A Pivoting Gripper for Feeding Industrial Parts

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To be cost effective and highly precise, many industrial assembly robots have only four degrees of freedom (D.O.F.) plus a binary pneumatic gripper. Such robots commonly permit parts to be rotated only about a vertical axis. However it is often necessary to reorient parts about other axes prior to assembly. In this paper we describe a way to orient parts about an arbitrary axis by introducing a rotating bearing between the jaws of a simple gripper.

Based on this mechanism, we are developing a rapidly configurable vision-based system for feeding parts. In this system, a camera determines initial part pose; the robot then reorients the part to achieve a desired final pose. We have implemented a prototype version in our laboratory using a commercially-available robot system.

1 Introduction

To automate the assembly of mechanical components, parts must precisely oriented prior to packing or insertion. A *parts feeder* is a machine that orients parts. Currently, the design of parts feeders is a black art that is responsible for up to 30% of the cost and 50% of workcell failures [21, 3, 5, 30, 31]. *"The real problem is not part transfer but part orientation."*, Frank Riley, Bodine Corporation [27, p.316, his italics]. Thus there is a demand for a parts feeder that can be reprogrammed rather than physically modified when part geometry changes.

Our feeder design combines machine vision with a high-speed robot arm. The system is programmed based on the type of part to be fed. During operation, a collection of like parts are randomly scattered on a flat worktable where they are subject to the force of gravity. An overhead vision system determines the pose (position and orientation) of each part. The robot arm then picks up each part and moves it into a desired final pose as illustrated in Figure 1.

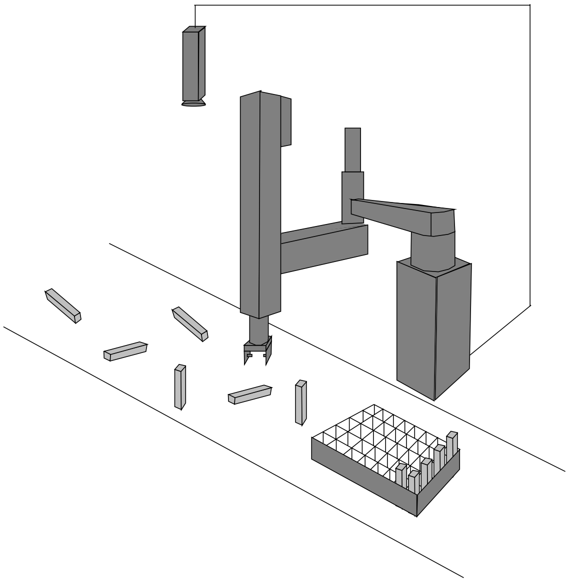

Figure 1: A parts feeder using a commercially-available system that integrates machine vision, high-speed robot arm, and pivoting gripper. This illustration shows the system feeding rectangular parts into a square pallet.

To be cost effective, fast, and highly precise, commercial assembly robots usually have only four degrees of freedom (4D.O.F.). However parts must be reoriented and repositioned through six degrees of freedom (6D.O.F.). To close this gap, we have designed a gripper with a rotational pivot between its jaws to provide an extra degree of freedom. Since cost and weight are critical, we note that the pivoting axis need not be actuated: it is possible to pick up each part along an axis offset from its center of mass and use on the force of gravity to rotate the part as illustrated in Figure 2.

In this paper we describe related work on parts feeders and robot gripper mechanisms. In Sections 3 and 4 we describe the pivoting mechanism in detail and our experiments with a vision-based parts feeding system. Last, we discuss the advantages and disadvantages of the proposed system and describes avenues for future research.

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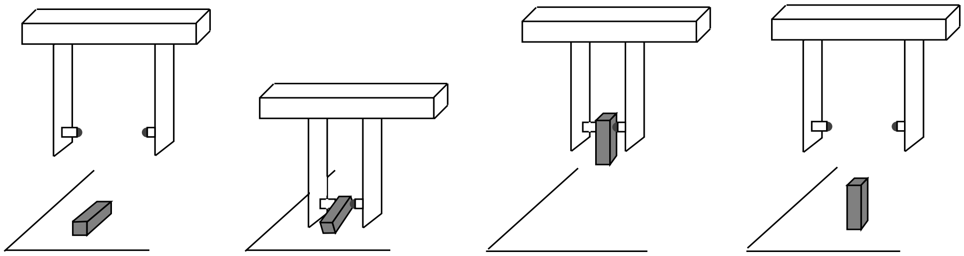

Figure 2: The figure shows 4 snapshots progressing from left to right. The gripper grasps the rectangular part along an axis offset from its center of mass, lifts it off the table, and uses the force of gravity to rotate the part into a standing orientation.

2 Related Work

To feed parts, manufacturers generally rely on passive devices that use mechanical filters to reject all parts except those in a desired orientation. Rejected parts are recycled for another pass through the filter. The most common type of feeder is the *vibratory bowl feeder*, where parts in a bowl are vibrated with a rotary motion so that they climb a helical track. As they climb, a sequence of baffles and cutouts in the track creates a mechanical "filter" that causes parts in all but one orientation to fall back into the bowl for another attempt at running the gauntlet [3, 27, 29]. To improve feedrate, it is sometimes possible to design the track so as to mechanically rotate parts into a desired orientation (this is known as *conversion*). Related methods use centrifugal forces [5], reciprocating forks, or belts to move parts through the filter [26]. The biggest disadvantage with such methods is that when part geometry changes, the filters must be mechanically redesigned with a manual trial-and-error process.

There are currently no systematic methods for designing filters; it is a "black art" performed by specialists through trial and error. Filters must be tested and incrementally modified when they cause parts to jam. The difficulty is that a tweak that avoids parts jamming in one orientation may cause parts to jam in another [8, 39].

Sony's APOS parts feeder [12] uses an array of nests (silhouette traps) cut into a vibrating plate. The nests and the vibratory motion are designed so that the part will remain in the nest only in a particular orientation. By tilting the plate and letting parts flow across it, the nests eventually fill up with parts in the desired orientation. Although the vibratory motion is under software control, specialized mechanical nests must be designed for each part and jamming must be avoided as with bowl feeders [19]. Singer and Seering [32] proposed several designs for programmable parts feeders where programmed vibration was used to drive parts into a stable orientation. These methods can be useful for bringing parts into one of several "low-energy" poses where its center of mass is as low as possible.

In the early 1980's, several researchers used sensors to determine the pose of parts delivered by a vibratory track [26]. Sensors such as tactile probes [9, 36], photocells [10], fiberoptic sensors [23], and machine vision systems [11, 33] were employed. Once part pose was determined, air-jets and trapdoors were used to group parts in similar poses. Adept Technology Inc. has several commercial installations that use a 4DOF robot to reorient parts in the plane. We know of no system that combines vision with a 4 DOF robot to rapidly orient parts in 6 DOF.

Developing a task-based robot motion planner has been a goal in robotics since the early days [22, 34, 16]. Paul's HAND EYE system for solving the "instant insanity" problem was the first to automatically generate intermediate part poses when a transformation could not be accomplished in a single motion due to limits on reachability or arm kinematics. Since then, a variety of algorithms have been developed for robot motion planning [15]. In particular Tournassoud, Lozano-Perez, and Mazer [35] considered the problem of moving polyhedral parts from one pose to another using a sequence of *regrasping* actions with a 6 DOF robot and parallel-jaw gripper. The authors took advantage of the fact that parts generally have a finite number of stable poses. We note that both HAND EYE and HANDEY used a 6 DOF arm to reorient parts by regrasping. Quoting from [35]:

> *Part motions during which the object remains in contact with the hand...can only be performed by a dextrous hand as they rely on precise control of forces exerted on the object.*

The authors suggest how a dextrous hand might reorient a pen by grasping it below the center of mass and relaxing the grasp force so that it rotates into a new orientation. In this paper we show that such manipulation can be achieved without precise force control using a mechanical modification to the parallel-jaw gripper.

The text by Kato and Sadamoto [13] includes detailed photos and drawings of over 150 novel mechanisms for robot end effectors. Perhaps the closest ancestor of our pivoting design is the mechanism developed by John Birk at the University of Rhode Island, which was also motivated by the need to orient parts. Birk's hand [1] has a powered belt that causes parts to rotate about an axis parallel to the gripper jaws rather than about an axis perpendicular to the jaws as in our design. A similar pivoting joint is standard on most C-clamps available in hardware stores. We note that such clamps only have a pivot on one jaw so that the pivot is immobilized once the part is grasped.

Figure 3: An exploded view of the mechanism for one pivoting pad. Frictional resistance to torsional and axial forces are reduced with needle and thrust bearings as illustrated. The contacting pad can be of flat hard rubber (in our case a pencil eraser). The pad turns with the part, thereby insuring frictional resistance to slip as the part is lifted and transported.

Goldberg and Furst developed a parallel-jaw gripper with a *translational* bearing rather than a rotational bearing. The translating bearing serves to reduce effective friction parallel to the support plane and thus aids in achieving a stable grasp. One similarity to the pivoting gripper is that the additional degree of freedom does not require an active servo system. Also, both grippers were designed for application to parts feeding [6].

3 The Pivoting Gripper Mechanism

Our idea for rotating parts requires two "hard finger" contacts, which are defined as contacts that can apply forces pointing into the friction cone but cannot resist torques about the contact point [28]. Clearly, a grasp with two hard finger contacts cannot achieve form closure as the part is free to rotate about the contact axis. Indeed, [17] showed that 4 hard finger contacts are both necessary and sufficient to achieve form closure on a polyhedron. However for feeding parts we do not require form closure; we want to insure that the part will not *translate* when lifted, and in contrast to most work on grasping, we want to insure that the part *will* rotate about the grasp axis.

One way to achieve hard finger contacts is to use sharpened points. Such point contacts are sensitive to small variations in part orientation and do not have the "self-aligning" benefits of flat contacts. Furthermore, point contacts may damage the part. To implement true hard finger contacts, the biggest problem is eliminating frictional resistance to torques about the pivot axis.

We propose to use a bearing mechanism as illustrated in figure 3.

An important consideration is that the bearing mechanism have a small footprint and also permit the pivoting axis to reach as close as possible to the worksurface to grasp small parts. Machining such a mechanism poses practical difficulties. We machined our own bearing races and used custom needle bearings to build a prototype with footprint 13×22mm permitting the pivot axis to be lowered to within 6mm of the worktable. We used flat-topped pencil erasers to provide high frictional resistance to translational forces.

We mounted a pair of these bearings on a commercial pneumatic parallel-jaw gripper. When the jaws are closed under air pressure, compressive forces tax our thrust bearings and introduce frictional resistance to rotation. Fortunately, we have found that it is a simple matter to achieve compliant rotation by brushing parts against a fixed "lip" in the environment. The brushing movement can be achieved with a combination of vertical and horizontal movements of the arm, thus requiring no actuation at the pivot.

4 The Parts Feeding System

Our feeder design is based on a commercially-available system that integrates machine vision with a high-speed robot arm. The system is programmed based on the type of part to be fed. During operation, a collection of like parts are dropped and randomly scattered on a flat worktable where they are subject to the force of gravity. A set of conveyor belts is used to singulate parts and transport them into the field of view of an overhead camera. Note that in general, parts will only have a finite number of stable poses under the influence of gravity. Each of these is treated as a unique pattern by the vision system, which identifies each pattern and its pose (position and orientation). Each pattern indexes into a pre-programmed manipulation routine for the pivoting gripper which picks up the part, reorients it if necessary, and moves it into a desired final pose. The process is then repeated for all parts that can be identified by the vision system. Remaining parts are recycled for another pass through the system.

We implemented a prototype system in our laboratory using a commercially-available robot system: Adept 604-S SCARA type arm, standard CCD camera, and Adept's AIM vision software. Figure 4 shows a photo of the system in our laboratory. In one case we placed registration marks on the parts to cope with ambiguous and symmetric poses (one method for locating such marks is described in [24]). We also used diffused overhead lighting to reduce shadows and specularities.

In our initial experiments, we hand-singulated the parts by dropping them one-by-one into the camera's field of view. We also hand-coded the grasp points for each pattern. After the robot reorients the part and places it into a pallet, it returns to a home position and waits for the next part to be dropped into its field of view. We tested the system with two sets of parts: rectangular parts made of steel and orange insulating caps made of plastic. The latter parts were sufficiently lightweight that gravity did not provide sufficient torque to overcome friction; in this case we brushed parts past a fixed lip to achieve the same effect.

The resulting system worked quite reliably. We achieved feed rates of 5 seconds per part, including visual recognition of pose. In an industrial setting, the vision and manipulation can be pipelined to speed operation. The system was able to successfully feed parts about 90% of the time. Failures were typically due to errors in visual recognition, grasp location, or incomplete pivoting along the lip. A videotape of these experiments is available.

5 Comparison with Existing Feeders

Our goal is to develop a programmable system that efficiently feeds a broad class of industrial parts. Parts to be fed will be singulated with the aid of vibration and a series of conveyor belts traveling at different speeds; parts that are not recognized or are unable to be reoriented will be rejected and recirculated.

This design for a programmable feeder offers the following advantages over previous methods:

- **Fast set-up and changeover**: The camera, robot arm, and gripper can be used for a wide variety of part shapes. To set-up for a new part, only the vision and manipulation routines must be changed.

Figure 4: Experimental system in our laboratory.

- **Less damage to sensitive parts**: The proposed feeder is highly suited for delicate parts such as electronic or optical components.
- **Compatibility** with large and small parts. Vibratory bowls are generally limited to parts of diameter five inches or less due to restrictions on bowl diameter.
- **Less Likely to jam**: No mechanical filters are required.
- **Lower Noise**. OSHA Noise limits are 90 dBa, maximum employee exposure over eight hours. Shrouds to contain noise can add up to 25% to the cost of vibratory bowls [39].

This feeder design is not intended as a universal panacea. The initial investment for the first feeder will be higher than that for conventional (hard-tooled) feeders. And certainly conventional feeders will be more cost effective for high-volume parts such as fasteners and washers. But our hunch is that the flexibility of the vision-based system will be cost effective in the long run for a variety of industrial applications.

6 Planning Algorithms

To configure such a system for a new part, two changes in software are required: vision and manipulation routines. In our initial experiments the former was programmed using proprietary statistical decision software from Adept, and the latter was hand-coded. We are now working to develop planning algorithms for automatically programming the system based on part geometry.

Given a CAD model of a part and its center of mass, the first step is to determine all of the part's stable poses under the force of gravity. For polyhedral parts, we can compute the convex hull of the part and check if the center of mass projects into each face. Clearly, a polygonal part with n faces can have no more than n stable poses. For more general classes of curved parts, we are working with Dave Kriegman to build on a recent algorithm described in [14].

Each stable pose presents a projective image that can be identified by the vision system. Well-known methods exist for automatically generating shape recognition routines (some of these have been incorporated into Adept's commercially-available software). We are also studying algorithms for automatically locating registration marks to reduce ambiguities.

A primary challenge is to develop algorithms that, given a CAD model of a part, will automatically plan appropriate grasp strategies for each stable pose. Given polyhedral part shape and coefficient of friction as input, the problem is to find a (possibly empty) set of grasps that will achieve the following objectives [25]:

- The line connecting these contacts (the contact axis) is parallel to the worktable (due to the limited kinematics of the robot arm),
- The part will not slip as it is lifted off of the plane,
- The part will rotate about the contact axis as it is lifted due to the force of gravity and come to rest such that:
- When the part is replaced on the table it will assume the desired pose.

Automatic planning software would permit offline analysis of the "feedability" of a proposed part, thereby providing designers with rapid feedback [38]. It may also be possible to to predict feedrates offline using a probabilistic analysis of pose stability, ie, system feedrate is related on the probability that a part will land on each of its stable faces [20, 7]. We have implemented a method similar to that presented in [2], which starts with the convex hull of the part. Each face of this hull is projected onto a unit sphere centered on the part's center of mass. This projected face defines a "capture range", a set of contact orientations that will converge on enclosed face as the part falls under quasi-static conditions. An $O(n^2)$ implementation is described in [37]. We acknowledge that more accurate prediction of pose probabilities would require us to model the complex dynamics of frictional collisions which is notoriously difficult [18].

Many variations of the above system are possible. We might also include an active clutching mechanism for locking the pivot when part rotations are undesirable. This would, for example, allow the same gripper to be used for feeding and inserting parts.

The system described in this paper is an example of what might be called a "RISC" approach to industrial robotics: **R**educed **I**ntricacy in **S**ensing and **C**ontrol [4]. The idea is to reduce complex manipulations to a sequence of primitive operations that can be performed with simple mechanisms such as the pivoting gripper. A challenge is to develop robust planning algorithms that will automatically perform this reduction. We believe that such algorithms can have near-term application to manufacturing.

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