited, change parameters based on switch or keyboard inputs, input data, calibration of data, perform logic tests, format the data for the displays, etc. Each of these subroutines is a complete logical entity, so that new functions may be added by simply inserting new calls. A similar approach has been taken for the lower levels of subroutines. The program data structures have been designed so that they allow an EPROM version of the programs. Thus to perform tests only a small fraction of the computer system is needed. Further the operation of the system for demonstrations is simplified.

The program for displaying proximity sensor data from the sensors on the JPL/CURV arm and performing event logic is typical of the display computer programs. The first level structure is shown in part A of Fig. 15. The actual process for getting the data, processing and displaying it are shown in part B of Fig. 15. The modularity of the structure was a significant help in adding the event logic and display to the prior programs. All that was necessary was to add the two blocks which perform the event logic tests and which time and display the event blinker. Likewise, when changing the JPL/Ames arm proximity sensor program to accept data from the JPL/CURV arm proximity sensors all that was necessary was to change the "Read Sensor Data" subroutine. The subroutines, incidentally, were taken from a previous force-torque sensor program.

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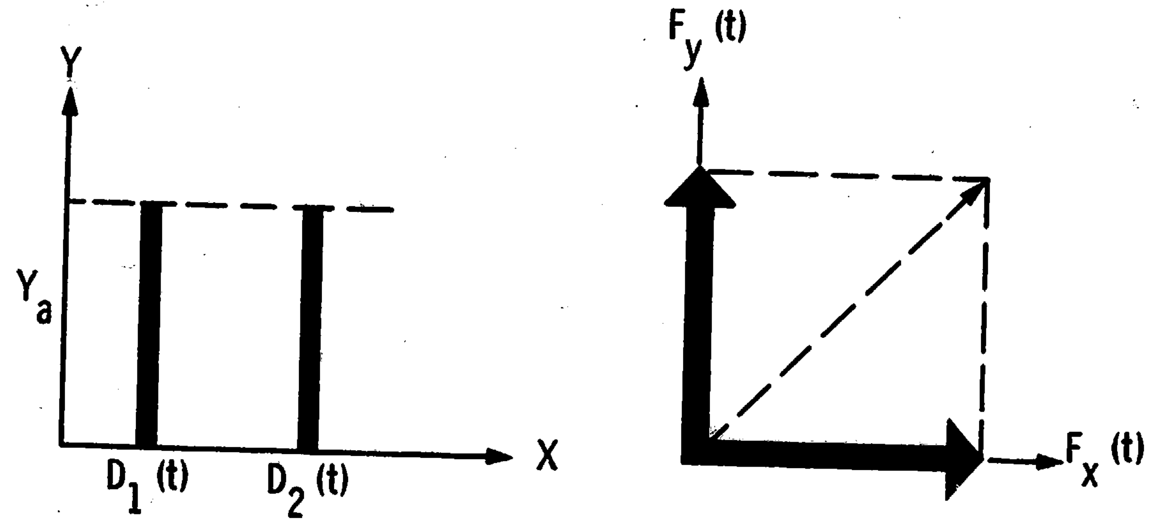


EQUAL LENGTH (Y_a) OF TWO BEAMS (D_1 AND D_2) CAN BE AN "EVENT"

EQUAL MAGNITUDE OF TWO ORTHOGONAL FORCE COMPONENTS CAN BE AN "EVENT"

Figure 1. Examples for Event Definition

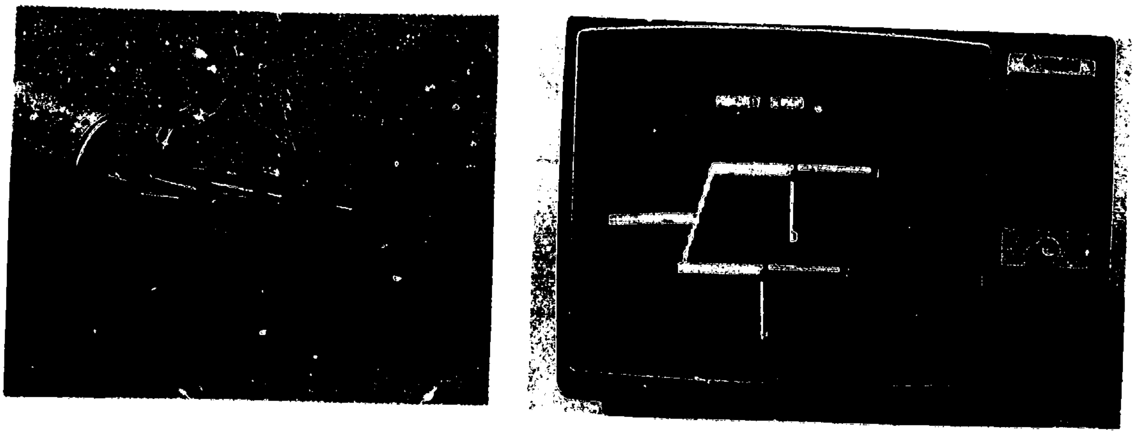
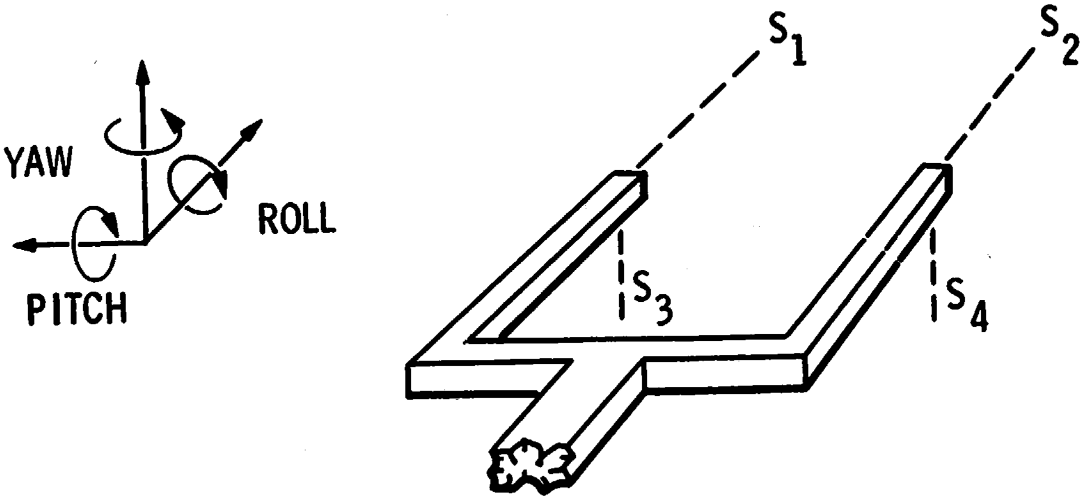


Figure 2. General Graphics Display of Proximity Sensor Beams



S_i = RANGE MEASURED BY SENSOR " i ", $i = 1,2,3,4$

D = DISTANCE } PRESET PARAMETERS
T = TOLERANCE }

LOGIC DEFINITIONS FOR EVENT $E_i = \{K\}$

$E_i = 0$ FOR $K \geq 0$: EVENT ISN'T THERE, BLINKER "OFF"

$E_i = 1$ FOR $K < 0$: EVENT OCCURED, BLINKER "ON"

EVENTS	LOGIC EQUATIONS
1. YAW ALIGNMENT AT "D" WITH "T" TOLERANCE	$E_1 = \{\lvert S_1 - D\rvert - T > 0\} \bullet \{\lvert S_2 - D\rvert - T > 0\}$
2. YAW ALIGNMENT ONLY WITH "T" TOLERANCE	$E_2 = \{\lvert S_1 - S_2\rvert - T > 0\}$
3. ROLL ALIGNMENT AT "D" WITH "T" TOLERANCE	$E_3 = \{\lvert S_3 - D\rvert - T > 0\} \bullet \{\lvert S_4 - D\rvert - T > 0\}$
4. ROLL ALIGNMENT ONLY WITH "T" TOLERANCE	$E_4 = \{\lvert S_3 - S_4\rvert - T > 0\}$

Figure 3. Proximity Sensing Events Example

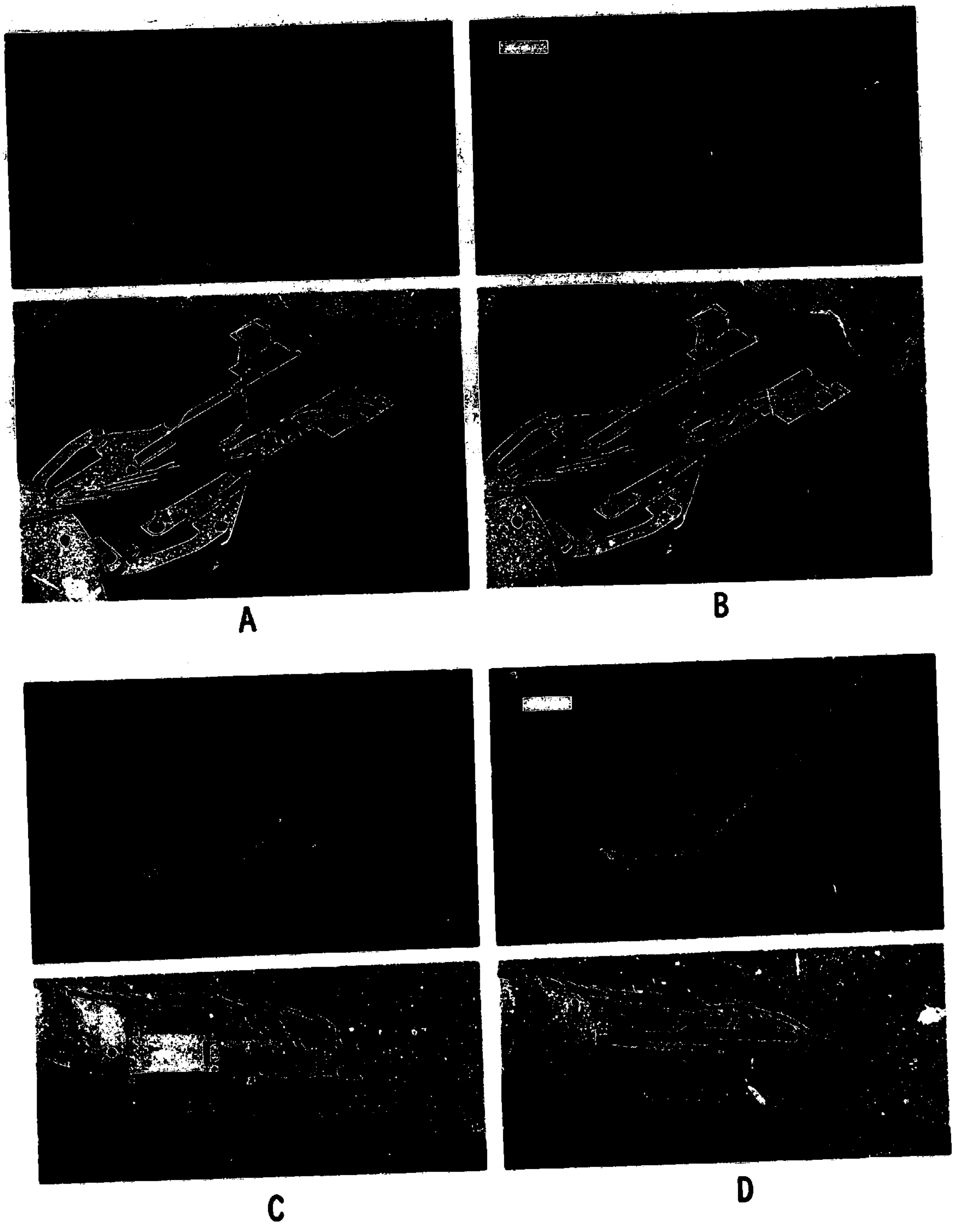


Figure 4. Proximity Sensing Events Graphics Display

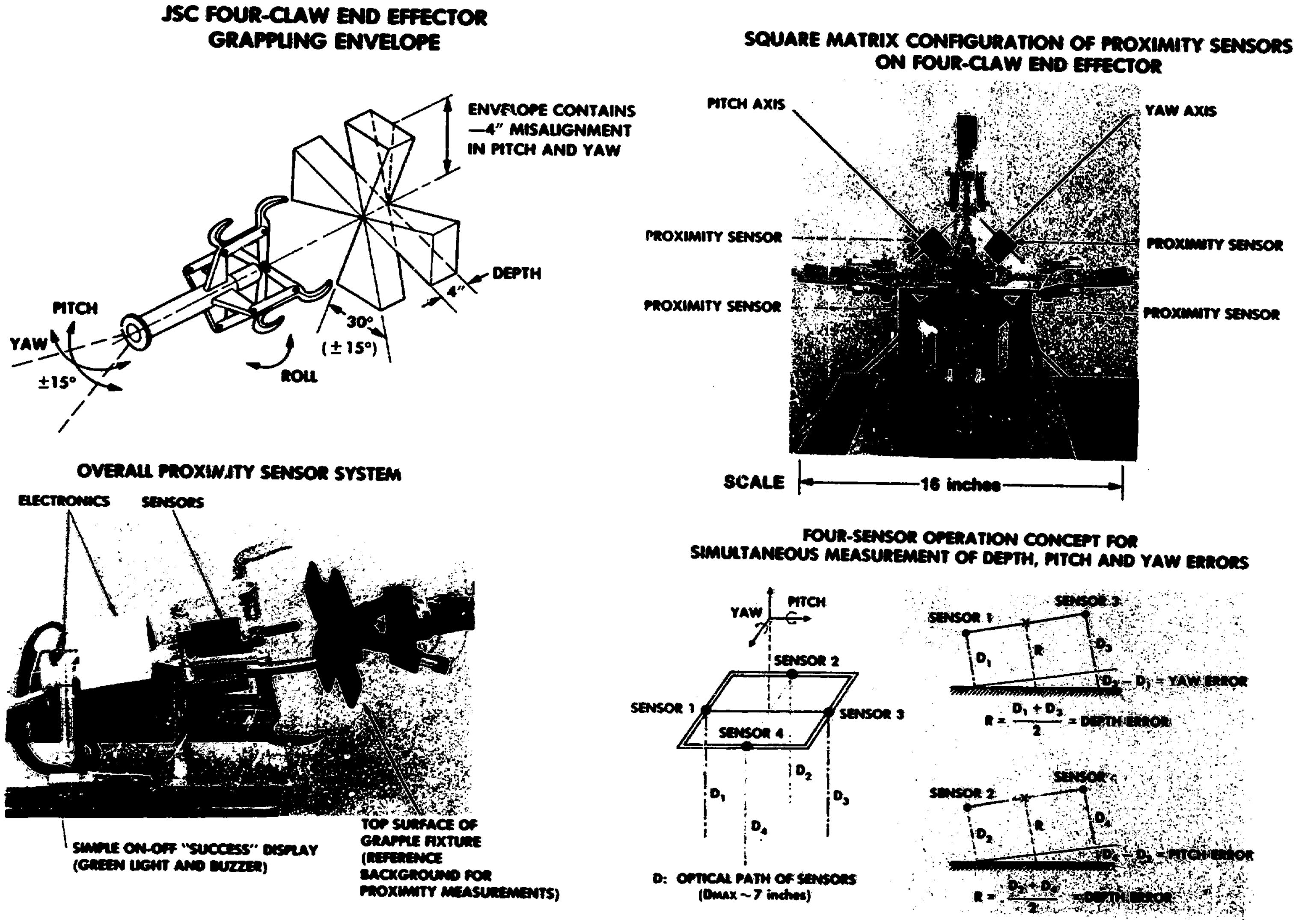
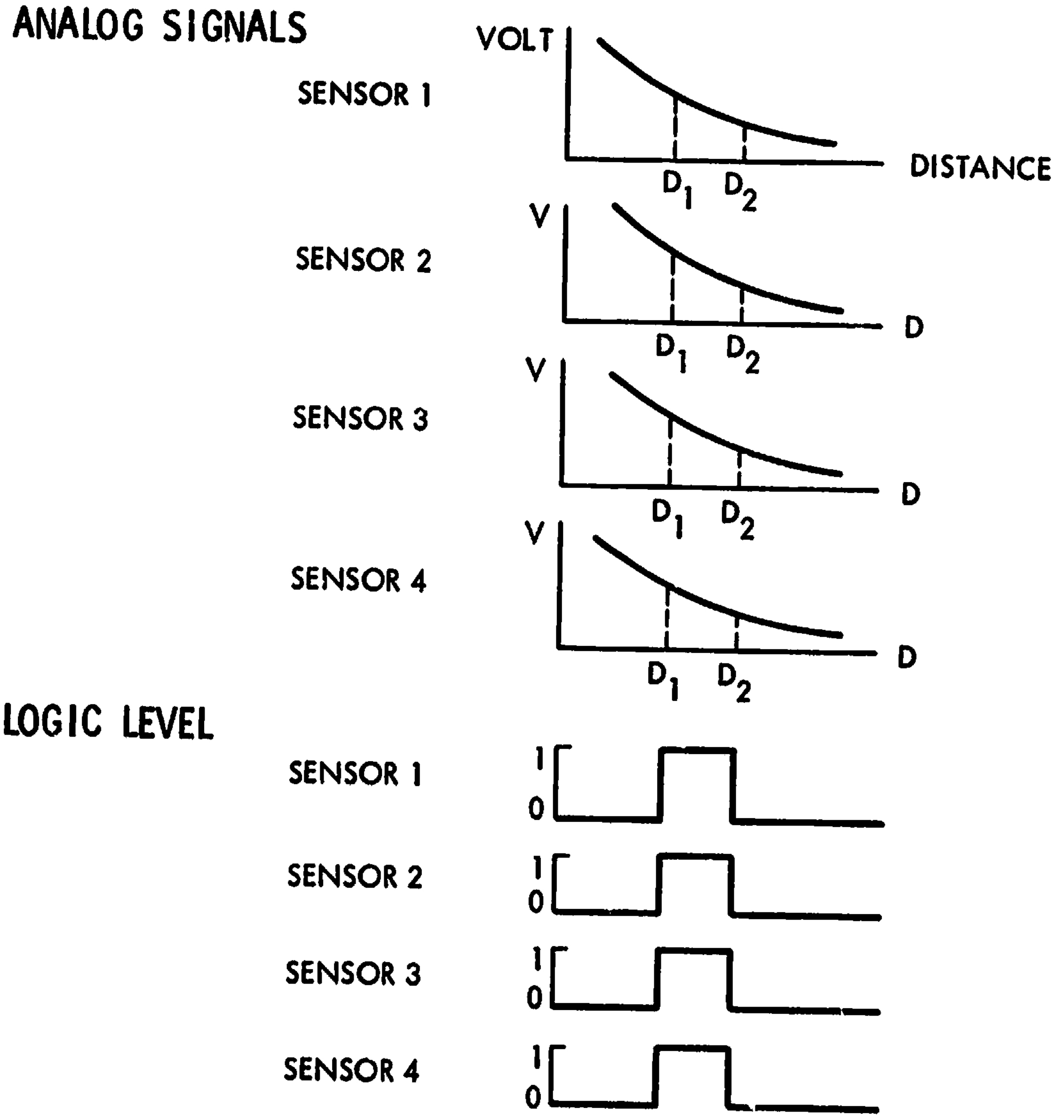


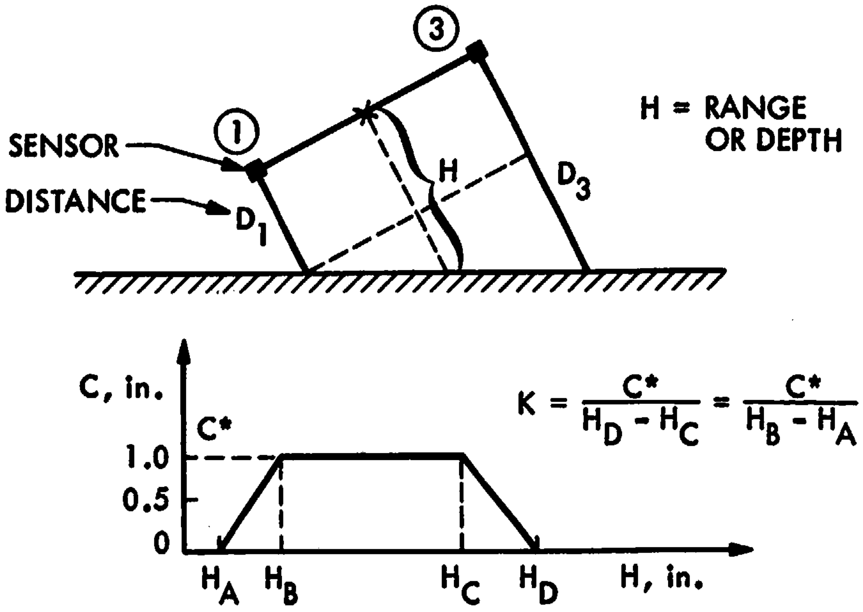
Figure 5. Four Proximity Sensors on JSC Four-Claw End Effector



SUCCESS: EACH OF THE FOUR SENSORS OUTPUT IS IN LOGIC STATE "1" (THEN TONE AND/OR GREEN LIGHT ARE AUTOMATICALLY TURNED ON INDICATING TO OPERATOR THAT DEPTH POSITION AND PITCH AND YAW ALIGNMENTS OF END EFFECTOR ARE OK FOR SUCCESSFUL GRASP OF TARGET)

Figure 6. Analog "Event Logic" Indicating Acceptable Combinations of Range, Pitch and Yaw Errors for Successful Grasp Using Four Proximity Sensors Integrated with JSC Four-Claw End Effector

- MEASUREMENTS -



$$K = \frac{C^*}{H_D - H_C} = \frac{C^*}{H_B - H_A}$$

C IS A MEASURE FOR PITCH AND YAW ERRORS; C = f(H)

- SUCCESS LOGIC -

① $H_A \leq H \leq H_D$

WHERE $H = 1/2\,(D_1 + D_3)$

$1/2\,(D_2 + D_4)$

② $(D_1 - D_3)^2 + (D_2 - D_4)^2 \leq L$

WHERE $L = C^2 = [f(H)]^2$

IF BOTH CONDITIONS ARE TRUE THEN LIGHT/BUZZER ARE ON, OTHERWISE OFF

H_A, H_B, H_C, H_D AND K (AND IMPLICITLY ALSO C*) ARE PRESET CONTANTS

f(H) IS GIVEN BY THE TRAPEZOID FORMULA SHOWN ABOVE

Figure 7. Conic Algorithm Indicating Acceptable Combinations of Range, Pitch and Yaw Errors for Successful Grasp Using Four Proximity Sensors Integrated with JSC Four-Claw End Effector

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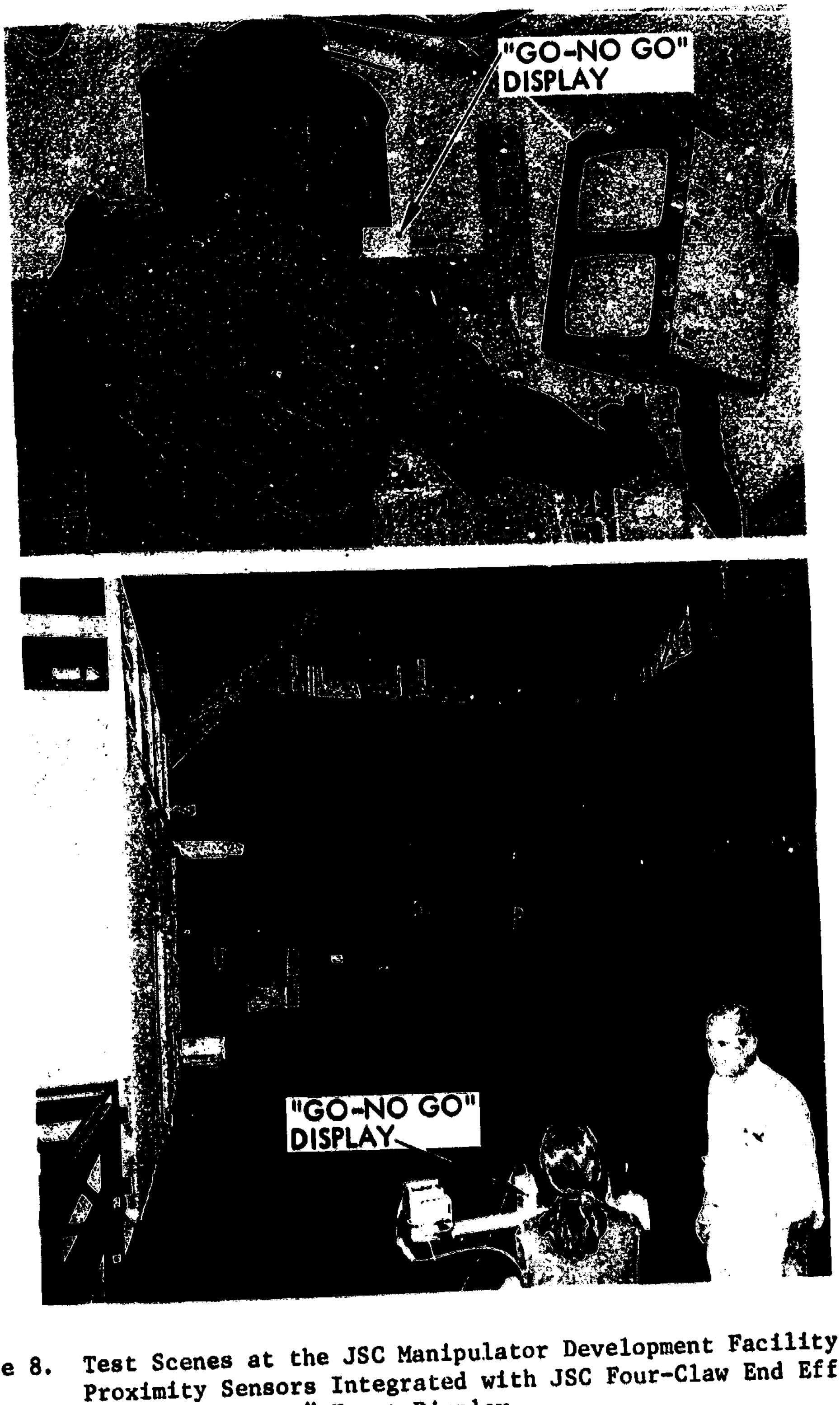
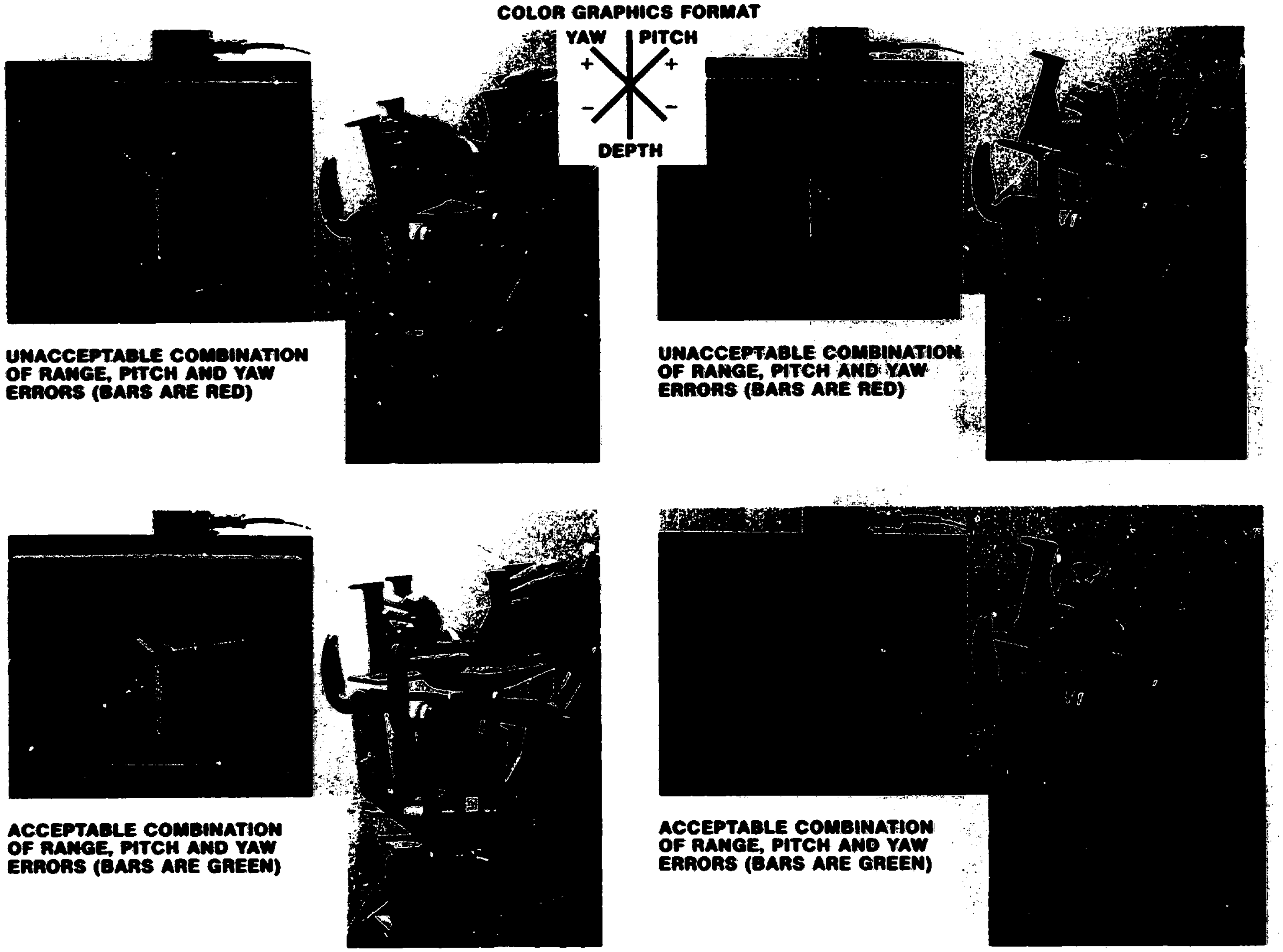


Figure 8. Test Scenes at the JSC Manipulator Development Facility Using Four Proximity Sensors Integrated with JSC Four-Claw End Effector and Simple "Go-No Go" Event Display



UNACCEPTABLE COMBINATION OF RANGE, PITCH AND YAW ERRORS (BARS ARE RED)

UNACCEPTABLE COMBINATION OF RANGE, PITCH AND YAW ERRORS (BARS ARE RED)

ACCEPTABLE COMBINATION OF RANGE, PITCH AND YAW ERRORS (BARS ARE GREEN)

ACCEPTABLE COMBINATION OF RANGE, PITCH AND YAW ERRORS (BARS ARE GREEN)

Figure 9. Graphics Display Concept Indicating Both Success and Details of Error States

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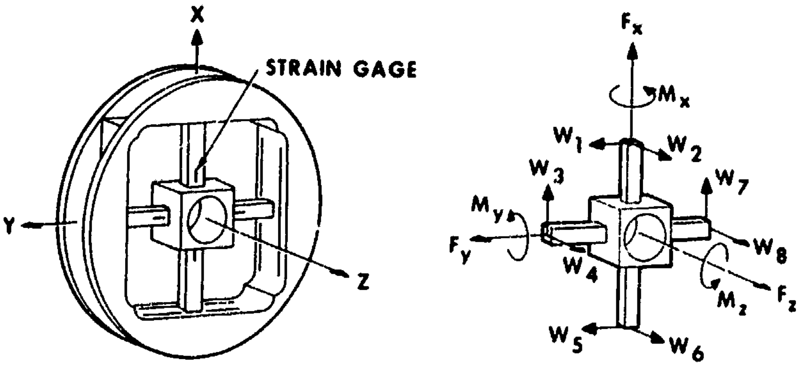


TRANSFORMATION MATRIX
UNDER IDEAL CONDITIONS

$$\begin{array}{c}\text{FORCES}\\\text{AND}\\\text{TORQUES}\\\text{REFERENCED}\\\text{TO}\\\text{X-Y-Z}\\\text{SENSOR}\\\text{COORDINATES}\end{array}\begin{bmatrix}F_x\\F_y\\F_z\\M_x\\M_y\\M_z\end{bmatrix}=\begin{bmatrix}0&0&k_{13}&0&0&0&k_{17}&0\\k_{21}&0&0&0&k_{25}&0&0&0\\0&k_{32}&0&k_{34}&0&k_{36}&0&k_{38}\\0&0&0&k_{44}&0&0&0&k_{48}\\0&k_{52}&0&0&0&k_{56}&0&0\\k_{61}&0&k_{63}&0&k_{65}&0&k_{67}&0\end{bmatrix}\begin{bmatrix}W_1\\W_2\\W_3\\W_4\\W_5\\W_6\\W_7\\W_8\end{bmatrix}\begin{array}{c}\text{FORCES}\\\text{SENSED}\\\text{AT}\\\text{SPOKE}\\\text{ELEMENTS}\end{array}$$

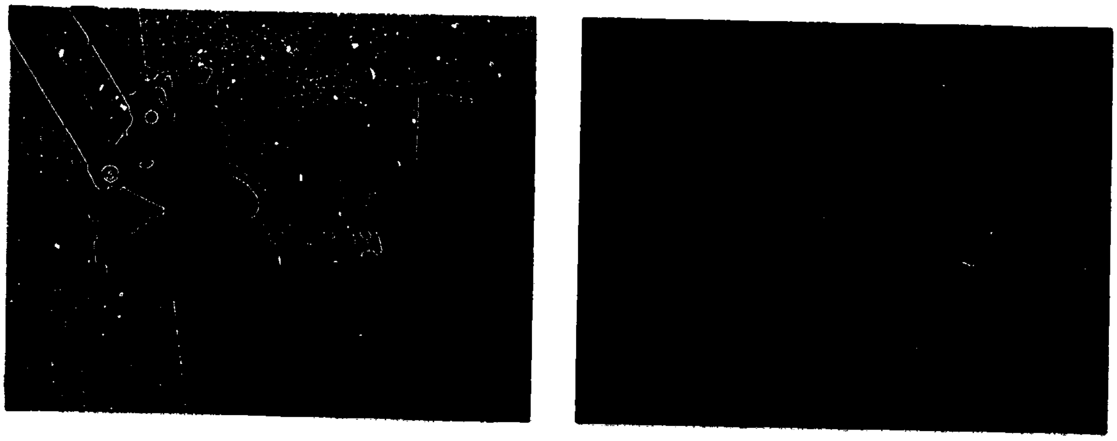


Figure 10. Force-Torque Sensor Measurement Transformation and Graphics Display

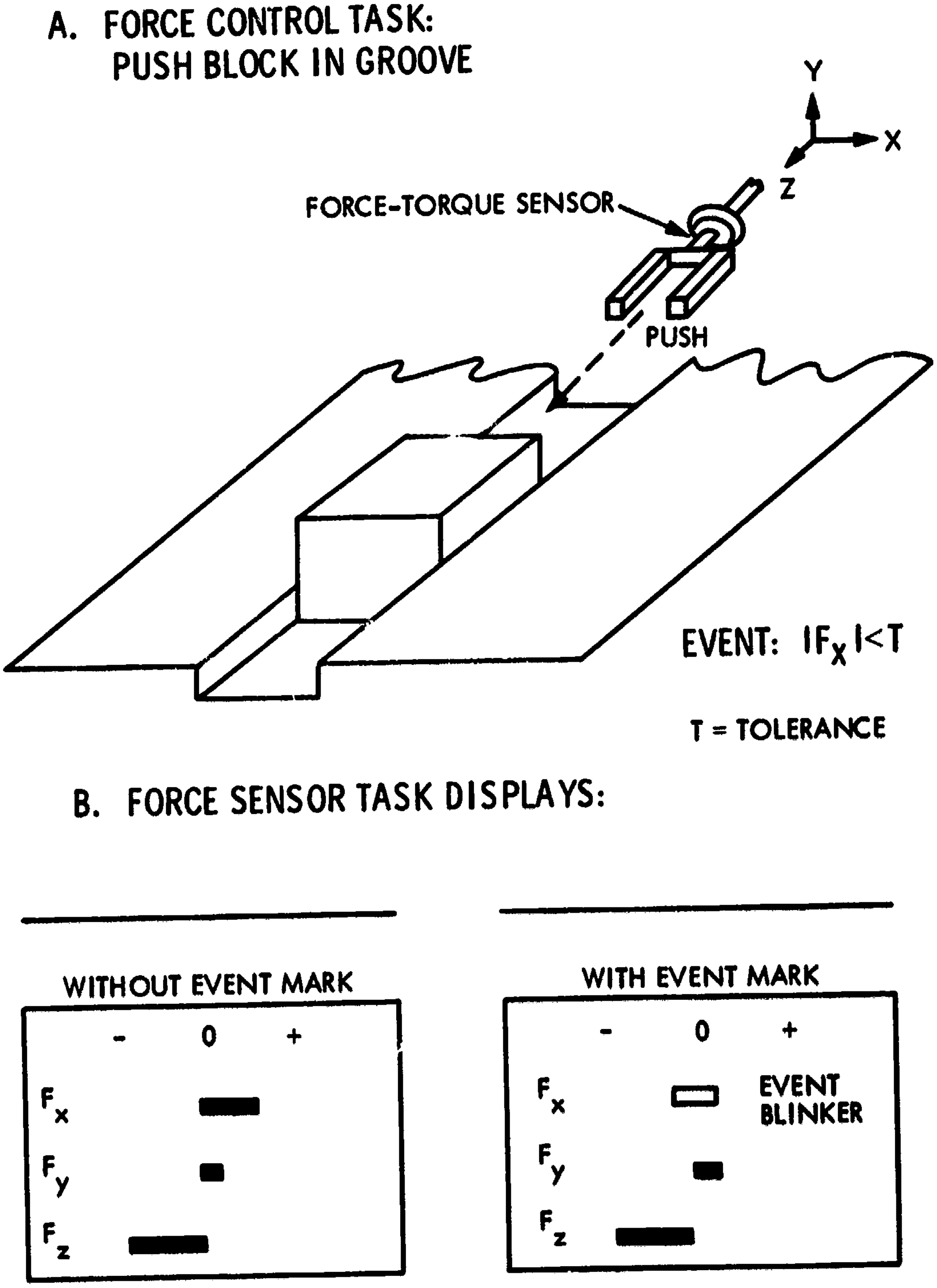


Figure 11. Force-Torque Sensing Event Example

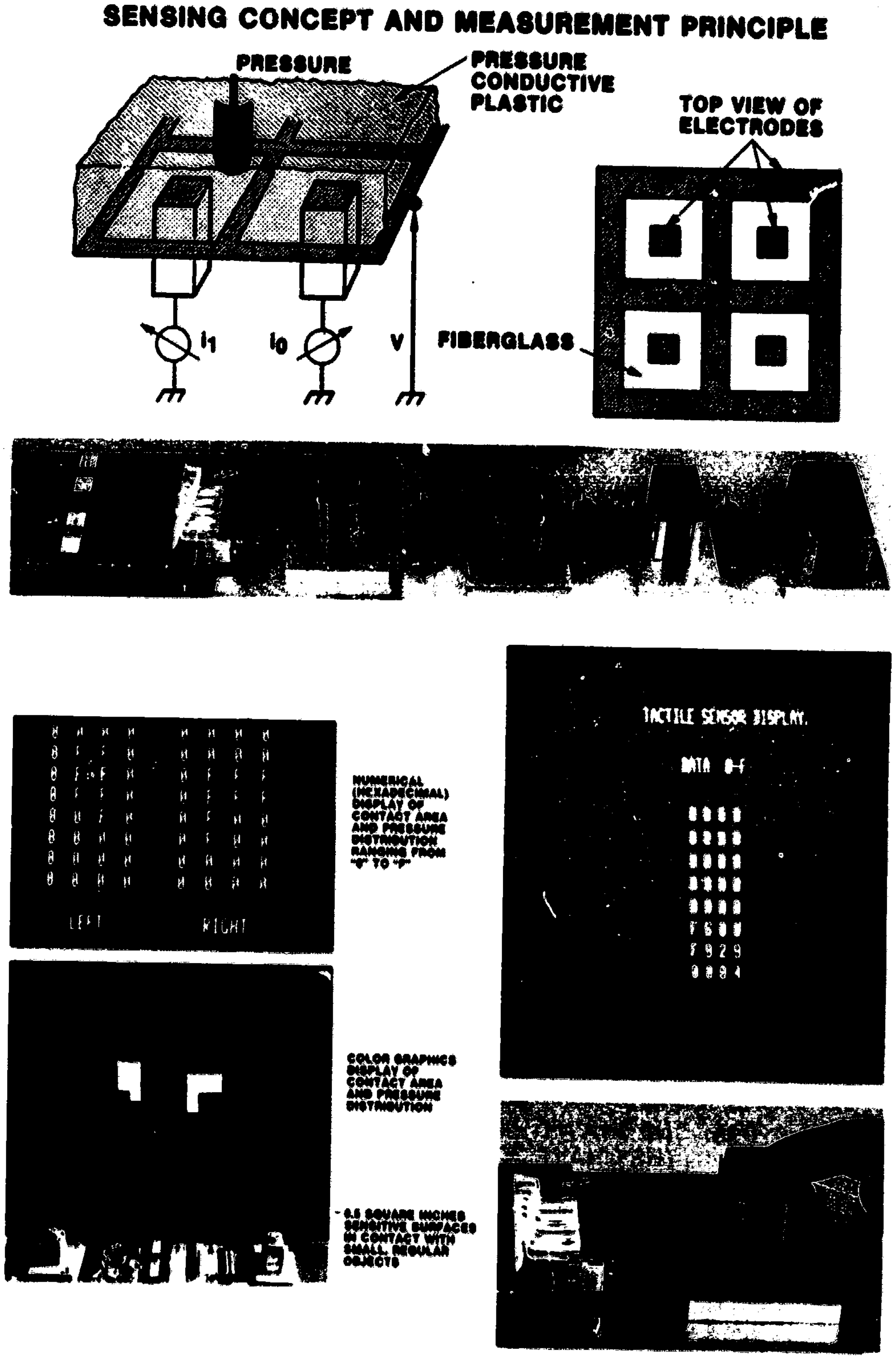
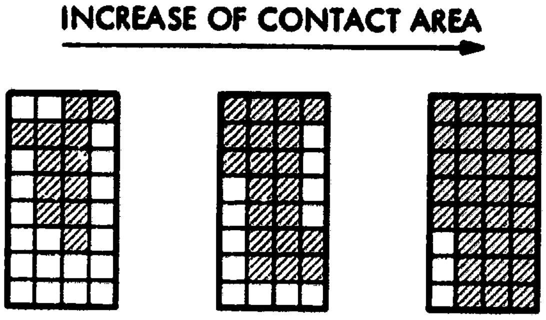


Figure 12. Multipoint Proportional Touch Sensors with Numeric and Color Graphics Displays

EVENT:

DISPLAY FORMAT OF 4x8 = 32 SENSITIVE CELLS:



IF NO. OF SENSITIVE CELLS (SC) UNDER PRESSURE IS:	$SC < 16$	$16 \le SC < 24$	$SC \ge 24$
THEN COLOR IS:	RED	YELLOW	GREEN

(NB: THE SHADED CELLS ARE THOSE UNDER PRESSURE. THEY HAVE TONES IN THE RESPECTIVE COLORS DARKER THAN THE UNSHADED CELLS.)

Figure 13. Touch Sensing Event Example

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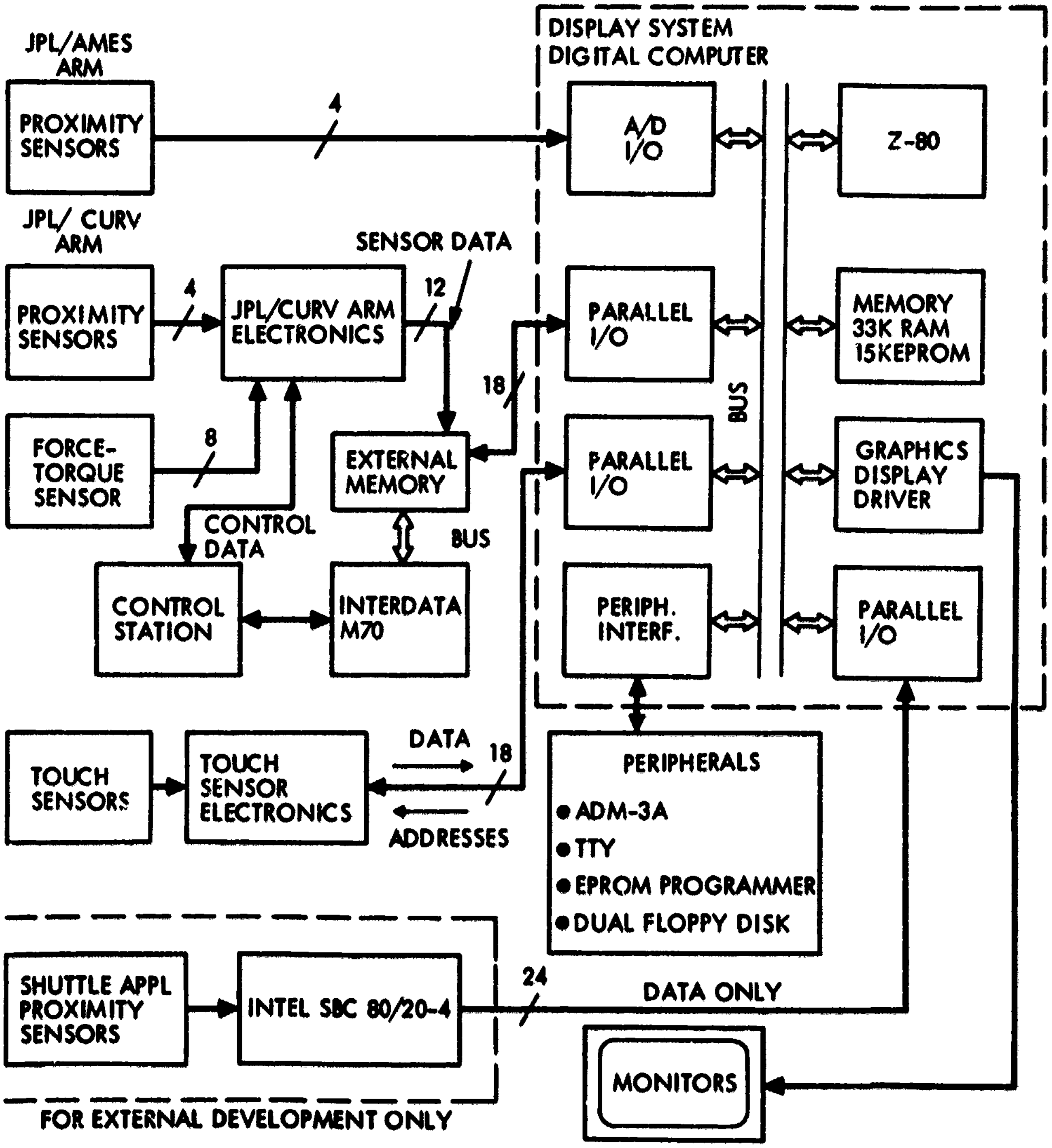

Figure 14. Computer System for Sensor Data Graphics Displays in the JPL Teleoperator Project

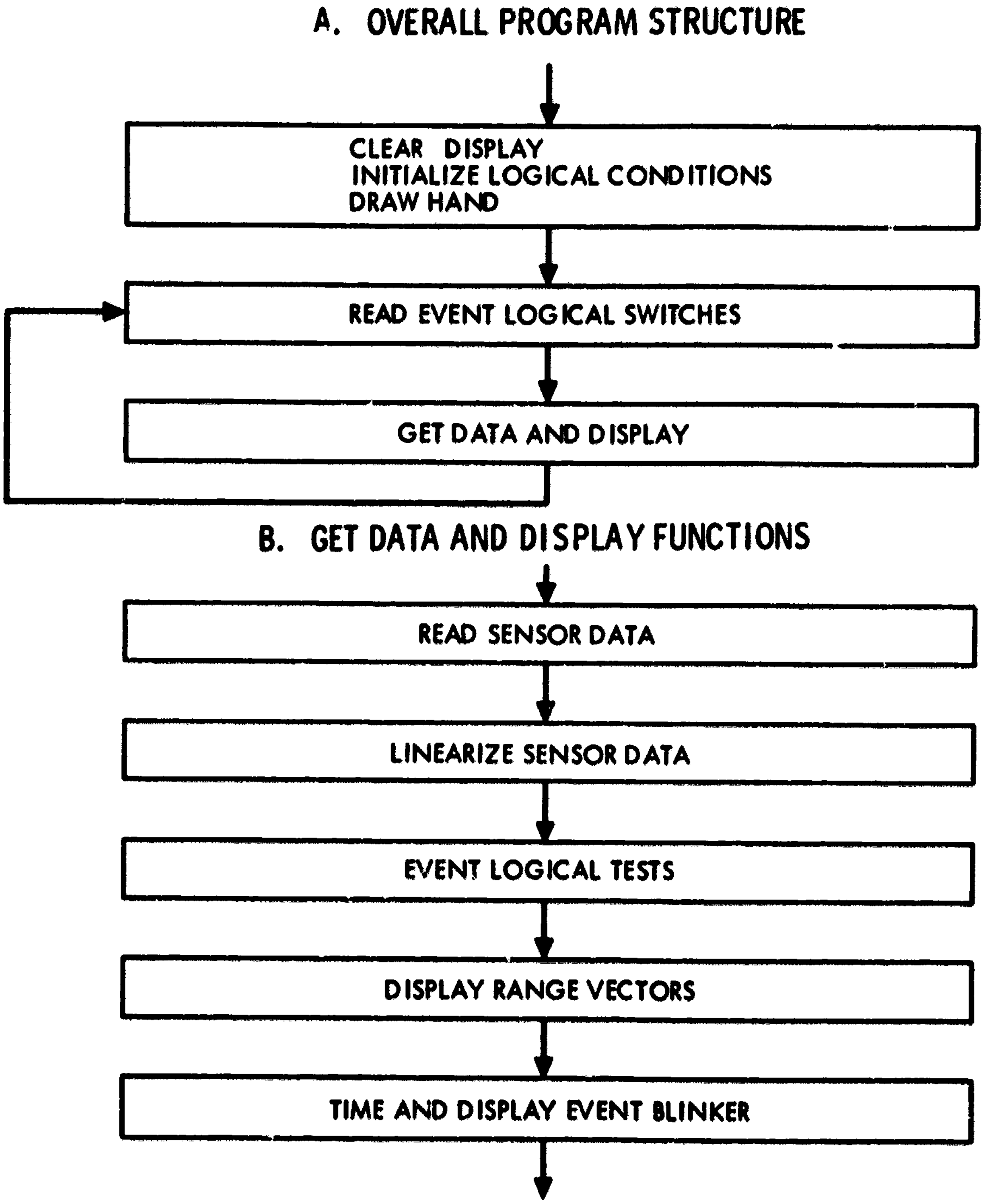

Figure 15. Software System Structure for Proximity Sensor Data Graphics Display in the JPL Teleoperator Project