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MANIPULATION BASED ON SENSOR-DIRECTED CONTROL: AN INTEGRATED END EFFECTOR AND TOUCH SENSING SYSTEM*

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ABSTRACT

~~This paper des~~cribes a hand/touch sensing system that, when mounted on a position-controlled manipulator, can greatly expand the kinds of automated manipulation tasks that can be undertaken. Because of the variety of coordinate conversions, control equations, and completion criteria, control is necessarily dependent upon a small digital computer. The sensing system is designed both to be rugged and to sense the necessary touch and force information required to execute a wide range of manipulation tasks. The system consists of a six-axis wrist sensor, external touch sensors, and a pair of matrix jaw sensors. Details of the construction of the particular sensors, the integration of the end effector into the sensor system, and the control algorithms for using the sensor outputs to perform manipulation tasks automatically are discussed.

INTRODUCTION

Current industrial robots are devices that move from position to position under preprogrammed control. Semmerling (1972) describes them as follows:

> ... easily programmable, operatorless handling devices that can perform simple, repetitive jobs that require few alternative actions and minimum communication with the work environment. They are unable to think, see, hear, smell, or taste, and only in some instances can they be given a rudimentary sense of feel.

Whenever there are sufficient variations in the positions of objects to be picked up or motion constraints on an object to be moved, the conventional, position-controlled manipulator cannot carry out the task. Research at SRI and other laboratories in the United States and in Japan has begun to show how touch and force sensing in robots, together with the proper control system (usually based on a small computer), can be used to solve these problems and to make robots more useful.

Table 1 lists several areas in which touch sensing can be used to expand the range of manipulation tasks. Each of these uses requires particular touch sensors and a particular control algorithm for accomplishing the task. Thus, in designing a touch sensing system for automatic manipulation, both the quantities to be sensed and the type of control algorithms available must be considered. The sensing system described in this paper includes sensors that can be used in all of the tasks in Table 1.

Table 1

USES OF TOUCH INFORMATION

Correcting position errors
- Bringing mating parts together
- Starting pins into holes
- Locating surfaces, corners, edges, and the like

Acquisition
- Aligning jaws to objects
- Extracting one part from a bin of parts

Constrained motion
- Sliding parts
- Final insertion of pins into holes
- Turning cranks, or hinged doors

Error detection
- Collisions
- Acquisition failures
- Task completion failures

Training (or programming) the manipulator by pushing on hand
- Steering through tasks
- Setting force levels

Classification of objects
- Size
- Weight
- Shape
- Motion constraints

TOUCH CONTROLLED MANIPULATION

To assemble parts, information from touch sensors can be used to steer the hand as it closes and moves. A simple example of this procedure is that of aligning the hand to an object without disturbing it, as illustrated in Figure 1. This alignment procedure may be required either to pick up an object without knocking it over or to calibrate the hand to part of any object for subsequent mating of parts to that object. For such purposes, sufficiently sensitive sensors are needed on the gripping surfaces of the fingers to detect finger contact with an object without pushing it away.

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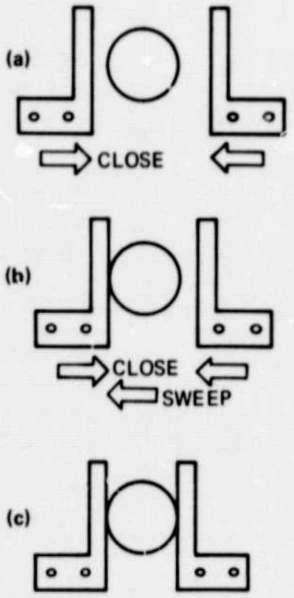

FIGURE 1 ALIGNING FINGERS TO OBJECT

Jaw closes (a) until light touching contact is made (b). Then entire hand is moved at jaw closing speed until both tongs contact object (c).

As the improperly centered fingers shown in Figure 1(a) close on the object, contact against one finger is made. The computer control system must then cause the hand to sweep in a direction from one finger to another, in a coordinate system determined by the hand, while the fingers continue to close [Figure 1(b)]. Closing and sweeping proceed until both fingers contact the object, as shown in Figure 1(c). At this point, the control system must terminate the grasping process and activate the next step in the assembly algorithm. This example shows that several separate abilities are required for successful manipulation based on touch control:

- Motion in different coordinate systems.
- The ability to steer the hand relying on touch.
- Determination of critical forces for carrying out the task.
- Determination of task completion criteria based on touch.
- The means for measuring these critical forces.

In the following four sections, the implications of the above requirements are briefly discussed, and their importance to the design of a general purpose end effector with a built-in touch sensing system is described.

Coordinate Systems

Before describing how sensors are used to control the manipulator, it is necessary to define the coordinate systems in which the manipulator must move. Any manipulator is controlled in an arm coordinate system that is uniquely determined by its own geometry; there are as many coordinates as there are movable joints in the manipulator. Arm coordinates, however, are of little use in the automatic manipulation tasks of interest here. To assemble parts, it is necessary to move the manipulator holding the daughter part in the coordinate system of the mother part. On the other hand, when maneuvering in the working area, it is necessary to move in the coordinate system of the work space. This is particularly useful when maintaining the hand at a certain height above the floor and tables and still being able to slide objects across them. By placing parts on a motorized turntable, and by using jigs and fixtures, it is possible to cause the coordinate system of the mother part to coincide with that of the work space, thus simplifying the manipulator control problem. Similarly, by either carefully designing the end effector to mate with the daughter part or by designing jigs to hold or align the part as it is being picked up, the coordinate systems can be fixed with respect to one another, again simplifying the control equations.

The two most important coordinate systems in which the arm must be able to move for automatic-controlled assembly operations are therefore work-space coordinates and hand coordinates. These are illustrated in Figure 2. The mathematics for moving a manipulator in these coordinate systems for particular applications has been discussed by both Whitney (1969) and Paul (1972).

Control Algorithms

To perform useful tasks, the information from touch sensors must be used to control the position of the manipulators. When the hand is close to the area of the object to be picked up, the motion of the hand must be steered by the actuation of sensors so that (1) the object will not be knocked about and (2) a secure grip will be maintained.

The situation can be compared to the hypothetical requirement that a yardman in a railroad switchyard walk up to a 100-ton engine and push it along the track with his bare hands. The problem can be solved simply by installing the throttle (a proportional touch sensor) on the front of the engine within reach of the yardman. By exerting a pound or so of force on the throttle, he can then move the 100-ton engine. The harder he pushes, the faster the engine will go.

Similarly, the "power steering" required for the self-centering grip shown in Figure 1 causes the hand to sweep left or right, depending on whether the left or right gripping surface of the finger is pushed. The harder the push, the faster the hand should sweep. To accomplish this task, the control algorithm must move the joints of the manipulator in a particular

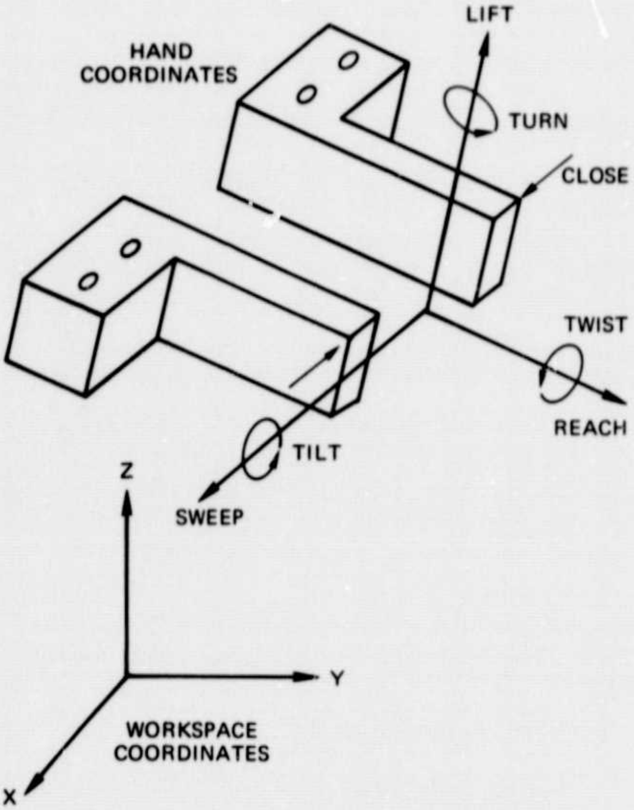

FIGURE 2 TWO IMPORTANT COORDINATE SYSTEMS

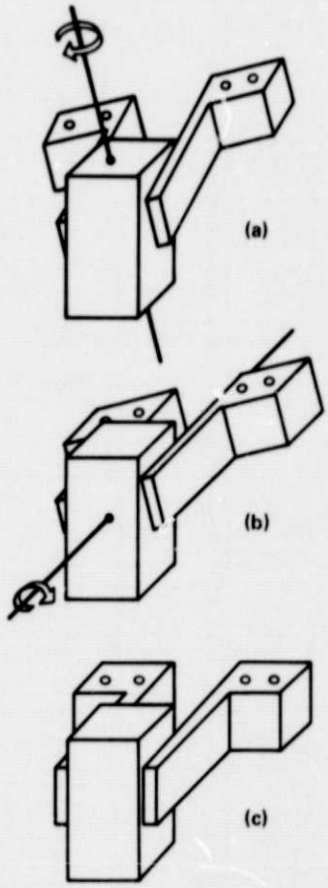

FIGURE 3 ROTARY ALIGNMENT TO OBJECT

As the jaws close, the hand is driven first to turn (a) and then to tilt (b) by signals derived from proportional force sensors on jaw surfaces to achieve desired orientation (c) for grasping.

coordinated fashion in response to the proportional inputs from touch sensors on the inside surface of the jaw. Like power steering, a small force will cause an otherwise immobile manipulator to move freely.

A second example of an acquisition strategy illustrating a particularly desirable combination of sensor-directed motions is shown in Figure 3. After sweeping, the hand is directed to move about the turn and tilt axes by signals from touch sensors on the gripping surfaces of the jaws. This strategy is useful for acquiring objects without moving them or for determining the position, size, and orientation of an imprecisely known object. The task requires sensing both small, proportional torques used to drive the turn and tilt axes and the light proportional pressure developed on the inside surface of the tongs used to drive the sweep axis. The closing of the hand generates these forces, and task completion is indicated by the attainment of some threshold gripping force. For this task, the most appropriate location for sensors is on the inside surfaces of the jaws.

A different example, a placement task, is illustrated in Figure 4. Here the task is to push a block into a mating corner. The control problem is simplified both by the proper alignment of the coordinates of the mother part with the work-space coordinates and the proper alignment of hand coordinates to block coordinates using the previous acquisition strategy. The first step in the placement task [Figure 4(a)] involves the assumption of the parent-part coordinates by the end effector. This is done by allowing the hand to tilt and turn to nullify torques that build up as the block is lowered to and pressed against the parent surface. When a threshold reach force builds up, the first portion of the task is complete, and the hand must then be controlled to lift, to maintain reach pressure, and to nullify twist torque. This brings the second block face to mate with the second parent surface [Figure 4(b)]. When a threshold lift force is obtained [Figure 4(c)], the task is complete. The jaws are then opened while holding the hand in its position.

Control Equations

Control of the manipulator to assume various positions, to move at different rates, and to apply forces, is accomplished by selecting and implementing the

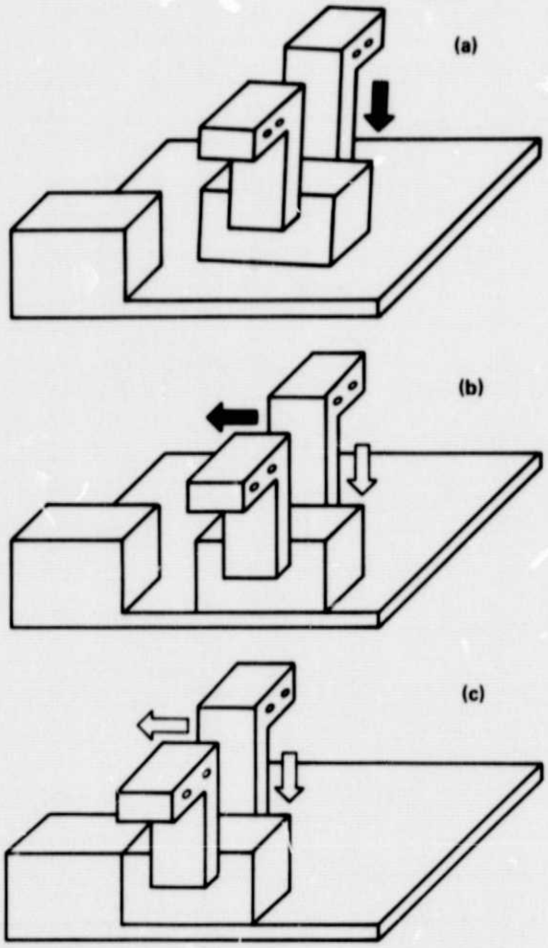

FIGURE 4 AUTOMATIC PLACEMENT OF BLOCK

Block is placed flat against a surface (a) by lowering it until contact force is measured at wrist and then rotating hand on two axes to null misalignment torques. As downward pressure is maintained (light arrow in b) on block, it is slid left (dark arrow in b) until sufficient contact force is built up (c).

proper control equation for each of the coordinate axes. The well-known equation for position is

$$\text{Rate} = K_p \, (P_c - P) \quad , \qquad (1)$$

where K_p is the position gain, P_c is the commanded position, and P is the actual position. For control in hand coordinates, Rate, P_c and P can be considered to be 1 x 7 matrices that specify the corresponding rates or positions of the seven hand coordinates. To obtain sliding along a particular axis, the control equation is more simply expressed as

$$\text{Rate} = R_c \quad , \qquad (2)$$

where R_c is the command rate matrix. To control force, the general force generating equation is

$$\text{Rate} = K_f \, (F_c - F) \quad . \qquad (3)$$

If K_f, the force gain, is zero, the hand is stiff and will not respond to external forces: if K_f is large, then the hand moves quickly to generate or respond to external forces. If the command force vector, F_c, is zero, the hand moves freely wherever it is pushed. If F_c is not zero, the hand moves until forces are developed on particular force sensors (F) that match F_c. There can be one or many more than seven force sensors.

It is useful to combine Eqs. (1), (2), and (3) into the general control equation given below.

$$\text{Rate} = K_p \, (P_c - P) + R_c + K_f \, (F_c - F) \quad . \qquad (4)$$

By properly choosing the gains in Eq. (4), the hand can be made to perform the following actions simultaneously:

- To push on one axis.
- To move on another at a fixed rate.
- To hold a third fixed.
- To make the remaining four axes passive to external forces or torques.

Performing the sequences of tasks previously shown in Figures 3 and 4 requires (1) a sequence of different control equations based on Eq. (4), and (2) proportional sensors to measure those forces pertinent to the task.

Completion Criteria

To determine when the transition from one set of control equations to another should be made, completion criteria must be established and continuously tested. Some examples of these criteria, based on force sensing, are given in the previous tasks (Figures 1, 3, and 4). In general, many different completion conditions must be specified during any manipulation task. Equally important to subtask completion are those criteria that indicate improper operation of the system. Examples of both kinds of criteria are given in Table 2.

With each control equation, it is necessary to specify both a list of completion criteria and the new actions and control equations to be used if any of these criteria are met. This suggests that a branching structure associated with a computer language is required to specify both the manipulation task and any required emergency procedures. These procedures should cause the hand to stop in midtask and should inform the human supervisor of any difficulties and their symptoms.

Table 2

EXAMPLES OF COMPLETION CRITERIA

Workspace coordinates
* Exceeded work space
* Entered obstacle area
• Height greater than 52 inches
• Incremental height greater than 6 inches

Arm coordinates
* Exceeded allowable range
* Elbow torque greater than 50 foot-pounds
• Wrist increment greater than 90°

Hand coordinates
* Excess hand force
• Grip greater than zero
• Squeeze less than 10 pounds
• Reach increment greater than 5 inches
• Lift greater than 15 pounds

Individual sensors
• Any touch sensor on
• Right fingertip force greater than 0.1 ounce
• Both jaw forces greater than 1 pound

Elapsed time
* Time greater than preset limit

Note: Asterisks denote emergency criteria, and bullets denote operational criteria.

MEANS OF MEASURING THE CRITICAL FORCES

To carry out the above manipulation tasks, various contacts with and pushes against objects in the environment must be sensed. Several methods of sensing these forces using manipulators are described in the following paragraphs.

Joint Forces

The force or torque at each joint in the manipulator can be sensed by measuring either the motor current in electric systems or the back pressure in hydraulic systems. This is particularly easy in electrically driven manipulators because the torque motor itself is used as the sensor, thus requiring no additional sensors.

The use of joint forces as measures of contact between the object and the end effector is limited by several factors. Joint forces are contaminated by the weight of both the manipulator segments and the load. In addition, when the arm is in motion, changing acceleration forces, changing centripetal forces, and reaction forces developed due to motions in other joints, all further contribute to the joint force contamination.

Joint force measurements are also limited by the back-drive friction of the individual joints. Depending on the gearing, more than 10 percent of the force exerted by a given joint is likely to be required to back-drive that joint. Though capable of driving 10 pounds, such a joint could sense only 1 pound. A force applied to the hand may back-drive some joints (the freest ones) but not others, thus giving false information concerning the applied force vector.

In spite of these limitations, Goto (1972) has used joint forces to pack blocks tightly on a pallet. Inoue (1971) compensated joint forces for gravity loading by measuring and storing static joint forces before task initiation. Using changes in the joint force, he programmed a manipulator to insert a pin into a hole and to turn a crank. Considerably refining the technique, Paul (1972) compensated joint forces for both gravity and acceleration loading and demonstrated several placing and sliding tasks. Another use of joint forces is the detection of collisions against an obstacle. Restricting the use of joint forces to the range from 30 to 100 percent of a joint's maximum force capability should avoid many of the complexities of compensation and back-drive limitations.

Separate Sensing Couple

Another means of measuring contact between the end effector and the environment is to measure the force couple at some point on the manipulator. The force couple consists of a torque vector and a force vector. Together, these forces completely describe the reaction force at the point where the manipulator is cut. The obvious place to make this measurement is between the end effector and the last joint of the arm, as suggested by Scheinmann (1969). Here the sensing is in close proximity to the load and, because the factors influencing the signals from external contact are due only to the gravity and acceleration loading from the combined hand-object mass, the sources of contamination are significantly reduced.

Thus, in moving from the joints to the wrist, the sensing problem becomes greatly simplified. The major portion of the weight and the varying geometry are both removed from the sensing scheme. Assuming the weight of the end effector to be one-tenth the weight of the arm, wrist sensing rather than joint sensing expands the useful force range by a factor of 10, allowing smaller forces to be measured. A wrist sensor for computer control of an arm was used by Groome (1972) to permit sliding a pin in a closely toleranced hole and aligning the wrist to a flat object.

Touch Sensing

The most sensitive and direct method of measuring contact between an object and the end effector is to mount sensors on the outer surfaces of the end effector. Such sensing plates can have a mass of only a few grams, and they in no way reduce the magnitude of the forces applied to the arm. With such a low mass, it is not necessary to compensate for either gravity or arm acceleration, and forces on the order of grams can be sensed directly. Uncompensated touch sensors are easily 1000 and 100 times, respectively, more sensitive to measuring contact forces than compensated joint and wrist sensing.

Using touch sensors on the inside of the jaw, it is possible to pick up lightweight objects automatically without disturbing them. This was done by Goto (1972), Hill and Sword (1973), Inoue (1971), Ernst (1962), and Paul (1972) by compensating in various ways to reduce errors in positioning either the object or the hand. Using touch sensors on the outside of the fingers, Goto (1972) was able to package small boxes on a pallet.

DESIGN OF A HAND WITH TOUCH AND FORCE SENSING

The hand system shown in Figure 5 was designed based on (1) the requirement to perform automatic manipulation and assembly tasks using touch sensing and (2) the limitations of the sensing systems previously discussed. The system consists of the following integrated parts:

- Six-axis wrist sensor
- Motor driven hand
- External touch sensing plates
- Jaw sensor matrices
- T-handle tool holder.

In addition, jaw position potentiometer signals and jaw motor drive current signals are available. These signals will allow the control computer to sense and control both the jaw opening and the total jaw gripping force.

Wrist Sensor

The wrist sensor measures both the three components of force, which correspond to the reach, lift, and sweep directions, and the three components of torque, corresponding to the twist, turn, and tilt directions (Figure 2). The wrist sensor is situated at the base of the drive housing, and its operation is based upon deflection across the deformable suspension located at the hand-wrist junction.

The key elements of the wrist sensor are the four sensing blocks arranged as shown in Figure 6. Each block consists of several light-emitting diode (LED)/

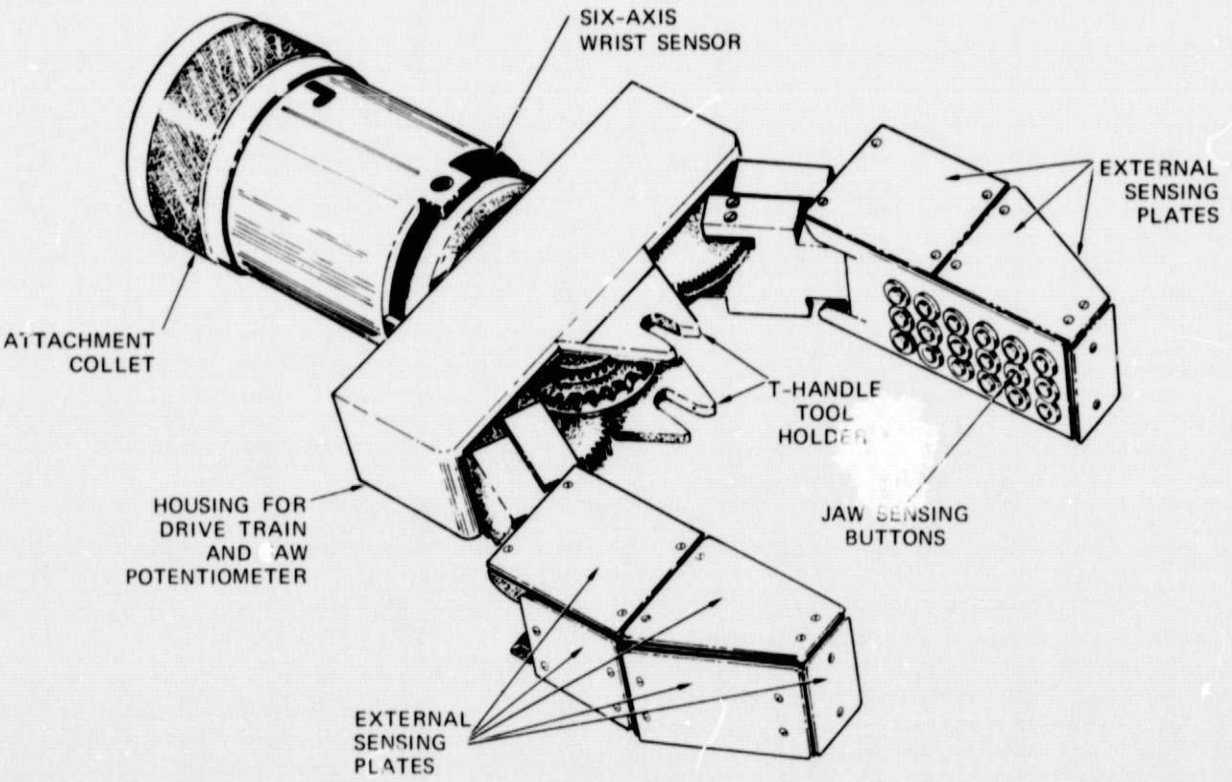

FIGURE 5 END EFFECTOR WITH PROPORTIONAL TACTILE AND SIX-AXIS WRIST SENSOR

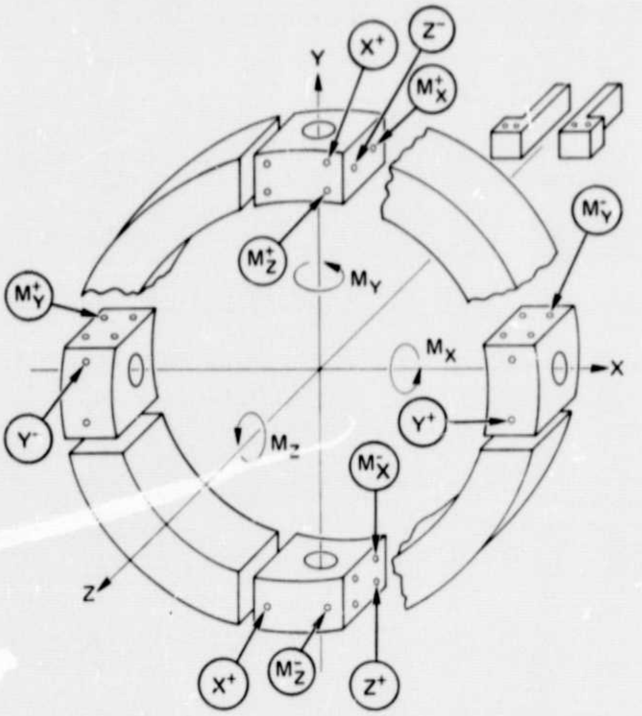

FIGURE 6 SIX-AXIS WRIST SENSOR GEOMETRY

phototransistor light paths, which are broken by pins attached to the hand yoke. The motion of these pins will change the position of the shadow cast upon the square light-sensitive area of the phototransistors by the edge of the pin. Electrical signals corresponding to the three forces and three torques are obtained directly by subtracting the two constituent photocurrents.

A useful feature of this system is that the weight of the hand drive motor balances the weight of the jaws, as shown in Figure 7. Thus, the torques measured at the wrist sensor do not reflect hand weight. Proper balancing permits manipulation with lighter loads. This is similar to the mathematical compensation previously described, except that it is done prior to sensing and hence does not require such highly linear sensors.

Touch Sensors

The seven external sensing plates that cover each jaw activate proportional sensing elements. These plates are uniformly sensitive to force over their surface and deflect approximately 1 mm under load conditions. Since the sensors were incorporated directly into the jaw, they are very rugged. Because of the experimental nature of the hand, the external sensing plates seen in Figure 5 were designed to be replaceable and can be constructed of hard rubber or metal. The force range for each sensor depends upon a compliant element that can be easily changed to vary the full scale sensitivity from 5 g to 5 kg. Since the sensors are linear over a 100- to -1 range of force, a single sensitivity can be used for different tasks. The addition of composite or nonlinear compliant elements will permit the force range to be expanded greatly.

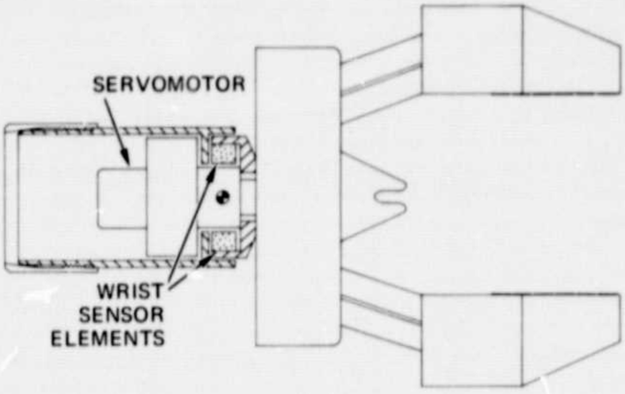

FIGURE 7 WRIST INTERIOR SHOWING HOW WEIGHT OF SERVOMOTOR BALANCES WEIGHT OF HAND

Integral to the inside surface of each jaw is a 3 x 6 matrix of sensing buttons, each with the same properties as the external sensing plates, as shown in Figure 8. With this array of sensors, it is possible to derive simply control signals that will permit turn, twist, and sweep during jaw closure to be governed by the contours of the object, as previously shown in Figure 3. The tactile information from the jaw sensor matrix can be used to find the location of objects in the jaws and to compensate for faulty positioning by motions in reach and lift.

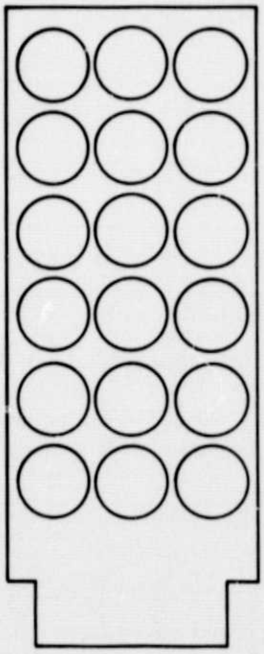

FIGURE 8 THREE-BY-SIX SENSOR ARRANGEMENT ON INSIDE SURFACES OF JAWS (FULL SIZE)

Finally, the base of the jaw contains deep notches for attachment of tools directly to the wrist. A switch in the wrist indicates that the T-handle is firmly seated and that the tool can be grasped. The inside jaw sensors signal when proper grasp has been achieved and the tool firmly grasped. Then, using the wrist sensor, forces on the tool can be detected, and further sensor-controlled manipulations can be performed.

The configuration of the touch sensors within one jaw is shown in the cross section of Figure 9. Transduction from external force to electrical signal occurs in two stages. First, a compliant washer in each sensor determines the deflection of a light vane from the external force. Then, the vane controls the light falling on a phototransistor, as shown in Figures 10 and 11.

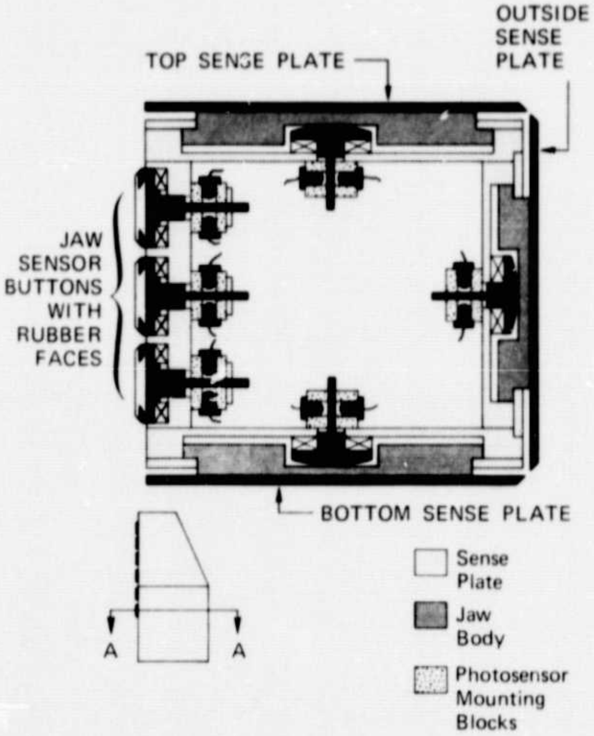

FIGURE 9 CROSS SECTION THROUGH JAW

Section is shown at line A-A of insert.

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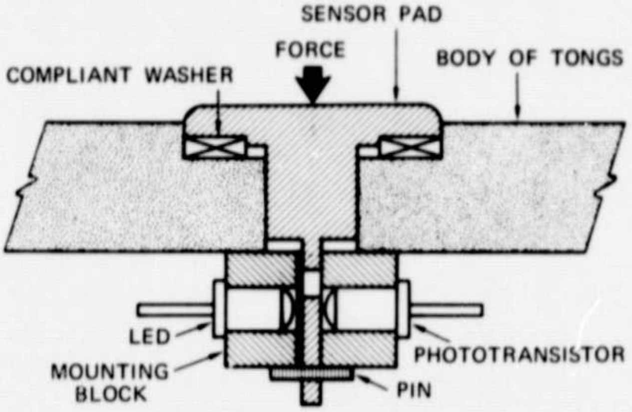

FIGURE 10 CROSS SECTION OF SENSOR WITH COMPACT SHUTTER

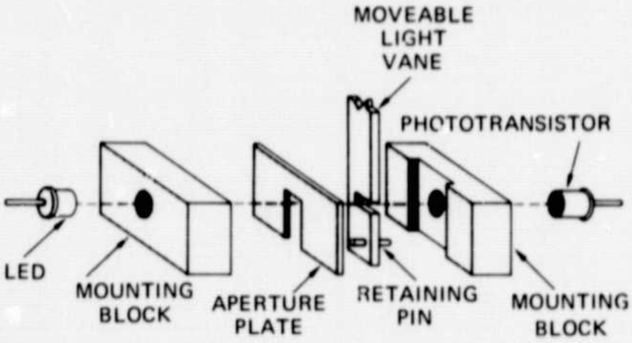

FIGURE 11 EXPLODED DRAWING OF SHUTTER

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