Dextrous Micromanipulation Based on Two 1 DoF Probes and 3 DoF Translating Stage

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Abstract

Rao, Kriegman and Goldberg showed that any six degree of freedom (DoF) rotation plus translation can be achieved with a four DoF manipulator having 3 DoF of translation plus rotation about the Z axis, plus a passive pivoting axis. The present paper extends this work to consider the range of rotations of a workpiece achievable if the angle of rotation about the Z axis is produced by two 1 DoF probes plus a 3 DoF translating stage. An algorithm is presented which determines the grips that will rotate a workpiece from an initial to a desired orientation, if the orientation can be reached. The algorithm has O(n3) computation time for an n-sided polygonal slice through the workpiece. The algorithm is implemented in a Java applet at:

http://www-inst.eecs.berkeley.edu/~jat/probes

1 Introduction

The ability to orient a workpiece is as important in microassembly as it is in more conventional assembly. However, conventional manipulators such as a parallel-jaw gripper are not as readily available at the micron scale. This paper is motivated by a new type of gripper based on a simpler mechanism which can be more easily implemented at the micron scale. This paper analyzes the orienting capabilities of this new micromanipulator by providing a gripping algorithm.

1.1Rotation about the Z axis

The mechanism is shown in figure 1.

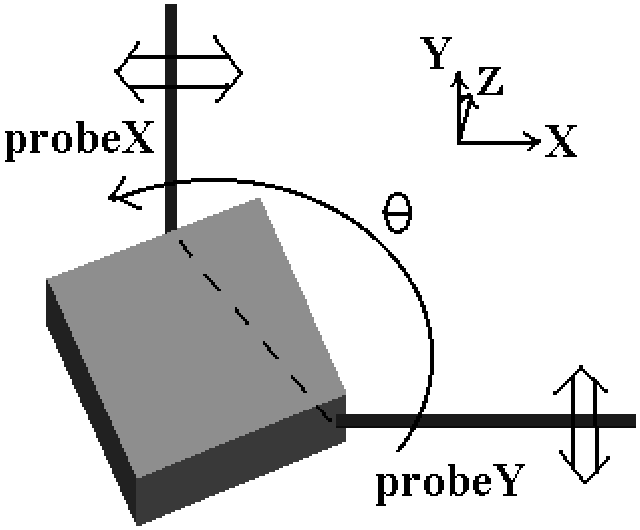


Fig. 1 Manipulator mechanism

The workpiece is grasped by two 1 DoF probes called probeX and probeY. ProbeX is so called because it can only move in the +/- X direction, and probeY only moves in the +/- Y direction. The workpiece is resting on a 3 DoF translating stage which prepositions the workpiece where the probes can grip it. The probes rotate the workpiece by θ around the Z axis. The dotted line shows the grip axis formed by the two probe contacts, which must be within the friction cone from the surface normal.

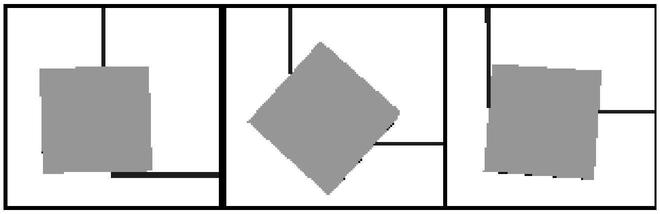


Fig. 2 Probes rotating the workpiece by 90°

Figure two shows a single grip rotating the workpiece by θ=90°. Note that the rotation is not really around the center of the workpiece but rather the center must move to meet the constraints that probeX does not move in the Y direction nor does probeY move in the X direction. If possible, the reader should view the Java applet which more clearly animates the operation.

ProbeX is actually a long probe mounted on a pivot far in the positive Y direction. (Similarly for probeY.) Because the probe is much longer than the diameter of the workpiece, a very small rotation of the probe around its base causes a sufficient deflection of the tip in the X direction and almost no displacement in the Y direction. A pivoting mechanism with a small angle of rotation is easy to implement in a microdevice.

1.2Rotation About the Grip Axis

Although not analyzed in this paper, when the workpiece is gripped by the probes, it is possible to rotate it around the grip axis by pushing it against a static barrier. In Rao, Kriegman and Goldberg (1996), it is shown that the combination of a rotation around the Z axis and a rotation around a grip axis in the X-Y plane can achieve any orientation of the workpiece.

1.3Need for an algorithm

The cube workpiece shown in figure 2 can be rotated by 90°, and by regrasping can be rotated another 90° and so on to achieve full rotation. But other shapes are not so trivial.

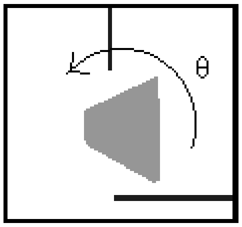


Fig. 3 Cannot rotate by grasping edges.

Figure 3 shows the square shape from figure 2 modified into a trapezoid. ProbeY cannot contact the lower face as it did in figure 2 in order to rotate by increasing θ. However, what appears as a vertex in the two dimensional cross section is actually a vertical edge of the surface. An advantage of using probes is that we can grip on these convex edges as well, as shown in figure 4, which will allow the rotation.

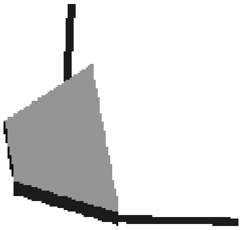


Fig. 4. Gripping at an edge where two faces meet

Even allowing grips on convex edges where two faces meet, there are still configurations that the probes cannot grip.

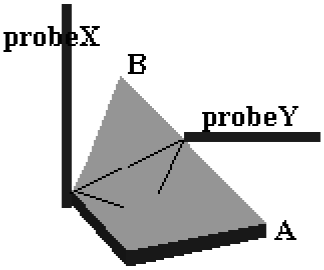


Fig. 5. No better grip possible for increasing θ

Figure 5 shows a configuration where it is not possible to rotate more by increasing θ. If the probeY contact moves more toward A, then the grip axis is outside its own friction cone. And if the probeY contact moves more toward B or the workpiece rotates by increasing θ, then the grip axis is outside the friction cone for the probeX contact causing the workpiece to slip along probeX. Thus the problem is non-trivial and an algorithm is needed to find what orientations can be achieved.

2 Related Work

Rao, Kriegman and Goldberg (1996) analyze rotation based on a 4 DoF "Scara" manipulator having translation in 3 axes and rotation about the Z axis. To achieve full rotation of the workpiece they consider passive rotation about the grip axis due mainly to gravity, although they describe a process of pushing the workpiece against a static barrier if gravity is not sufficient to rotate it. Using a static barrier is the primary mechanism considered in the present paper.

Because they utilize a manipulator with full rotation about the Z axis, their concern is with the possible grips to rotate the workpiece about the grip axis. In the present paper, though, it is the reverse. We are dealing with microparts with very small mass, and we assume that torque caused by separation of the center of mass from the grip axis is not an issue. Therefore, most any grip accessible to the probes can be used to lift it and rotate it about the grip axis against the static barrier. In fact, it is often difficult to have a micropart not remain attached to a gripper. (See Fearing 1995.) Instead, the concern here is with finding grips to rotate about the Z axis. Even though it is difficult to release a micropart from a grip, we assume that a mechanism can be found to do this such as using a third object to hold the workpiece while the grip releases.

Smith, Lee, Goldberg, Bohringer, and Craig (1999) describe an algorithm for computing optimal parallel-jaw grips (without concern for subsequently orienting the workpiece). The relevance to the present paper is the attention Smith et al give to optimizing the accessibility of the grips. If fact, because their algorithm has similar concerns as the present paper, it also yields an $O(n^3)$ algorithm.

The Smith et al algorithm concerns itself mainly with finding grips which minimize the friction dependence of the grip and the torque due to gravity. However since the present paper is dealing with microparts with very low mass, it is concerned only with maximizing accessibility.

3 Algorithm

Here is the overview of the algorithm for generating the grip sequence to achieve a desired rotation. The input of the algorithm is a three dimensional workpiece and a desired direction of rotation (increasing or decreasing) around the Z axis. The workpiece is given as a boundary representation where the surface is a set of polygons each with a surface normal facing out from the object. Curved surfaces are not supported.

1) Divide the workpiece along the Z axis into sections and create the set ***Z*** of the z value for each section. Determine the sections by sorting all surface vertices by z value and examining each interval between different z values. If the interval is greater than a predefined threshold value Δz_{min} then add the midpoint of the interval to ***Z***. (The threshold prevents considering too many slices based on a horizontal surface rotated slightly out of the X-Y plane.) Set the iteration step i to zero and set the initial rotation θ_0 to zero.

2) For each z in ***Z***, create a slice $S(z,\theta_i)$ which is the two dimensional cross section of the workpiece at z where the workpiece has been rotated about the Z axis by the angle for this iteration θ_i. $S(z,\theta_i)$ consists of a set of n lines which are the intersection of the XY plane with the workpiece surface. The number of lines n is used in estimating algorithm complexity. In this iteration, there is one $S(z,\theta_i)$ for each z in ***Z***.

3) For each slice $S(z,\theta_i)$, determine the grip which allows the maximum rotation $\Delta\theta(S(z,\theta_i))$ in the desired direction starting from angle θ_i. There is one $\Delta\theta$ for each z in ***Z*** given the θ_i for this iteration. $\Delta\theta$ is positive if the direction of rotation is increasing, negative if decreasing. This step has many sub parts which are detailed below and, as shown, takes $O(n^3)$ computation time. Typically there are only one or two slices in a workpiece, so the overall computation time for the algorithm is still $O(n^3)$.

4) Choose the best $\Delta\theta_{max}(\theta_i)$ which is the maximum rotation $\Delta\theta(S(z,\theta_i))$ starting from angle θ_i among all the slices. If $\Delta\theta_{max}(\theta_i)$ is zero, terminate. Otherwise, record its associated grip and z value.

5) Set θ_{i+1} to $\theta_i + \Delta\theta_{max}(\theta_i)$. If $\theta_{i+1} \geq 2\pi$ (or $\leq -2\pi$ for decreasing rotation) then terminate. Otherwise, increment i and go back to step 2

using the new θ_i.

The output of the algorithm is the value of $\Delta\theta_{max}(\theta_i)$ for each i: $0 \leq i \leq i_{max}$ and the grip at the slice $S(z,\theta_i)$ which achieves each $\Delta\theta_{max}(\theta_i)$. The set of $\Delta\theta_{max}(\theta_i)$ defines a sequence of grips which rotate the workpiece in the specified direction (increasing of decreasing) to achieve a final angle $\theta_{final} = \theta_{i\,max} + \Delta\theta_{max}(\theta_{i\,max})$. It is necessary to run the algorithm for both increasing and decreasing angle of rotation because the desired θ may be only accessible from one direction and not the other.

The bulk of the algorithm is in step 3. The following provides detail for this step which determines the maximum rotation $\Delta\theta(S(z,\theta_i))$ for a given slice. The sub algorithm for step 3 is as follows:

3.1)Limit the accessibility of the probes along an edge by ε from each vertex. This accommodates positioning uncertainty and prevents the probe from slipping off an edge. Note that what we call an "edge" in the 2-D slice is actually a face of the 3-D surface, and what we call a "vertex" is actually a vertical edge of the 3-D surface where two faces meet.

3.2)Determine the set $\boldsymbol{A}_{probeX}$ of edge segments which are accessible to probeX, limiting by ε as defined in the previous step. There may be multiple segments along an edge due to other occluding "islands" in the slice which break up accessibility by the probe. (Consider the "island" in the slice of a coffee mug created by its handle.) For a point on an edge segment to be accessible to probeX, a ray going from that point to +∞ in the Y direction (which is the probe itself) must not intersect any edge. This is an $O(n^2)$ operation because each of the n lines on the slice boundary must be checked against all other n lines. Likewise determine $\boldsymbol{A}_{probeY}$ for probeY. In figure 6, the circles show a radius ε from each vertex and the thick dark lines show the accessible edge segments.

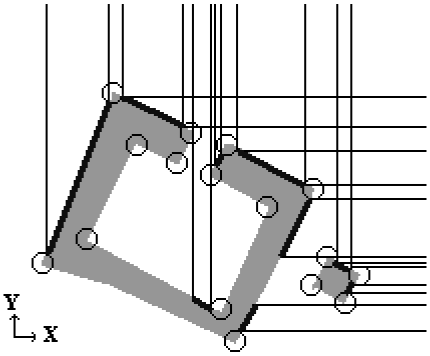


Fig. 6. Thick dark lines are accessible edge segments. Circles are radius of ε from each vertex

3.3)Add to $\boldsymbol{A}_{probeX}$ the set of convex vertices of the slice which are accessible to probeX. Conceptually, a vertex is an infinitesimal edge segment and so can be included with the other edge segments. For a vertex to be accessible to probeX, a ray going from that vertex to +∞ in the Y direction must not intersect any edge. In addition, the edges intersecting at the vertex must point away from the vertex in the positive X direction. This is because probeX must apply a force at this vertex toward probeY. This is also an $O(n^2)$ operation. Likewise add to $\boldsymbol{A}_{probeY}$ the convex vertices accessible to probeY.

3.4)Let $A_{probeX,\,j}$ be the jth edge segment in the set $\boldsymbol{A}_{probeX}$ and $A_{probeY,\,k}$ be the kth edge segment in the set $\boldsymbol{A}_{probeY}$. For each j and k, determine $\Delta\theta(A_{probeX,\,j},A_{probeY,\,k})$ which is the achievable rotation given that pair of edge segments. First, probeX is positioned in an optimal location along $A_{probeX,\,j}$ and the probeY contact is moved along $A_{probeY,\,k}$ as necessary to meet requirements of friction cones. Then probeY is positioned in its optimal location and probeX is moved as necessary to meet friction cones. The achievable rotation $\Delta\theta(A_{probeX,\,j},A_{probeY,\,k})$ for this edge segment pair is the lesser of these two possibilities. (To compute the achievable rotation of a probe gripping at a contact point, compute what the rotation would be of each vertex in the slice rotating to contact the probe and the result is least rotation.) There are n^2 edge pairs and the computation to determine the achievable rotation must check a candidate probe orientation for collision with all n vertices in the slice. Therefore this step takes $O(n^3)$.

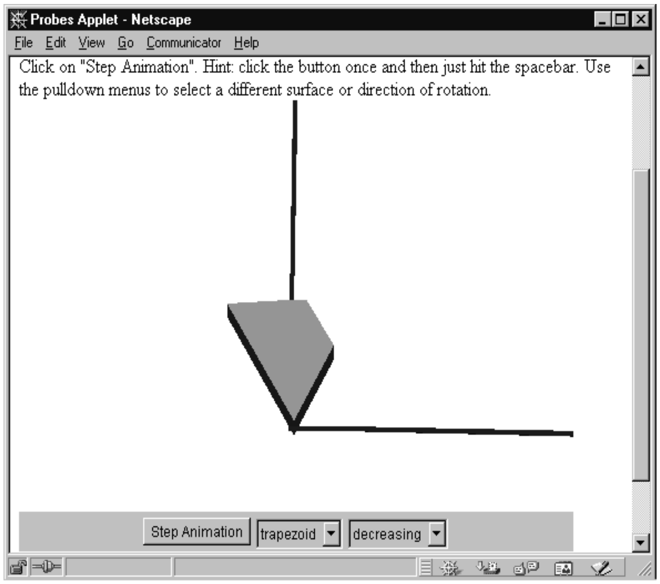
3.5) As the result of step 3 we need the overall achievable rotation $\Delta\theta(S(z,\theta_i))$ for this slice which gives the best overall grip. This is simply the maximum of $\Delta\theta(A_{probeX,\, j}, A_{probeY,\, k})$ for all j and k.

4 Analysis

Since the algorithm considers slices for multiple Z levels in the workpiece, it can achieve greater rotation than if it only analyzed one slice. For example consider a slice Z level z_1 which has a grip which only yields orientations in the ranges $0 \geq \theta \geq 3\pi/4$ and $5\pi/4 \geq \theta \geq 2\pi$ and a slice at Z level z_2 which can only grip at $\pi/2 \geq \theta \geq 3\pi/2$. The algorithm will use the slice at z_1 to rotate the workpiece from 0 to $3\pi/4$, and since this is within the range $\pi/2 \geq \theta \geq 3\pi/2$, the algorithm will next use the slice at z_2 to rotate to $3\pi/2$, and since this is in the range $5\pi/4 \geq \theta \geq 2\pi$ it will switch back to the slice at z_1 to complete the rotation to 2π. Without switching Z levels, a full rotation could not be achieved.

This example brings up an important question. An accessible range of rotation for a slice may have been calculated for a grip contacting the workpiece when $\theta = \pi/2$ and rotating it to $\theta = 3\pi/2$. But we may want to access the slice by contacting it when θ is in the middle of this range. Are we certain this contact is accessible? Yes because the probe extends from the contact point out to infinity during the entire rotation, so it is always possible to insert the probe to the contact location at any rotation in that range. (The answer might not be as simple for a parallel-jaw gripper which moves in locally during the rotation and then exits.) Therefore if the set of $\Delta\theta_{max}(\theta_i)$ define a sequence of rotations achieving a final rotation θ_{final}, then it is possible to begin a rotation starting from any θ between 0 and θ_{final}. Furthermore, since each rotation can be run in reverse, it is possible to start at θ and rotated in the other direction back to 0.

Finally, if the final angle achieved $\theta_{final} \geq 2\pi$ (or $\leq -2\pi$ for decreasing rotation) then the workpiece can be fully rotated about the Z axis and it is possible to fully rotate the workpiece in the opposite direction as was just shown. Therefore, it is possible to choose which direction to rotate in order to achieve a particular desired θ.



Click on "Step Animation". Hint: click the button once and then just hit the spacebar. Use the pulldown menus to select a different surface or direction of rotation.

Fig. 7. Screen shot of the Probes Java applet

Please view the Probes Java applet at:
http://www-inst.eecs.berkeley.edu/~jat/probes

5 Conclusion and Future Work

In conclusion, an $O(n^3)$ algorithm was presented which finds the maximum rotation about the Z axis of a workpiece using two 1 DoF probes. The algorithm is needed because, even for a simple workpiece geometry, some orientations cannot be gripped and finding them is non-trivial. The algorithm improves on previous work because it:

- Uses a simple-to-manufacture mechanism for micromanipulation based on two long 1 DoF probes each mounted on a small angle pivot

- Considers multiple slices along the Z axis to increase the search space for possible grips
- Allows grip contacts on the edges where two faces meet (instead of just on the faces).

The algorithm runs in "real time", as demonstrated by the Java applet. It is possible to incorporate the algorithm into a computer aided design package so that a part can be tested for manipulability as it is being designed.

There are improvements to the algorithm that can be made in the future. The algorithm does not consider the width of the probe which may further limit accessibility. The algorithm does not choose among "better" paths. For example it may be better to choose a grip on a face with the widest Z distance, or the least travel for the translating stage, or the widest clearance for inserting a probe.

Also, because the algorithm limits access by ε from every vertex, it does not consider the case where two edges meet in a concave recess. This may be important because the probe may slip along the edges but would lodge and contact in the recess. The algorithm can be extended in the future as experience illuminates what optimizations should be made.

6 References

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