FEELING BY GRASPING

by

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ABSTRACT

This paper specifies constraints based on the geometry of the grasped object, on geometry of the hand and the kinematics of the constrained object which determine how to grasp an object.

INTRODUCTION

The purpose of this paper is to specify the theoretical framework and its components that are necessary for grasping.

We are starting from the following assumptions: We have a suitable representation of the three-dimensional object which we are grasping. We assume that the object is graspable, i.e., is compact, hard and its surface has a known friction. Its shape is such that there are at least parts of the grasped object which the hand can encompass. Otherwise there are no other limitations on the shape of the object. Its weight is no more than 3 pounds, which is the limit for our (PUMA) endeffector, and its size must be such that at least the part which is going to be grasped is not wider than the extended reach of the hand. The object to be grasped rests initially on a horizontal surface and the space around is not cluttered, i.e., the hand can reach it from any angle in the three-dimensional space.

The gripper is a three fingered hand with seven degrees of freedom under computer control. The inner surfaces of the fingers are equipped with an array of pressure sensitive devices which can detect the magnitude of the pressure force.

The goal of this paper is to specify under the above assumptions what are the necessary computational steps for guiding the hand where to grasp a given object so that it is restrained. Previous works on grasping that should be mentioned are: *Shimano*[11], Salisbury and *Craig*[10], and others. The difference between these researchers and our work is that we are integrating the constraints from the three different sources: the object to be grasped, the geometry of the hand and the kinematics that follow from the position of the object.

The question may arise why is this a problem? Glancing through the scenario, just think how many different ways one can grasp an object. Hence our task is to specify the constraints which will eliminate the many ways of grasping into a few (perhaps one) which will be optimal with respect to some criterion.

The Constraints

The first constraint comes from the GOAL of the GRASPING. Grasping is executed for: a) feeling the three-dimensional object. Here one may or may not fully grasp the object but the intent is not to move the object, b) holding the object. Here one grasps and picks up the object to hold it, perhaps just to free the occupied space, etc. c) manipulating the object. Here one grasps, and picks up the object with a specific follow-up action in mind. An example of this is to pick up a cup to give it somebody or to put it into a dishwasher. These two different goals will result in different grasping processes.

In this paper we shall concentrate only on the first goal, the grasping for feeling of the object.

The second constraint will come from the REPRESENTATION of the THREE DIMENSIONAL OBJECT. There are two aspects of shape of a 3D object: the surface and volumetric descriptions. The surface description usually entails different ways of describing surfaces, enclosing edges and corners. The volumetric characterization is presented in terms of either some volumetric primitives, such as spheres, cylinders, polyhedra and the like, or some topological descriptions like compact objects versus objects with holes. Other intrinsic parameters of shape are symmetric axes and symmetric surfaces. In the past we have dealt with both of these representations as it is documented in Dane and *Bajcsy*[4], and Mohr and *Bajcsy*[7]. We feel that for the problem of grasping one needs both of these representations. The volumetric representation provides classification of objects first into two topologically distinct categories: objects without holes and with holes, and the second into three gross categories: elongated, round and flat objects. It is clear that each of these categories requires different grasping strategies. The symmetric axis reveals not only the skeleton of the object but also the points where joints are and where the holes are, i.e., the topological

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properties. One simple criterion for finding the grasping points can be around the center of gravity of the object. This is clearly true in the case of convex objects. However, this may not be true always with objects that have joints and/or holes. Take an example of a vase. One would intuitively grasp it at the point of the joint between the base and the cup, though the center of gravity must not be there. More to the point is a toroid, where the center of gravity is in the hole. All these points can be predicted from the volumetric representation. On the other hand, the surface representation is important for specifying the graspable surface. It is known from Salisbury's work, for example, that point and line contacts are less stable than plane contact. Therefore, this stage of the analysis will provide a set of points corresponding to centers of planar patches or patches with the smallest surface curvature.

The third constraint will come from the KINEMATIC ANALYSIS of forces for a given object and determination of the graspable spots so that the object is restrained, i.e., that the object is in equilibrium between the external force and force exerted by the hand. Before we launch into the details of the kinematic analysis of the grip of a three fingered hand some definitions are in order. We use theory of *screws*[2] to represent forces distributed in space as "wrenches" and the instantaneous motion of a rigid body as a "twist". Forces acting on a rigid body in space may be reduced to a pair of vectors $\underline{F}$ and $\underline{C}$ bound to a unique line in the body, the central axis of the force system. $\underline{F}$ is the resultant of the set of forces and $\underline{C}$ is the moment of the force system about the central axis. Taken together, $\underline{F}$ and $\underline{C}$ are called a WRENCH. Similarly, the velocity field of a moving rigid body may be reduced to the colinear vectors $\underline{v}$, the linear velocity, and OMEGA, the angular velocity of the body. These vectors are bound to a unique line in the body known as the instantaneous screw axis. We will call the pair $\underline{v}$ and OMEGA a TWIST of the body.

The grasp of a three fingered hand may be separated into normal and frictional forces. In this paper we shall consider only those normal forces which constrain the object, since here we are interested only in the special case of feeling by grasping. The complete analysis is described *in*[6]. Hence we shall be concerned with that component of the force which is generated at a point of contact $\underline{P}$ with the object, which is directed along the common normal $\underline{n}$ of the contacting surfaces. We assume that this force can be of any required magnitude. The screw $\tilde{N}$ representing the normal force in space is given by

$$\tilde{N} = <F\underline{n}; \underline{p}x(F\underline{n})> = F<\underline{n}; \underline{P}x\underline{n}>, \qquad (1)$$

F is the magnitude of the force, $\tilde{N}$ is a line screw. The set of twists $\tilde{T}$ compatible with $\tilde{N}$ is given by the expression

$$g(\tilde{N},\tilde{T}) = k \geq 0 \qquad (2)$$

where the inequality is true if the contact is maintained during the twist, otherwise contact is broken. The function g stands for a special dot product between the two variables. The coefficient k indicates whether the object remains restrained under a given twist. In a specific case of a three-fingered hand we have three normal forces which restrict the allowable twists $\tilde{T}$ to those satisfying the inequalities

$$\begin{aligned} g(\tilde{N}_1,\tilde{T}) &= k_1 \geq 0 \\ g(\tilde{N}_2,\tilde{T}) &= k_2 \geq 0 \qquad (3) \\ g(\tilde{N}_3,\tilde{T}) &= k_3 \geq 0 \end{aligned}$$

where $\tilde{N}_1$, $\tilde{N}_2$ and $\tilde{N}_3$ define the geometry of the grasp.

The twists which maintain contact with each of the fingers lie in the three system defined by the set of screws when $k_1=k_2=k_3=0$. All the twists compatible with the geometric constraint of the three fingers lie on hyperplane three systems with non-negative values of k_1, k_2 and k_3. *Ohworvoriole*[8] calls this a repelling three convex.

Consider the characteristics of the grasp defined by N_1, N_2 and N_3 which satisfy the added requirements that these screws be mutually contrary:

$$\begin{aligned} g(\tilde{N}_1,\tilde{N}_2) &< 0 \\ g(\tilde{N}_2,\tilde{N}_3) &< 0 \qquad (4) \\ g(\tilde{N}_3,\tilde{N}_1) &< 0 \end{aligned}$$

It has been *shown*[6] that for this particular grasp it is only the three-system of twists that maintains contact with the three fingers are the only motions allowed. Under the above assumptions we can compute those triplets of $\tilde{N}_i$ which satisfy the conditions of (4). Or the other way, given all possible contact points $\tilde{N}_i$ we can compute all allowable twists.

The fourth constraint follows from the MODEL of the PARTICULAR GRIPPER--in this case the Pennsylvania Articulated Mechanical Hand, PAMH, shown in figure 1. In this section we shall first present the hardware of the hand which includes the mechanical design and the attached sensors, then the control mechanisms of the actuators, the space where the fingers can reach and where they collide and finally the control of the finger positions in order to accomplish the grasp.

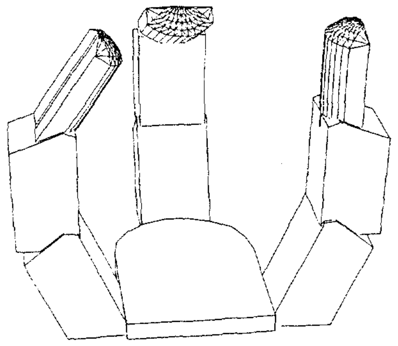


Figure 1 - PAMH: Pennsylvania Articulated Mechanical Hand

PAMH is computer controlled and has three fingers connected to a planar palm. Each finger is comprised of three rigid links or digits. The two fingers in the foreground of figure 1 act in opposition to one another. They each have two degrees of freedom (each has its first digit fixed to the palm). The remaining finger, or thumb, has three degrees of freedom. Its first digit can rotate around the semicircular portion of the palm. Thus PAMH has seven degrees of freedom. PAMH is equipped with 63 resistive type tactile sensors, 21 on each finger. There is a three by three planar array of sensors on the ventral surface of each of the second and third digits of all three fingers. The remaining nine sensors are placed on each fingertip in three by one planar arrays. The fingertip sensors are most useful in approaching, locating, and scanning the surface of an object. The other sensors are most useful for controlling the pressure of a grasp and determining the local geometric quantities of the object being explored.

The hand is controlled with position and force feedback. To minimize the complexity of the servo controller for PAMH, a special cam (lever arm) actuation system was designed. The actuation linkage is pictured in figure 2. Its special feature is that when the threaded rod advances against the cam, the angle of the joint rotation is directly proportional to the angle of rotation of the threaded rod. This design has two very nice consequences which considerably simplify the synthesis of the control algorithms. First, during pure position servoing (i.e., no external forces act on the hand), if the friction in the actuation linkage is negligible, then a simple linear controller may be used very effectively. This is particularly nice for the case of using PAMH to feel an object, because in feeling an object, the most important thing is to position the fingers accurately. This allows for an accurate topological map of the object in question. Second, during force servoing, the friction in the threads is no longer negligible, but it is only a function of the torque being applied at the finger joint. It is independent of the current joint angle and thus becomes only a function of the output torque of the servo motor.

When considering a particular grasp defined by N_1, N_2, N_3 and inequalities (4), we must determine whether or not the grasp is feasible from the point of view of the geometry of the hand. The requirements of a feasible grasp are threefold. First, each point of application of the screw, N_i, must lie within the workspace of a different finger. Otherwise, a single fingertip might be required to be in two separate positions in space simultaneously. In satisfying the first requirement, we can assign each fingertip a contact point on the object. This will define the grasp configuration. The second requirement is that all of the fingers must be able to contact their assigned points simultaneously, i.e., one finger may not prevent another from accomplishing its goal. The third grasp feasibility requirement is that after PAMH has been guided to the grasping configuration, she must be able to exert the required forces on the object. If she can not, then the grasp is not feasible and a new grasp must be considered. All these requirements further limit the number of graspable points.

The first grasp feasibility requirement mentioned above shows that the workspace of PAMH, which we will call W, define below. Figure 3 shows the relationship between the finger and palm coordinate systems. In this figure point $p^{i,j}$ is on the surface of $digit_{i,j}$, and point $q^{0,0}$ is in the palm coordinate system, $Pamh_{0,0}$. (All superscripts of the form i,j indicate that a quantity is given with respect to the coordinate system, $Pamh_{i,j}$.) Let $WP_{i,j}$ be defined as follows

$$WP_{i,j} = [\, q^{0,0} : q^{0,0} = p^{0,0} \,] \tag{5}$$

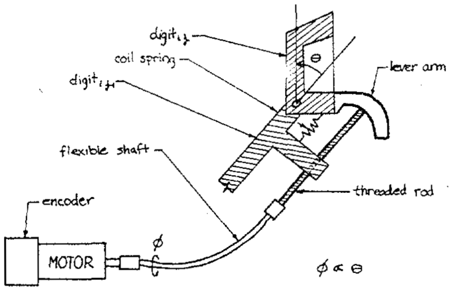
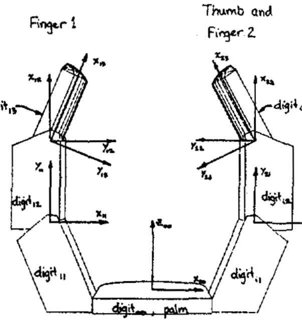


Figure 2 - PAMH finger actuation system



Coordinate Systems

$Pamh_{ij} \triangleq \{x_{ij}, y_{ij}, z_{ij}\}$; i=0,1,2 , j=0,1,2,3.

Note: i=0,2 $digit_{0j}$ is on thumb ; i=2 implies finger 2.

Figure 3 - The pamh coordinate systems. Finger 2 and the thumb possess the same coordinate system orientations. All coordinate systems are right handed.

where i = 0, 1, 2, and j = 0, 1, 2, 3. In words, equation (5) means that $WP_{i,j}$ is the set of all points $q^{0,0}$ such that $p^{i,j}$, on $digit_{i,j}$ can be made to contact $q^{0,0}$ given the proper joint angles. Next let WD_i be defined as

$$WD_i = \bigcup_{j=0}^{j=3} WP_{i,j} \tag{6}$$

where i = 0, 1, 2 and j = 0 indicates the palm. So we see that WD_i is the workspace of $Finger_i$. Finally, we get W, the workspace of PAMH, by the union of the WD_i

$$W = \bigcup_{i=0}^{i=2} WD_i \tag{7}$$

W represents the volume of all points $q^{0,0}$ which can be contacted by some part of the hand.

The second grasp feasibility requirement compels us to define the collision space, CS, of PAMH. The collision space is defined here as any point in the workspace, W, which can be touched by any two fingers. Using the definition of WD_i given in equations (6), CS becomes

$$CS = (WD_0 \cap WD_1) \cup (WD_0 \cap WD_2) \cup (WD_1 \cap WD\text{(8)}$$

We use CS as follows. We check to see if two contact points of the grasp lie in the corresponding fingers' collision space (i.e., $WD_i \cap WD_j$ i,j = 0, 1, 2 ; i ≠ j). If no pair does, then no further collision analysis is necessary. If two or more contact points do lie within CS, then one must analyze the contact points and the hand geometry further to determine whether or not the fingers actually interfere with one another. Based on the outcome of this analysis, one either rejects the grasp as infeasible or moves on to explore the last requirement of a feasible grasp.

The last grasp feasibility requirement is that PAMH be capable of generating the proper forces in the grasp configuration. The forces applied to the object by the hand are a function of the torques about each joint and the angle of each joint. These quantities may be computed when the friction in the threaded rods and the torque outputs of the motors are known.

Given that a feasible grasp is known, we must be able to compute the angles of the joints necessary to position the fingertips at the contact points. To find these relationships, we must first determine the kinematic equations of PAMH. Figure 3 shows the coordinate systems, $Pamh_{i,j}$ (i = 0, 1, 2 ; j = 0, 1, 2, 3) which have been assigned to the links of the hand. The assignments have been made as suggested by *Paul*[9]. Note that the coordinate systems $Pamh_{1,1}$ and $Pamh_{2,1}$ are fixed with respect to the palm, but have been assigned for convenience. Let $A_{1,1}$ represent the transformation relating $Pamh_{1,1}$ to $Pamh_{0,0}$ such that

$$Pamh_{0,0} = A_{1,1}\, Pamh_{1,1} \qquad (10)$$

Similarly, define $A_{1,2}$ and $A_{1,3}$ to relate $Pamh_{1,3}$, $Pamh_{1,2}$, and $Pamh_{1,1}$.

$$Pamh_{1,1} = A_{1,2}\, Pamh_{1,2} \qquad (11)$$

$$Pamh_{1,2} = A_{1,3}\, Pamh_{1,3} \qquad (12)$$

This gives the relationship between $Pamh_{1,3}$ and $Pamh_{0,0}$.

$$Pamh_{0,0} = A_{1,0}\, A_{1,1}\, A_{1,2}\, A_{1,3}\, Pamh_{1,3} \qquad (13)$$

where $A_{1,0}$ is defined to be the identity matrix. The other finger and the thumb give equations identical to (13) with the first subscript changed to 0 for the thumb and to 2 for the other finger. Note that $A_{2,0}$ is the identity matrix, but $A_{0,0}$ is not. For the definitions of the $A_{i,j}$ matrices *see*[1,9].

One use of the kinematic equations is the following. Given a list of the tactile sensor locations defined by the vectors, $\vec{f}^{\,i,j}_{i,j}$ on $digit_{i,j}$ let $S^{i,j}$ be the matrix with columns $\vec{f}^{\,i,j}_{i,j}$. Then

$$S^{i,j} = [\, \vec{f}^{\,i,j}_{i,1} \mid \cdots \mid \vec{f}^{\,i,j}_{i,9} \,] \qquad (14)$$

and $S^{i,j}$ can give the locations of the tactile sensors in the palm coordinate system, $Pamh_{0,0}$, by

$$S^{p} = A_{i,0}\, A_{i,1} \cdots A_{i,j}\, S^{i,j} \qquad (15)$$

where

$$S^{p} = [\, \vec{f}^{\,p}_{i,1} \mid \cdots \mid \vec{f}^{\,p}_{i,9} \,] \qquad (16)$$

This information is essential for reducing the tactile sensor data from the various fingers to spatial information in a common reference frame. Another use of the kinematic equations is without tactile sensation, the fingers can be positioned on the surface of the object. The kinematic equations give the positions of the finger surfaces in space. Since they are in contact with the surfaces of the object, we can make inferences concerning the boundaries of the object.

For the purpose of positioning the finger tips at their assigned contact points on the object to be grasped, we must know the joint angles as a function of the fingertip positions. The kinematic equations give us the finger tip location as a function of the joint angles. Therefore we need to derive the inverse kinematic *relationships*[9] With the inverse kinematic equations solved, we can directly compute the joint angles necessary to perform a given grasp.

Conclusions:

In this paper we have presented in a systematic way the constraints that can be computed as necessary in order to grasp an object. They come from four different sources:

the goal of grasping,
the geometry of the object to be grasped,
the kinematic analysis of how to restrain the object,
the model of the gripper.

We have analyzed each of these sources individually. It is clear that the number of possible points where an object can be grasped is large. The purpose of this paper is to find the process of elimination of those points that are not suitable as grasping points. The results of this analysis are only partially implemented (the three-dimensional object recognition). This paper is a report on progress.

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