Sensorless Parts Feeding with a One Joint Robot

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A rigid object in the plane has three degrees of motion freedom, but it does not follow that a planar manipulator must have three independently actuated and controlled joints. As previous work has demonstrated, there are a variety of methods to perform manipulation tasks using fewer actuators than motion freedoms. The method explored in this paper is to use a single joint robot to push an object on a constant speed conveyor belt. This paper summarizes the approach, previously described in [3], and extends the approach to include the problem of orienting polygonal objects without a sensor.

1 Introduction

This paper describes an approach to planar manipulation called "1JOC" (One Joint Over Conveyor, pronounced "one jock") [3]. Initially the approach was conceived as a variation on the Adept Flex Feeder (see Figure 1), which is used to feed parts in automated factories. The Flex Feeder uses a system of conveyors to recirculate parts, presenting them in random orientation to a camera and robotic manipulator. Those parts that are in a graspable configuration may then be picked up by the robot and assembled into a product, placed in a pallet, or otherwise processed.

The question is whether, at least in parts feeding applications, we could replace the four-degree-of-freedom robotic manipulator with a simpler single-degree-of-freedom device. Figures 2 and 3 show a possible variation using a fence driven by a single revolute joint. By a sequence of pushing operations, punctuated by drift along the conveyor, the fence can move a part from an initially random pose to the entry point of a feeder track which carries the part to the next station.

A previous paper [3] focused on the simplest version: a straight fence, collinear with the joint axis, working above a constant velocity conveyor. This paper introduces the *sensorless 1JOC* to address the issue of sensorless manipulation. Other variations include a 2JOC, multiple 1JOCs working in parallel, curved fences, and so on.

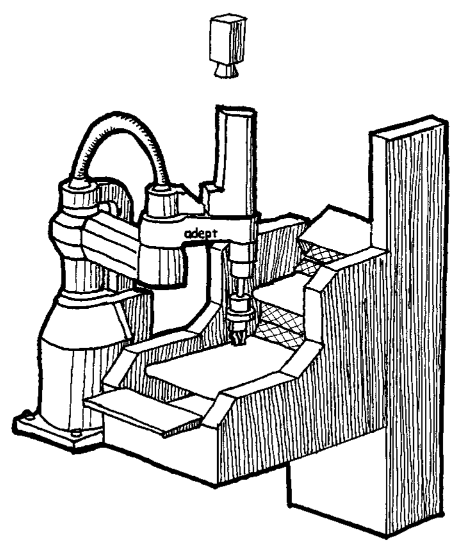

Figure 1: *The Adept Flex Feeder System. A SCARA robot picks parts off the middle of three conveyors. These three conveyors, along with an elevator bucket, circulate parts; an overhead camera looks down on the back-lit middle conveyor to determine the position and orientation of parts.*

There are many different measures of manipulation. For example, a system with *small-time local controllability* could move the object along an arbitrary trajectory. A system with *global controllability* could move the object from an arbitrary start to an arbitrary goal. The 1JOC posesses neither of these properties. How-

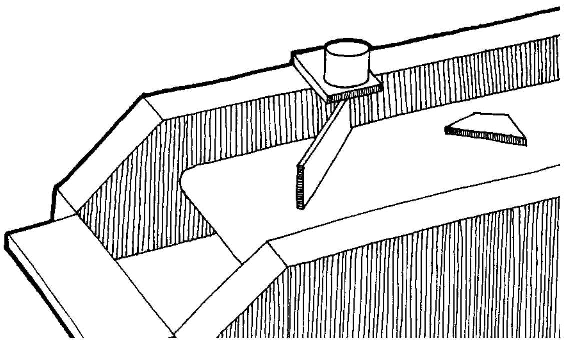

Figure 2: *The Flex Feeder with a rotatable fence.*

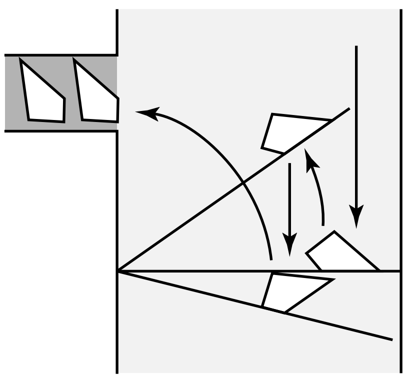

Figure 3: *We can feed a part by alternately pushing it with the fence and letting it drift along the conveyor.*

ever, the 1JOC can function as a parts feeding device. We formalize a measure of manipulation called the *feeding property*:

> A system has the *feeding property* over a set of parts $\mathcal{P}$ and set of initial configurations $\mathcal{I}$ if, given any part in $\mathcal{P}$, there is some output configuration $\mathbf{q}$ such that the system can move the part to $\mathbf{q}$ from any location in $\mathcal{I}$.

Our main results for the 1JOC are:

- 1JOC has the feeding property over the set of all polygons.
- For any polygon, a planner can determine a suitable goal, and can construct a sequence of pushes and drifts from any initial configuration to the goal.

The feeding property is proven for an infinite length fence and infinitely wide conveyor. The planner takes bounds on fence length and conveyor width into account. We have also successfully demonstrated some plans in the laboratory.

Our primary result for the sensorless 1JOC is:

- The sensorless 1JOC can orient any polygon without sensing provided the polygon does not have a symmetric *push function* [13].

We have demonstrated an example plan on our system.

1.1 Previous Work

This paper touches on a number of topics, so that an adequate discussion of our intellectual precedents seems impossible in the space available. The interested reader should refer to [3, 11, 20].

Much of this work was inspired by industrial parts feeders such as bowl feeders and the APOS system (Hitakawa [16]). Related research includes dynamic parts orienting on a vibrating plate (Böhringer *et al.* [7], Swanson *et al.* [30]). Other forms of nonprehensile manipulation are parts orienting by tray-tilting (Erdmann and Mason [12]), tumbling (Sawasaki *et al.* [29]), pivoting (Aiyama *et al.* [2]), tapping (Higuchi [15], Huang *et al.* [17]), two pin manipulation (Abell and Erdmann [1]), and two palm manipulation (Erdmann [11], Zumel and Erdmann [32]).

Much of the work on underactuated manipulation has exploited dynamic coupling among freedoms. Research on underactuated manipulators includes that of Oriolo and Nakamura [26] and Arai and Tachi [5]. Arai and Khatib [4] demonstrated rolling of a cube on a paddle held by a PUMA. Their motion strategy was hand-crafted with the assumption of infinite friction at the rolling contact. In work closely related to the work reported here, Lynch and Mason [22, 20, 21] report automatic planning of rolling, throwing, and snatching tasks using a single degree of freedom robot. A good introduction to nonlinear control is given by Nijmeijer and van der Schaft [25], and nonholonomic robotic systems are discussed in the texts by Latombe [18] and Murray *et al.* [24].

Work on orienting parts using the task mechanics, with and without sensing, goes back to Grossman and Blasgen [14], whose system brought objects to a finite number of orientations in a tilted tray, where their orientation was determined by a tactile probe. Erdmann and Mason [12] developed an automatic sensorless tray tilting system based on the task mechanics. Peshkin and Sanderson [27] used results on the motion of a pushed object to find a sequence of fences to automatically orient a sliding part. Brokowski, Peshkin, and Goldberg [8] designed curved fence sections to eliminate uncertainty in the orientations of parts being oriented by the fences. Goldberg [13] developed a backchaining algorithm to orient polygonal parts up to symmetry using a frictionless parallel-jaw gripper. Wiegley *et al.* [31] developed a complete algorithm to find the shortest sequence of frictionless curved fences to orient a polygonal part.

Minimalism in robotics has also been studied by Donald *et al.* [10], Canny and Goldberg [9], and Böhringer *et al.* [6]. Raibert [28] and McGeer [23] constructed simple, elegant machines that use dynamics for stable locomotion.

2 Planar Manipulation with 1JOC

This section describes the 1JOC approach, sketches the proof that the 1JOC has the feedability property, and describes the planner. We adopt some conventions to simplify the presentation. We assume an origin coincident with the fence pivot, and we assume the belt's motion is in the $-y$ direction. The fence angle is measured with respect to the x axis. We will only use the right half of the belt, i.e. the half plane $x > 0$. The object's position along the fence is characterized by a *contact radius* r.

2.1 1JOC Primitives

We use four primitive actions, illustrated in Figure 4. A *stable push* means that there is no motion of the object relative to the fence. A *turn* rotates the object, changing the edge in contact with the fence. It starts with a stable push to a fence angle of θ^+, followed by drift, until the object is caught at a fence angle of θ^-, followed by another stable push back to a fence angle of 0. A *jog* is a way of moving the object inward or outward along the fence, decreasing or increasing the contact radius r without changing the angle of the object. An inward jog is accomplished by slowly raising the fence a small angle θ, then quickly lowering it back to horizontal, and waiting while the object drifts back to the fence and settles back on the original edge. This moves the object inward by a distance $r(1-\cos\theta)$. An outward jog is similar: the fence is quickly lowered by small angle θ, the object settles on the fence, the fence is slowly raised. The net effect is an outward motion of $r(\sec\theta - 1)$. The last primitive is a *convergent turn*, which is only required when an object must be turned through 180 degrees. A regular turn cannot get all the way to 180 degrees, but some objects will complete a full 180 degree turn, provided we allow the rotation to be completed after the catch.

The 1JOC manipulates objects as follows. Given a polygon and center of mass a goal is chosen, in most cases any stable edge aligned with the fence, at any radius. Now each time a polygon arrives, the camera identifies the initial orientation. The fence is held at zero degrees until the object comes to rest on the fence. The object is rotated to the desired edge by a sequence of turns (sometimes including a convergent turn) and jogs. A final jog brings the object to the desired contact radius. That this scenario always works, and just how to choose the parameters, are shown below.

2.2 Feedability

Here we sketch the proof of the feedability property.

- A stable edge is defined to be an edge that will remain in stable contact with the fence, with the fence at zero degrees plus or minus some small angle.
- Every polygon has at least one stable edge. This follows from the observation that the center of mass is in the interior of the polygon.

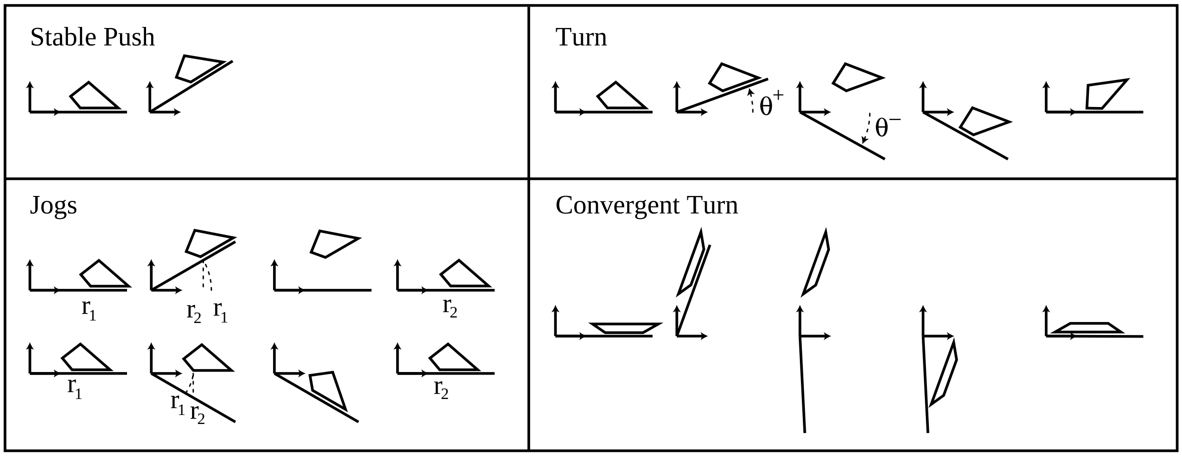

Figure 4: *Step by step illustrations of the 1JOC primitives.*

- A stable push is possible for any stable edge, provided that the contact radius is higher than some minimum. This minimum contact radius depends on the edge, on the object shape, the center of mass, the angular rate of the fence relative to the conveyor speed, and the coefficient of friction. Any stable push may be preceded by jogs to move the object out to the minimum contact radius.

- For most polygons, a counterclockwise rotation from one stable edge to another stable edge can be accomplished with turns. Every polygon has at most one stable edge from which it is impossible to rotate the polygon counterclockwise to another stable edge. There is one kind of polygon, with exactly two stable edges, parallel to each other, which requires a convergent turn.

- Given a polygon, we choose the goal configuration as follows. If there is a stable edge from which it is impossible to rotate counterclockwise to the next stable edge, then that edge is chosen as the goal edge. Otherwise any stable edge will serve. The goal contact radius is arbitrary.

The feeding property follows in a straightforward way. Given an arrival configuration, the fence can catch the polygon on a stable edge, use jogs as necessary to move the part far enough out on the fence for turns, use turns, and possibly a convergent turn, to rotate to the goal edge, then use jogs to move the object to the goal radius.

2.3 Planning

Each 1JOC plan is a sequence of turns (possibly including a convergent turn) interleaved with jogs, rotating from the initial edge through a sequence of stable edges to the goal edge. We consider every sequence of stable edges from initial to goal edge that do not rotate more than 360 degrees. For every such sequence we must determine parameters for each primitive to minimize the total time required. Given a fence and conveyor of known dimensions, given the shape and center of mass of the polygon, and given the coefficient of friction, we formulate the constraints as follows:

- The contact radius must always exceed the minimum for any turn.
- The fence rotation must stay in valid ranges.
- The part must stay on the belt.
- The contact radius must not exceed the fence length.
- The fence does not contact the part during drift.
- The start and end configurations must match the given start and goal.

We use an approximation for the time required for the jogs, and find a plan minimizing the time, using a nonlinear programming package GINO [19]. Details of the jogs are planned afterwards. A feasible solution to the above problem always exists, unless the belt is so narrow or the fence so short that the minimum contact radius cannot be satisfied for stable pushes. When this condition is satisfied, a plan with a maximum of three rotations exists, although it may not be the fastest plan.

3 Sensorless Parts Feeding

We have so far assumed that a camera gives us the initial position and orientation of the part after it first contacts the fence. The question we now ask is: Can we perform sensorless orienting and feeding with a one joint system over a conveyor? The answer is yes, with modifications to the 1JOC. We show that for our modified system, we can orient any object with an asymmetric *push function* [13]. We assume a rigid planar polygon with known shape and center of mass, quasistatic mechanics, uniform coefficient of support friction, and a frictionless fence.

The problem is to bring an object in an unknown initial orientation and position on the fence to a known orientation and position on the fence using a one joint system over a conveyor.

3.1 The Sensorless 1JOC

Our system to perform sensorless orienting and positioning consists of a frictionless fence, with a pivot in the center, with stops at both ends; we will refer to it as the *sensorless 1JOC* (see Figure 5). The pivot joint is not a simple revolute joint. Rather, the fence rolls without slipping on a circle, so that each point on the fence follows an evolute. If this pivot circle has diameter D, then when the fence has rotated 180 degrees CW (CCW), it will also have moved up the belt by D, and to the left (right) by $\pi D/2$. That makes 180 degree turns feasible—it leaves a space between the fence's dropping position and the fence's catching position, and an object being caught will not be too close to a stop.

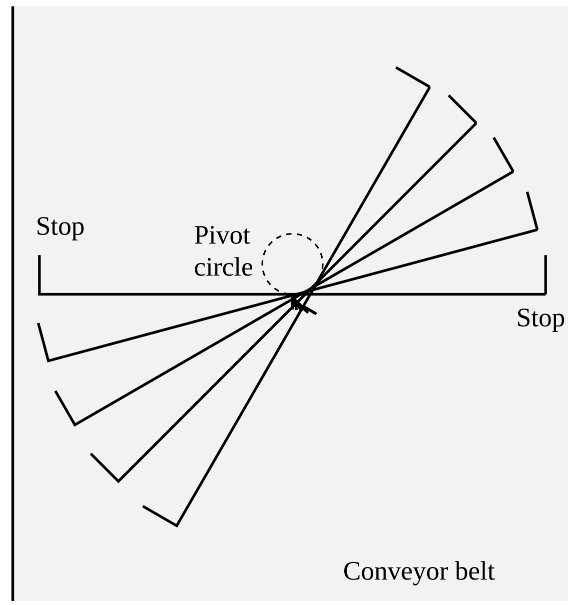

Figure 5: *The sensorless 1JOC.*

3.2 Sensorless Primitives

The primitives for sensorless orienting of polygons are (Figure 6):

1. *Catches:* A catch occurs when a part on the conveyor contacts the fence held stationary at 0 degrees and rotates onto a stable edge. An edge is stable if the perpendicular projection of the center of mass to the edge is in the interior of the edge segment. An edge is metastable if the center of mass projects to a vertex. If the polygon has metastable edges, slight rotations of the fence after the catch will destabilize metastable edges without affecting stable edges. Catches are used at the start of the orienting phase when the part drifts down the conveyor, and when the fence reacquires the part after each rotation by a stable push.

2. *Tilts:* A tilt is a CW or CCW rotation of the fence so that a part resting on a stable edge on the fence at 0 degrees slides without rotating to the right or left stop. A tilt eliminates positional uncertainty of the part by moving it into contact with a stop. To make sliding as fast as possible, we choose the

steepest tilt angle that does not cause the part to rotate. For a given stable edge, the object can be tilted through any angle for which the fence contact forces can balance the support friction forces. From the contacts that occur on the object once the slide is complete, we find the maximum tilt angle allowed for the edge. We find the smallest angle, up to 90 degrees, for the set of possible stable edges for the tilt and use that as the fence tilt angle. The angular velocity of the fence during downward motion should be small enough that the object does not lose contact with the fence.

3. *Stable pushes:* These actions are executed when the part is at one of the stops of the fence and we want to rotate the part CW or CCW. For a CW (CCW) rotation, the part has to be at the left (right) stop. This stable push differs from the stable pushes of earlier sections because we have more than just line contact, and there is zero friction. For a stable push, the contact forces due to the fence and stop should balance the frictional support force. We can show that by choosing a large enough fence angular velocity and a long enough fence, the contact force provided by the fence and the stop can balance the the support friction force for any pressure distribution.

   These stable pushes allow the fence to rotate the part by up to 180 degrees in the CW or CCW direction. After the stable push, the fence comes to 0 degrees to catch the part, which then rotates to a stable edge.

3.3 Planning

A sensorless orienting plan begins with a catch to acquire the part, followed by a sequence of stages; each stage consists of tilt, a stable push, and a catch. The sequence of stages will take the part to a unique edge on the fence. The final step of the plan is a tilt to bring the part to a known stop of the fence. So at the end of the plan, the part is in a known orientation at a known position on the fence.

During a catch, the part rotation depends on the part shape, center of mass, and initial orientation. For a frictionless fence, the catch is effectively a normal push and the part rotation can be determined from the radius or push functions [13]. Since fence rotations in the range $[-180, 180]$ can rotate the part by an arbitrary amount, we can use Goldberg's backchaining algorithm [13] to generate a sequence of fence rotations (that is, the stable push angles). It follows that any part can be oriented up to symmetry in the push function and that a plan for an object with n stable edges has a length of $O(n)$ stages. The tilt directions are determined from the rotation direction of the succeeding stable push, and the tilt angles are determined from the set of edges that may be stable at each stage.

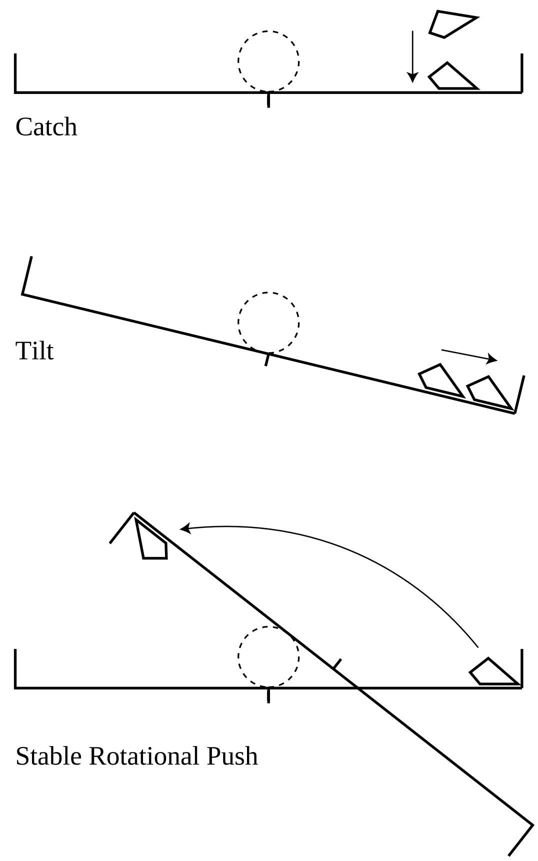

Figure 6: *Primitives used for sensorless orienting.*

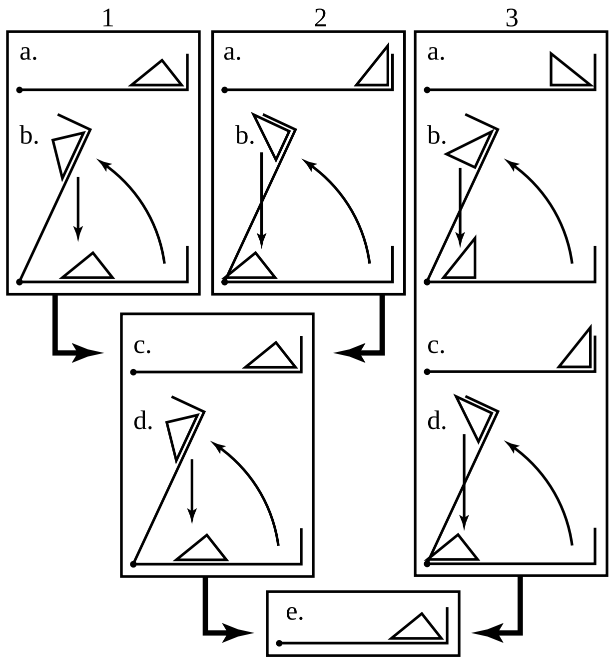

Figure 7: *Example sensorless feeding plan. Three different initial orientations converge to a single final orientation. For this plan only the right half of the sensorless 1JOC is used.*

3.4 Implementation

Most objects do not require rotations of 180 degrees, and do not require a frictionless fence. Our implementation of the sensorless 1JOC uses rotation about a fixed pivot point. We manually constructed a three stage plan to orient a right triangle, and tested it successfully. We used a conveyor velocity of 20 mm/sec and fence angular velocities of 20 degrees/sec and 12 degrees/sec for the stable pushes and tilts respectively.

The time for catches and tilts to proceed to completion, and the relative magnitudes of the conveyor velocity and fence angular velocity to guarantee stable pushes can be computed.

4 Conclusion

We have demonstrated two systems with one controlled degree of freedom to orient and feed parts. The original 1JOC system requires a sensor to give it the part's initial pose, while the variant system requires no sensing, except perhaps to know when a part has arrived. The sensorless variant has another advantage over the plain 1JOC. The sensorless variant appears to be more robust to errors in orientation and position of the fence and conveyor because of the uncertainty eliminating nature of the mechanical stops on the fence.

The sensorful 1JOC has advantages, too. Most obvious is that it can control the contact radius, and that it will often have shorter plans.

It may be possible to combine the two ideas, using the variant to bring the part to a known pose, followed by a plain 1JOC to reposition the part.

There are a number of other variations we would like to study. So far we have assumed singulated parts; we would like to explore the use of 1JOC to perform part singulation. Other variations of interest include three-dimensional parts, multiple part shapes, out-of-plane contact forces, faster motions, and pipelined 1JOCs.

Acknowledgments

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