11-19-90 JS(1)

SAND--90-7085

DE91 002953

Sand90-7085 for Contract 75-2608
Contact Sensing Palm for the Salisbury
Robot Hand

David L. Brock
Massachusetts Institute of Technology
Cambridge, MA 02139

July 18, 1990

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Abstract

This report summarizes work performed on tasks 5 and 6 under Sandia Contract Number 75-2608. Task 5 involves the design and development of a palm for the Salisbury robot hand and task 6 is an investigation and incorporation of contact sensors into the palm design.

Acknowledgements

First I would like to thank Sharon Stansfield for discussions on sensing and behavior, which facilitated this sensor design. Second I would also like to thank Ricky Olegario for the initial palm prototype, as well as, the transient contact analysis. Third I am grateful to Tomas Masse for the optical sensor palm design and construction. Finally, I am indebted to Ken Salisbury for for the project overview, management and design concepts.

This research has been supported by the Sandia National Laboratories under contract 75-2608.

Introduction

Recently there has been a shift in emphasis in the robotics research community from fine grained tactile sensing involving image processing and pattern recognition techniques to more coarse grain contact sensing whose sparse tactile data provide practical information for feature recognition and dynamic robot manipulation. Tactile sensing originally involved flat rectangular arrays of force sensing elements based on resistive rubber, piezoelectrics, acoustics, capacitance, magnetic and mechanical transduction, optics and others (see Nicholls 1989 for a review). The general approach was to employ image processing routines to extract relevant features from a single tactile impression. This however ran counter to common robotic manipulation in which relatively large objects were dynamically grasped and manipulated. Furthermore the flat sensors were incompatible with the curved manipulator geometries, and cabling and connector issues were often ignored.

Currently the tactile sensors in common use are contact resolving sensors (Bicchi 1987, 1989, 1990; Brock 1985, 1989; Gordon 1989, Salisbury 1984, 1985), and sparse tactile arrays incorporated into the manipulator surface (Berkemeier 1990). The data extracted from these sensors is relatively crude — for example, sparse contact information for gross object recognition (Grimson 1984) and grasp stability (Bicchi 1989), sparse tactile profiles to resolve the axis of a revolute surface (Berkemeier 1990) and simple binary contact data for behavior modification (Chamas 1990, Greiner 1990). The information provided by these sensors is, however, of immediate and practical importance for object manipulation and identification.

Another trend which has gained some acceptance is the use of *every* surface of the robot for both sensing and manipulation. This concept has been embodied in the Whole Arm Manipulator (Salisbury 1987, 1988) in which the cylindrical links were explicitly designed to contact the environment. In addition, recent work with the Salisbury Hand has included the use of the inner phalanges both grasping and sensing (Chamas 1990, Stansfield 1988a, 1988b, 1989, 1990). The use of robot surfaces other than the end effector is of course necessary in unstructured environments, since it is impossible to guarantee that contacts will occur only at the end point.

This leads naturally to the construction of compliant sensing surfaces on many parts of the robot besides the end points and in particular to the incorporation of palm for a multifingered hand. A palm provides a compliant

surface for the most stable and fundamental grasp possible for a multifingered hand, a "wrap" grasp, in which all the fingers encircle an object. A palm can also provide simple contact on/off information to trigger the presence of an object or an obstacle.

This report provides an outline of the palm design, including both its geometry and sensors. The palm is contoured to conform naturally to the hand design and incorporates robust optic sensors which provide basic force and contact information. The palm is also quite compliant allowing it to interact easily with rigid objects.

Task 5: Palm Design

The area in which the palm must be incorporated is quite restrictive. Figure 1 illustrates the volumetric constraints imposed by the proximal joints of the hand. An initial palm design used a flat plate mounted on flexible supports instrumented with strain gauges. Using a simple algorithm (Salisbury 1984, Brock 1985), it was possible to determine the location and magnitude of the normal force of a point contact or the centroid and normal component of an area contact. The rigid, planar palm however did not facilitate grasping and stability, though it did provide a convenient surface for sensing. Alternate designs considered included a compliant stretched fabric, compliant modular arrangement of sensing elements and a suspended pivoting surface. While these ideas were interesting, the primary design objectives were ruggedness, that is it should be able to withstand arbitrary loads up to the strength of the metal; compactness, the sensor should not present any obstruction to other parts of the hand; simplicity, minimum sensors and processing should allow easy implementation and analysis; and conformity, the palm should conform to objects both within the grasp and within the environment. For this reason it was decided to construct a simple saddle shape in which one principle axis corresponded to the axis of the arc formed by the fingers and the thumb and the other to the arc formed by the proximal joints of the fingers.

The resulting prototype consisted of binary microswitches supporting a roughly hyperbolic paraboloidal surface. The initial prototype employed four microswitches placed in a rectangular configuration. This configuration was chosen for convenience, since this allowed easy conversion of input to the polar coordinates of the wrist. The dimensions of the microswitches, however,

severely restricted the size of the contacting surface. A five sensor configuration was considered in which two microswitches were placed on either side of the thumb, two under the fingers and one between the fingers, but this unduly restricted the motion of the thumb. By removing the two sensors on either side of the thumb, the another prototype palm was produced, as illustrated in figure 3.

Although this prototype was functional, it was not as robust as desired, since the palmar surface was supported by the microswitches (force limiting stops were found to be too bulky in the restrictive space). Therefore it was decided to employ optical range sensors to deduce the position of a palmar surface supported by simple mechanical springs, figure 4. This had the advantage of simplicity, reliability and ruggedness.

Figure 1 Volumetric constraint imposed by the robot hand.

Figure 2 A rigid, planar palm provides a convenient surface for contact resolution, but does not facilitate grasping and stability.

Figure 3 The initial prototype incorporated binary microswitches to deduce regions of contact.

Figure 4 Optical range sensors deduce the position of the palmar surface supported by simple mechanical springs, producing a simple, reliable and rugged sensor.

Task 6: Contact Sensing

Perhaps the most practical use of the palm sensors is not in locating the position of an object in a stable grasp, but in finding its general position during grasping transitions. Suppose we use the optical sensors as simple binary contact switches by thresholding the input. Then the temporal sequence of the sensor transitions reveal the general location of a contact and imply a simple strategy to secure the object. Let us model the sensor as a plane supported by four springs as shown in figure 5 and let the sensors be label $A, \dots, D$. If we mark off quadrants $1, \dots, 4$ we can, based on the sequence of binary transitions, determine the quadrant of the contact. For example, suppose sensor A goes on first, then we know the contact must be in quadrant 1. Therefore we rotate the wrist about the x and y axes to align the object toward the center of the palm. If then sensor B triggers next we continue to rotate about the x axis until finally sensors C and D go on. Using this simple algorithm we have been able to actively align the palm to arbitrary objects. Also since the problem is symmetric we need only consider the one sequence, that is A, B, C, D .

Now consider a more general version of this approach. Suppose the palmar surface is divided into 16 regions, 16 line segments and a single point "O", as shown in figure 6. Given a particular sensor sequence, we can determine the location of a contact within these 33 regions. Table 1 lists the regions and the corresponding sensor sequences. The commas denote transitions and the hyphens simultaneous states. For example, $A, B - C - D$ denotes sensor A triggers first then sensors B, C and D trigger simultaneously.

Figure 5 Using simple binary sensors it is possible to determine the position of a contact within a particular quadrant of the palmar surface. A simple algorithm that rotates the wrist about pivot points defined by the active sensors aligns the palm with an object.

Region	Sequence	Region	Sequence
$\overline{AE}$	A	1	A, B
$\overline{BG}$	B	2	B, A
$\overline{CH}$	C	3	B, C
$\overline{DI}$	D	4	C, B
$\overline{AO}$	A, B - C - D	5	C, D
$\overline{BO}$	B, A - C - D	6	D, C
$\overline{CO}$	C, A - B - D	7	D, A
$\overline{DO}$	D, A - B - C	8	A, D
$\overline{iO}$	A, B - C - D	9	A, B, C - D
$\overline{iiO}$	B, A - C - D	10	B, A, C - D
$\overline{iiiO}$	C, A - B - D	11	B, C, A - D
$\overline{ivO}$	D, A - B - C	12	C, B, A - D
$\overline{iE'}$	A - B	13	C, D, A - B
$\overline{iiG'}$	B - C	14	D, C, A - B
$\overline{iiiH'}$	C - D	15	D, A, B - C
$\overline{ivI'}$	A - D	16	A, D, B - C
		O	A - B - C - D

Table 1 Each of the 33 regions correspond to unique sequences on sensor input. Note $\overline{XO}$ denotes the line excluding the origin. All other line segments include their endpoints.

Figure 6 There are 33 possible regions that produce distinct sensor sequences. Therefore we can determine the location of a contact within a particular region based on the sensor transition states.

The exact contact location can be resolved through static force analysis. The location of a contact and the normal force is given by

$$\begin{aligned} f &= f_1 + f_2 + f_3 + f_4 \\ x &= h(-f_1 - f_2 + f_3 + f_4)/f \\ y &= w(f_1 - f_2 - f_3 + f_4)/f, \end{aligned}$$

where f_i is the force at the i th sensor and h and w are the distance from the origin to the sensors, as shown in figure 7. To calculate the forces f_i , the sensor must of course be calibrated. To derive the calibration curve for each of the sensors, a series of known forces may be applied each sensor (one at a time) and tabulated against sensor outputs. A curve may be fit to each set of data and used to obtain the sensor output/force relation. The calibration is approximately quadratic, which makes the computation of the contact location slightly more difficult. While this is not a real problem, the primary function palm and, in fact, the motivation behind its design, was to provide basic contact information for behavior modification as outlined in the previous discussion.

Figure 7 The location of a force through a point contact can be resolved easily knowing the force at each corner.

The preceding analysis was based on a planar sensor and this particular palm is of course non-planar. Error introduced by the non-planar surface can be computed quite simply, by projecting the friction cone onto the plane defined by the four sensors then back projecting this region onto the surface, figure 8. For this sensor the maximum position error for a point contact located in the cylindrical region between the sensors is approximately 0.2 in. (assuming a coefficient of friction of 1 and negligible transducer error). In the region beyond the square defined by the sensors, the errors are of course larger, but the general contact regions as outlined in figure 5 can still be resolved.

Figure 8 Errors introduced by the non-planar surface can be computed by projecting the friction cones on the palmar surface onto the plane defined by the optical range sensors, then back projecting this region onto the surface.

Conclusion

A sensate palm for the Salisbury Robot Hand has been constructed which provides practical information for contact recognition and grasp modification. The palm is also robust and compliant; designed for rough interaction in unstructured environments.

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