

# Design of a Flexible Parts Feeding System

Greg C. Causey, Roger D. Quinn  
Department of Mechanical and Aerospace Engineering  
Nicholas A. Barendt, David M. Sargent, Wyatt S. Newman  
Department of Electrical Engineering and Applied Physics

Case Western Reserve University (CWRU)  
Cleveland, Ohio 44106

## Abstract

This paper describes the design and implementation of a flexible parts feeding system. While flexibility encompasses every part of the workcell design, including hardware and control software, the ability to feed parts in a wide variety of sizes and shapes is crucial. Conventional feeding methods, such as vibratory bowl feeders, are not practical for flexible workcells because of their specialized nature. This system is composed of three conveyors working together. The first conveyor is inclined and lifts parts from a bulk hopper in a quasi-singulated manner. Parts fall from the first conveyor onto the second, horizontally mounted, conveyor. An underlit window at the end of the second conveyor presents a silhouette image of the parts to a vision system. After the pose of a part has been determined, a robotic arm is used to acquire it. Parts which are in unfavorable orientations or are overlapping are returned to the bulk hopper by a third conveyor. Guidelines for part design which improve the feeding system's performance are also presented.

## 1. Survey of Previous Approaches

Flexible parts feeding has been and continues to be the most difficult and elusive piece of the agile puzzle. As current trends in production continue towards agility<sup>1,2</sup>, non-flexible feeder designs become less and less viable. Rapid changeover between products and rapid introduction of new assemblies is hampered if the feeders cannot be quickly reconfigured<sup>3,4</sup>. Several current designs are discussed below.

Genex, Inc. markets a feeder (also called the Adept FlexFeeder 250) that has seen limited commercial use<sup>5,6</sup>. This feeder uses a short horizontal conveyor to hold bulk parts. An underlit window located in the end of a second horizontal conveyor, mounted below and forward of the first, is used to present parts to the vision system. A third conveyor returns unused parts to a bucket which transports them to the first conveyor for recirculation.

The FPF 2000, marketed by Intelligent Automated Systems, uses a different approach. A bin with a trap door is used to drop parts onto a vibrating plate. The plate ends on an underlit conveyor which presents the parts to the vision system. A second conveyor returns



Figure 1: Flexible Parts Feeder

unused parts to a bucket which drops them back into the bin for re-feeding.

Robotic Production Methods Inc. has designed several feeders which utilize a similar technique<sup>6</sup>. Parts are lifted from a hopper using a conveyor belt or a vibrating plate. In one design, parts are presented in a vision window that uses overhead lighting; and in another, specialized modular tooling plates are used for orientation. In either case, parts not in the correct orientation fall back into the hopper.

AT&T has a feeding system that uses a combination of vibrating plates covered with structured carpet to transport parts around a rectangular loop. At one end, a vision system employing overhead lighting is used for pose estimation.

## 2. Current Design

In keeping with the goals of rapid change-over, the parts feeders need to deliver a wide variety of parts to the workcell with minimum mechanical alteration. This is accomplished in the current design with the use of multiple conveyors in a unique arrangement. Figure 1 shows two views of the feeding system. In the first, LEGO<sup>TM</sup> blocks are going up the inclined conveyor and dropping from the return conveyor into the hopper (not shown). In the second, sockets are spilling from the inclined conveyor onto the horizontal conveyor. Figure 2 shows a schematic view of the feeding system.

### 2.1. Conveyors

Three conveyors work together to present parts to the workcell for assembly. The first conveyor, under servo control, is mounted at an inclined angle and is used to lift parts from a bulk hopper. By varying the angle of

inclination and motion profile, a wide assortment of parts are deliverable from the hopper. Some part geometries, spherical for example, have no stable pose which allows them to be carried up an incline. In these cases a different type of belt (e.g. cleated) is needed. Currently a 12'' wide, 72'' long QC 125 series conveyor is being used.

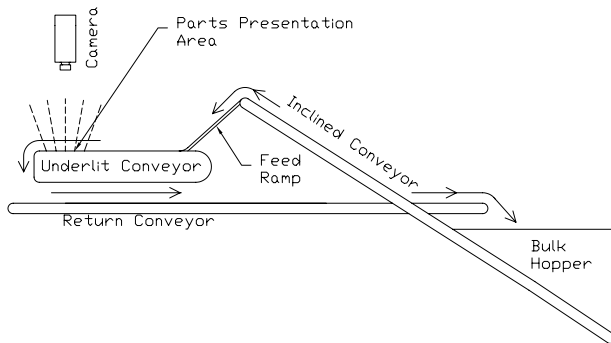


Figure 2: Flexible Feeding System

Parts slide down a ramp at the end of the inclined conveyor and onto the horizontal conveyor. The horizontal conveyor terminates within the work envelope of the robot, where a window is machined. Lights are installed in this window, under the translucent conveyor belt, to provide backlighting for binary vision. Two layers of translucent white Plexiglas with several layers of photographic diffuser are installed in the window to serve as a bed for the conveyor belt as well as to produce a uniform light field. An 8'' wide, 36'' long Dorner 3100 series conveyor, under servo control, is used. This model was chosen because it is 3'' thick, allowing more room for lights. A 1'' end roller attachment is used which allows the vision window to be located nearer the end of the conveyor than with the standard end roller.

Parts which are not in useful orientations or are overlapping are dropped from the end of the horizontal conveyor onto the return conveyor. The return conveyor transports the parts back to the bulk hopper for re-feeding. A 6'' wide, 8' long QC 125 series conveyor is used.

## 2.2. Servo Control

Initially, it was hoped that open loop velocity control would be sufficient for operating the feeders. Unfortunately, since most moves were only several inches, it proved difficult to regulate the distance each conveyor traveled as well as the distance they traveled relative to one another. Therefore, servo control is used for the inclined and horizontal conveyors.

A Galil 1500 stand alone motion controller is used in this implementation. The horizontal and inclined conveyors are driven by encoder equipped DC motors. Inline transmissions are used to match the output speed range of each motor to the desired speed range of each conveyor. The motor controller communicates with the workcell system controller<sup>2</sup> via a number of digital I/O lines.

The use of a closed loop system allows for more precise control of the conveyors. For example, rapidly shaking the horizontal conveyor back and forth can, in some instances, help singulate parts or move them into a more desirable pose. Rapidly shaking the inclined conveyor can also increase the throughput of the feeder. Without shaking, if the angle of the conveyor is not steep enough, too many parts tumble onto the horizontal conveyor making vision and grasping impossible. By shaking the conveyor, parts in marginally stable poses and those that are stacked on top of one another are dislodged and fall back into the hopper. This yields a more steady flow of parts through the system than would be the case by increasing the angle of the inclined conveyor.

The return conveyor runs continuously and is driven by a fixed-speed AC motor, which only needs to be turned on and off by the controller at system startup and shutdown. This is accomplished by a relay attached to a single digital output from the Galil controller.

## 2.3. Backlighting/Overhead Binary Vision

Part recognition is performed using CCD cameras mounted over the vision window in the horizontal conveyor. Backlighting was selected for many reasons: it is easier to produce uniform backlighting than overhead or oblique lighting; overhead lights may limit the robot's workspace; conveyors lend themselves to backlighting; reliable binary images are easily produced; and backlighting is less part specific than other lighting methods.

Binary images were chosen because greyscale images are more difficult to work with and require more complicated algorithms to determine the pose of a component. Binary images are also faster to process than greyscale images, which is important in a manufacturing system since the assembly cycle time should not be hampered by the vision system.

## 2.4. Lighting Subsystem

The lighting system used in the horizontal conveyors has undergone several iterations. Compact fluorescents were initially chosen as the light source for several reasons, including size constraints, uniformity of light, frequency spectrum, and cost.

In the first design, three standard incandescent light sockets with compact fluorescent adapters, utilizing electronic ballasts, were mounted in the conveyor. Fluorescent bulbs were placed in each adapter. Several problems were immediately noticed with this design. The uniformity of the lighting was inadequate: the center of the window was found to be much brighter than the edges. Adapter life was also a problem. Heat buildup in the end of the conveyor was found to be partly responsible for adapter failure.

In an attempt to improve the uniformity of the backlighting, a second iteration of the design was initiated. Four lights were placed in the conveyor using

slimmer mounting adapters and standard fluorescent ballasts. In an attempt to control heat, the ballasts were moved outside the conveyor. While the light was more uniform, heat was still a problem. After 2 - 4 hours, temperatures inside the conveyor reached 250 °F.

In the third design, two pancake fans were placed inside the conveyor to force air over the bulbs and out vent holes. This lowered the steady state temperature to an acceptable 100 °F. Figure 3 is a drawing of the 1<sup>st</sup> and 3<sup>rd</sup> generation designs.

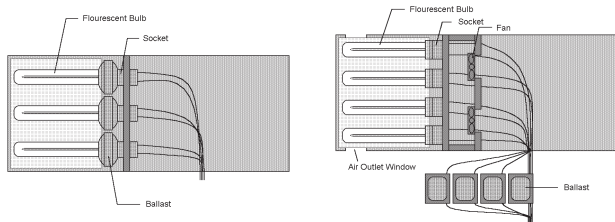


Figure 3: Lighting Design Evolution

The uniformity of the lighting still needs improvement. Several options are being explored including ultra-thin cool-cathode fluorescent bulbs or the use of an array of LEDs. A custom woven fiber optic pad is also being examined. Although the price of such a system would be much greater than the current setup, it may be necessary to achieve the desired results. However, before such an expense can be justified, less expensive designs need to be explored.

### 2.5. Conveyor Belt Selection

The selection of the conveyor belt can have a major impact on the function of both the inclined conveyor and the horizontal conveyor. A belt with a high coefficient of friction is needed for the inclined conveyor to provide the force which lifts the parts from the bulk hopper. The belt surface also needs to be durable to withstand the parts tumbling in the hopper. Parts which will not travel up an inclined conveyor may need a cleated or roughly textured belt to lift them from the bulk hopper.

The selection of the belt for the horizontal conveyor is also important. The belt needs to be translucent and have a homogeneous construction to permit uniform lighting. Many translucent conveyor belts currently being manufactured have black anti-static fibers woven into them. These fibers can interfere with the vision system and degrade the uniformity of the lighting.

## 3. Design for Feeding

Designing parts for use in a flexible feeder can have profound results on the overall effectiveness of the system. Alterations in part designs do not have to be drastic, often only a redistribution of mass is necessary to improve the probability of a particular stable rest position. A slight shifting of a vision fiducial can be sufficient to

provide an asymmetry which can be used to determine pose. Several general guidelines have been determined to facilitate the design of parts for flexible feeding. Two distinct areas affect throughput of the feeder; features to enhance the static stability of parts and features to enhance vision recognition. While other guidelines<sup>7,8,9</sup> for parts design for assembly (static stability) have been compiled, we have also developed several guidelines which enhance vision recognition. Some of our guidelines contradict guidelines for assembly listed by others. For example, "If complete symmetry is not possible then exaggerate asymmetric features<sup>7</sup>". An exaggeration of an asymmetric feature is not necessary for a vision system and could effect the aesthetic appearance of the part. A slight asymmetry is all that is needed for the vision system to determine the pose of the part.

### 3.1. Physical Guidelines

Lacking any specialized orientation hardware, parts tend to settle onto the horizontal conveyor in statically stable orientations. Because of this, it is important to consider the feeding system when designing parts.

The first guideline is to minimize the number of stable poses of a part. This increases the probability that a part will land in a suitable orientation. Consider, as an example, two test parts shown in Figure 4. A snap ring has two stable orientations, face up and face down, which are identical. Since it does not matter which side is up, all snap rings on the horizontal conveyor which are singulated are potential candidates for assembly. In contrast, LEGO™ blocks have 3 - 4 stable poses; top (or nubs) up, bottom up, side up, and in some instances, end

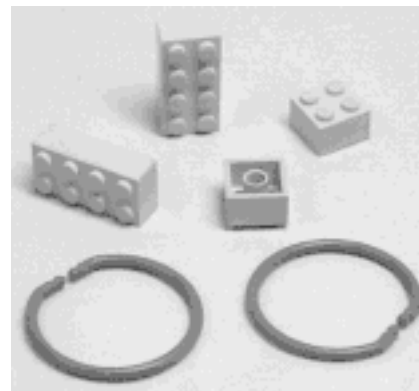


Figure 4: Plastic Snap Rings & LEGO™ Blocks

up. A singulated LEGO™ block on the horizontal conveyor has less probability of being in the correct pose for assembly.

The second guideline is to design parts to have stable orientations which are consistent with the given assembly. For example, if a part needs to be inserted into an assembly with side A down, then it is useful for the part to have a statically stable orientation with side A

down. This can lead to difficulties during the design. In some situations, it is impossible to satisfy the above criterion. For example, long, slender parts needing to be inserted lengthwise from above (e.g. a pin into a hole) are a problem since it is impossible to design the pin to be stable standing on end. Rotary jaw grippers<sup>2,10</sup> or specialized hardware may be employed to grasp the part in its stable orientation and then rotate it for assembly.

The third guideline is to design parts to prevent tangling and nesting. Coiled springs have this problem. A hopper full of springs could quickly become one large tangled mass after a few minutes of operation. The plastic snap rings also exhibit this problem. A slight design change that could alleviate this problem is to mold a strand of plastic across the gap of the ring which could be broken by the grippers during assembly, but which would prevent interlocking.

The fourth guideline is to design parts which are not easily damaged by the feeder. In the bulk hopper, parts tumble and rub against one another; if they are fragile or have an easily marred surface finish, they could be damaged. If they are recirculated during feeding, they must fall from the end of the horizontal conveyor to the return conveyor, then from the return conveyor back into the bulk hopper. Both these drops have the potential to cause damage. As an example, parts with transparent areas, such as display covers for automotive dashboards, could be scratched.

Finally, parts need to be designed so as not to damage the feeding system. For example, heavy parts with sharp corners could damage the belts of the conveyors when being fed.

### 3.2. Vision Recognition Guidelines

While getting the parts to the vision window in a singulated, usable pose is important, it is only one design consideration. Given a candidate part, the vision system must be able to identify the pose of the part and determine whether it is graspable<sup>11</sup>. This, as stated above, is in the context of backlit, binary vision; the information to the vision system is a silhouette of the given part.

The first principle is, if possible, to design parts with rotational invariance. This means that a part can be assembled in more than one rotational orientation, much like a washer or a nut. Parts which can be assembled in such a manner do not require that the pose be uniquely determined. This means that the vision system need only determine if a part is in an acceptable location and report the position to the robot. The orientation of the part is not important.

Often, it is not possible for the part to be designed with rotational symmetry. Other times, the part may have rotational invariance, but have an up/down orientation that must be determined. In such cases it is important to design parts with an asymmetry such that its pose may be uniquely determined. It is not, however, necessary to make the asymmetry extreme. Such

asymmetries allow the angular orientation and the up/down orientation to be determined. Several examples of such design features follow.

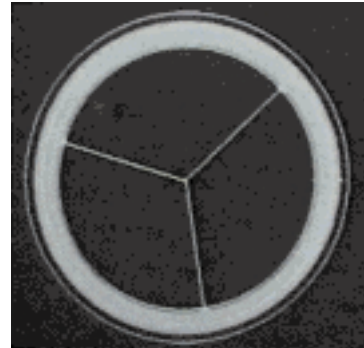


Figure 5: Vision Processed Image of 3 Asymmetric Nubs

Three nubs may be placed on the inner circumference of a ring or on the outside diameter of a disk at slightly differing relative angles,  $116^\circ$ ,  $120^\circ$ , and  $124^\circ$  for example. If the relative angles between nubs are always determined in one direction (i.e. always clockwise or always counter-clockwise) then the order of appearance of each angle creates an orientation signature that can only have two states, if viewed as a circular list. If the list is shifted such that the smallest value is first, then examining the value of the second element reveals the up/down orientation as well as the rotational orientation. Figure 5 shows the image of a ring with three internal nubs after vision processing. While not readily apparent to the eye, the vision system easily finds the  $4^\circ$  offset.

Two “shoulders” of a part may have slightly different lengths to create an asymmetry. Consider, for instance, a small plastic thumb switch found in many electronic devices, shown in Figure 6. The pose of the switch is easily determined by examining the length of each shoulder relative to the location of the end of the base. After acquiring an image, the major axis of the part is determined. By examining the distance to the edge of the part to the left and right of the axis, the up/down orientation can be determined. If the smaller distance is to the right of the axis, the part is face up. If, conversely, the

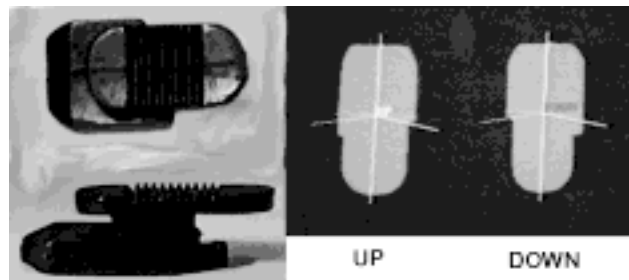


Figure 6: Switch & Visioned Processed Image

smaller distance is to the left of the axis, the part is face down. The unequal “shoulders” presented by the



switch's silhouette make determining its orientation straightforward. Figure 6 shows the switch and the corresponding image after vision processing.

The third principle is to avoid translucent parts. Plastic lenses on display panels are an example. Vision on clear parts is, obviously, difficult at best. Often though, the parts are mounted in an opaque housing which obscures the perimeter of the lens. It is then possible to place a opaque band around the exterior of the part without affecting its performance. Sandblasting the relevant area of the mold, for example, will produce a frosted area which can be seen by the vision system. This can be done without adding a step to the part's manufacture.

## 4. Testing/Results

Various parts were fed and data collected to quantify feeder performance. The test parts included different sized nuts, plastic snap rings, plastic sockets, clear plastic disks, and various shaped LEGO™ blocks (see Figure 7). During the testing, physical parameters of the system (angle of inclination, conveyor belt material, etc.) were not altered. Only the servo control program was changed. A button was attached to a digital input of the motor controller so that the feeder could be advanced manually.

### 4.1. Testing Procedure

The testing proceeded as follows. First the hopper was loaded with the parts being tested. Next, both conveyors were cycled continuously until steady state had been reached. Then the feeder was advanced and the number of graspable parts (parts which had sufficient clearance for the gripper to approach) was recorded. At times, as one part was removed, other parts would become graspable. When no more parts were removable, the conveyor was advanced again. 300 advances were performed for each part type.

During testing, the following scheme for conveyor control was followed. Rather than advance both conveyors together, an approach was taken which would "load" the horizontal conveyor at regular intervals. This was accomplished by running the horizontal conveyor rapidly for a distance approximately equal to its length. At the same time the inclined conveyor would be advanced a lesser amount. Then only the horizontal conveyor would be indexed (distance = width of window - major part dimension) to bring more parts into the vision window. After the entire length of the horizontal conveyor had been examined, the "loading" process would begin again. Shaking the inclined and horizontal conveyors would only take place after a "loading" operation had occurred.

Throughput is listed as the average number of parts acquired per feeder advance (averaged over 300 conveyor advances) and not as the quantity of parts per

minute, which is highly dependent on the speed of the vision system and the robot being used. Table 1 shows the results of the testing.

Part Name	# of Parts/Advance
Nuts	1.75
Plastic Snap Rings	0.40
Plastic Sockets	1.00
Plastic Disks	0.55
LEGO™ Blocks	1.44

Table 1: Feeder Throughput - Manual

Further testing was done on nuts and sockets using an Adept 550 robotic arm to remove parts from the underlit window and drop them onto the return conveyor

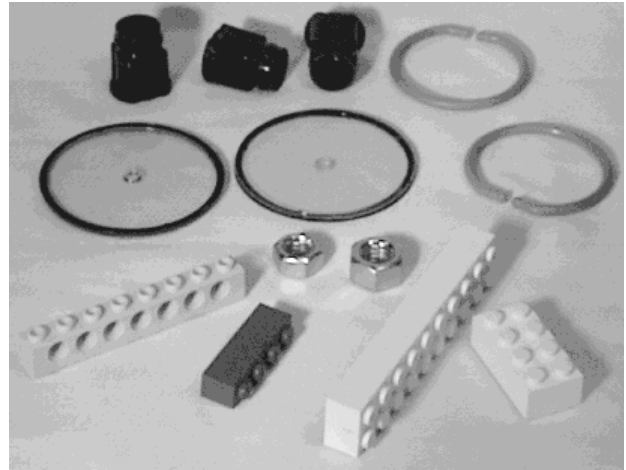


Figure 7: Array of Test Parts

for recirculation. In both cases, the system was run for 12 hours and data collected. Three performance criteria were derived for each test case. The first criterion included only time used in incrementing the feeder. This is an upper bound on the physical throughput of the feeder. Vision processing time and robot motion was not included. The second criterion included feeder movement and vision processing time. The third criterion included feeder movements, vision processing, and robot motions. This was the total number of parts fed divided by the total time of the test. Table 2 shows the results of the automated testing. Values listed are parts per minute.

	Feeder	Feeder + Vision	Total
Sockets	75	15	8
Nuts	147	20	9

Table 2: Feeder Throughput - Automated

As can be clearly seen, the throughput of the feeder is limited by the speed of the vision processing system and the speed of the robotic arm. During testing, the robot was operated at 75% of its rated speed.

## 4.2. Part Description and Feeding Strategy

### 4.2.1. Nuts

Two different sized hex nuts, 3/8" and 5/16", were used for the test. A small parallel jaw gripper was designed to manipulate the nuts, therefore little clearance was needed. The hex design and rotational invariance of the nut allows for 3 possible locations for pickup. Both the inclined and horizontal conveyors were shaken during feeding.

### 4.2.2. Plastic Snap Rings

The plastic snap rings are approximately 1.75" in diameter with a circular cross section of 0.125". The gripper grasps the rings from their inside with a spreading motion, therefore no clearance was needed. A small amount of singulation was necessary for locating a part. Only the inclined conveyor was shaken during feeding. Shaking the horizontal conveyor decreased the throughput by causing singulated rings to slide together making vision segmentation difficult.

### 4.2.3. Plastic Sockets

The plastic sockets are approximately 0.75" on a side by 1" long. They have a hollow center and are closed on one end. A rotating jaw gripper<sup>2</sup> was used to manipulate the sockets, therefore some clearance was needed for pick-up. Both the inclined and horizontal conveyors were shaken during feeding.

### 4.2.4. Plastic Disks

The transparent plastic disks are approximately 2.125" in diameter and 0.125" thick. A thin black band was marked around the perimeter so that the vision system could locate the parts. A suction cup gripper was used to manipulate the disks, therefore no clearance was necessary. A small amount of singulation was necessary for locating each part. As for the snap rings, only the inclined conveyor was shaken during feeding.

### 4.2.5. LEGO™ Blocks

An assortment of LEGO™ blocks were tested for feeding. Sizes from one nub wide by two nubs long to two nubs wide by 14 nubs long were included. The small parallel jaw gripper used for the nuts was also used to grasp the LEGO™ blocks. Since all the blocks (regardless of size) were grasped from the center, some clearance in that area was necessary. Only the horizontal conveyor was shaken during feeding. Shaking the inclined conveyor caused too many parts to tumble back into the hopper.

## 5. Conclusions

A functional flexible parts feeding system has been designed and implemented. The system consists of

three conveyors working together. Two of the conveyors are under closed-loop servo control while the third, return conveyor is driven by a fixed-speed AC motor.

Guidelines for designing parts for use in a flexible feeding system have been developed. They include guidelines for physical design to improve the probability of parts arriving at the vision window in the correct orientation and guidelines for designing parts such that their pose may be readily determined by a binary vision system.

The system has been shown to feed a variety of parts with no physical modifications and only slight modifications to the control code based on the geometry of the part.

## 5.1. Acknowledgments

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<sup>1</sup>R.D. Quinn et al. Design of an Agile Manufacturing Workcell for Light Mechanical Applications. *IEEE International Conference on Robotics and Automation Proceedings*, 858-863, 1996.

<sup>2</sup>F.L. Merat et al. Advances in Agile Manufacturing. *CAISR Technical Report TR96-104. IEEE Conference on Robotics and Automation Proceedings*, 1997.

<sup>3</sup>T. Lynch. Smart Parts Feeder Speeds Agile Assembly. *Design News*, 8/14/95.

<sup>4</sup>D. Boehlke. Smart Design for Flexible Feeding. *Machine Design*, 12/12/94.

<sup>5</sup>F. Buchi. Breakthrough in Economic Flexible Parts Feeding. *RIA 3<sup>rd</sup> Annual Workshop on Flexible Parts Feeding for Automated Handling and Assembly*, 1995.

<sup>6</sup>E.M. Ross. Flexible Parts Feeders for Vision Guided Robots. *RIA 2<sup>nd</sup> Annual Workshop on Flexible Parts Feeding for Automated Handling and Assembly*, 1994.

<sup>7</sup>A.J. Scarr et al. Product Design for Robotic and Automated Assembly. *IEEE International Conference on Robotics and Automation Proceedings*, 796-801, 1986.

<sup>8</sup>G. Boothroyd and P. Dewhurst, *Product Design for Assembly*, Boothroyd Dewhurst, Inc., March 1991.

<sup>9</sup>G.J. Kim et al. A Shape Metric for Design-for-Assembly. *IEEE International Conference on Robotics and Automation Proceedings*, 968-973, 1992.

<sup>10</sup>B. Carlisle et al. A Pivoting Gripper for Feeding Industrial Parts. *IEEE International Conference on Robotics and Automation Proceedings*, 1650-1655, 1994.

<sup>11</sup>David Michael Sargent. A Framework for Computer Vision in Agile Manufacturing. Master's Thesis, Case Western Reserve University, 1996.