A Tapping Micropositioning Cell

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Abstract

In this paper, we describe the use of tapping actuators in a "micropositioning cell." Tapping actuators are fixed (both in position and orientation) about the perimeter of the cell. A part in the cell can be precisely positioned by firing a sequence of tapping actuators (sensing the position of the object after each tap for feedback control). Such a system could be used for micropositioning tasks or in parts feeding applications. We show the controllability of this system for circular parts, describe an algorithm to position these objects, and present the results of simulated experiments. We conclude with some future directions and address the issues in extending this work to more efficient algorithms that work on a broader class of parts.

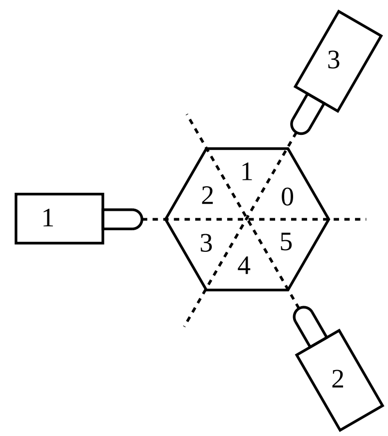

Figure 1: An illustration of the tapping positioning cell. Three tapping actuators intersect at a common point. The "bands" where the tapping actuators can strike the object intersect to form a hexagonal region which we divide into 6 cells.

1 Introduction

Many industrial tasks require precise positioning, and using tapping as a mode of manipulation is well suited for these tasks because it can effectively deal with static friction. Parts feeding is another area where tapping could make effective use of impact and friction in order to orient parts quickly. Tapping has the advantage of being able to use simple actuators, and these actuators can position parts precisely, even when there is imprecision in the actuators themselves.

This paper addresses the question of controllability for a positioning device that makes use of tapping actuators. The proposed platform features a number of tapping actuators arranged about the perimeter of a "cell". These actuators have fixed position and orientation. A part in the cell can be positioned by firing a sequence of actuators, using sensory feedback after each tap for closed loop control.

In this paper, we address the simplest question of whether a circular part is controllable in a positioning cell with just three tapping actuators, spaced 120 degrees apart and intersecting at a common point (illustrated in Figure 1).

After reviewing related work, we describe the model of the tapping actuators and their effect on part configuration. We then demonstrate that a circular part is controllable to the center of the cell. This demonstration leads naturally to an algorithm to operate such a positioning cell, and we present the results of simulated experiments to position a part.

2 Related work

This work builds upon our previous work on the mechanics, planning, and control for using tapping as a mode of manipulation (Huang and Mason [7, 6]).

The foundation of this work lies in the study of friction and impact. Goyal *et al.* [3, 4] proposed the limit surface for representing the relationship between frictional force and velocity on a planar part. Voyenli and

Eriksen [10] analyzed the physics of sliding rotating disks and rings which resulted in insights into the state space behavior of sliding objects that have been useful in basic motion planning for tapping. For impact analysis, we use Routh's method (more recently presented in Wang and Mason [11]) in conjunction with Poisson's hypothesis. We should also note that Higuchi [5] and Yamagata and Higuchi [12] have previously used impulsive forces for micropositioning.

This paper addresses issues of controllability for a tapping micropositioning cell. These and similar conditions have been proven for systems that manipulate parts by pushing (Lynch [8] and Akella *et al.* [1]).

One possible application of this work is in parts feeding; there has been recent interest in novel methods for programmable parts feeding systems. Böhringer *et al.* [2] apply ideas based on "squeeze grasps" to orienting parts on a vibrating plate. Akella *et al.* [1] use pushing motions of a rotary fence over a conveyor belt to position and orient parts. Reznik and Canny [9] use the controlled motion of the support surface to position and orient parts by creating force fields based on time-averaged frictional forces.

3 Models for tapping

The basis of this work is the mechanics of tapping which can be found in our previous work, e.g. Huang and Mason [7]. Here, we adapt it to the situation where the tapping actuators have fixed position and orientation. We then look at the position of the object relative to the tapping device to determine whether that tapping device should be fired.

3.1 Tapping device model & assumptions

We make the following assumptions about the tapping devices:

- The tapping device operates linearly, i.e. they send a striker out along a "line of action".

- The tapping device can deliver the same impulse to an object regardless of how far (within some range) the object is from the tapping device. What matters is the contact point on the object, the location of the COM with respect to the contact point, and the angle of incidence of the striker relative to the contact normal.

- A tapping device has some limit on how large the angle of incidence can be in order to tap an object.

The last assumption implies that a circular part can only be tapped only when its COM lies within a given distance from the line of action of a tapping device. Thus there is a "band" about the line of action of a tapping device in which the COM must lie.

3.2 Tapping model & assumptions

From the mechanics of tapping an object, we abstract the following qualitative properties of that model (under the assumption of an axisymmetric support distribution). Assume we define a tapper coordinate system with the variables l and h, where the l axis defines the line of action of the tapper and $\hat{l} \times \hat{h} = \hat{z}$. We describe the position of a circular object with respect to the tapper by its h coordinate.

In our previous work, we have shown that under the axisymmetric mechanics, a part will always slide in a straight line. When the angle of incidence of the striker is fixed (relative to the object), all displacements will have the same ratio of rotation to translation. In this paper, we will define $k = \frac{\theta_f}{x_f}$ where θ_f is the rotation and x_f is the distance of the translation. By varying the amount of impulse the striker delivers, we get different values for x_f and θ_f, but the ratio k is the same. The direction of the translation is determined by the mechanics of impact. We measure the angle a of the direction of displacement with respect to the l axis of the tapping device.

The following properties describe the relationship between the object's h coordinate before the tap and k and a, the displacement ratio and angle of displacement respectively:

- If $h < 0$, then $k < 0$ and $a < 0$, i.e. if the COM of the object is "below" the line of action, the object will move downwards slightly and will undergo a negative rotation. Similarly, if $h > 0$, $k > 0$ and $a > 0$, and if $h = 0$, then $k = 0$ and $a = 0$.

- Consider two different h values, h' and h''. If $|h'| < |h''|$ then $|k'| < |k''|$ and $|a'| < |a''|$.

See Figure 2 for an illustration. The relationship between h and k and between h and a is nonlinear; the former must be determined numerically.

4 Controllability of disks

In this section, we show that a disk is controllable with three tapping actuators spaced 120 degrees apart and intersecting at a common point.

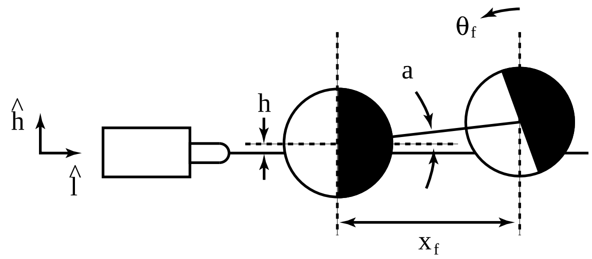

Figure 2: Illustration of the coordinate frame for each tapper and the motion of a tapped object.

From our assumptions, there is a band about the line of action of each tapping device which defines the object COM locations where the object may be tapped. The intersection of the three bands from these three tapping actuators is a regular hexagon. In this hexagon, the object may be tapped by any tapping actuator. We consider the interior of this hexagon as our domain.

We take the goal to be the center of this hexagon at some desired orientation. Although some preliminary results suggest that the part is controllable to any position (and orientation) in the interior of the hexagon, we will show here that a part is controllable to this single goal position (and any desired orientation).

The three tapping actuators provide three unilateral controls which affect the configuration of the object. The position of the object within the hexagon determines an h value for each tapping actuator. We denote these h_1, h_2, and h_3. Each point in the hexagon corresponds to a unique set of h_i.

For each h_i, we can compute a corresponding k_i and a_i that will result from a tap. These values can be used to determine a control vector in the configuration space (x, y, θ) of the object: a_i determines its (planar) angle relative to $\vec{l}_i$ and k determines the elevation of the control vector above or below the xy plane. This control vector is the direction in which the configuration can change with a tap.

At each position in the hexagon, we have a unique set of three control vectors. Note that these control vectors are fixed with respect to the global frame and do not move or rotate with the object.

It is not apparent from these vector fields whether the object is controllable, so we will take a more constructive approach, showing: (1) that the object can be moved to the center without any net rotation, and the (2) that the object can be rotated to any orientation. We conclude this section with an algorithm to position an object at a goal configuration.

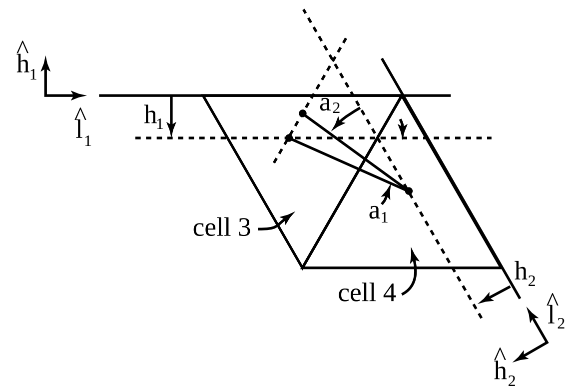

Figure 3: Illustration of two taps that translate the part with no net rotation. (Only the location and path of the COM of the object is shown.)

4.1 Pure translation

We will number the tapping actuators and the "cells" of the hexagon as shown in Figure 1. Without loss of generality, we assume the object's COM starts in cell 3, and we examine the effect of a tap by Tapper 1 followed by a tap by Tapper 2 such that there is no net rotation.

Suppose the first tap takes the object to the point at which $h_2 = -h_1$ (note that $h_1 < 0 < h_2$). See Figure 3 for an illustration. For the second tap, we will also have $a_2 = -a_1$ and $k_2 = -k_1$. Because the k values are equal and opposite, the distance of the two taps must be the same in order to get a net zero rotation. In addition (because the a values of the two taps are equal and opposite), the object has been displaced up and to the right at an angle of 60 degrees (with respect to $\vec{l}_1$). This is true so long as $-30 < a_1 < 0$.

For some configurations, the above two-tap sequence may result in a large displacement of the object which may be too much. We can achieve a smaller displacement by reducing the size of the first tap.

If the first tap does not move the part quite so far, then before the second tap $h_2 > -h_1$. This implies that $k_2 > -k_1$ and $a_2 > -a_1$. In general, this will still result in the object being moved upwards and to the right, but the exact direction will depend on how far the object is tapped by Tapper 1 and the specific object properties. The actual condition is that the increase angle a_2, combined with the increase in k_2 (which makes the translation distance shorter for a given rotation) must still move the object upwards. More formally, this condition is:

$$\frac{\sin(120 + a_2)}{\sin a_1} < \frac{-d_1}{d_2} < 0$$

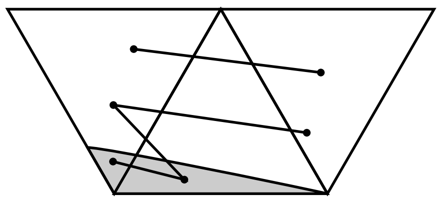

Figure 4: Illustration of a rotation step and a region which cannot make a rotation step.

where d_i is the translation distance of tap i.

By using repeated two-tap sequences, we can move the object up and to the right until it either reaches the center or until it reaches the line of action of tapping actuator 1. From there, we can use a single tap to move the object to the center without rotation.

For an object whose COM starts in cell 4, we can perform the same procedure except that tapping actuator 2 will be used first. The two-tap sequence will be repeated until the object reaches the center or reaches the line of action of actuator 2. For other cells, the same operations can be performed with other pairs of tapping actuators.

4.2 Rotation

We can rotate an object using repeated taps which move the object around the center of the hexagon until it reaches the proper orientation.

Consider an object whose COM lies in cells 3 or 4. From these cells, the object can be tapped by actuator 1 which will impart a negative rotation to the object. We would like the position of the object after the first tap to be in cell 5. From there, actuator 2 can impart a negative rotation to the object, and after the second tap, we would like the object to be in cell 1, where actuator 3 can continue.

The only problem with this scheme is that there are some positions in cells 3 and 4 which cannot reach cell 5. The reason is that when an object is "below" the actuator's line of action, it will move further down, so therefore locations towards the bottom of cells 3 and 4 cannot reach cell 5. Figure 4 illustrates this region.

The solution to this problem is to apply a two-tap translation step to move the object out of this region and into the upper region of cells 3 and 4. In fact, this need not be a pure translation step — we may also be able to impart some negative rotation to the object in doing so.

Note that the "radius" of the rotation sequence (about the center of the hexagon) can be controlled by choosing how far into the target cell the object is tapped. By just barely tapping the object into the target cell, the next tap will have a small h value (and therefore small k and a values) so subsequent taps can bring the object close to the center of the hexagon. Conversely, this radius can be increased by tapping to the far side of the target cell. The higher the radius, the more rotation that can be achieved with each orbit.

For positive rotations, we can simply reverse the direction of this cycle.

4.3 Positioning algorithm

Since we can perform a pure translation but not a pure rotation, we must position an object by first rotating it to the proper orientation and then translating it to the center. We note that the actual domain of this algorithm (the set of states that can be brought to a goal state) is actually larger than the interior of the hexagon.

5 Simulation results

We have implemented a simulation of the tapping micropositioning cell for positioning disks. Figures 5 and 6 show the sequence of taps executed to accomplish the positioning task. For both runs, the positioning tolerance was 0.5 mm and 0.5 degrees.

Our implementation makes some simplifying assumptions, namely that the object can always be tapped so that it can reach either the first or second cell in the clockwise or counterclockwise direction. This works so long as the object does not get too close to the edge of the hexagon. In addition, we also choose the goal location for a tap to be halfway between its entry and exit point in the goal cell. This also helps keep the object away from the hexagon boundaries.

For the positioning phase, we can choose the size of the first tap. This affects the net distance and direction that the object moves from a two-tap positioning step. We have chosen the first tap distance as

$$\sqrt{3}d\frac{|\vec{p}|}{r} \quad (1)$$

where $\vec{p}$ is the current object location (COM), r is the radius of the circle that circumscribes the hexagon, and d is the distance from $\vec{p}$ to the edge of the cell along the tapper's line of action. Although this formula is perhaps not important in its detail, we note that it attempts to keep the object in the current cell after a two-tap positioning step.

Start		-6.0	-1.0	10.0
cell	tapper	x	y	θ
Reorienting				
3	1	4.2	-1.3	9.3
5	2	0.7	6.1	7.5
1	3	-4.9	-2.2	5.8
3	1	4.2	-2.8	4.4
5	2	0.1	5.4	3.0
Repositioning				
1	3, 1	1.1	3.2	3.0
1	3, 1	0.9	1.7	3.0
1	3, 1	0.6	1.1	3.0
1	3, 1	0.5	0.9	3.0
1	3, 1	0.4	0.7	3.0
1	3, 1	0.3	0.6	3.0
1	3, 1	0.3	0.5	3.0
1	3, 1	0.3	0.5	3.0
1	3, 1	0.2	0.4	3.0

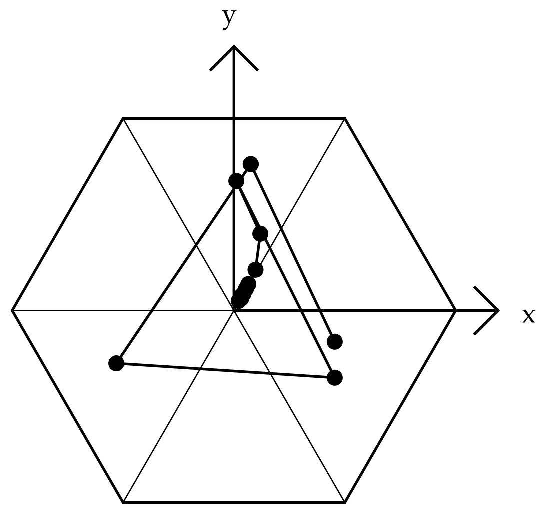

Figure 5: A sample run requiring negative rotation. The x and y coordinates are in mm; θ is in degrees. The object is a disk of radius 2.5 cm and of mass 100 g. Its coefficient of friction is 0.2, and its coefficient of restitution is 0.75. (Figure will be computer drawn for a final draft!)

Start		3.0	7.0	0.0
cell	tapper	x	y	θ
Reorienting				
1	1	4.2	7.2	0.6
0	3	-2.4	-4.3	0.6
4	2	-6.5	1.1	2.7
2	1	4.2	1.5	3.6
0	3	0.6	-6.1	5.3
4	2	-4.9	2.1	7.0
Repositioning				
2	1, 3	-3.2	-0.4	7.0
3	1, 2	-1.8	-0.1	7.0
3	1, 2	-1.2	-0.0	7.0
3	1	-0.0	-0.0	7.0

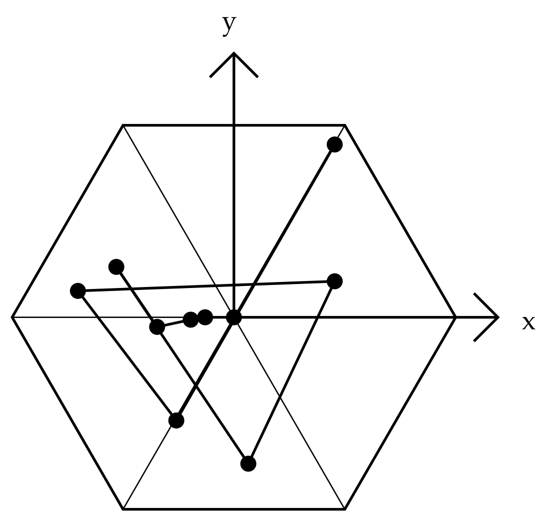

Figure 6: A sample run requiring positive rotation. Note that after the third "repositioning" tap, the object lies on the line of action of tapping actuator 1, so it is then translated directly to the goal location. The object and its material properties are the same as in Figure 5. (Figure will be computer drawn for a final draft!)

Because of these assumptions, the resulting algorithm is not optimal; however, the point of these experiments was to demonstrate an algorithm that can perform positioning tasks.

These simulations do not currently add noise to displacements which would naturally occur due to model inaccuracies or other variations, so we are not yet able to comment on the robustness of this algorithm.

6 Conclusions

In this paper, we have demonstrated controllability of a disk in a tapping micropositioning cell using three tapping actuators, both via a constructive algorithm and through simulated experiments.

There is much room for improvement of these results. The hexagon that is the domain of our algorithm is small because of the limitation on the angle of incidence of the striker. This assumption can be relaxed to some extent, but to achieve a far larger domain, it seems that either more tapping actuators are needed or the tapping actuators should have another degree of freedom (e.g. being able to rotate in place or to rotate about the center of the cell).

Our algorithm for positioning an object can do so successfully, but it takes many taps. The translations in particular can take a long time to reach the goal. An optimal version of this algorithm can be constructed that would carefully choose the size of taps in the rotation steps so that the translation is minimized. It is also possible to write an optimal algorithm for this problem, but we fear it would be significantly more computationally intensive.

We are interested in the interaction of part shape and controllability, so we are currently developing results for rectangular and polygonal parts. Preliminary results suggest that (particularly with the angle of incidence limitations) rectangular parts will not even be controllable with three tapping actuators.

We are currently in the process of building tapping actuators for a micropositioning cell and hope to have experimental results in the near future.

Acknowledgements

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