TOUCH SYSTEMS FOR OBJECT IDENTIFICATION AND MANIPULATOR PROTECTION

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ABSTRACT

Touch Systems for Object Identification and

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Various types of touch sensors which are currently being developed for use in Robotics are discussed. Three touch systems of varying degrees of complexity are then proposed. A simple, or basic, system is composed of force and moment, and contact sensors. An intermediate system using force and moment, slip, and binary tactile sensors. An advanced system is composed of four touch sensors: force and moment, temperature, analog tactile, and contact. These systems provide the robot with an increasing amount of information for object identification and manipulation.

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CHAPTER I

INTRODUCTION

The goal of recently developed touch systems is to create a sense of touch which is equal to or greater than that of a human. Touch sensors for Robotic systems have been under development for a number of years by such organizations as Charles Stark Draper Laboratory, Inc. [1], Stanford University [2], and Westinghouse R & D Center [3].

The types of sensors which are described in this report are:

Contact	Section 2.1
Slip	Section 2.2
Force and moment	Section 2.3
Tactile	Section 2.4
Temperature	Section 2.5
Position	Section 2.6
Moisture	Section 2.7
Colour	Section 2.8

The purpose and sensing technique used by each type of sensor will be reviewed.

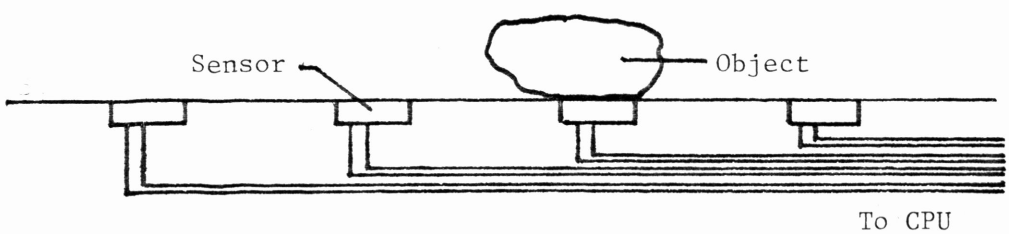
Three sensing systems are analyzed which are based upon these sensors. The three touch systems vary in complexity from a basic system which provides the minimal information for object manipulation to a complex system which is capable of object manipulation and identification.

CHAPTER II

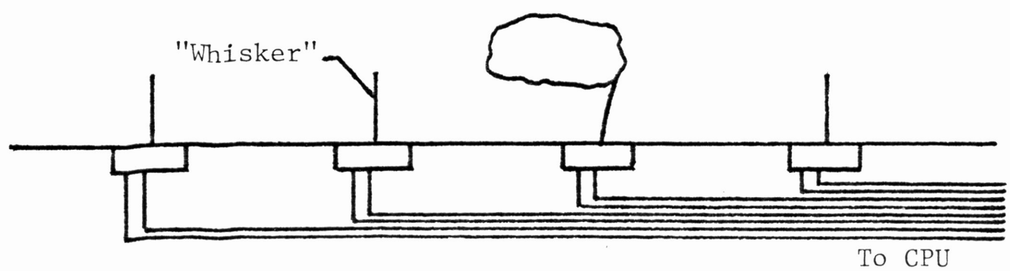
TOUCH SENSORS

2.1 Contact

As the name implies, the contact sensor provides information as to when an object has entered the sensor's domain. Such a sensor is usually based upon a self-resetting binary switch. "Contact" for such a sensor may be defined as the point at which the sensor and object actually touch (Figure 1a) or the point at which the object enters a set distance from the sensor. This may be achieved by using a "whisker"-type contact switch (Figure 1b). Due to the binary nature of most contact sensors, very little information may be gathered as to the magnitude of the contact.



(a) Surface Contact



(b) Displaced Contact - "Whisker"

Figure 1

CONTACT SENSORS

2.2 Slip

There are a number of methods to determine whether an object is moving relative to the supporting surface, ie. slipping. One method of determining slip is to use strain gages to find the normal and shear stresses on the contact area. With the values from the stress gages and the geometry of the contact area, the normal and shear forces may be determined. These forces and an estimated coefficient of friction enable the determination of the possibility of slip. The reliability of slip sensors is not very high due to the complexity of the slip phenomenon. This lack of reliability results from the fact that not all of the factors that control slipping may be accounted for in a simple, fast sensor system. Slippage depends on the magnitude and direction of the force between the sensor and the object, the coefficient of friction, the deformation of the manipulator and object, and the geometry of the manipulator and object. In addition, the coefficient of friction is a function of the normal forces and the material[4]. One method which would avoid all of these factors is to use the time derivative of a tactile sensor (Tactile sensors are further discussed in Section 2.4).

A tactile sensor may be used to measure slip because slip requires the motion of the object relative to the sensor surface. A tactile sensor of sufficient resolution is capable of monitoring the surface features of an object. By repeatedly determining the location of these features on the sensor, the motion of the object relative to the sensor may be determined. If the locations of the surface features are not varying over a time period, then the object is not slipping relative to that sensor.

2.3 Force and Moment

Force and moment sensors are used to determine the mass and center of gravity of the object being held by the manipulator. Most force and moment sensors use strain gages to determine the strain at a specific location on the manipulator. The physical design of such sensors varies with the designer although the stress theories involved are the same. The basic design is composed of a machined part with strain gages attached such that the strain about various axes may be determined. Most force and moment sensors fall into the following four categories:

Joint Torque Sensors	Section 2.3.1
Pedestal Force Sensors	Section 2.3.2
Finger Force Sensors	Section 2.3.3
Wrist Force Sensors	Section 2.3.4

2.3.1 Joint Torque Sensors

These sensors are located at the joints of a manipulator and are made to determine the torque that is applied to the joint. The torques may be measured by special sensors such as strain gages or piezoelectric circuits. It is also possible to determine the torque by measuring a characteristic of the drive system[2]. For electrically driven systems, the motor amperage will determine the torque. For hydralic systems, the torque is determined by measuring the fluid pressure. Although they are easily implemented, joint torque sensors are not very useful for accurate work. The accuracy of such a system is limited by the degree to which the dynamic coefficients of the system are determined. The uncertainty of the friction and joint damping in a manipulator is usually sufficient to preclude the accurate measurement of small hand forces [1].

2.3.2 Pedestal Force Sensors

Pedestal force sensors use strain gages mounted on the pedestal which supports the work area. These sensors are very useful when machining operations are being performed on an object which is mounted on the pedestal. Draper Laboratories has developed a pedestal force sensor with good sensitivity and a high structural stiffness [1].

Even though the pedestal force sensors are a good choice for assembly and machining work, they are nearly useless for parts handling. Once the work piece is unlocked from the pedestal, the sensor readings become unreliable and once the part is picked up, no sensor readings are available.

2.3.3 Finger Force Sensors

Finger force sensors are very similar to the pedestal force sensors. The main difference is the location of the sensor. A finger force sensor is located at every contact point (ie. finger) on the manipulator. The advantage of the finger force sensors is that they are nearly unaffected by the dynamic response of the system, unlike the joint torque sensors described in Section 2.3.1. Furthermore, they provide data during parts handling operations. The data that the finger force sensors provide also enables the determination of the grip force. This is very important when the parts may be crushed by excessive gripping forces or when the grip force is used to determine if the part will slip.

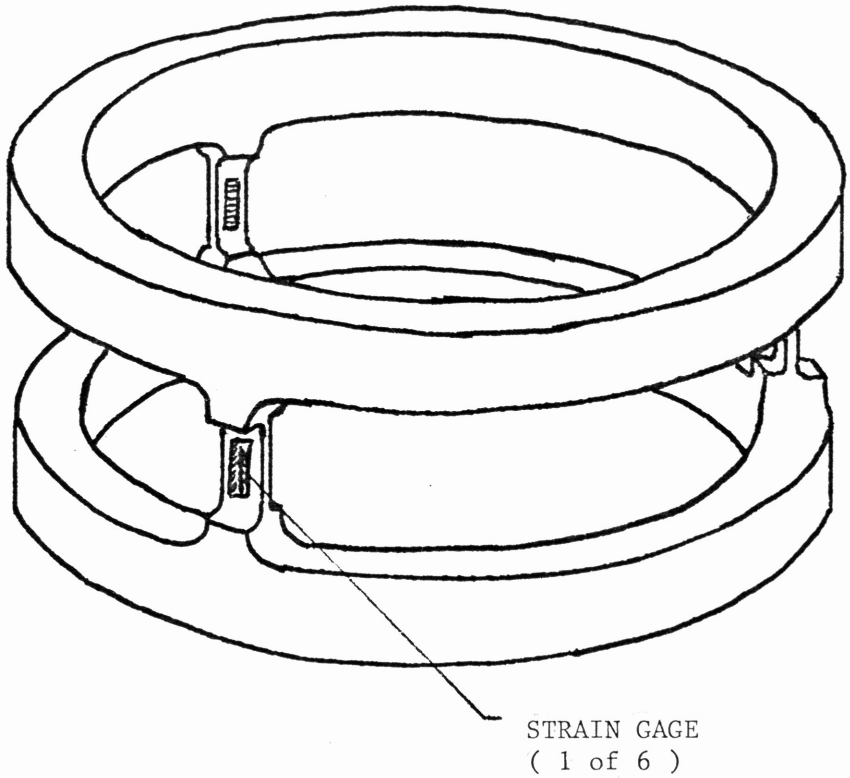
The primary disadvantage of finger force sensors is the complexity. While an individual sensor is relatively simple, multiple sensors are not. The complexity results from the fact that simultaneous equations must be solved for the entire sensor assembly. In addition, the amount of hardware is multiplied by the number of sensors in the assembly.

2.3.4 Wrist Force Sensor

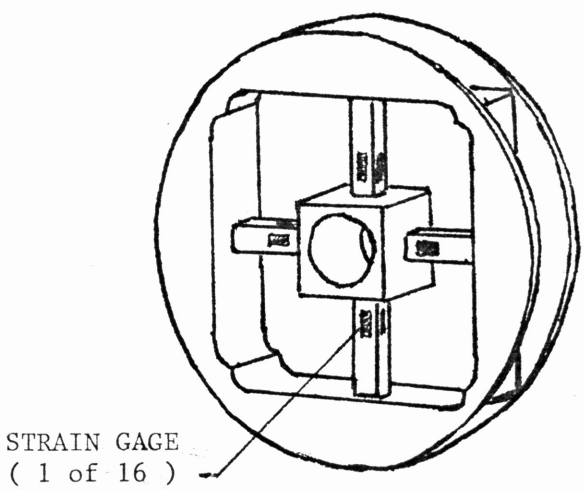
The wrist force sensor is a sensor assembly which is located at the robot's "wrist". This arrangement has several advantages over the previously discussed force and moment sensors. These advantages are:

1. No need to determine the dynamic characteristics of the manipulator (Section 2.3.1).
2. Information concerning the object being held is available during all phases of manipulation (Section 2.3.2).
3. Only one sensor is required rather than a set of sensors (Section 2.3.3).

With the exception of the grip force, the wrist force sensors provide as much information as the previously discussed force and moment sensors. The grip force, measured by the finger force sensors, is traded for the far greater simplicity of the wrist force sensor. As previously mentioned, the physical design of the force sensors varies greatly as can be seen in Figure 2.



(a) Prototype Force Sensing Wrist [1]



(b) Scheinman Force Sensing Wrist [2]

Figure 2

FORCE AND MOMENT SENSORS

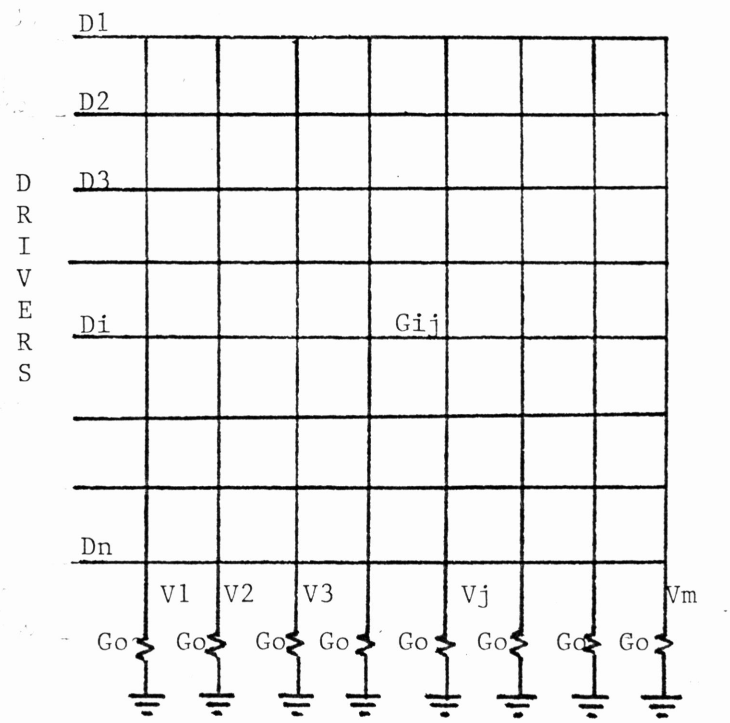
2.4 Tactile

Tactile sensors have the potential of providing the most versatile data. They are composed of an array of stress sensors. The two major types differ only in the type of stress sensor used: binary and analog. The data from a tactile sensor can be analyzed to identify the edges, surface contours, and texture of the object being held. Currently, the sensitivity required for texture determination is beyond the present tactile sensor's evaluation capacity. Furthermore, measurements of surface contour are questionable. In spite of their present limitations, tactile sensors are very useful. The data that is provided may be used to aid in the identification of the object, monitor slippage, and estimate the grip force.

The limitations on the present tactile sensors stem from the resolution of the sensor array. The resolution is presently limited by the amount of data processing required and the complexity of the individual stress sensors. As a result, increasing the resolution creates a more expensive tactile sensor with a longer response time.

A possible solution to the resolution problem of tactile sensors was introduced by M. Larcombe in 1976[5]. His proposal is based on the semiconductor characteristics of graphite fibers. By weaving or layering the fiber tows, a network of functions may be formed (Figure 3).

By using the tows along one axis as drivers and the remaining tows as voltage detectors, the conductance at each junction may be



DETECTORS

Let: $Dk=0$ if $k\neq i$, $Dk=V$ if $k=i$.
Let: Gij be the conductance between the i^{th} drive and the j^{th} detector.
Let: Go be the load conductance of the detectors.
Let: Vjk be the voltage detected on the j^{th} detector due to Dk.

Then:

$$Gij=GoVji\left(V-\sum_{k=1}^{k=n}Vjk\right)^{-1}$$

Figure 3

GRAPHITE FIBER NETWORK FOR A TACTILE SENSOR determined. A simple relationship between the conductance and the stress may then be used to map the stress patterns across the sensor.

Tactile sensors of this type are emerging slowly because of two unresolved problems. The first is the conductance-stress relationship. Initial tests which were performed by the author indicate that the graphite function has poor reliability for small stresses and poor sensitivity for larger stresses. This relationship is strongly dependent on the geometry of the function. Further improvements should increase the reliability and sensitivity. The second problem is a result of the over-all geometry and it can not be eliminated without radically changing the design. The problem is that the voltage detected on one tow is not the result of the conductance across one junction, but of the entire network of junctions. The easiest solution to this problem is to monitor the dynamic growth of the conductance or stress patterns. Unfortunately, this solution greatly increases the amount of processing required.

Once the stress distribution across the sensor has been determined, a pattern recognition algorithm should be used to reduce the data to the surface features. There are a number of such algorithms, but one described by Piero Zamperoni fits this application[6]. There are a number of uses for surface feature data. It can be used to supplement data from a vision system in identifying and locating the object relative to the manipulator. In addition, a time derivative of the surface features will determine if the object is slipping.

2.5 Temperature

Temperature sensors are very simple, reliable, and inexpensive. The two major forms are the thermocouple and the thermistor. Both types have been used for years.

2.6 Position

Position sensors are mentioned here, even though they are not a touch-type sensor, because it is necessary to know the object's instant location for certain touch sensor's analysis. For instance, joint torque sensors require position knowledge in order to convert properly from the measured torques to the mass and center of gravity of the object being held. The position data is also required to convert measurements in one coordinate system to another coordinate system (Figure 4).

The design of position sensors varies greatly with the requirements of the sensor. They are available in both analog and digital. A few designs determine the joint's velocity in addition to its position. All of these sensors combine high reliability and accuracy with relatively low cost[7].

2.7 Moisture

Moisture sensors are based on a very simple concept. The sensor is based on a piece of porous semiconductor. The conductivity of such a material is a function of the moisture content of the material. The primary disadvantage of this type of sensor is that it is easily clogged by insoluble material.

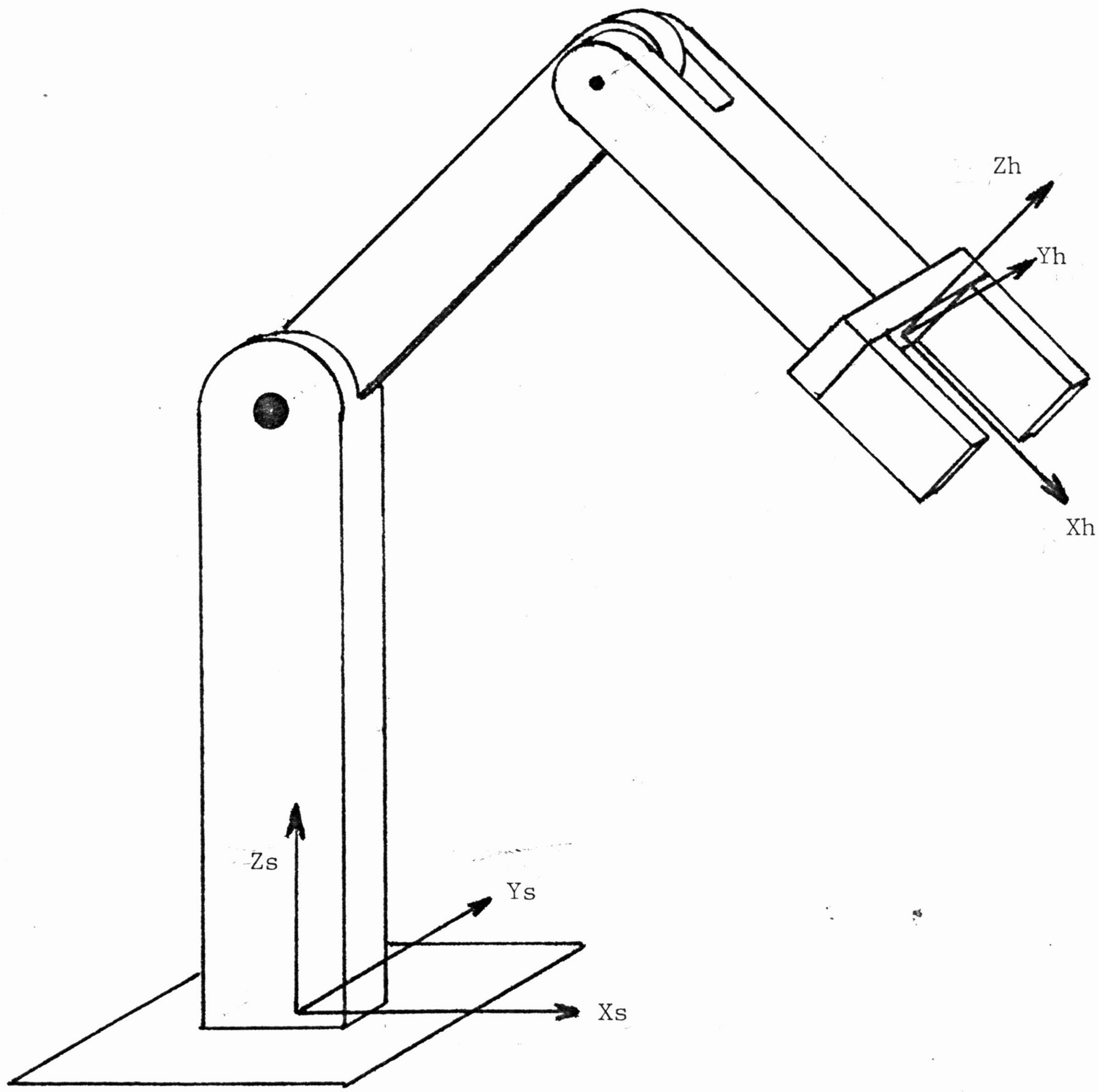


Figure 4

PRIMARY COORDINATE SYSTEMS FOR A MANIPULATOR

2.8 Colour

Colour sensors are used to determine the type of material in contact with the sensor. This is done by making a simple spectroscopic analysis of the material. The spectroscopic analysis is kept simple in order to avoid complexity. As a result, the usual method is to measure the relative intensities of the light after passing it through red, yellow, and blue filters. These values are then compared with the values of known materials.

Although the knowledge of what type of material is being used can be very useful, it is not usually required. Such knowledge may determine the coefficient of friction between the manipulator and the part, but a slip sensor would make this unnecessary.

In addition, a colour sensor is far easier to implement as part of a vision system rather than part of the touch system. The vision system has a large part of the hardware required for a colour sensor. The only additional hardware that may be needed is the color filters. Not only is the colour sensor easier to implement, it is now capable of classifying the object by material before the manipulator ever moves.

CHAPTER III

THE INTEGRATED SYSTEMS

When determining which sensors to use in a touch system, the limitations of each type of sensor must be considered in order to maximize the data obtained in a set interval of time. To demonstrate how different sensors may be chosen for a touch system, three systems will be described. The three systems will be designated basic, intermediate, and advanced in reference to the amount of data which is produced.

The proposed touch systems which are capable of object identification are restricted by two assumptions. These assumptions are needed to lower the design requirements to a level which will be attainable by the developing technology. The first assumption is that an object is identified by comparing the sensor data to prestored mathematical models of all objects which the manipulator must identify. The second assumption is that the touch system is not the primary source of data for object identification. These assumptions are necessary because the technology that is presently being developed is incapable of producing definitive data.

The first assumption is a result of the pattern recognition routines which are presently in use. These routines tend to detect a number of erroneous surface features. An additional difficulty of pattern recognition routines is that continuous surface features are usually identified as a series of discontinuous segments. As a result, a mathematical model based on sensor data usually correlates poorly with the physical object. The correlation may be greatly increased by using a technique known as clustering[8]. Clustering identifies an object by determining which pre-stored model is the closest match to the sensor data. Therefore, the manipulator must have a set of mathematical models with which object identification is made.

The requirement that a touch system is not the primary source of data for object identification is a result of time requirements. In order to identify an object by touch, the manipulator would need to grip the object at a number of different orientations. This could result in the manipulator taking several minutes to identify an object. In almost every case, object identification by touch alone results in unacceptable time requirements.

3.1 The Basic System

The basic system will enable the manipulator to determine when it is touching an object, and estimate the grip force required in order to hold the object. It will not provide the manipulator with any protective data.

This system is composed of three types of sensors: position, wrist force, and contact. The position sensors must be of a type which provides sufficient accuracy such that the accuracy of the touch data is not degraded. This results from the fact that the geometry must be accurately known when determining the calibration matrix for the wrist force sensor[2]. The wrist force sensor was chosen for the reasons discussed in Section 2.3.4. The contact sensors will be of the surface-contact type.

These sensors provide the minimum amount of data required in order to manipulate an object. The gripping force is the most important information which is not readily evident in the sensor data.

There are several methods by which a force and moment sensor may be used to determine if the object being held is slipping. One such method is as follows:

1. The manipulator touches the object and applies a pre-set minimum grip force.
2. The manipulator lifts its "hand" a short distance (about 1 mm).
3. The load which the "hand" is holding is monitored from the time at which the lift ended. If this load is decreasing, then the object is slipping. Actually, the load does not decrease, it is shifted back to the object's initial support.
4. If the supported load decreased, then increase the grip force and jump to step 2.

This method sets the minimum gripping force. This force will not guarantee a no-slip condition [4]. The easiest solution to this is to increase the gripping force by some percentage (10-20%). Even this will not guarantee no slippage, but it is far better than the minimum gripping force.

3.2 The Intermediate System

The intermediate system will start with the capabilities of the basic system. In addition to that, it will be able to determine when the object is slipping, and sense some types of surface features like sharp edges.

The intermediate system replaces the contact sensor of the basic system with a slip sensor and a binary tactile sensor. The slip sensor eliminates the largest problem of the basic system. With the slip sensor, a no-slip condition is guaranteed. The binary tactile sensor aids in object identification by locating possible edges on the surface of the object. This is done by using a pattern recognition algorithm to find the borders of the contact area[9]. These borders define edges on the object being held or regions where the surface of the object curves away from the sensor (Figure 5).

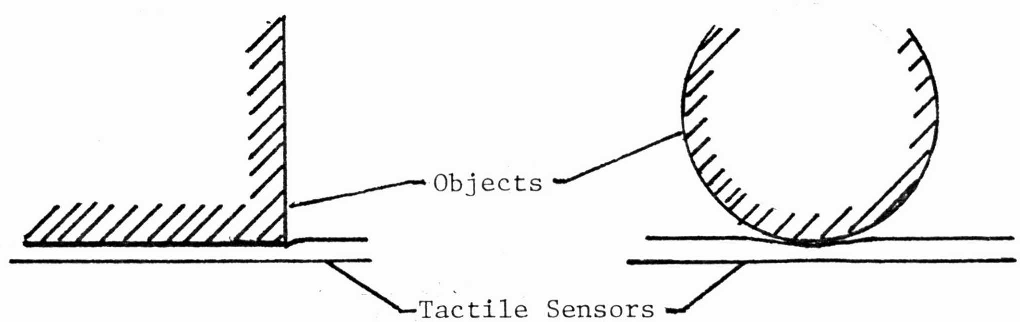


Figure 5

CONTACT BOUNDARIES

The possible edges may then be converted to a coordinate system with the data from the position sensors. Now the data for the edges may be input to a clustering algorithm in order to determine if the edge is part of a recognized model[8].

The data for the edges does help to identify an object and refine its position relative to the manipulator but it does not provide sufficient information by itself. As a supplement to a vision system, touch data is very useful and important.

3.3 The Advanced System

The advanced system builds upon the intermediate system by adding the abilities to determine the actual grip force, most surface features, and the temperature of the object. It also provides the robot with protection information. It is composed of three to five sensors, depending upon need. The three basic sensors are: position, force and moment, and tactile (analog). The optional sensors are temperature and a contact network. With these sensors, the manipulator's ability to identify surface features is improved and the manipulator may be optionally provided with protection data.

The analog tactile sensor is the greatest improvement over the intermediate system. This sensor requires a considerable amount of processing time, but the additional data is worth it. One method which may be used to overcome this difficulty is to use a microprocessor to preprocess the data. This microprocessor would be placed between the sensor and the central processing unit (CPU). The microprocessor would continuously monitor, by dynamic changes in the sensor , in order to calculate the stress distribution. The stress distribution is then transmitted, on demand, to the CPU. In addition to decreasing the processing time for the CPU, the microprocessor should decrease the size of the wiring harness leading into the CPU. The reason for this is that the digitized stress distribution from the microprocessor would require fewer connections than the sensor.

The data which the analog tactile sensor generates has three important advantages over the previously described sensors. First, the analog stress distribution allows the determination of surface features within the contact area. These features appear as local maximums and minumums on the stress distribution. Second, the shape of the stress distribution near the edges of the contact area will enable the CPU to determine whether the object curves away from the sensor or if the object has an edge at that point (Figure 5). Third, the sensitivity and resolution of the data will be high enough to monitor slippage.

The definition of slippage requires that the surface features of an object move relative to the tactile sensors. Tactile sensors locate the surface features of the object being held on a coordinate system inherent to the tactile sensor's design (Section 2.4). If the locations of the surface features move across this coordinate system, then the object is slipping. The simplest method to determine this motion is to compare the location of the surface features in the current stress distribution to those features which were identified in a stress distribution which was obtained at some previous time.

The binary tactile sensor used in the intermediate system can not perform this function because of a lack of resolution. The binary tactile sensor identifies only those surface features which define the region of contact between the sensor and the object. In many cases, the object will be large enough to come in contact with the entire sensor surface. In such a case, the object may slip an unacceptable distance before part of the sensor is no longer in contact with the object. Until this happens, there is no method by which the binary tactile sensor may determine if the object is slipping.

The two remaining sensors, the contact network and temperature, are used to provide data for a completely different purpose. The data from these sensors provides the manipulator with the ability to act for its own protection. These sensors are considered optional because their data is not often useful or meaningful.

The contact network is similar in design to the tactile sensor in the intermediate system. The two differences are:

1. Scale - The sensors in the tactile array are as close together as possible (one millimeter or less). The sensors in the contact network are spaced on the order of centimeters.
2. Contact Point - The tactile sensor measures contact at the surface of the sensor. The contact network uses "whisker" sensors to determine contact at a point above the surface (Figure 1).

For ease of assembly, such a network could be manufactured in a flexible sheet. Such a sheet could be easily cut to size and attached wherever needed. The sheet is then wired into the CPU as an override and the contact network is complete. The network performs in the following manner:

1. The manipulator approaches an object which the CPU does not recognize.
2. One of the "whiskers" touches the object and triggers the override in the CPU.
3. The CPU stops the manipulator before impact with

the unkown object.

The most important constraint on the design of this network is the length of the trigger wires. This length must be greater than the distance traveled by the manipulator from the time that the override is triggered to the time that the manipulator stops. In order that this distance be kept to a reasonable length, special braking mechanisms may be needed.

Two conditions must be met for this network to be worth implementing. The first is that the manipulator must be exposed to objects which randomly appear within its operating range. The second is that the manipulator does not have another sense, such as vision, which could determine the presence of such an object.

The temperature sensor has a similar purpose but far simpler design than the contact network. The purpose of this sensor is to determine when the manipulator is about to enter a region of dangerous temperatures which would damage the manipulator. In some cases, temperature sensing may be used to determine when an object has reached a desired temperature range.

In order to best fulfill its design purpose, the temperature sensor should be located as close as possible to the contact surfaces without interfering with the other sensors. This design assumes that the first portion of the manipulator to enter a region is its end effector or "hand".

The temperature sensor is considered to be optional for only one reason. This reason is that most of the operating situations involving high temperatures use manipulators specifically designed to operate in that temperature range.

CHAPTER IV

SUMMARY

Currently, most of the sensor-types discussed are in production use, with the exception of tactile sensors. In order to incorporate tactile sensors into the production process, considerable research is needed. This research is justifiable due to its great potential[3]. The present difficulty with tactile sensors stems from the processing time/resolution areas. Once this difficulty is surmounted, the manipulator's ability to feel its environment will be greatly increased.

Though the individual touch sensors are available for use, few robots depend upon touch systems for feedback. Of those equipped with touch systems, only a handful are above the level of the basic system. In addition, those systems which have complex touch systems have been designed for special purpose uses. Due to its desirability, touch systems will play an important role in increasing the versatility of future robots.

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