Robotic Hands With Rheological Surfaces

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The purpose of this paper is to analyze, in some depth, the processes involved in the manipulation of solid objects using robotic hands. Such an analysis has implications for design, control, and motion planning. We make a case for the use of finger surfaces which have a distributed compliance and show how such surfaces may be realized by fluid filled pods. The arguments given are based on an analysis of the complexity of the kinematic programming problem, an enumeration of the number of independent feedback control channels necessary for achieving a firm grasp and an examination of frictional forces. We emphasize the necessity of dealing with models which lead to well-posed problems throughout the grasping process and point out some of the ways that earlier models lead to ambiguous situations.

Introduction

In this paper we give arguments in support of the idea that an effective working surface for multipurpose, highly articulated robotic hands can be made by stretching an elastic membrane over an incompressible viscous fluid. We claim that such a design can, in comparison with designs based on rigid materials or conventional elastic materials,

(i) ease the kinematic programming problem;
(ii) enhance the frictional forces which make manipulation possible;
(iii) make available a reliable and useful feedback signal -- the fluid pressure.

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Our analysis is based, in part, on a rather detailed critique of the rigid-rigid hand-object interface model, including an analysis of the complexity of the kinematic control required for firm grasping. We then show that the self alignment provided by rheological surfaces enhances grasping stability.

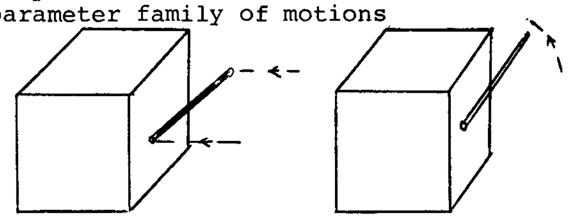
Earlier work on grasping is described in the well-known book on hands [1] and in several recent papers of which [2] and [3] are representative.

2. Preliminaries on Rigid-Rigid Interfaces.

A starting point with respect to the analysis of grasping is the elementary geometrical analysis which models the interaction between two solids as occurring when a point, line or plane associated with one of the solids touches a point, line or plane associated with the other. A multi-fingered hand would be modeled as an articulated collection of rigid bodies each rigid member having the possibility of contacting the object being manipulated in any of these ways. Analyses of this type have been carried out by Salisbury and Roth [2] with a view toward using them as a design tool in the configuring of hands. Our purpose here is to briefly critique this type of analysis from the point of view of the complexity of the kinematic programming necessary to make it work and from the point of view of the robustness of the grasp with respect to geometric uncertainty.

Let p and q take on the values 0, 1 or 2 accordingly as to whether the first rigid body contacts the second along a point, line or surface and the second contacts the first along a point, line or surface. We may imagine that contact inititally occurs as the result of relative motion of the two bodies. It is clear that unless one has a precise knowledge of the geometry, $p + q \geq 2$ is a necessary condition for relative motion to produce contact. We call p + q $\geq$ 2 the transversality condition.

On the other hand, if p + q > 2 then the model is subject to errors of a second kind. To arrange matters in such a way as to have a line lying on plane requires (in addition to the line being truly straight and the plane being truly flat) that the orientation of the line match that of the plane when they come into contact. The only way to achieve this pair of conditions, in any generality, is to achieve it as the result of a two parameter family of motions one of which is terminated on the occurrence of point on plane contact and the second of which is terminated on the occurrence of line on plane contact. (See figure 1.) If we make a similar analysis of the plane on plane situation we find that it can only be achieved as the result of a 3 parameter family of motions



(a) Point on plane contact. (b) Line on plane contact.

Figure 1: Achieving line on plane contact.

Having discussed single finger contact type and the process by which contact of a certain type can be achieved when, in fact, it is possible, we now turn to the simplest issues involving two finger contact. For our purposes we assume that the object to be manipulated is lying on a smooth table. We assume that through a vision system or through some other means, we know the size, shape and location of the object. Suppose the grasping strategy calls for the object to be squeezed between two fingers with sufficient force to insure that the frictional forces/torques required for stable retention will be forthcoming. We now want to argue that "srong grasping" is not stable for most two-finger rigid/rigid interfaces.

We begin with a more detailed explanation of what we mean by strong grasping. Suppose we wish to arrange our grasp so that the first finger presents a plane to a point on the body to be picked up and second finger does the same. In symbols, we are to attempt a (2,0) - (2,0) grasp. Once contact is made by the two fingers and the grasp is strengthened, the object being held may rotate in response to the face that the line along which the force applied by the first finger will not, typically, coincide with the line associated with the force of the second finger. (See figure 2.) In fact, the same can be said for two finger contact of the type (2,0) - (2,1) and most other combinations of two finger contact. The results of an analysis of all 36 possible two finger grasps is summarized in figure 3. The boxes which contain a U correspond to situations which are unstable with respect to strong grasping in the sense that a strong grasp will produce, generically, unbalanced torques.

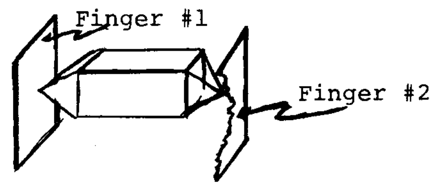


Figure 2: The instability of strong grasping.

Notice that any configuration involving a sum of p's and q's which is 6 or greater results in stability with respect to strong grasping. In figure 3 we display for the stable configurations the number of parameters which must be under the feedback control in order to achieve the order of contact which is required and the number of degrees of freedom which must be restrained by frictional forces. With respect to the former we see that a stable two-fingered grasp of a rigid object based on rigid-rigid interface requires the operation of a μ channel feedback control system with $\mu > 4$. The number of degrees of freedom which friction must restrain is shown as a fraction. This is explained in the appendix.

(p,q) \ p,q	(0,2)	(1,1)	(2,0)	(1,2)	(2,1)	(2,2)
(0,2)	U	U	U	U	U	3/4
(1,1)	U	U	U	U	U	3/4
(2,0)	U	U	U	U	U	3/4
(1,2)	U	U	U	3/4	3/4	$2\frac{1}{6}/5$
(2,1)	U	U	U	3/4	3/4	$2\frac{1}{6}/5$
(2,2)	3/4	3/4	3/4	$2\frac{1}{6}/5$	$2\frac{1}{6}/5$	$\frac{4}{3}/6$

Figure 3: The two finger grasping table showing the role of friction and the number of feedback channels required for achieving the desired effect.

In figure 4 we sketch out a schematic approach to a mechanization of the process of multi-finger grasping. It is to be emphasized that although two-finger grasping can lead to stable configuration, it can do so only if higher order contact is possible. If, for example, the finger surface is planar and if the object to be grasped is a smooth, strictly convex body, then the only possible contact is (2,0)-contact so we see that stable two-finger grasping is not possible in this case. Thus we see that this approach to grasping is severely limited.

Of course there may be situations in which three or more fingers would be involved in the grasping process. Whereas this may reduce the dependence or friction, it is known that without friction, to restrain a rigid object in 3 space against 3 rotational and 3 translational motions requires 7 points of contact. Moreover, each additional contact requires additional active feedback loops. For this reason two-finger grasping seems to be the most practical in many situations.

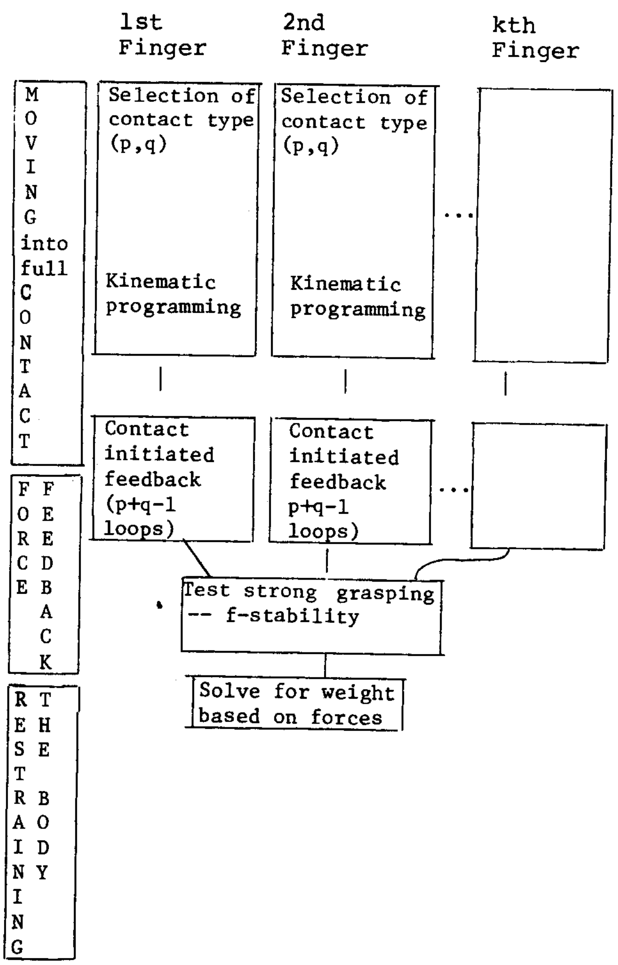


Figure 4: The steps for rigid-rigid interface grasping.

3. Rheological Compliance.

There are two conclusions which we wish to draw from an examination of the data presented in figure 3.

(i) higher order contact (p+q>2) is essential for robust two-finger grasping if rigid interfacing is used;
(ii) higher order contact between rigid members if permitted by the geometry of the mating pieces, can be achieved only through the use of multiple feedback loops.

Having presented arguments which illustrate how difficult rigid-rigid finger-object interaction is to achieve we now introduce a compliant model for the finger and argue for its usefulness. Our goals in introducing this model are fourfold:

(i) to reduce the number of feedback loops required for firm grasping;
(ii) to simplify the kinematic programming;
(iii) to enhance the stability of strong grasping;
(iv) to strengthen the frictional forces.

The model which we will investigate consists of an elastic membrane, a rigid plate and a viscous fluid assembled as shown in figure 5.

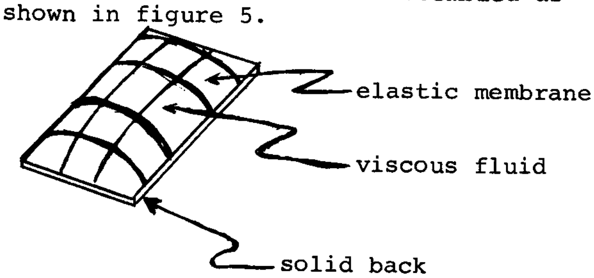


Figure 5: A rheological finger.

The working surface consists of the elastic membrane which is stretched over a rigid backing to form a chamber which is then filled with a viscous fluid. The elastic forces in the membrane serve to keep the finger surface in shape; the fluid serves to distribute the load over the surface of the finger in accordance with the law of hydrostatic pressure. The stiffness of such a surface can be adjusted by changing the amount of fluid in the chamber.

Figure 6 illustrates the deformation of the membrane under the effect of interaction with a rigid body. It is apparent that these models avoid completely the mathematical fiction of point contact since point contact would be associated with infinite pressure.

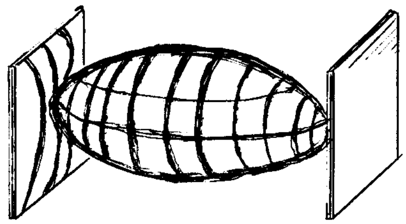


Figure 6: Illustrating the deformation of the membrane surface.

The analysis of the shape of the membrane is, in general, a difficult problem. However, there are two special cases which give some insight.

(a) If the rigid back is circular, then the membrane will assume the shape of a portion of sphere.

(b) If the rigid back is infinitely long and of finite width then the membrane will assume the shape of a portion of an infinitely long cylinder.

4. Kinematic Programming.

The scenerio for achieving a stable grasp which is suggested by figure 4 requires that the motion planning algorithm select a grasping site and then move the finger so as to create contact of the required type. If the finger surface is a segment of a plane, then not only the position of, say, the center of the finger surface but also the slant and tilt of the plane are important and must be precisely controlled. In the case of a compliant finger surface the situation is different. In this case there will be some solid angle of possible interface directions and interfacing along any line in this cone can be expected to result in a satisfactory interface.

Figure 7: The cone of admissible interface approaches.

The effect of this tolerance in the approach angle is to considerably ease the kinematic programming problem and to greatly increase the range of rigid objects which can be securely grasped by typical hand geometries.

This implies that the orientation of the finger surface does not need to be under feedback control and only needs to be correct to within something like ±45°. Effectively then a single feedback control loop, controlling the pressure of the fluid in the pod, can control the grasping process.

5. Experimental Work.

We are currently doing experiments with rheological fingers in the Harvard robotics laboratory. Sample finger surfaces consisting of rubber membrane material and grease for fluid have been constructed and used with an appropriately instrumented gripper. Preliminary results indicate significant improvements in grasp stability when using the rheologically compliant surfaces rather than rigid surfaces. We hope to report on the experimental aspects of this work soon.

ACKNOWLEDGEMENT

I would like to acknowledge the experimental work of David Schmitz, whose thesis research at Harvard has provided important insights about these matters.

References

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[2] J. Kenneth Salisbury and B. Roth, "Kinematic and Force Analysis of Articulated Mechanical Hands", J. of Mechanisms, Transmission, Automation in Design (ASME) vol. 105 (1983), pp. 35-41.

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Appendix on Inequalities

The number of degrees of freedom of a mechanical device is a familiar idea; informally it is the number of parameters required to specify a configuration once all the fixed geometry is known. This is a nonnegative integer with an obvious significance. In mathematics it has been recognized for some time that it is sometimes useful to assign a dimension to a set of points which is not integral. Hausdorff and others have given definitions which assign, under suitable hypothesis, a dimension to sets which are too complicated to be treated by the usual intuitive ideas. We will introduce fractional measures of dimension which are quite different -- in our context it is the idea of the number of constraints represented by a system of equalities and inequalities which we want to measure. In doing so one of the guiding principles will be to preserve the idea that typically a p-dimensional set in R^n and an r-dimensional set in R^n intersect to give a p+r-n dimension set of $p+r \geq n$.

In an n-dimensional space one inequality, say $x_1 \geq 0$ defines a set $\{x | x_1 \geq 0\}$ which is a half space. Two inequalities define a quarter plane cross R^{n-2}, and it's not until we have specified n+1 inequalities that we have a chance of specifying a finite volume in R^n. Even if we have n+1 inequalities in R^n there are a number of ways that they can intersect. They can be inconsistent. They can define a set with infinite volume because they are linearly dependent. They can define a finite volume. They can define a set of zero volumes such as an n-1 dimensional half space or even a single point.

It is this latter case which is particularly interesting to us. Notice that in almost any sense, generically n+1 linear inequalities in R^n will either have no solution or else will define a finite, nonzero, volume in R^n. Between these two cases lies a variety of possibilities but perhaps the simplest is the case where the inequalities define a single point. From this point of view, then we may argue as follows. If each equality in R^n, such as $\phi(x)=0$ generically counts for one constraint; what should $\phi(x) \geq 0$ count for? If we assign to it the dimension $k=n/(n+1)$, a number less than one and having the property that $(n+1) \cdot k = n$ we get a certain consistency. Since typically n+1 inequalities in R^n provide the same information as n equalities this seems to be the appropriate measure.

We note in passing that the result of Somov and Lakshminarayana which states that in the absence of friction it takes 7 points of contact to restrain a body against translations and rotation, is quite intuitive from this point of view. In fact, the set of rigid rotations in n-dimensional Euclidian space is $n(n+1)/2$ dimensional and so the number of inequalities to define a point in such a space is $1+n(n+1/2$. This yields 4 in 2 dimensions and 7 in 3 dimensions.