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The Initial Grasp Liftability Chart

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Abstract—**Engineering mechanics is used to develop the Initial Grasp LIftability Chart, IGLIC. Its primary usefulness is in planning and analyzing grasps for lifting frictionless objects. Candidate grasp configurations can be mapped onto the IGLIC to determine first whether the grasp can be used to lift the object and second the nature of liftoff. Even though the development is undertaken for the two-dimensional case, the results can be applied to three-dimensional objects which can be approximated as generalized cylinders, by considering appropriate cross sections of the cylinders.**

I. Introduction

ONE DESIRABLE application of robotic technology is in the area of automatic assembly using articulated mechanical hands and flexible fixturing systems. Assuming that the parts of the product to be assembled are within reach of the robot and the sequence of assembly operations is known, the following fundamental problems must be addressed: 1) part acquisition, by which is meant selection and achievement of a useful grasp; 2) fixture setup, which is closely related to grasp selection, but requires the synthesis of an accessible partial fixture [1] as an intermediate step; and 3) parts mating which requires path planning [2] and compliant motion control [11], [12], [21]. The focus of this paper is on the problem of part acquisition.

Suggestions as to how to choose a desired grasp for an articulated mechanical hand have been developed based on independent regions of stable contact [13], expected task forces and fine motion requirements [8], [10], the forces required to cause one or more contacts to slip [3], [6], minimizing the contact forces arising due to external forces [17], and the potential energy in compliant fingers [5]. However, none of these suggestions have included a means to achieve the grasp, nor have they dealt with the reality that the object is initially at rest on a supporting surface (Wolter [22] and Laugier [9] consider the support, but only for the case of a parallel-jawed gripper.) Others have considered dexterous manipulation of the object, but begin their analysis from the point of an achieved grasp. Okada controlled a hand to turn a nut onto a bolt [15], Kobayashi's experimental hand drew simple figures with a pencil [8], Fearing demonstrated "baton twirling" using the Stanford/JPL hand [4], and Kerr developed the general differential equations for dexterous manipulation [7]. All of these studies were done assuming that only rolling contacts exist. Enforcing this assumption requires that manipulation be carried out under force and position control and that the coefficient of friction be significant.

In this paper, we consider lifting objects which are slippery and therefore cannot be manipulated with rolling contacts. The analysis leads to the derivation of the Initial Grasp LIftability Chart, IGLIC, which provides a compact, qualitative description of how a frictionless object (initially at rest on a support) will rise when squeezed by a pair of fingers. Combining the information contained in the IGLIC with data from visual and tactile sensors would allow an intelligent robot to autonomously find an initial grasp for which squeezing would cause the object to be lifted in a prescribed manner.

Our work is similar to Mason's work on manipulation [12] in that the hand and object are assumed to move quasi-statically and the prediction of the object's motion is qualitative. However, this work differs in that we consider the object to be contacted by several "pushers" instead of one, the pushers lift the object away from a supporting surface instead of sliding it on the surface, and we assume that friction is negligible.

II. Liftability of Rigid Bodies

One reason to grasp an object is to gain complete control over its position and orientation. Thus we propose that an object is grasped by a robot if the object contacts only the robot. If other bodies such as the support were allowed to contact the object, then those bodies would usurp a portion of the control over the object's motion. Therefore, the first goal in grasping is to manipulate the object in such a way as to cause it to lose all contact with the support. For this to be possible, the object must be *liftable*. (The notion of liftability is a generalization of tippability, discussed in [20].)

Definition: An object is *liftable* if and only if there exist finger contact positions on its surface for which increasing the contact forces applied by the fingers causes at least one of the supporting contact points to break.

For the remainder of this paper, objects are assumed to be two-dimensional. However, the subsequent analysis can be applied to any three-dimensional object which can be approximated as a generalized cylinder by considering a suitable cross section of the cylinder.

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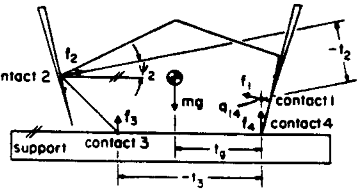

Fig. 1. Two-point initial grasp.

Consider the two-point initial grasp of the frictionless, rigid, planar object depicted in Fig. 1. The forces acting on the object are the finger contact forces (f_1 and f_2), the support contact forces (f_3 and f_4), and the weight of the object.

Under quasi-static conditions, the object must always satisfy the equilibrium relationships which may be written as

$$Wc = -w \tag{1}$$

$$c \geq 0 \tag{2}$$

[16], where W is the wrench matrix, c is the vector of contact force magnitudes, and w is the external wrench (i.e., force and moment) [14] acting on the object. Assuming that the external wrench w is due to gravity, the solution to (1) is given by

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ c_{30} \\ c_{40} \end{bmatrix} + c_2 \begin{bmatrix} n_{21} \\ 1 \\ n_{23} \\ n_{24} \end{bmatrix} \tag{3}$$

where

$$c_{30} = \frac{mgt_g}{-t_3} \qquad c_{40} = \frac{mg(t_3 + t_g)}{t_3} \tag{4}$$

$$n_{21} = -\frac{\cos(\psi_2)}{\cos(\psi_1)} \qquad n_{23} = -\frac{t_2}{t_3} \tag{5}$$

$$n_{24} = \frac{t_2}{t_3} + \frac{\sin(\psi_1 - \psi_2)}{\cos(\psi_1)} \tag{6}$$

where ψ_i is the angle of the ith inward contact normal, t_i is the moment arm of the ith contact force taken with respect to the summing point q, and g is the acceleration due to gravity.

The first term on the right-hand side of (3) is the vector of contact force magnitudes before the hand contacts the object. For the object to be in stable equilibrium prior to being picked up, c_{30} and c_{40} must be strictly positive. This requirement induces restrictions on the values of t_g and t_3 through (4)

$$t_3 < 0 \qquad t_g < 0 \qquad |t_3| > t_g. \tag{7}$$

Inequality (7) implies that the line of action of the object's weight must pass between the supporting contacts. In the limiting case as the supporting contacts move together, it is possible for the object to be in equilibrium on the support with only one contact, however, that case is considered elsewhere [19].

The second term on the right-hand side of (3) is the magnitude of the second contact force multiplied by the null space vector of the wrench matrix. This vector expresses how the contact force magnitudes must vary relative to one another to maintain equilibrium during squeezing. For this reason, the second term is called the internal grasp force [7], [16]. Equation (3) also implies that to lift an object with a particular initial grasp, at least one of the parameters n_{23} and n_{24} must be negative. If neither parameter is negative, then the object cannot be lifted; attempting to do so by squeezing presses the object against the support and jams the fingers. Before the hand contacts the object, c_2 is zero. After contact, the fingers begin to squeeze, increasing c_1 and c_2. Motion of the object begins when c_2 reaches the value c_2^*, given by

$$c_2^* = \begin{cases} \dfrac{-c_{30}}{n_{23}} & n_{23} < 0,\ n_{24} > 0 \\ \dfrac{-c_{40}}{n_{24}} & n_{23} > 0,\ n_{24} < 0 \\ \min\left\{-\dfrac{c_{30}}{n_{23}},\ -\dfrac{c_{40}}{n_{24}}\right\}, & n_{23} < 0,\ n_{24} < 0. \end{cases} \tag{8}$$

For a given object, (8), (5), and (6) show that the nature of liftoff depends on only three grasping variables: the contact angles, ψ_1 and ψ_2, and the moment arm of the second contact force t_2. Since every occurance of t_2 is divided by the constant t_3, the grasp configuration is completely specified by ψ_1, ψ_2, and t_2/t_3.

We now proceed with a closer examination of the null space vector. The first row of (3) can be written as

$$c_1 \cos(\psi_1) + c_2 \cos(\psi_2) = 0 \tag{9}$$

which is a statement that the sum of the x-components of the first and second contact forces must be zero. In addition, since c_1 and c_2 are restricted to positive values during grasping, the signs of $\cos(\psi_1)$ and $\cos(\psi_2)$ must be opposite. This fact leads to a natural partitioning of the perimeter of every planar object. Region S is chosen to be that part of the perimeter for which the x-component of the contact normal is negative. Similarly, Region S' corresponds to normals with positive x-components. These regions are illustrated in Fig. 2.

One should note that the perimeter on the underside of the object has not been partitioned, because it cannot be reached. Mathematically the regions are defined as

Region S:

$$\cos(\psi_1) < 0, \qquad \frac{\pi}{2} < \psi_1 < \frac{3\pi}{2} \tag{10}$$

Region S'

$$\cos(\psi_2) > 0, \qquad \frac{-\pi}{2} < \psi_2 < \frac{\pi}{2} \tag{11}$$

To break the third contact, c_3 must be driven to zero. Using the third row of (3) and inequality (2) one may deduce that the third contact may be broken only if n_{23} is negative

$$n_{23} = -\frac{t_2}{t_3} < 0. \tag{12}$$

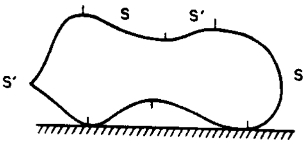

Fig. 2. Regions S and S'.

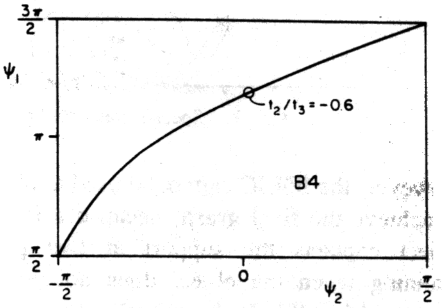

Fig. 3. Representation of inequality (15) for $t_2/t_3 = -0.6$.

Since t_3 is negative (see inequality (7)) t_2 must also be negative

$$t_2 < 0. \tag{13}$$

Therefore, an object is liftable if finger contacts can be found for which the line of action of the second contact force passes above the summing point q (see Fig. 1). More precisely, the forces f_2 and f_3 must produce moments of the same sense about q. The region in grasp configuration space defined by inequalities (10)–(12) is denoted by $B3$. Since the initial grasp configuration shown in Fig. 1 is within $B3$, the object can be lifted. However, before the precise nature of liftoff can be determined, the conditions under which the fourth contact can be broken must be considered.

To break the fourth contact, n_{24} must be negative

$$n_{24} = \frac{t_2}{t_3} + \frac{\sin(\psi_1 - \psi_2)}{\cos\psi_1} < 0. \tag{14}$$

Expanding the sine term and rearranging yields

$$\psi_1 > \tan\left(\frac{\sin\psi_2 - \frac{t_2}{t_3}}{\cos\psi_2}\right) \tag{15}$$

Using inequality (15) in conjunction with inequalities (10) and (11), and selecting a value for the moment arm ratio t_2/t_3 one can generate the plot shown in Fig. 3.

The region below the curve satisfies inequalities (10), (11), and (15) and is denoted by $B4$. It corresponds to grasp configurations which facilitate breaking the fourth contact. It is impossible to break the fourth contact using grasp configurations corresponding to the region above the curve.

By varying the value of the moment arm ratio one can generate the family of curves which defines the IGLIC (see Fig. 4). Using the IGLIC, one can determine the instantaneous outcome of squeezing any frictionless planar object using the following procedure which is illustrated by the flow chart in Fig. 5.

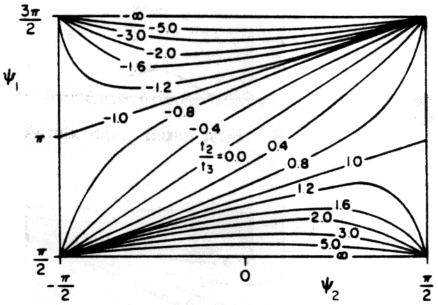

Fig. 4. The initial grasp liftability chart.

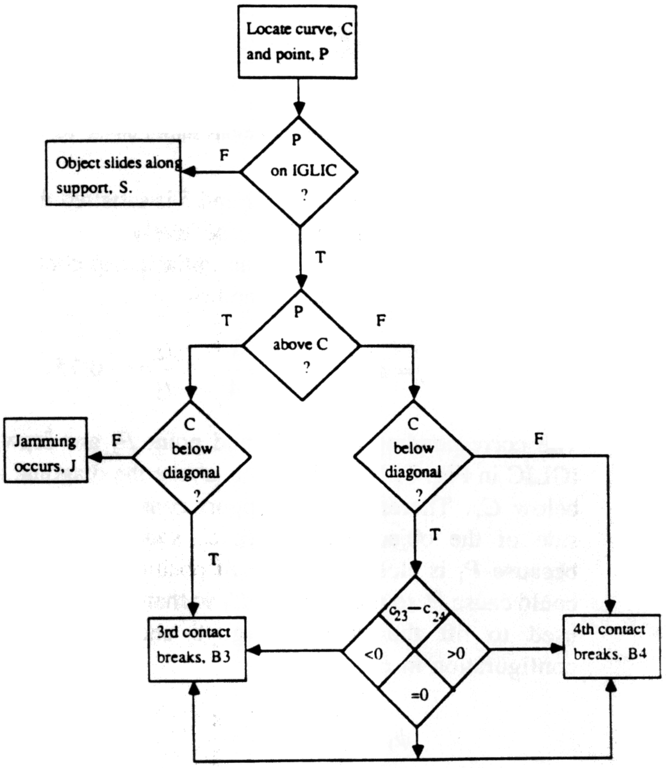

Fig. 5. Flow chart for use of IGLIC.

1) Locate the curve C on the IGLIC corresponding to the moment arm ratio of the grasp being evaluated.

2) If C lies below the diagonal (or equivalently if the moment arm ratio is positive), then the third contact can be broken, so the grasp configuration lies in $B3$, i.e., $n_{23} < 0$.

3) Find the point P on the IGLIC corresponding to the contact normals of the finger contacts.

4) If P lies outside the IGLIC, squeezing will cause the object to slide away from the hand along the support when squeezed.

5) If P lies on IGLIC below C, then the fourth contact can be broken, so the grasp configuration lies in $B4$, i.e., $n_{24} < 0$.

6) If P lies below C which lies below the diagonal, then either the third or fourth contact will break. The one which will break is the one requiring the smallest internal grasp force as indicated by (8), so the grasp configuration lies in $B3$ and $B4$, i.e., $n_{23} < 0$ and $n_{24} < 0$.

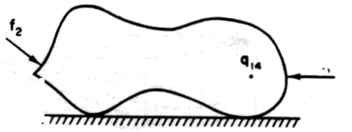

Fig. 6. First initial grasp configuration.

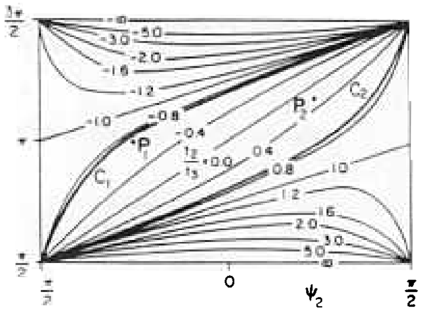

Fig. 7. Grasp configurations shown on the IGLIC.

7) If only one of conditions 2 and 5 is satisfied then the third or fourth contact will break, respectively.

Fig. 6 shows an object and an initial grasp configuration in $B4$. The configuration is defined by

$$\psi_1=\pi \qquad \psi_2=-\frac{\pi}{4} \qquad \frac{t_2}{t_3}=-0.75. \tag{16}$$

The corresponding curve C_1 and point P_1 are drawn on the IGLIC in Fig. 7. Note that C_1 is above the diagonal and P_1 is below C_1. Therefore, the support contact on the right-hand side of the object will break as squeezing begins. Also, because P_1 is close to C_1, small position errors in the robot could cause P_1 to move above C_1 so that the grasp could not be used to lift the object. Fig. 8 shows an initial grasp configuration in $B3$

$$\psi_1=\frac{7\pi}{6} \qquad \psi_2=\frac{\pi}{4} \qquad \frac{t_2}{t_3}=0.7. \tag{17}$$

The corresponding curve C_2 and point P_2 are shown in Fig. 7. Because t_2/t_3 is positive and P_2 is above C_2, squeezing will cause the support contact on the left-hand side of the object to break as long as P_2 is within the boundary of the IGLIC.

III. DISCUSSION

The nature of liftoff of a frictionless object depends on the grasp configuration, ψ_1, ψ_2, and t_2/t_3 (and in some cases on t_g (see the third row of (8) and (4))). The values of ψ_1, ψ_2, and t_3 (and t_g if needed) can be easily determined by data from tactile sensors distributed on the fingers and support. Determining the value of t_2 requires knowledge of the position of the center of gravity of the object which can be approximated using a vision system.

Presumably, an intelligent robot would formulate a plan of action which, if executed flawlessly, would produce a desired manipulation. Based on this presumption, the robot knows the desired trajectory of the object before grasping. Utilizing sensory data and the IGLIC, the robot can choose an initial grasp of the object consistent with the planned manipulation.

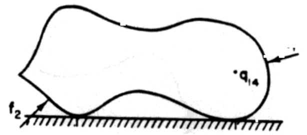

Fig. 8. Second initial grasp configuration.

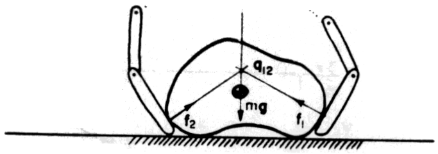

Fig. 9. Special grasp configuration.

However, the IGLIC cannot be used to plan finger trajectories to achieve the final grasp, because it is only valid when the object contacts the support at two points. Manipulation planning when the object does not contact the support is discussed in [20]. If the robot's planner has determined that the object rests in an unsuitable initial orientation on the support, then an object rolling maneuver can be initiated by selecting an initial grasp in either $B3$ (to roll clockwise) or $B4$ (to roll counter clockwise) and squeezing.

Near the beginning of Section II it was stated that the first goal of grasping is to cause the object to lose all contact with the support. If the initial orientation of the object is acceptable, then a grasp should be found for which squeezing causes both support contacts to break. For this to occur with just two finger contacts requires the very special type of grasp configuration shown in Fig. 9.

The line of action of the gravitational force must be intersected by the lines of action of the fingers' contact forces at a common point q_{12} above the object's center of gravity. When squeezed slightly, the object is free to rotate about q_{12}, but must do so such that its potential energy is minimized [18]. Thus as the objects rises, it will maintain its attitude since the center of gravity must remain directly below q_{12}. In practice, position errors make it impossible to achieve such an initial grasp. Therefore, the actual grasp will cause only one of the support contacts to break.

Including a third finger contact in the initial grasp simultaneously removes the need for unachievable precision and admits analysis of the initial lifting characteristic through the IGLIC. First, recall that the goal is to break the third and fourth contacts simultaneously. One method to find such a grasp is to first find a two-point initial grasp in $B3$. Second, find a third finger contact point which when considered with one of the other finger contacts represents a grasp configuration in $B4$. The resulting three-point grasp has the effect of breaking both support contacts simultaneously (see Fig. 10). If both two-point grasp configurations are in $B3$ or $B4$ or cause jamming, then the resulting three-point grasp will be in $B3$ or $B4$ or cause jamming, respectively. However, if one of the two-point grasp configurations causes jamming and the other is in $B3$ or $B4$, then it is possible (but not certain) that the object can be lifted by translating the hand upward.

Errors in the positions of the hand and object cause errors in the grasp configuration, ψ_1, ψ_2, and t_2/t_3. Generally, small

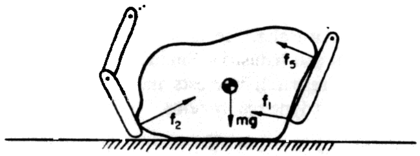

Fig. 10. An initial grasp for breaking both support contacts.

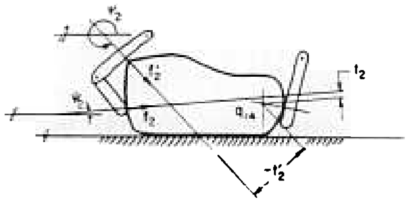

Fig. 11 A poorly chosen initial grasp.

position errors produce similarly small errors in ψ_1, ψ_2, and t_2/t_3, which, in turn, cause small excursions of the point P and the curve C on the IGLIC. Therefore, in planning one should choose an initial grasp for which the magnitude of t_2/t_3 is large and values of ψ_1, ψ_2 which locate P on the side of the diagonal opposite C. When $|t_2/t_3|$ is large only large position errors can cause the nature of liftoff to change. Another benefit is that the magnitude of the internal grasping force necessary to initiate liftoff shrinks as $|t_2/t_3|$ grows according to (5), (6), and (8). Choosing P to be on the side of the diagonal opposite C is important, because for a grasp configuration in $B4$, if P crosses C, it will become impossible to lift the object. Choosing ψ_1 and ψ_2 in this way reduces the chance of position errors causing P to cross C, resulting in a jammed initial grasp.

For some initial grasp configurations, small position errors could cause large variations in ψ_1, ψ_2, and t_2/t_3. For example, a poor choice of the joint angles could result in surfaces of links not intended to contact the object to be close to it. In Fig. 11, a small position error could cause contact to occur at the point 2′ rather than 2, drastically changing the values of t_2/t_3 and ψ_2 and changing the nature of the grasp from liftable to unliftable. However, this kind of error condition could be detected with tactile sensor sheaths on the fingers after which corrective action could be taken.

Another similar error can occur when attempting a grasp near a concavity (see Fig. 12). Again, the intended and erronious contact points have dramatically different values of ψ_2 and t_2/t_3 which change the nature of liftoff from $B4$ to $B3$.

The possibility of these kinds of errors dictates that when planning to lift and manipulate a slippery object, one must first make sure that the redundant degrees of freedom are utilized to reduce the chance of contacts occurring on the wrong link and second, grasp points in concavities should be chosen with caution or avoided altogether. In other words, grasp sites should be chosen for which the perimeter of the object coincides with its convex hull. At first this recommendation may seem counter-intuitive. In static grasping where stability is the primary concern, concavities are the best grasping sites. However, when dexterous manipulation is the goal, the stability added by a concave grasp site comes at the expense of relative freedom of manipulation and, as just discussed, increased sensitivity of the nature of liftoff to position errors.

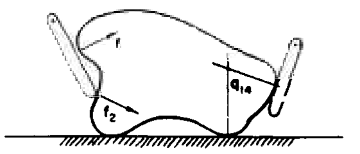

Fig. 12. Grasping near a concavity.

IV. Conclusion

The Initial Grasp LIftability Chart (IGLIC) has developed through studying the solution of the equil equations of a frictionless two-dimensional object while in contact with a support. The IGLIC provides concise description of the dependence of the liftability object on the geometry of the initial grasp. For any pr two-point initial grasp, the IGLIC reveals not only whethe object can be lifted, but also yields the nature of liftoff, which support contact will break. The liftability of three initial grasps may be analyzed as the combination of two point grasps.

The IGLIC is also useful in grasp planning. It ca incorporated into a grasp selection algorithm to find an grasp which will yield a specific mode of liftoff, wil insensitive to position errors, and will initiate lifting w relatively small internal grasp force. Without using knowl of mechanics, achieving a grasp with these attributes woul particularly difficult (possibly accidental) especially for tionless objects. The analysis also led to the some counter-intuitive recommendation that when initiating poseful manipulation of a frictionless object it is usually choose grasp sites where the boundary of the object co with its convex hull.

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