Grasp Stability and Feasibility for an Arm with an Articulated Hand

Nancy S. Pollard and Tomás Lozano-Pérez

The MIT Artificial Intelligence Laboratory
545 Technology Square
Cambridge, MA 02139

1 Abstract

This paper presents a system for generating a stable, feasible grasp of a polyhedral object. A set of contact points on the object is found that can result in a stable grasp, and a feasible grasp is found in which the robot contacts the object at those contact points. The algorithm described in the paper is designed for the Salisbury hand mounted on a Puma 560 arm, but a similar approach could be used to develop grasping systems for other robots. Simulations show that the system can generate a wide range of grasps in difficult situations.

2 Introduction

In this paper, we will explore the grasping problem for the Puma arm with the Salisbury hand [19] (Figure 1(L)). Our goal is to produce a relatively fast grasp planner that works in a variety of situations and exploits the flexibility of the hand.

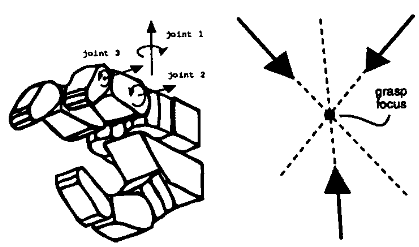


Figure 1: (L)Model of the Salisbury hand. (R)The grasp focus.

The robot and hand together have fifteen degrees-of-freedom. To somewhat narrow the search space, we will consider only fingertip grasps where the contacts are modeled as hard finger contacts with friction. A world model is used, and all objects in the world are modeled as polyhedra.

There are three requirements for a given grasp to be valid: stability, feasibility, and reachability. A grasp is *stable* if the forces on the object are in equilibrium and if small external disturbance forces do not cause the contacts to slip or separate from the object. A grasp is *feasible* if the configuration of the robot is collision-free. A grasp is *reachable* if there exists a collision-free path from the starting position of the robot to the final grasp configuration.

The plan of attack in this paper is to first find a set of fingertip contact points that can result in a *stable* grasp, and to then use the remaining degrees-of-freedom to generate a *feasible* grasp with the fingertips at those contact points. The issue of reachability is addressed in [18].

2.1 Previous Work

In the area of stability, work most relevent to this paper includes that of Hanafusa and Asada [6], who find a grasp on a two-dimensional object cross-section by minimizing the energy stored in springs at the contact points; Baker, Fortune, and Grosse [1], who show that a stable grasp of a polygon can be formed by placing contacts at points of intersection of the polygon with the maximum radius circle that can fit inside it; Markenscoff and Papadimitrious [14], who optimize a stable grasp of a polygon with respect to the compressive forces required to balance external objects; Jameson [7], who maximizes a goodness function for grasp stability once the robot is in contact with an object; and Nguyen [16], who discusses finding maximal independent contact regions that can produce a stable grasp of an object.

Other relevent work, mostly in the area of stability analysis, includes that of Barber et al. [2], Mishra et al. [15], Jameson [7], Cutkosky [4], and Kerr and Roth [8].

In the area of feasibility, most of the work has concentrated on finding free contact and approach areas around an object for a two-fingered hand. Examples of this include Pertin-Troccaz [17], Laugier [10], Wingham [20], and Lozano-Pérez [12, 11].

Work on local methods for avoiding collisions is also relevent. Some examples of work in this area include Khatib [9], who combines an attractive potential toward the goal with repulsive potentials from nearby objects to move a robot, and Faverjon and Tournassoud [5], who combine an attractive force toward the goal with *constraints* imposed by the obstacles.

Solutions to many of the subproblems that are addressed here have been implemented on a Puma arm with parallel jaw grippers [13]. The primary goal of this paper is to address the additional concerns involved when the robot has a three-fingered hand. Thus, the new problem with respect to [13] is how to select a grasp when we have a manipulator with a large number of degrees of freedom.

3 Stability: The Contact Points

In this section we show how to find three contact points on a given object from which we can generate a stable, fingertip grasp. As in [16], we will set a goal of maximizing the sizes of valid, independent regions of contact about the contact points in order to minimize our chances for failure due to uncertainty or to errors in modeling the environment.

In this paper, we assume that our contact points will be on faces of the target object, and that we know which face each finger will contact. This gives us a six dimensional problem, with two degrees-of-freedom in placing each finger on its given object face.

To achieve a stable grasp with our hand, it is sufficient to achieve *equilibrium* of three contact forces on the object. Specifically, Nguyen [16] has shown that a non-marginal equilibrium grasp of a polyhedron formed from three hard finger contacts can be made stable.

A necessary condition for equilibrium of three contact forces is that their lines of direction all meet at a point in the plane of the contact points [3] (see Figure 1(R)). We will call the point of intersection the *grasp focus* (as in [3]).

Since the grasp focus and the forces applied at the contact points must all lie within the plane of the contact points, it is natural to break the problem into finding this plane and then placing the contacts within the plane. This is the approach we will take.

3.1 Grasp Plane

A grasp plane can be specified by an orientation and an offset. A method for choosing these parameters is discussed below.

3.1.1 Orientation

Effective Coefficient of Friction: We know that the fingertip contact forces will lie within the grasp plane we choose. It is a useful concept, therefore, to define an *effective coefficient of friction* for the cross-section of each contact face within the grasp plane (that is, for each *contact edge*). This captures the idea that only a slice of the friction cone of the contact face is seen in the grasp plane. It will allow us to reduce the problem of finding contact points to a planar problem. The contact faces are reduced to contact edges, each with an effective coefficient of friction. Note that for polyhedra the effective coefficient of friction depends only on the orientation of the grasp plane, not on its offset, or location in space.

We assume that the real coefficient of friction is the same for all faces and is equal to μ. If the grasp plane is at angle θ_i from the face normal, then it slices the friction cone so that the effective coefficient of friction is:

$$\frac{\sqrt{\mu^2 - \tan^2\theta_i}}{\sec\theta_i} \qquad (1)$$

The effective coefficient of friction of a contact edge is largest (and equal to μ) when the normal of the corresponding face lies in the grasp plane. In choosing a grasp plane orientation, we wish to maximize the size of the smallest effective coefficient of friction in the grasp plane. We can say that this defines a *natural* plane orientation for each type of configuration of face normals.

Natural Orientation: To characterize the natural plane orientation for a given configuration of faces, we look at the normal vectors of the three faces.

If all three faces are parallel, then we have a one degree-of-freedom range of grasp plane orientations possible in which the grasp plane is perpendicular to all three faces and all three effective coefficients of friction are at their maximum possible values (μ). Figure 2(L) shows some of the grasp plane orientations possible for one such configuration.

If only two of the faces have independent normals, then we can choose a unique grasp plane orientation (using these normals as basis vectors for the plane) in which the plane is perpendicular to all three faces, and the effective coefficients of friction are all, again, μ. This case is shown in Figure 2(C).

If we have three faces with independent normals, then we cannot find a plane perpendicular to all three faces. We settle here for finding the unique plane orientation in which the three effective coefficients of friction will be equal. Figure 2(R) demonstrates the grasp plane found for this type of configuration.

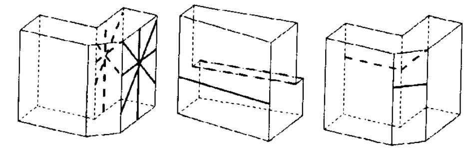


Figure 2: Natural orientations for three different face configurations.

Leeway: We can also define another concept, the *leeway* of a particular orientation. Intuitively, this is the amount that the grasp plane orientation can *change* before contact forces pointing into the grasp plane will cause the fingers to slip.

The axis of rotation of the grasp plane that we use to measure this change lies within the plane, and thus is a function of a single variable. The leeway about an axis (α) can be defined as the minimum angle of rotation of the grasp plane about α that would result in zero coefficient of friction in any contact edge formed by the plane.

To understand why this concept is useful, refer to Figure 2(C). The natural grasp plane orientation we found with these three faces passes through the edges of two of the contact faces. This would make it very difficult to grasp the object, since two of the fingers would have to contact their respective faces at these edges.

This is a problem, because the example is not so different from that in Figure 2(L), in which we have an extra degree-of-freedom in choosing our grasp plane orientation. For the case in Figure 2(C) we can characterize this similarity by noting that we can obtain a good grasp with a grasp plane at any orientation perpendicular to one of the normals of the contact faces. This can be expressed as having a leeway of 2π about the normals of the contact faces.

In Figure 2(R), where no qualitatively different grasp plane orientations will work, a leeway calculation will tell us that there is not much room to deviate from the natural grasp plane orientation.

Thus, from natural orientation and leeway information, we can come up with a set of *candidate* grasp plane orientations for each configuration of contact faces. In cases where all the faces are nearly parallel, such as in Figures 2(L) and 2(C), we will have a range of possibilities. In other cases, such as in Figure 2(R), we may have only one real orientation, with a small amount of leeway.

When we generate a feasible grasp with a grasp plane in one of these candidate orientations, we can use the leeway in the orientation to adjust the grasp plane and change the grasp. This may be necessary if we need to move the hand out of the way of obstacles around the target object, or out of the way of other parts of the object itself.

3.1.2 Offset

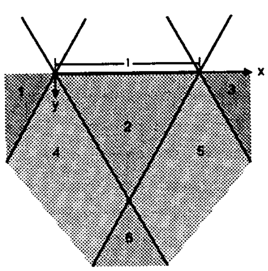
We now have a grasp plane orientation, and we need to compute its offset in space. Our primary concern is that the grasp plane intersect each of the faces. If the grasp plane intersects a face too near a face edge, however, the valid contact regions will be cut off at that face edge. If it is too far away from the face edges, the plane may not be reachable.

3.2 Focus Point

For a given grasp plane, we need to find a set of fingertip contact points. We achieve this by first choosing a focus point for the grasp plane. This is the point at which the lines of force at the three contacts will intersect, and so it defines valid regions for contact point placement within the grasp plane (contact segments). Contact segments are found by projecting the friction cones of each of the edges (using the effective coefficient of friction at that edge) from the focus point back onto the edge. As long as each contact point lies within its contact segment, all contact force lines can pass through the focus point without the object slipping. Our goal here is to maximize the size of the smallest contact segment.

Consider Figure 3. This figure shows equations for the size of a valid contact segment on an edge shown as functions of focus point position in each of six different regions. The regions are bordered by lines with the slope of the effective friction cone on that edge. μ' is the effective coefficient of friction of the edge, l is the length of the edge, and $[xy]^T$ represents the focus point position in the coordinate frame illustrated.

Since we have three contact edges, we have 64 non-zero regions to consider. To maximize the size of the minimum segment, we can perform an optimization within each of the regions.



		Size
1,3	=	0
2	=	$2\mu' y$
4	=	$x + \mu' y$
5	=	$(l - x) + \mu' y$
6	=	l

Figure 3: The size of a contact segment as a function of focus point position.

3.3 Contact Regions

A contact region is an area of fingertip contact where the stability of the grasp is preserved. As long as each fingertip contacts the object within its contact region, the given grasp will be stable. The contact region thus represents the error that can be tolerated in the placement of the fingertips. Contact regions *within* the grasp plane were introduced (as contact segments) in the section above. As long as the contact points are all in their contact regions and are not all in the same half of a circle formed by the contact points, then the forces can be equalized with the lines of force passing through the chosen focus point. Three-dimensional contact regions can be defined in a similar manner for a given focus point and a given quasistatic control law [18].

3.4 Contact Points

Contact points can be placed in the centers of the contact regions. Figure 4 shows focus points and contact points calculated for the three objects shown earlier.

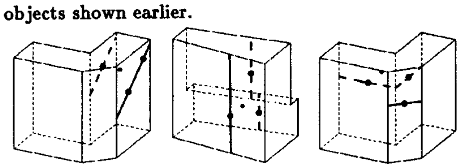


Figure 4: Contact points for three different face configurations.

4 Feasibility: The Wrist Configuration

A second subproblem is to find a collision-free configuration of the robot with the fingertips at the selected contact points. Since we have already specified three fingertip contact positions (nine degrees-of-freedom), we have six remaining degrees-of-freedom. We can specify these by picking a wrist position and orientation.

Our method is to first ignore the objects in the world and choose a wrist configuration that is *kinematically* feasible and approximately centered about the finger contact points. If the resulting arm/hand configuration does result in collisions between the robot and objects in the world, we set up a quasistatic spring model of the joints of the robot and let assumed forces at the points of collision nudge the robot into free space. While the grasp is being adjusted for collisions, the grasp plane itself can be altered to better accomodate the new collision-free grasp.

4.1 Selecting a Default Wrist Configuration

The default configuration for the wrist, along with the set of contact points given for the fingertips, defines a grasp configuration for the robot. We would like this configuration to be as close as possible to an *ideal grasp*.

The ideal grasp is chosen to equalize the amount that the fingers are required to reach, and to minimize the size of the hand profile (see [18]). Figure 5 shows three different ideal grasps. The default configuration of the wrist is chosen to approximate the ideal grasp. Figure 6 shows an example of a default wrist configuration.

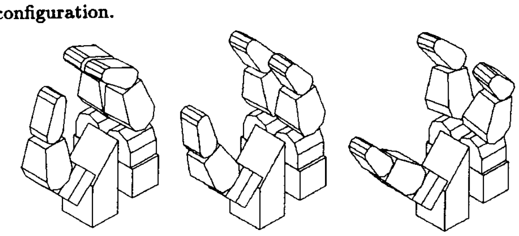


Figure 5: Ideal grasps for different fingertip spans.

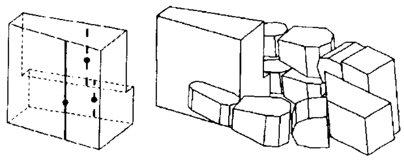


Figure 6: A default wrist configuration for the contact points shown.

4.2 Eliminating Object-Robot Collisions

If the default wrist configuration is not feasible, we use information on the location of object-robot collisions along with robot joint-limit information to attempt to push the robot into a feasible configuration. This is a local, potential field method. It is used to eliminate collisions rather than to avoid them, since the robot begins in an infeasible configuration. In setting up a solution, we:

- Fix the fingertips in their current positions;
- Create a spring model of the joints with equilibrium at the current joint position;
- Model the collisions as forces placed on the links at the collision points;
- Add a repulsive torque to any joint near its limit; and
- Calculate a new position for each of the joints in response to these forces and torques.

The new position becomes a new equilibrium point and we iterate until either there are no collisions or we give up.

The collision equation is:

$$\Delta\theta_{\mathbf{robot}} = K^{-1}\tau_{\mathbf{ext}} + K^{-1}J^T(JK^{-1}J^T)^{-1}(\Delta\mathbf{x_{tips}} - JK^{-1}\tau_{\mathbf{ext}}) \quad (2)$$

where $\Delta\theta_{\mathbf{robot}}$ is the incremental robot joint motion, $\tau_{\mathbf{ext}}$ is the torque applied about the robot joints by the environment and by its own joint limits, $\Delta\mathbf{x_{tips}}$ is used to compensate for any error in fingertip position that resulted from previous iterations (and an assumption of very small joint motion at each step), J is the robot Jacobian, and K is the diagonal stiffness matrix incorporating the stiffnesses of all the joints.

External torque ($\tau_{\mathbf{ext}}$) is calculated as follows:

$$\tau_{\mathbf{ext}} = \sum_{l=links} {J_l}^T \mathbf{f_l} + \tau_{\mathbf{joint-limit}} \quad (3)$$

where J_l^T is the Jacobian *to link l*, and $\mathbf{f_l}$ is the force on link l.

Joint limit torque is expressed as:

$$\tau_{j,joint-limit} = c_j\left(\frac{d_o}{d_j}\right)^2 \quad (4)$$

$$|d_j| < d_o \quad (5)$$

where c_j determines the relative weight of joint limit external torques, d_j is the distance of the joint angle j from its joint limit, and d_o is the magnitude of the cutoff distance.

4.3 Adjusting the Grasp

If collisions or joint limits have forced the wrist away from the intial configuration, we attempt to adjust the grasp plane to bring the final grasp closer to an ideal grasp. To do this, we choose the new grasp plane orientation that best matches the current orientation of the hand while remaining within the leeway of the grasp. We then calculate a new grasp plane with this orientation, new contact points, and a new feasible grasp. This step is only appropriate when the faces are nearly parallel and so there is a large amount of leeway in the grasp plane orientation.

4.4 An Example

Figure 6 shows an example of a default wrist configuration for a given set of contact points on an object. Figure 7 shows the world, with the robot feasibly grasping the object.

When the robot is grasping the object in the default configuration, there are collisions between the robot wrist and the table, and between the upper fingers and the block between the target object and the robot base. These collisions and Equation 2 are used to push the robot into free space. Plots of the robot behavior (see Figure 8) show that it first moves up from the table (the positive z direction) and then away from the block (the positive y direction). Changes in wrist orientation are minor, and are not shown here.

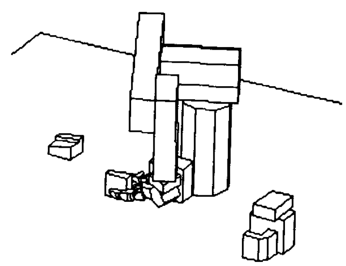


Figure 7: A feasible grasp.

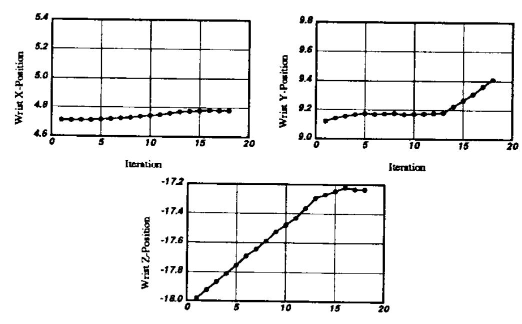


Figure 8: Plots of wrist position by iterations of the collision avoidance step.

Figure 9 shows the new grasp plane found by adjusting the plane orientation to match the feasible hand configuration. This plane is within the orientation leeway of the faces. The figure also shows the default wrist configuration with the contact points in the new grasp plane. This grasp is feasible.

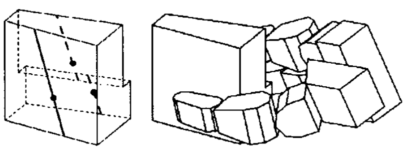


Figure 9: The default wrist configuration for the contact points in the new grasp plane.

5 Conclusions

Grasping is a hard problem, where brute force methods would be too time consuming on any realizable computer system. Even if we specify the problem as finding a stable, feasible three-fingered grasp for the Puma with the Salisbury hand, the search space is still large, with six degrees-of-freedom to be constrained from each of the two subproblems.

In order to cut down these problem spaces we made a number of assumptions, using heuristics constrained and guided by the problem geometry to find a solution. This proved to be adequate for solving a wide range of grasping problems. A different set of constraints, or modifications of the constraints discussed in this paper, could be used to handle a different range of situations.

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