5 Gripper Design Guidelines

5.1 Introduction

The design of the end-of-arm tooling for a robotic assembly system is of the highest importance. This is the piece of the workcell that physically interacts with the environment. While well designed grippers can increase throughput, improve system reliability, compensate for inaccuracy in the robot itself, and perform value added functions to the assembly, poorly designed grippers can drop or damage parts, hold parts inconsistently, and decrease system and flexible feeder throughput.

Clearly the design of grippers is of importance. Not providing the necessary time, monies, and expertise for the task is asking for system troubles. The design of grippers is, however, not a trivial task. Often, the finalized parts and assembly sequence is handed to a designer, who must then devise grippers. A better approach is to design the grippers concurrently when designing the rest of the system. Often a small feature added to a part can greatly increase the reliability of the gripper. Other times, a proper gripper design can simplify the overall assembly, increase the overall system reliability, as well as decrease the cost of implementing the system.

The requirements and expectations placed on gripping systems have increased greatly because of the introduction and acceptance of modular manufacturing concepts and vision-based flexible parts feeding. In non-flexible automation systems, the grippers had but one purpose: pick a part from one location and place it at another. Usually grippers were mounted on pneumatic slides which created a pick and place motion. With the proliferation of industrial robots in recent years, however, many new problems and challenges have arisen. Robots themselves have limited payload capacity, limited accuracy, and fixed repeatability. In a hard automation system, the uncertainty comes from the machine stops in the bowl feeder and on the pneumatic slides. In the case of a flexible workcell, there are many more sources of error including: the accuracy and
repeatability of the robot, the vision system, the robot-camera calibration, and the tool offsets. Properly designed grippers can help compensate for these unknowns.

Lately there has been an initiative in the manufacturing community to use readily available, off the shelf components to build up automation systems in a modular way (as discussed in the introduction, i.e. Adept's Rapid Deployment Automation). This catalog potpourri approach to machine design has many benefits including ease of replacement of defective and worn-out parts, cost savings, quicker design and building of the machine, and leveraging the expertise of component builders. Many gripper manufacturers have also taken this approach. It is easy to buy a quick connect, a rotary wrist mechanism, a remote center compliance device, and two pneumatic actuators from the same vendor, bolt them together, and have a fairly complex and sophisticated gripping system. While this is a wise approach to the construction of a gripping system, when the gripper fingers are designed, interaction with specific parts must be accomplished. For this task, off-the-shelf tooling simply will not work reliably. For a positive, nimble, self-centering grasp, the gripper fingers themselves must conform to the shape of the part they are holding. While it is possible in some circumstances (and, unfortunately, necessary in others) to use simple flat plates or “V” grooves, it is simply inviting disaster to do so. Agility would dictate using the most generic, adaptable grippers available to handle the widest variety of parts without changing tools, but with current technology, this is simply not possible. While there has been some promising research in the area of dexterous hands for parts manipulation [99][100], there is not a cost effective, easily controllable hand available. Until that time, the best that can be done is to design the gripping system such that it can be quickly and reliably switched between different manipulators.

Currently, automated design tools exist for many aspects of assembly cells. Gripper design, however, has no such tools currently commercially available. Usually the knowledge and experience of an expert is required to design new grippers. There has been
some work on automated gripper design, but it is still relatively new [101]. Some of the work has centered on examining the quality of the grasp of various gripper finger shapes[102][103][104]. Brost [105][106] has examined grasp planning and planar manipulation tasks that are robust in the face of uncertainty. Others have examined the planning of fixtures which hold parts [107][108]. While not directly gripper design, the same underlying principles apply to both gripper and fixture design. Cutkosky [109] examines grasping by studying the grasp used by humans for various tasks. From this study, a expert system, Grasp-Exp, was devised to determine the grasp for manipulating objects by asking a series of question such as: “What is the dexterity requirement ?”, “What is the stability requirement ?”, “What is the object size ?”, etc. Others have examined the design of chamfers on parts which engage during insertion (i.e. snap fits, etc.) which will not cause the parts to jam relative to one another [110]. Another gripper design project [111][112] has been concerned with the design of grippers to handle multiple parts and the examination of the quality of the grasp when handling multiple parts. Other design guidelines have appeared, but are not applicable to automated design solutions [113][114].

The rest of the chapter is divided into three main sections. The first section deals with the issue of gripper footprint. This is an important concept when designing grippers, especially when designing grippers for use on a flexible feeder. The second section presents guidelines to assist in designing grippers. These are arranged into three major categories: guidelines to increase throughput, guidelines to increase reliability, and guidelines to save cost. Obviously, some of the guidelines are applicable to more than one category while others are mutually exclusive (i.e. designing a reliable and inexpensive gripper may not be possible in all cases). In each case, to further clarify the concept, an example will be given. The final section is a review of the grippers designed for use in a flexible manufacturing workcell. As each gripper is examined, the following will be discussed: what guidelines were followed or ignored and why, any revisions to the
gripper and why, what parts are handled by the gripper, an explanation of the clearance required by the gripper, and how successful was the design.

5.2 Gripper “Footprint”?

An important concept in the consideration of a gripper design is the “footprint” of the gripper. That is, how much additional area around the object being retrieved is required to physically situate the gripper such that it can retrieve the part without a collision. In conventional manufacturing and robotic systems, this was not an important concept because the parts were always presented to the system in the same orientation and location. The clearance for the gripper was consistent and did not change. However, this parameter becomes important in flexible feeding applications where the spacing between parts is random and variable sized. The standard procedure for retrieving a part from a flexible feeder is to first locate the part using the vision system. After a candidate part has been located, then a check must be performed to ensure that there is enough clearance for the gripper to reach the part without colliding with other parts or the feeder itself. A larger “footprint” means less candidate parts will be retrieved simply because the gripper is too big. Since flexible feeding is a random process, it is advantageous to grasp as many parts from the feeder as possible. Letting a part, which could be used for assembly, pass by and be recirculated by the feeder is inefficient and decreases feeder throughput. Unnecessary system delays could occur because an excessively large gripper could not safely approach most of the parts the vision system has identified and located.

An apparently obvious definition of footprint is the vertical projection of the gripper’s fingers when open. This definition is consistent with the implication of the term “footprint” (e.g., the 2D outline left on a plane from a 3D object). However, it is easy to show this definition is overly simplified. In addition, the term “footprint” does not convey the correct mental picture. A better term would be “interference measure”. Further examination reveals that the interference measure is dependent on many factors,
including the physical size of the gripper (in all dimensions, not just the vertical projection), the design of the gripper fingers themselves, the method used to grasp the parts (i.e. vacuum, parallel jaw, pneumatic bellows, ...), the design of the gripper finger actuator, the location and part feature used for grasping, the location of the part on the feeder (in the case of a flexible feeding system), and the material used to construct the gripper fingers, parts, and feeder table.

An example in which the simple, definition fails is a gripper that approaches a part from the side (Figure 5-1). In this case, the gripper, jaws closed, “plows” through the parts until it is close to the desired part. Its jaws then open, the gripper moves to the final retrieval location, and it grasp the part. The interference measure for this gripper part combination would be a narrow channel along which the tip of the gripper moves followed by a larger, rectangular region where the jaws are opened and moved to the final retrieval location.

Another counter example (Figure 5-2) is a complicated wrist mechanism. One gripper approaches from an angle which could allow a second gripper to collide with parts. In this case, the interference measure is not the gripper fingers, but part of the pneumumatic actuator and the second gripper.

A more general and complete definition of the interference measure of the gripper is as follows:
The three dimensional space which must be free of obstructions for a gripper to successfully grasp a part.

A metric (the interference metric) could then be stated based on the interference measure:

The three dimensional volume surrounding the candidate part which must be void of obstructions such that the gripper may approach the part retrieval location without a collision.

There are many nuances and subtleties in the definition and metric. The space does not necessarily have to be adjacent to the part. In the example in Figure 5-2, part of the space that needs to be vacant is displaced by several inches from the front of the part being retrieved.

Another example, Figure 5-3, is a gripper with a large chamfer on the leading edge which would push neighboring parts out of the way as it approached its target part. In this case, the required clearance about a target part would be small relative to the vertical projection of the gripper fingers. In addition, the part and gripper finger material and the material of the feeder surface would also affect the interference measure. For example, if the gripper fingers were made of plastic, the disks metal, and the feeder surface translucent plastic, the coefficient of friction between the parts and gripper fingers and the parts and feeder table would be low, allowing the gripper to push the parts in its path out of the way. However, if the gripper fingers were aluminum, the disks rubber, and the feeder table translucent plastic, the coefficient of friction between the parts and the gripper fingers and the parts and feeder table would be high and the parts would not slide out of the way as the gripper approached.

The possibilities of gripper interference measures are as widely varied as the grippers themselves. The important concepts are that the interference measure of the gripper is not necessarily the vertical projection of the fingers, and that the interference measure should be minimized.
5.3 Gripper Design Guidelines

The following guidelines have been determined while constructing grippers for use in two flexible manufacturing workcells. They are qualitative in nature and suggest ideas for improvements to gripper designs. The first sub-section deals with guidelines to
increase overall system throughput, the second sub-section deals with guidelines to
increase gripper reliability, and the third sub-section deals with guidelines to reduce
gripping system cost.

5.3.1 Design Guideline to Increase Throughput

The purpose of the following guidelines is to increase the throughput of the
workcell. This can be achieved in many ways; increasing the robot speed, decreasing the
chance of waiting for a part to arrive in the flexible feeder by increasing feeder
throughput, or increasing the function of the gripper to do more than just handle parts
are all valid approaches to increasing throughput.

5.3.1.1 Minimize Interference Measure

An obvious design feature which can increase system throughput is designing
grippers to have the smallest interference measure possible. This is important in flexible
feeding applications where parts may be situated close to one another and at random
orientations. If the interference measure of the gripper is too large, then many of the
parts which are correctly located will not be retrievable simply because the gripper is too
big. Depending on the required feed rate for the assembly, unnecessary delays could
occur, not because the feeder is incapable of the proper throughput, but because the
gripper cannot reach most of the parts the vision system has identified and located.

5.3.1.2 Chamfer the Exterior Surfaces of Gripper Fingers

In much the same way as minimizing the footprint of the gripper, chamfering the
outside of the gripper fingers can help increase the throughput of a flexible feeder. The
chamfer can allow the gripper to approach parts that would not normally be accessible by
giving it the ability to push other parts out of the way during the approach. While this is
another technique to reduce the interference measure of the gripper, it is such a simple
and often overlooked procedure, it warranted separate mention.

Consider, for example, a gripper whose fingers are each \( \frac{1}{4} \) of an inch thick. Then
an additional \( \frac{1}{2} \) of an inch of clearance around the desired part will be required for the
part to be retrieved. By chamfering the outside edges of the grippers (Figure 5-3 for example), parts within that $\frac{1}{2}$ of an inch of area can be safely pushed aside as the gripper approaches the desired part. This, of course, requires that a picture be taken after each part has been retrieved to ensure a true location of parts on the feeder are known.

5.3.1.3 Minimize Weight

While the previous two guidelines have dealt with features and rules that help to increase the throughput of the flexible feeding sub-system of a manufacturing cell, this guideline seeks to increase system throughput by allowing greater robot speed. Each robot has a fixed payload capacity; by minimizing the mass of the end-of-arm tooling, the robot can run at higher speeds before overshooting or ringing occurs. Most industrial robots can be modeled as open kinematic chains ending with the gripper. The motors in the robot can only apply a finite amount of torque to each joint. As the mass at the end of the arm increases, the inertia of the arm increases as well. At fixed control gains, an increase in inertia leads to both lower speed of response and greater oscillation.

Ringing or overshoot can be damaging to the workcell hardware, since the robot passes the desired location. If the desired location is adjacent to an existing subassembly or fixture (e.g. the gripper is transferring a part to a fixture location and the gripper fingers are in close proximity to the fixture), then by overshooting the robot could collide with the table hardware. This can damage the grippers as well as the assembly and fixtures.

Weight reduction can be achieved in many different ways. Often it is possible to drill holes through parts of the fingers that serve no grasping purpose. Other places to examine for possible weight reduction are areas that do not directly affect the gripping surface (e.g., the outside of jaws). Also, by making gripper fingers thinner and slimmer, a weight savings can be realized.
5.3.1.4 Ensure a Secure Grasp of Part

As in the previous guideline, an increase in the speed of the robot is one of the desired effects (system reliability will be examined in the next section). Any part has mass, and attempting to accelerate this mass as it is moved from the parts feeder to the assembly area requires force. This force comes through the grasp the gripper has on the part. While it is best to design the gripper to fully encompass the part and not rely on friction, this is often not practical. Assembly itself usually requires the part be added to an existing subassembly or placed into a fixture. In these situations, it is necessary to have the insertion end of the part completely free of the gripper fingers. In cases where gripper fingers cannot fully enclose the part, friction must be relied upon to secure it. Obviously, the more secure the grasp on the part, the faster it can be accelerated and decelerated and therefore the faster the robot can be moved.

Consider a squat, hollow, cylindrical plastic part being grasped from above and placed into a circular hole. The bottom half of the cylinder must remain free so that it may be inserted into the hole. Possible solution to this situation include using two flat plates or two V grooves as gripper fingers. However, in practice, it was found that a more appropriate solution was to use gripper jaws contoured to match the radius of the part at actuator closure. Such a design provided a more secure grasp of the part (the part was more difficult to move or wiggle while being held in the gripper’s jaws) than was achieved with a simplified finger design.

Using Coulomb friction (F = \( \mu \cdot N \)) as a model, there is no difference in holding force between gripper fingers which are constructed as: 1) a flat plate and a “V” groove, 2) two opposing “V” grooves, and 3) contoured fingers which match the shape of the part. These constraints are based on three assumptions: the parts are rigid, the gripper jaws are rigid, and the jaws are perfectly aligned. However, these assumptions are often violated in light mechanical assembly: light, plastic parts typically deform under gripper closure forces; gripper fingers, while relatively rigid, are mounted to an actuator which allows
the fingers to flex (in the direction of closure) as the gripper closes; and imprecise finger
mounting practices can allow the fingers to be mis-aligned when attached to an actuator.
In the absence of these constraints, a contoured gripper finger provides a more secure
grasp.

Since the part and gripper fingers are not rigid, as the gripper closes the force of
closure produces deformation in the part. Using a simple “V” jaw, the local stresses in the
part are high and deformation occurs. If too large a force is used, an excessive amount of
deformation will occur because the contact area between the gripper and part is always
small (not much greater than a line contact). The part may be damaged and the
deformed shape could make the assembly operation difficult or impossible. Using a
contoured jaw, local stress in the part also cause the part to deform. However, as soon as
a small amount of deformation occurs, the contoured gripper jaws contact a larger
surface area of the part. The force of closure is then distributed over a larger area of the
part and much less deformation occurs for a given closure force. Therefore, a higher
closure force may be used to grasp the part which results in a higher frictional force
being produced. In addition, the reduction in deformation prevents the part from being
damaged and does not interfere with the subsequent assembly operation.

Care must be taken to ensure that the contoured finger does not create a
situation in which an over sized part may wedge in the jaws. This can be alleviated by
chamfering the portions of the jaw where the angle between the line of closure of the
gripper and the part geometry is shallow. The area of a cylinder near the jaw’s parting
line or a the sides of a rectangular pocket are examples.

5.3.1.5 Avoid Tool Change

A design guideline which does not have a direct application to the actual design
of the gripper fingers themselves but rather to the gripping system and assembly
procedure as a whole is to avoid tool changes. Tool changes, while automatic, are time
consuming in contrast to most robot motions. The robot must be operated slower during
the tool change to be sure the gripper has been properly placed in its fixture. If the tool is not properly aligned when released, it could be dropped or could come to rest improperly in the tool holder. This could cause problems the next time the gripper is retrieved.

Tool changes also require that the grippers are all within the reach of the robot (unless a complex, secondary mechanism is used to move the grippers into and out of the reach of the robot). Given the size of the work envelope of many industrial robots, real estate within their work envelope is at a premium. Adding several grippers to the amount of hardware that must be reachable by the robot can make laying out the workcell that much more difficult. Cycle times will also increase as the robot is required to cover more of its work envelope during each assembly cycle.

Consider an assembly consisting of three small parts added to an existing subassembly. Assume the subassembly arrives at the workcell on a pallet and that the work occurs directly on the pallet. At first glance, it would appear that three separate grippers would be needed and that many tool changes would be required. By designing the grippers to handle multiple parts and designing multiple grippers onto a single wrist unit (the next two guidelines), the entire assembly can be done without wasting time performing tool changes. Valuable space within the work envelope of the robot can also be conserved.

5.3.1.6 Grasp Multiple Parts with a Single Gripper

As mentioned in the previous section, avoiding tool changes will increase cycle time. One approach to avoiding tool changes is to design each gripper to handle more than one part. While at first it seems as though it would compromise the quality of each grasp, a clever design can usually result in a good gripper.

There are several ways to design a gripper to manipulate many different types of parts. If the parts are of similar shape and size (from a common parts family), then it could be possible to design different features into the jaws themselves that would accommodate various parts. Cylindrical parts are an example. By machining various
diameters into the jaws, multiple different diameter parts can be retrieved. Figure 5-4 shows a gripper finger designed to grasp two different sized cylinders from a horizontal orientation. Diameter 1 is used for the smaller cylinder while diameter 2 is used for the larger diameter (see Section 5.4.4.13 for a complete gripper description).

![Figure 5-4: Gripper Finger to Grasp Two Diameter Cylinders](image)

Another method of grasping multiple parts with a single gripper is to design different features offset from one another on the gripper jaws. This is synonymous with designing two different gripper jaws and mounting them on the same actuator. This approach works well for parts that are vastly dissimilar. Figure 5-5 shows one such gripper finger. Feature 1 is used to grasp a disk shaped part while feature 2 is used to grasp an odd shaped body (see Section 5.4.4.14 for a complete gripper description).

A third method of designing multi-use gripper fingers is to grasp some parts from their outer surface and others from their inner surface. This is especially applicable if some parts have holes through them or pockets in them.
5.3.1.7 Use Multiple Grippers on a Rotary Wrist

There are many parts that are too widely varying in size and shape to be manipulated using a single set of gripper fingers. In these cases, it is often possible to design a separate gripper for each part and mount the grippers on a rotary wrist. The wrist rotates, bringing different grippers into positions in which they can be used. The wrist can be as simple as a pneumatically-driven, two-position actuator which rotates between two different grippers to something as complex as a servoed axis of the robot which can rotate between several different grippers. Often this concept and the previous can be combined to create a sophisticated gripping system capable of manipulating multiple objects without a tool change.

An additional benefit of the rotary wrist design is manipulating multiple parts at once. This can often result in decreased cycle times because of the reduction in robot motions. The robot could go to the first feeder, retrieve a part, then go to a nearby second feeder and retrieve another part before beginning the assembly. This saves time if the feeders are close together relative to the assembly area.

Imagine needing to manipulate two parts for a given assembly. The first is a cylindrical LED which is fed from a bowl feeder, grasped from above and placed into a
recessed socket. The second is a lens which is placed over the LED. In this case, a small pneumatically-actuated, angular-motion gripper would be appropriate for the LED while a suction cup would be used for the lens. In this case, a rotary wrist could be used to swap between the two different grippers. Without the rotary wrist, the robot would have to go and get an LED and place it in the socket, then it would have to go and get a lens and place it over the LED. Using a rotary wrist, the robot could get an LED and a lens at the same time and then place the LED in the socket and the lens over the LED. Only one trip would be required to the feeding area rather than two.

5.3.1.8 Functionality in Gripper Jaws

The last guideline to gripper design tailored to increase system throughput is to design extra functionality into the grippers themselves. Often the gripper can be designed such that its performs an extra assembly function as the part is being placed. The possibilities of functions performable by a gripper are widely varied and dependent on the particular assembly. As examples, two different hypothetical assemblies will be examined.

Consider a rubber foot, such as one found on the bottom of many computer cases, which is to be attached to a case using a screw. The rubber feet are fed using a bowl feeder. The screws are molded into the feet so that the foot and screw can feed as a single unit. A first approach to this assembly would be to place the foot on the case with the robot then use a dedicated mechanism to tighten the screw. Designing a rotary mechanism in the gripper would allow the screw to be tightened as the gripper places the foot on the case, thereby decreasing the number of assembly operations and decreasing the cycle time.

As a second example, consider an open top container into which a seal must be pressed (an actual gripper, designed for this type of operation, has been built and will be examined further in Section 5.4.4.11). The conventional approach to this problem would be to design a gripper to place the seal into the container and then use a dedicated press
to drive the seal into position. Again, this would take additional time as the robot moves out of the way and the seal press is actuated. A better approach would be to design an extra linear degree of freedom into the gripper itself and then use the gripper to press the seal into location. This saves the time that would have been spent on the robot releasing the seal, moving out of the way, then regrasping the assembly. In some cases this approach also greatly increases system reliability, but that will be further discussed in Section 5.3.2.10.

5.3.2 Design Guidelines to Increase Reliability

As the previous section concentrated on guidelines which can increase system throughput, this section will concentrate on design guidelines which help to promote system reliability. System reliability is generally enhanced by designing grippers to work in the presence of errors and maintain a sure and accurate grasp of components. These errors can arise from many sources including inaccuracies in the calibration of the vision system, repeatability and accuracy limits of the robot, inaccuracies in taught locations and tool offsets, degradation of repeatability due to wear of components, and variances of the sizes of the parts themselves. These errors usually manifest themselves as parts not mating together correctly, parts missing fixture locations, or parts not being grasped correctly. Most of the following guidelines will then concentrate on techniques to help overcome inaccuracies in the system. Designing grippers to have and maintain a sure grasp of objects usually involves including features in the gripper fingers themselves that help them align and maintain proper contact with the object being grasped.

5.3.2.1 Ensure a Secure Grasp of Part

The first guideline deals with designing gripper fingers that maintain a secure grasp of the object being held. This prevents the object from moving in the gripper fingers during robot movements. Most industrial robots are capable of high accelerations and decelerations. While many parts are small and lightweight and therefore do not generate large inertial forces, it is still possible for them to shift during robot motions.
This type of error is often difficult to identify due to its un-repeatable, random nature. Some of the time the system works well, while at other times the robot misses part placement locations.

Generating and maintaining a secure grasp of the object can be accomplished in many ways. The first way is to design the gripper fingers to match the contour of the gripping surface of the part being manipulated. This was discussed in Section 5.3.1.4. If a cylindrical object is being held, then the gripper fingers should have curved surfaces whose radii match the radius of the cylinder. If the object is rectangular shaped, then the grippers should have rectangular shaped pockets that constrain motion in both the \( x \) and \( y \) directions (using care in both cases to ensure a wedging condition cannot occur).

Sometimes it is not possible to encompass the part, a multifunction gripper may require a rather generic flat surface to grasp several different parts, for example. In cases such as these, it is important to increase the friction of the surfaces of the jaws to help grasp the parts during robot motions or to provide a compliant surface so the gripper may, to a small extent, conform to the part being held. This can, for example, be accomplished by attaching a thin rubber surface to the jaw face. While a compliant surface does affect the precision of the gripper, a flat surface has no contours with which to align parts, therefore the small difference in the final position of the part due to the compliance is negligible compared to the inaccuracy due to the flat plate design.

5.3.2.2 Minimize Finger Length

The length of the gripper fingers can have an effect on the ability of the gripper to maintain a positive grasp on the part. Fingers which are too long cannot hold parts as rigidly as shorter gripper fingers. The problem arises from the distance between the actual gripping surface and the source of the closure force (e.g., a pneumatic actuator). When the gripper fingers are too long, a large bending moment is created at the base of the gripper jaws where they attach to the actuator. This moment causes the fingers to flex rotationally about the mounting point thereby reducing the gripping surface from a
large area over the surface of an object to a line contact at the top edge of the object. Most gripper manufacturers list maximum finger length in the literature included with the actuator. If the fingers are longer than those recommended by the manufacturer, damage to the actuator can result.

There are trade-offs, however, in the length of fingers vs. the height of the parts vs. the gripper footprint. Generally it is a good idea to design the fingers to be only slightly longer than the height of the part. This will result in a much smaller footprint (than if you had to include the entire actuator in the footprint). Another item to keep in mind, in the case of flexible feeders, is the height of the sidewalls of the conveyor. If the gripper fingers are too short, then parts near the walls of the conveyor will not be retrievable because the actuator would hit the conveyor.

5.3.2.3 Design Necessary Approach Clearance

This guideline attempts to increase system reliability by ensuring that the gripper can lower itself into the final grasping position without actually hitting the part it is trying to grasp. This rule, while apparently obvious, has two subtle implications. The first is in grasping parts from a location that is slightly in error. In these instances, if little clearance is allotted for the approach of the gripper to the final pick location, then the likelihood of the gripper colliding with the part is greatly increased. Depending on the part geometry and gripper design, this could cause the retrieval operation to fail. In a worst case situation, the gripper or feeder could also be damaged.

The second situation involves the design of gripper fingers for multiple parts. In this situation, it can be difficult to visualize all the required clearances. Often a careful analysis of all the relevant dimensions at each open and close position must be examined. This analysis must begin when the gripper design is begun and must continue until the gripper design is complete. Often the final shape of the gripper and the location of the contacting surfaces is as much determined by the clearance constraints as it is by the geometry of the parts being grasped.
5.3.2.4 Design Chamfers on Approach Surfaces

This design guideline helps to re-center parts when the expected part location is imprecise. This rule parallels the design guideline listed in Section 5.3.1.2. In that rule chamfers are used to push unwanted parts out of the way. This rule attempts to push parts which are slightly out of position into the correct location. A chamfer (approximately \( \frac{1}{2} \) the thickness of each gripper finger) on the bottom edge of the gripper fingers allows for extra tolerance in misalignment during part retrieval.

This chamfer must, of course, be balanced with the chamfer on the exterior of the gripper fingers, mentioned in Section 5.3.1.2. Naturally, the larger the chamfer on the inside of the gripper jaws, the smaller the chamfer becomes on the outside of the jaws. Each gripper / part combination must be examined individually to determine where and to what extent a chamfer would benefit the particular assembly.

5.3.2.5 Design Grippers to Align Parts as They are Grasped

This is another design rule that attempts to improve the reliability of part retrieval systems. While the purpose of several of the previous guidelines was to align parts as they were being approached by the robot, the goal of this rule is to design grippers which align parts in the jaws even if they were misaligned when the grippers begin closing. In contrast, flat, parallel jaw grippers do not center parts as they are being grasped.

The most often added feature to gripper fingers that allows them to align parts as they close is chamfers on the parting line or other constraining feature of the gripper jaws. This chamfer helps to guide parts into location as the gripper jaws are closing. Care must be used, however, to ensure the chamfer does not form a taper in which parts may wedge.

Another technique to help the jaws align parts as they close is to design the jaws using low friction material. For example, nylon and aluminum have lower coefficients of friction than rubber or compliant surfaces. The part material also plays a role. It would
be less than ideal to design gripper jaws out of aluminum if the parts were also aluminum, since aluminum rubbing on aluminum tends to stick and gall more than slide against one another. A more appropriate choice for the jaws would be a nylon, plastic type of material, or anodized aluminum.

![Figure 5-6: Gripper With and Without Part Alignment Chamfers](image)

Consider a cylindrical peg. Gripper fingers matching the shape of the peg would have half circles in each finger. Examining the surface contact, it's fairly easy to see that the first 20° - 30° of each finger from the parting line do not contribute greatly to the holding power of the gripper. The angle between the line of force produced by the actuator and the surface normal of the gripper is too high. In addition, this area of the gripper finger could cause the part to wedge in the gripper if the part is slightly oversized, so a chamfer also relieves this problem. By chamfering this surface a much larger area is produced to guide the peg into the gripper. Figure 5-6 shows two pseudo grippers (chamfer angle of 45°). The angle of the chamfer (relative to the parting line) can be determined by examining the coefficient of friction between the gripper fingers and the part. A shallower angle may be used if the coefficient of friction is low since the part will slide relative to the gripper under less force. A steeper angle is necessary for
parts with a higher coefficient of friction. Care must be used (as mentioned previously) to ensure an oversized part will not wedge in the chamfer due to friction.

Next, consider a rectangular block. Gripper fingers that match the shape of the block would have a rectangular pocket in each half. In this case, with no chamfer, if the fingers were at all misaligned, the gripper would fail to grasp the part. If the part were slightly oversized, it would wedge in the gripper. By chamfering the entire side wall, the gripper will be capable of aligning the part as it is grasped. If the part is oversized, it will not be completely seated in the gripper’s fingers, but it will not be wedged. As previously, care must be used (by examining the coefficient of friction between the gripper fingers and part) to ensure the part will not wedge due to the part locking in the angle of the chamfer (taper lock).

5.3.2.6 Design Gripping Surface to Complement Frictional Coefficient

In many cases the material from which the gripper surfaces and parts are constructed is nearly as important as the geometric shape of the surface. The properties of the interaction between the part and the gripper material determines to a large extent how well the gripper will perform.

In many cases, it is best to design grippers that match the contour of the part being retrieved. In these situations, chamfers are usually added to the gripper fingers. These chamfers, as previously discussed, help to guide the part into a reliable and repeatable grasp. The grasped part is held in place by friction generated between the fingers and the part. Gripper fingers that have a low coefficient of friction between the gripping surface and the part work best to align the part since it is desirable to allow sliding between the fingers and the part during grasping.

At other times, it is impossible to design the gripper fingers to contour the parts being retrieved. In these cases, usually flat, parallel jaws are used. Jaws such as these cannot align the parts as they are being retrieved (since there is no surface to apply side forces to the part as the gripper fingers are closing). In these cases, the part is held in the
gripper by the friction between the flat finger and the part, so it is best to maximize the friction between the part and finger for a secure grasp. Since it is not intended for the part to slide relative to the gripper jaw during the time the jaw is closing, a low coefficient of friction is not desired. A second consideration is that a flat plate (in most circumstances), does not match the shape of the part. Fixing a compliant layer of material to the surface of the gripper jaws can also increases the secureness of the grasp (due to most compliant materials having a high coefficient of friction when interacting with most other materials, i.e. rubber).

5.3.2.7 Design Fingers to Encompass Mounting Points

This guideline, unlike the others before it, addresses the problem of the interface between the gripper jaws and the actuator. The best designed and constructed gripper jaws will still perform inadequately if the interface between the fingers and actuator is insecure or misaligned. Relying on the mounting screws to locate the jaws is not reliable since there is usually much clearance (the standard screw clearance is $\frac{1}{64}$ of an inch) between the screw and the screw hole. Even if care is taken during construction, a small amount of clearance between the screws and screw holes can cause undesirable misalignment at the end of the gripper fingers. The length of the gripper fingers is usually 3 - 5 times as long as the distance between the screws. Such a distance can greatly multiply any misalignment due to the screw hole clearance.

The solution to this problem is to design the gripper fingers to provide positive mounting location to the actuator. In most cases, this involves designing and machining a pocket in the finger mounts which encompasses the mount post on the actuator. In some actuator designs, dowel pin holes may be provided for location. Ideally, two holes are provided for location since one hole only constrains 2 of the 3 possible degrees of freedom. One dowel hole is better than only relying on the screws for location, but it would be wise in such cases to still design the finger to encompass the mounting point. It is best to avoid actuators that do not provide a way to positively mount the fingers to the
actuator, although sometimes a certain actuator may be used if it fits the application at hand. Figure 5-7 shows gripper fingers that are and are not designed to encompass the actuator mounts.

Designing the gripper finger to positively locate on the actuator has some other benefits as well. Often it is necessary to remove a finger from a gripper to repair it or to perform minor modifications on it. Perhaps the robot has crashed and left a burr on the gripping surface, or maybe it is desired to increase a chamfer to help align the parts during retrieval. Unless the gripper finger is accurately located on the actuator, a new tool offset must be calculated every time it is removed. By accurately locating the finger, it is usually possible to remove the finger, perform the necessary work, and replace the finger without redoing any tool offsets.

5.3.2.8 Do Not Rely on Parts Added to Assembly for Location

This is a subtle, but important guideline to follow to increase system reliability. As a product progresses through a manufacturing system, parts are added to the assembly and processes are performed on the assembly. In subsequent manipulation operations, avoid relying on parts added to an assembly for locating a part in the gripper (or on a fixture). If an operation failed earlier and an added part was not placed on the
assembly, or if an added part was placed incorrectly, relying on that part for location could cause problems. The part could be gripped inaccurately, could damage the grippers, or could damage the assembly hardware. It's best to grip a part from a place on the body to which parts are being added rather than rely on the added part. If it is unavoidable, and an added part must be used for gripping, then there should be a check somewhere earlier in the system to ensure that the added part has actually been added correctly to the assembly.

Consider a stubby shoulder bolt assembly (a bolt, washer, and a nut which are assembled and sold as a single unit) that has had a thick washer added to it during a prior assembly operation. The bolt is picked up from the thread end and placed into a fixture to have the nut added in a piece of dedicated hardware. Designing the gripper to locate the bolt vertically using the top surface of the washer (which is resting on the shoulder of the bolt) is not a good solution. The washer could have not been placed on the bolt, in which case a good location of the bolt is not obtained. In a worse case, the washer could be hung up partially down the shank of the bolt. In this case, when the gripper attempts to grasp the bolt, it would hit the washer instead. A better approach would be to locate the bolt / washer subassembly in the gripper vertically on the end of the bolt, which is consistent regardless of whether the washer was added or not.

5.3.2.9 Design Lead-in Chamfers on Assembly Grippers

This guideline deals exclusively with grippers used for assembly; grippers whose purpose it is to remove parts from a feeder and add them to an existing subassembly. In such cases, it is a good idea to design a generous lead-in chamfer or guide on the gripper which helps to align the part and the subassembly before the part is inserted or joined. There are many different types of lead-in chamfers or guides that could be designed. Their design is dependent on the actual geometry of the parts, subassembly, and insertion location. As an illustration, consider the following example:
A circular tube is fixtured upright on a pallet. The robot must press a lid into the top of the tube. A poor design would be a gripper that only holds the lid from the top and then attempts to place the lid into the tube. Unless there is a large chamfer on the lid or the inside of the tube, there is a high probability that the operation will be unreliable. A better solution would be to design the gripper longer than the lid such that the gripper centers the lid in line with the tube before the tube is inserted. Depending on the design of the feeder, it may not be possible to design the grippers in this manner, but some lead-in chamfer is much better than just holding the lid by the top. Figure 5-8 shows the two grippers described above. The gripper on the left has a long lead-in chamfer to align the parts before insertion whereas the gripper on the right has no prealignment capabilities.

Figure 5-8: Grippers With and Without Assembly Chamfers

5.3.2.10 Functionality in Gripper Jaws

The final guideline to increase system reliability is the same as the last for increasing throughput, namely designing functionality into gripper jaws. Increasing the functionality of grippers increases system reliability by decreasing the opportunities for the gripper fingers to err. The more times grippers must place and pick up a part, the more opportunities there are for the grippers to mishandle a part. By designing the grippers to manipulate the part without releasing it there is less opportunity for an error.
Consider again the example given in Section 5.3.1.8. An open top container is held in a fixture and a seal is to be pressed into the bottom of the tube. The robot itself is not strong enough to press the seal into place, so an external mechanism must be designed. Designing an external press to do the job requires the gripper to retrieve a seal and place it into position, then release it. After the pressing operation is performed, the gripper must then retrieve the seal/tube assembly. However, a clever gripper design can perform all this functionality without releasing the seal (as previously mentioned, this gripper was designed and is described in Section 5.4.4.11). The gripper would have an additional linear degree of freedom that would be used to press the seal into place. In this way, all that would need be done is to place the gripper in position over the tube and actuate the linear action which would seat the seal. If a suction action were to be used to hold the seal on the gripper, then this suction could also be used to lift the seal/tube combination. This design would allow the seal to be seated and the subsequent assembly to be manipulated without ever releasing the seal, thus decreasing the chances of a gripper malfunction.

5.3.3 Design Guidelines to Reduce Cost

While the past two sections have dealt with design guidelines that are intended to have a physical impact on the workcell itself, system throughput and system reliability, this section describes gripper design guidelines that can reduce the cost of the gripping system. While designing the cheapest grippers possible may not be the best solution for saving money as the next paragraph discusses, the following rules will help lower the cost of the gripping system.

Note that the final cost of the workcell is dependent on many factors and simply trying to reduce total cell cost by cutting corners in gripper design is an ill conceived plan. Many times the financial implications of gripper design choices are not easy to see. An extra 10% spent in initial capital investment to ensure an efficient and reliable gripper design may reap large rewards, since without this the workcell may need
continual operator attention due to the grippers dropping or mishandling parts. Add to
that the loss of revenue because the workcell is not operating at 100% and the extra cost
of doing a proper gripper design job is inconsequential. For example, designing added
functionality into gripper designs often costs more, both in design time and in
fabrication. But, when the savings in dedicated hardware and decrease in cycle times is
included in the equation, the added cost is well spent.

5.3.3.1 Use Parallel or Rotary Motion Pneumatic Actuators

One source of cost savings is in the selection of the gripper actuator. As the next
section will address, using off the shelf components for the gripper design whenever
possible is helpful in reducing cost, but by selecting certain types of actuators, an added
savings can be realized. Many gripper actuator manufacturers have a wide product line.
While, at first, it may appear that a more expensive actuator is required for the job at
hand, a careful and clever design can often utilize one of the less expensive units.
Generally, the parallel or rotary motion actuators are less expensive (except, of course,
for suction cups, which are the least expensive). These actuators use two opposing finger
mounting posts which travel in a parallel or rotary fashion to and away from each other.
More expensive actuators use other techniques than two simple jaws. For instance, some
have three jaws which move in a circular concentric fashion maintaining a consistent
centerline as they close. Other actuators use more innovative ideas, such as inflatable air
pockets which wrap around the part being grasped as they are inflated, or a small array
of needles which extend from a flat face and pierce the part being grasped.

5.3.3.2 Use Off-The-Shelf Components in Gripper Designs

The most obvious place to save money in gripper design is in using readily
available, off-the-shelf components whenever possible. While it may seem that no one
makes the correct style of gripper needed for a particular task, it is often advantageous to
design a solution that works with the best readily available gripper. These actuators
usually have a large installation base of users who have already debugged the design.
They are also specifically designed for their intended purpose and are usually lighter and more reliable than custom designs.

Besides direct cost savings in the purchase price of the actuator itself, other cost savings are realizable if off-the-shelf components are used. When a part of the gripping system fails (wear and tear on the system makes component failure inevitable), using readily available components makes repair and replacement a quick and easy process. Using custom designs, repair means using old drawings and determining what parts need to be replaced. Replacement means having the entire mechanism remade. These actions can take a substantial amount of time, which directly relates to lost revenue due to the workcell being down. Using standard components, a replacement part can be ordered and repair made much more quickly. Many of the smaller actuators are inexpensive enough to simply keep an extra on hand for replacement. After replacing the damaged part, the system can be returned to service almost immediately. A reteaching of a tool offset might be required, depending on the application and specific gripper geometry.

5.3.3.3 Handle Multiple Parts with a Single Gripper

It is often tempting when designing a gripping system that handles two different parts (especially if they are different), to simply design two different grippers and mount those grippers on a rotary wrist assembly. This, however, is often not necessary. Rotary wrist mechanisms are expensive and when only two parts are to be handled should be avoided unless absolutely necessary. It is usually the case that a single actuator with fingers designed to handle multiple parts can be used in place of two actuators and a rotary wrist. There are, obviously, situations where this is not possible; two parts which need to be handled at once or one part which uses a suction cup and another which uses a parallel jaw gripper are examples. However, whenever possible, designing fingers to handle multiple parts should be examined before utilizing a rotary wrist.
5.4 CWRU Designs and Examples

In this section, the grippers designed during the past several years of the agile manufacturing project will be discussed. Their strengths and weaknesses in light of the previous guidelines will also be examined. In all, eighteen grippers have been designed. Most of the guidelines developed and presented in the previous section have come from the design of these grippers.

Before discussing the grippers, however, it is necessary to discuss the parts being handled and the assembly processes which occur. Without knowledge of the parts and assembly, the reasoning behind the gripper designs is meaningless.

5.4.1 Parts Descriptions

The following describes the parts which are handled by the grippers. There are three categories of parts, flashlight parts, parts used for the Eaton Reconfigurable Assembly Cell (RAC), and miscellaneous nuts and fittings used for feeder testing. Flashlight parts were originally chosen for initial testing in the workcell for several reasons: flashlights are made of many small, light weight, plastic and metal parts; they come in a variety of sizes and styles from many manufactures, this was important for testing the flexibility and extensibility of the workcell; and they are widely available from many local stores at reasonable prices. Seven grippers were designed for use in Eaton’s Reconfigurable Assembly Cell. This cell is designed as a prototype to a standard reconfigurable assembly system which could be quickly deployed for a wide variety of automation tasks. The prototype cell is used for demonstrations and taken to trade shows throughout the country to highlight several companies’ expertise in automation. Two different assemblies are manufactured on the cell and are composed of four different components each. Finally, various nuts and socket connectors were selected to test the flexible parts feeding system (Chapter 2). They were selected because of their relatively small size and low cost availability from local hardware stores.
5.4.1.1 Bottom Cap

The bottom cap is the part which screws on the back of a flashlight. It is approximately 2 inches in diameter and 1\(\frac{1}{2}\) inches tall and is made of opaque plastic. It is a cylindrical component with one end open and the other end closed. It has a shoulder on its outside diameter approximately half way up its side. A ring, for hanging the flashlight is attached to the at this shoulder. The bottom half of the outside diameter is serrated for a more sure grasp. The very bottom is a solid ring. Figure 5-9 shows a view of the bottomcap. The bottomcap has three stable rest orientations. The first is open end down, the second is open end up, and the third is open end up at an angle resting on the rim of the closed end and on the shoulder. The gripper needs to handle the parts in both the open end up and closed end up configurations.

Figure 5-9: Bottom Caps

5.4.1.2 Plastic Snap Ring

The plastic snap ring is a circular plastic ring (torus like) approximately 1\(\frac{3}{4}\) inches in diameter with a revolving circle diameter of approximately \(\frac{1}{8}\) of an inch. The ring is split to allow it to be attached to the bottom cap. At each end of the ring, by the split, there is a small bump which snaps into the bottomcap. Figure 5-10 shows a view of
the snap ring. The snap ring has only one stable rest configuration, lying flat on its side. This is the orientation from which the gripper must retrieve the part.

The spare-lamp holder is a flat plastic disk with a single rectangular tab protruding from one side for grasping and two rectangular posts protruding from the opposite side designed to hold a spare flashlight bulb. There are two flats on opposing sides of the disk which align with features in the bottom cap. The disk is approximately 1 ½ inches in diameter. The grasping tab is about ⅛ of an inch wide by ¾ of an inch long by ¼ of an inch high. The bulb holding feature has a combined width and length equal to that of the grasping tab but is ⅜ of an inch in height. Figure 5-11 shows this part. This unique shape gives the part a stable pose of either the grasping tab down and the bulb holding feature up at approximately a 70° angle (from horizontal) or the bulb holding posts down and the grasping tab up at approximately a 50° angle (from horizontal). The part must be retrieved using the grasping tab as the pick point (which protrudes at the angle mentioned above).
5.4.1.3  Spare Lamp Holder

Figure 5-11: Spare-Lamp Holders

5.4.1.4  Coil Spring

The coil spring is a conically spiralled shape made of \( \frac{1}{16} \) inch diameter copper. It is approximately \( 1\frac{3}{4} \) inches in diameter at its base, tapers to \( \frac{1}{2} \) of an inch diameter at its top and is about \( 1\frac{1}{2} \) inches high. Both its ends are open coiled, so it tangles easily (and completely). Figure 5-12 shows the spring. Since the part tangles so easily, only one pose is allowed during feeding, sitting on its base with the small end up. This is the pose required for assembly.

Figure 5-12: Coil Springs
5.4.1.5 Lens Ring

The lens ring is the circular ring of plastic which screws on to the front of the flashlight. It contains the lens, the bulb, and the reflector. The lens ring is approximately 2\(\frac{3}{8}\) inches in diameter and about 1\(\frac{1}{8}\) inches tall. Its back end is open while its front end has a sizable overhang which is used to hold the lens in place. Its outside diameter is serrated toward the front for an improved grip while the back \(\frac{1}{8}\) of an inch is solid. Figure 5-13 shows the lens ring. The lens ring has two stable poses (it is marginally stable on its side and prone to rolling). The first is front down and the second is back down. The desired retrieval pose is front down, gripping the part from the back.

![Figure 5-13: Lens Rings](image)

5.4.1.6 Lens

The lens is the translucent plastic disk that is used to protect the bulb and bulb retainer from damage. It is not used to focus the light, but is used only as a protector. It is about 2\(\frac{3}{8}\) inches in diameter and is about \(\frac{3}{16}\) of an inch thick. It has a dark band around its perimeter for vision recognition. Figure 5-14 shows the lens. It has a single stable pose, lying flat. Since the part is symmetrical, either side up is usable. The gripper needs to manipulate the part from this pose.
5.4.1.7 Reflector

The reflector is used to focus the output of the bulb into a beam. It is made of plastic with a metallic rim on the back for conductive purposes. The front of the reflector is open and its inside surface is parabolic shaped and is plated to increase its reflective properties. The outside surface is also parabolic shaped. The large end of the reflector is approximately $2\frac{1}{8}$ inches in diameter. A circular opening in the smaller end of the reflector is about $\frac{3}{8}$ of an inch. The conductive metal rim is cup shaped and is about $1\frac{3}{8}$ inches in diameter. Figure 5-15 shows the reflector. There are three poses for the reflector. The first pose, which is marginally stable and prone to rolling, is sitting on its side supported by the conductive rim and the large end. The second, stable, pose is resting with the reflective end up, this is the pose which is arrived at when the first pose is disturbed. The final, stable, pose is reflective end down. This is the pose from which the part is retrieved.
5.4.1.8 Bulb

The bulb is a circular shaped, standard flashlight bulb (Phillips model PR2). It is about one inch long and about \( \frac{3}{8} \) of an inch in diameter. One end of the bulb is solid metal while the other end is glass. There is a metal rim at the mid point of the bulb. It has a “V” notch cut into it. Figure 5-16 shows the bulb. There is only one stable pose in which the bulb sits. It is resting on its side with the metal end down and rotated until the “V” groove is down. This is the pose from which the bulb is picked up. Bulbs also rest with the “V” groove not down, which is a marginally stable pose.

5.4.1.9 Bulb Retainer

The bulb retainer is a cylindrical plastic part which is used to hold the bulb in place on the back of the reflector. It is approximately \( \frac{5}{8} \) of an inch in diameter by \( \frac{3}{4} \) of an inch long. The front of the bulb retainer is open and accepts the metal end of the bulb. The back end of the retainer is closed except for a \( \frac{1}{8} \) inch diameter through hole. On the back lower half of the retainer body, there are four smaller cylindrical shaped protrusions running lengthwise to the main body at 90° intervals. The protrusions run for approximately \( \frac{3}{2} \) of an inch of the length of the main body. The protrusions give the
back of the body a square appearance. They are approximately $\frac{3}{16}$ of an inch in diameter. Four cross holes through the open (front) end of the retainer are used for vision recognition. Figure 5-17 shows the bulb retainer. There are three stable poses of the bulb retainer. The first is open end up, the second is open end down, the last is on its side. The parts are retrieved from the third pose, from their side.

Figure 5-16: Bulbs

Figure 5-17: Bulb Retainers
5.4.1.10 Water Valve Body

The water valve body (model N86) is a piece of a water distribution system in a refrigerator. It diverts water between the ice maker and the front door cup fill point. It is an injection molded plastic part approximately 1\(\frac{3}{8}\) inches by 2 inches by 2\(\frac{1}{2}\) inches. The front of the body has a circular opening facing forward and a vertical circular extension with a circular opening. The back of the body has two vertically orientated pockets with threaded posts extending downward. Figure 5-18 shows the components of the water valve assembly including the body. While there are many stable orientations, the parts are fed using a tray system and are presented only in a single pose. That orientation has the two threaded posts sitting in pockets with the single circular extension near the front in a vertical orientation. This is the orientation which is required for subsequent assembly.

5.4.1.11 Brass Fitting

The brass fitting is approximately 1\(\frac{1}{4}\) inches long and has a \(\frac{1}{2}\) inch hexagonal cross section. One end of the fitting is threaded to 7\(\frac{1}{16}\)-24, the other end is round and has two O-ring grooves. A 3\(\frac{1}{16}\) inch diameter hole runs through the length of the fitting. The fitting is placed into the vertical circular extension of the water valve body. Figure 5-18 shows the brass fitting. The stable poses of the fitting are standing on either end (marginally stable due to the length vs. diameter ratio) and lying on its side. The latter pose is that which is retrieved during assembly.

5.4.1.12 Guide

The guide is a slender circular part which sits in the two circular pockets on the body. In an actual assembly, these parts would have a metal core and would be driven by a coil in a vertical motion to open and close the valve. In this situation, there is no metal core. The parts are a hollow plastic tube approximately 2 inches in length and 3\(\frac{1}{8}\) of an inch in diameter. The inside of the tube is hollow. The open end of the tube has a 11\(\frac{1}{16}\) of an inch diameter shoulder and has three rectangular extensions at 120° intervals. Figure
5-18 shows the guide. The only stable pose is lying on its side resting at a slight angle being supported by the shoulder and the closed end of the tube. This is the pose in which the part is retrieved for assembly.

Figure 5-18: Parts of the Water Valve Assembly

5.4.1.13 Spin Ring

The spin ring is a flat plastic disk with a center hole which fits over the guide. The top of the spin ring has three symmetric, unidirectional ramps. The bottom of the ring has several tapered grooves which are used in a spin weld operation to secure it to the body. The spin ring has an outside diameter of 1\(\frac{3}{8}\) and a through hole diameter of 3\(\frac{3}{8}\) of an inch. A rim protrudes from the top outside edge of the spin ring. The ring is 3\(\frac{1}{16}\) of an inch thick while the rim is 1\(\frac{1}{10}\) of an inch thick. Figure 5-18 shows the spin ring. There are two stable configurations, top up and bottom up. The parts are retrieved for assembly in the top up configuration.
5.4.1.14 Tire Valve Cap

The tire valve cap is a standard Schroeder valve stem cover. It is open on one end with a threaded inside diameter and is closed on the other end. The open end is turned to approximately a \(\frac{3}{8}\) inch diameter while the closed end is a hexagonal cross section with \(\frac{3}{8}\) of an inch across the flats. The very end of the cap has a small circular nub extending from it. It is approximately \(\frac{1}{16}\) of an inch high by \(\frac{7}{32}\) of an inch in diameter. The overall length is \(\frac{1}{2}\) of an inch. Figure 5-19 shows the parts of the tire valve assembly including the cap. There are two stable poses of the cap. The first is lying on its side resting on one of the hexagonal flats. The second is setting at an angle with the open end in an upward orientation. The cap is supported by the end of one of the hexagonal flats and the small circular nub extending from the closed end. The tire valve caps are picked from the side pose.

5.4.1.15 Seal

The seal is a small rubber disk designed to fit at the bottom of the closed end of the tire valve cap. It is approximately \(\frac{1}{10}\) of an inch thick by \(\frac{5}{16}\) of an inch in diameter. A \(\frac{1}{8}\) inch diameter hole is through the center. Figure 5-19 shows the seal. The only stable pose of the seal is lying on its side. Since the seal is symmetric from both sides, there is no differentiation between which side is up. This is the pose from which the part is retrieved.

5.4.1.16 Container

The container is a thin walled plastic tube closed on one end. The container is used to hold four tire valve caps. The tube is approximately \(2\frac{1}{2}\) inches long and is \(\frac{3}{2}\) of an inch in diameter. It is relatively weak and can be crushed if squeezed with moderate force. Figure 5-19 shows the container. Different names are printed on the side of the container depending on which company is displaying the workcell. The container is marginally stable when sitting on either of its ends. Its third stable pose is resting on its side. This is the pose from which it is retrieved.
5.4.1.17 Lid

The lid is used to close the open end of the container. It has a flat circular shaped top with a circular body. The body is open at one end and is closed at the other end by the top. The cap is approximately $\frac{3}{8}$ of an inch tall and about $\frac{1}{2}$ of an inch in diameter. There is a small lip formed by the top overhanging the body. There is also a small chamfer at the open end of the body to help guide it into the tube. The cap is held in the tube by friction between the outside of the cap body and the inside of the tube. Figure 5-19 shows the cap. The cap has three stable orientations. The first is top up, the second is top down (open end up), and the third is on its side. Lids in the top up orientation are used for assembly.

5.4.1.18 Parker Fittings and Nuts

These parts were donated by the Parker Hannifin Corp. primarily for testing the flexible parts feeding system. There was no assembly associated with these parts,
however, grippers were needed to manipulate them. Both parts are from a hydraulic hose fitting assembly. The nut is a circular cylinder made of metal. The lower half of the outside diameter is a hexagonal cross section with $\frac{15}{16}$ of an inch across the flats. The top half of the outside diameter is turned round and has a diameter equal to the distance across the flats of the bottom half. The overall length of the nut is $\frac{7}{8}$ of an inch. The center hole through the nut is about $\frac{3}{4}$ of an inch in diameter with half of the inside diameter being threaded and the other half being a smooth bore. Figure 5-20 shows the nuts for the hydraulic fittings.

![Figure 5-20: Nuts for Hydraulic Fittings](image)

The fitting is a long tubular part and is about $3\frac{1}{2}$ inches in length and about $\frac{1}{2}$ of an inch in diameter. It has a larger diameter section in the middle to which a hose would seat against. The end that goes into the hose has several barbed features that hold the hose. The other end is a smooth diameter with a shoulder at the end to hold on the nut. In the actual hose fitting assembly, the nut fits over one end of the fitting while the other end of the fitting is inserted into the hose. Figure 5-21 shows the nut and fitting. The nut has three stable poses, hex end down, hex end up, and on its side. The fitting has only one stable pose, on its side. The nuts and fittings are both retrieved from their sides.
5.4.1.19 Hex Nuts

The hex nuts are standard 5/16 inch and 3/8 inch nuts that are readily available. These parts were also obtained to test the flexible feeding system. Two different sized nuts were used to test multiple parts in a single feeder. They were purchased from a local hardware store. The 5/16 inch nuts are approximately 3/4 of an inch thick and measure 3/2 of an inch across the flats. There is a 5/16-18 tapped hole through the center of the nut. The 3/8 inch nuts are approximately 0.325 of an inch thick and measure 0.550 of an inch across the flats. There is a 3/8-16 tapped hole through the center of the nut. Figure 5-22 shows the two different sized nuts. The nuts have two stable orientations. The first is
lying flat on either side, the second is standing upright resting on one of the six flats. Parts are retrieved from the pose when they are lying flat.

5.4.1.20 Plastic Sockets

The plastic sockets are also used to test the feeder. They are similar to the bulb retainers described in Section 5.4.1.9. They are, in fact, bulb retainers that have not been modified for assembly. Their description is identical to those in Section 5.4.1.9 with the exception that they do not have the holes in the open end for vision recognition and they have additional protrusions from the back surface that are intended as tabs to help remove the bulb retainer from the back of a reflector. Figure 5-23 shows the socket.

![Figure 5-23: Plastic Sockets (Unmodified Bulb Retainers)](image)

There are four stable poses of the socket. The first is standing upright with its open end up, the second is upright with its open end down, the third is on its side with the tabs facing sideways, the final is on its side with the tabs in a vertical orientation. The parts are retrieved from the third stable pose, lying on their sides with the tabs facing sideways.

5.4.2 Assembly Descriptions

Out of all the parts listed in the previous section, a total of four different assemblies were made. It is important to understand the assembly sequence being
performed since that has a direct effect on the design of the grippers. The assembly sequence determines the number of parts each gripper must handle, the clearance required for each gripper, and what the gripper has to do with the part. While most of the parts were pieces of a larger assembly, several parts were not involved in any assembly. They were used to test the characteristics of a flexible parts feeding system. The requirements for these grippers were different than for the assembly grippers. These grippers’ only job was to retrieve parts from the flexible feeder.

Of the four assemblies, two were performed on the workcell at CWRU (as described in this document) while the other two assembly operations were performed on the RAC developed by Eaton Corporation. The assemblies dealing with the flashlight parts were performed at CWRU. This is the assembly of a bottomcap and headcap of a hand-held flashlight. The assemblies dealing with the N86 Water Valve Assembly and the Tire Valve Cap Package were performed on Eaton’s RAC workcell. The following table depicts the assemblies and the parts that were associated with them.

<table>
<thead>
<tr>
<th>Flashlight Bottomcap Assembly</th>
<th>Flashlight Headcap Assembly</th>
<th>N86 Water Valve Assembly</th>
<th>Tire Valve Cap Package</th>
<th>Parts used for Flexible Feeder Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottomcap</td>
<td>Lens Ring</td>
<td>N86 Water Valve Body</td>
<td>Tire Valve Cap</td>
<td>Parker Fittings and Nuts</td>
</tr>
<tr>
<td>Bail</td>
<td>Lens</td>
<td>Brass Fitting</td>
<td>Seal</td>
<td>Hex Nuts</td>
</tr>
<tr>
<td>Spare Lamp Holder</td>
<td>Reflector</td>
<td>Guide</td>
<td>Container</td>
<td>Plastic Sockets</td>
</tr>
<tr>
<td>Coil Spring</td>
<td>Bulb</td>
<td>Spin Ring</td>
<td>Lid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bulb Retainer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1: Assemblies and The Parts They Contain

5.4.2.1 Bottom Cap Assembly

The bottomcap assembly consists of the four parts listed in Table 5-1. The bottomcap serves as the part to which the other three pieces are assembled. The assembly is divided between two robots. Each robot performs half the assembly. Partially completed assemblies are transferred between robots on pallets, which have pockets
machined on them to hold the bottomcaps. Figure 5-24 shows two completed bottomcap assemblies.

![Completed Bottom Cap Assembly](image)

The assembly at the first robot proceeds as follows. A bottom cap is retrieved from a flexible parts feeder. Next, while still holding the bottom cap, a bail is retrieved from a second flexible parts feeder. The bottomcap is then placed into a fixture and held with a vacuum. The fixture is a flat plate with a shallow pocket machined into it. Next, the bail is placed on the bottomcap. The split section of the bail fits over a mounting block on the bottomcap. The ends of the bail are inserted into mounting holes on the mounting block. Next, the bottomcap / bail subassembly is moved under a vertical press. This movement is accomplished using a linear pneumatic slide. During the motion, a specially bent copper tube is used to rotate the bail into a location over the shoulder of the bottomcap. The vertical press uses a conically shaped tool to transfer the vertical motion of the press into a radial force on the bail. This force snaps the ends of the bail into the mounting block. The completed bottomcap / bail subassembly is then returned to its original position. The slide is necessary because the vertical press would interfere with the vertical operation of the Adept 550 SCARA robot. The robot then picks the
finished subassembly from the fixture and places it into a pocket on the pallet for transportation to the second robot. When a pallet is filled (16 subassemblies), it is sent to the second robot.

After arriving at the second robot, the assembly continues as follows. First, the bottomcap must be inverted so that the spare lamp holder and spring may be inserted. The robot retrieves a subassembly from the pallet and places it on a staging area in the jaws of a rotary mechanism. The rotary mechanism grasps the bottomcap and the robot lets go of it. Next the rotatory mechanism inverts the bottomcap at the same time that it is placing it into a table fixture. The table fixture is a parallel jaw actuator mounted upside-down on the assembly table. The actuator has gripper fingers which are in the shape of the bottomcap. After the fixture has a firm grasp on the part, the rotary mechanism is returned to its original position. Next, the robot retrieves a spare bulb holder from a flexible parts feeder. The bulb holder must be grasped by the holding tab and so must be picked up at its stable angle. The lamp holder must then be rotated into a vertical orientation and inserted into the bottomcap. Next, the robot retrieves a spring. The springs are retrieved from a conveyor. While the robot is retrieving a spring, a special “spring funnel” is lowered into the bottomcap. The spring funnel is mounted on a dual action linear pneumatic mechanism that lifts the funnel from its storage position, rotates it into a location over the bottomcap and then lowers the funnel into the bottomcap. The funnel is a chamfered tube and has an outside diameter slightly less than the inside diameter of the bottomcap. A spring passes through smooth the inside diameter of the funnel which is slightly less than the outside diameter. This ensure the spring is fully seated in the bottomcap. The spring is pushed into position by the gripper. After placing the spring, the robot moves out of the way and the spring funnel is retracted. Finally, the robot retrieves the finished assembly from the table fixture and returns it to the same pocket on the pallet from which it was originally retrieved.
The desire was to perform this entire assembly without any tool changes. This required that three parts be manipulated at the first robot (the bottomcap, the bail, and the bottomcap / bail subassembly) and that 4 parts be handled at the second robot (the bottomcap / bail subassembly, the spare lamp holder, the spring, and the complete assembly). Some of the other constraints on the gripper design were the following: The bottomcap gripper at the first robot had to retrieve the bottomcap from a flexible parts feeder where small gripper footprint is important. The same gripper also had to be capable of picking the subassembly from the fixture and placing it onto the pallet. The bail gripper had to be able to lift a bail from the flat surface of the parts feeder while at the same time spreading the bail so that its ends would reach around the sides of the mounting block and be inserted into the mounting holes.

The grippers at the second robot had an even more challenging task. The bottomcap had to be handled in both an upright and up-side-down orientation. The spare bulb holders had to be retrieved from the flat surface of a flexible parts feeder. To accomplish this, the gripper had to approach the part at the angle which corresponds to its stable pose and grasp the part from its holding tab. The part then had to be rotated into a vertical orientation (bulb holding feature pointing down) and inserted into the bottomcap. The springs had to be retrieved from a conveyor and pushed through the spring funnel into their final assembly location. The following table lists the assembly steps at each robot.

<table>
<thead>
<tr>
<th>First Robot</th>
<th>Second Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Get a bottomcap</td>
<td>1. Get a subassembly from the pallet</td>
</tr>
<tr>
<td>2. Get a bail</td>
<td>2. Invert the sub-assembly</td>
</tr>
<tr>
<td>3. Place the bottomcap in the fixture</td>
<td>3. Get a spare lamp holder and place it into the bottomcap</td>
</tr>
<tr>
<td>4. Place the bail on the bottomcap</td>
<td>4. Insert the spring funnel into the bottomcap</td>
</tr>
<tr>
<td>5. Seat the bail with a pneumatic press</td>
<td>5. Get a spring and place it into the bottomcap</td>
</tr>
<tr>
<td>6. Place the finished subassembly on the pallet</td>
<td>6. Place the finished assembly on the pallet</td>
</tr>
</tbody>
</table>

Table 5-2: Bottomcap Assembly Steps at Each Robot
5.4.2.2 Head Cap Assembly

The headcap assembly consists of the five parts listed in Table 5-1. As with the bottomcap, half the assembly is performed at the first robot and half the assembly is performed at the second robot. Pallets, with machined pockets, are used to transport the subassemblies between the two robots. Figure 5-25 shows two completed headcap assemblies.

![Completed Headcap Assembly](image)

Figure 5-25: Completed Headcap Assembly

The assembly at the first robot proceeds as follows. First, a lens ring is retrieved from a flexible parts feeder and placed into a fixture. The fixture is a circular pocket on the top of a post mounted to the table. Next, a lens is retrieved from a flexible parts feeder. While the lens is held, a reflector is also retrieved. The lens is then placed into the lens ring and the reflector is placed on top of the lens. The robot then moves out of the way and a vertical press is used to seat the reflector and lens into the lens ring. In this assembly, the press is mounted on a linear pneumatic slide and moved into position over the fixture. This is again necessary because of the vertical operation of both the robot and the press. After finishing, the press moves back out of the way. The robot then
grasps the finished subassembly and places it into a pocket on the pallet. After all the pockets have been filled (total of 9), the pallet is routed to the second robot.

Assembly at the second robot proceeds as following. This is a slightly more complicated operation than at the first robot because of the parts staging operation. Both the bulbs and bulb retainers are fed using flexible parts feeders and therefore are retrieved from their sides. Because they are inserted into the back of the reflectors in a vertical orientation, they have to be rotated 90° before they are usable. First, before the pallet arrives, bulb retainers are retrieved, rotated, and placed into a temporary fixture. The fixture consists of a block with pockets machined into its top. The bulb retainers are held in the pockets until they are needed for assembly. Next, bulbs are retrieved and placed into the back of the reflectors. The assembly occurs directly on the pallet so handling of the lens ring subassembly is not necessary. After the bulbs are inserted, the bulb retainers are retrieved from the fixture and pressed into the back of the reflector. The robot does the pressing operation, no dedicated hardware is necessary. After all nine assemblies are complete, the robot begins to refill the fixture with bulb retainers while complete pallet leaves and a new pallet arrives.

As in the case of the bottomcap, it was desired to perform the entire assembly without any tool changes. This required the first robot to handle four different parts (the lens ring, the lens, the reflector, and the lens ring subassembly). All the parts had to be retrieved from flexible parts feeders where gripper clearance was a concern. The first gripper had to be able to handle the lens ring, the lens ring subassembly and the reflector. The second gripper needed to be able to retrieve the lens and place it into the lens ring.

As in the case of the bottomcap assembly, the grippers at the second robot had a much more difficult task. Both the bulbs and the bulb holder needed to be retrieved from flexible parts feeders while lying on their sides. The clearance of the gripper was a concern because of the random nature of the feeder. Next, both parts needed to be rotated...
90°. The bulb had to be placed directly into the back of the reflector while the bulb retainers needed to be placed into a fixture. The second gripper had to grasp the bulb retainers from the closed end and press them into the back of the reflectors. The pressing operation takes a fair amount of force and the gripper needed to be capable of securely holding the parts while they were being seated. The following table lists the assembly sequence at each robot.

<table>
<thead>
<tr>
<th>First Robot</th>
<th>Second Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Get a lens ring</td>
<td>1. Fill the fixture with bulb holders</td>
</tr>
<tr>
<td>2. Place it into the fixture</td>
<td>2. Get a bulb and place it into the reflector. Continue until all reflector have a bulb.</td>
</tr>
<tr>
<td>4. Get a reflector</td>
<td></td>
</tr>
<tr>
<td>5. Place the lens into the lens ring</td>
<td></td>
</tr>
<tr>
<td>6. Place the reflector into the lens ring</td>
<td></td>
</tr>
<tr>
<td>7. Seat the reflector / lens using a press</td>
<td></td>
</tr>
<tr>
<td>8. Place the subassembly on the pallet</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-3: Headcap Assembly Steps at Each Robot

5.4.2.3 Tire Valve Cap Package Assembly

The tire valve cap package assembly takes place on Eaton’s RAC cell. The assembly is composed of the four parts listed in Table 5-1. There are, however, four of the tire valve caps included in each assembly. There are two robots performing the assembly with subassemblies and parts being carried between robots on specialized pallets. Figure 5-26 shows the completed assembly.

The following “kitting” operation is performed at the first robot. Parts are simply retrieved from feeders and placed on pallets; the actual assembly is performed at the second robot (discussed below). First the robot retrieves four tire valve caps and places them into pockets on the pallet. The caps are retrieved from a Genex flexible parts feeder. They are retrieved while lying on their side and must be rotated into a vertical position for insertion into the pallet pockets. Next a container is retrieved from an RPM vibratory feeder. This feeder presents the containers on their sides in a “V” groove. The parts must be rotated 90° and placed into a pocket on the pallet.
Finally, the lid is retrieved and placed on a post on the pallet. The lids are retrieved from an RPM brushed feeder and are picked with the closed end (top) up. The loaded pallet then is sent to the second robot.

At the second robot, the following assembly operations are performed. First, a seal is retrieved from a bowl feeder. The seal is presented at the end of a slide leading from the bowl feeder and is grasped from above in a horizontal orientation. The seal is then seated into a cap. The cap/seal assembly is then placed into the container. This process continues three more times. Finally, the lid is placed on the top of the container and the container is then placed into a finished bin.

At the first robot, a total of three different parts must be manipulated (the tire valve cap, the container, the lid) with two of the parts needing to be rotated 90°. The caps and lids are retrieved from flexible parts feeders, so, again, gripper clearance is an issue. The first gripper must be capable of retrieving both the caps and containers and rotating them 90°. The second gripper must be capable of grasping a cap from a crowded flexible parts feeder. Since the most stable orientation of the caps is open end up, only 10% of the caps going through the vision window are in the correct orientation. This put a high priority on the size of the grippers footprint, since every part which is a valid candidate needs to be retrieved.
At the second robot, the emphasis is not on gripper footprint, but rather on functionality. The first gripper must retrieve a seal from the bowl feeder and seat it into the cap. It must then pick up the cap and place it into the tube. The second gripper must retrieve the lid from its post on the pallet and insert it onto the top of the container. It must then lift the final assembly from the pallet and place it into the finished hopper.

The following table lists the assembly sequences at each robot.

<table>
<thead>
<tr>
<th>First Robot</th>
<th>Second Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Get four tire valve caps and place them on the pallet</td>
<td>1. Get a seal from the bowl feeder</td>
</tr>
<tr>
<td>2. Get a container</td>
<td>2. Insert the seal into the cap</td>
</tr>
<tr>
<td>3. Place it on the pallet</td>
<td>3. Place the cap / seal into the container</td>
</tr>
<tr>
<td>4. Get a lid</td>
<td>4. Repeat above three steps three more times</td>
</tr>
<tr>
<td>5. Place it on the pallet</td>
<td>5. Insert the lid into the container</td>
</tr>
<tr>
<td></td>
<td>6. Place the finished assembly in a hopper</td>
</tr>
</tbody>
</table>

Table 5-4: Tire Valve Cap Package Assembly Steps at Each Robot

5.4.2.4 N86 Water Valve Assembly / Disassembly

The N86 Water Valve assembly was also performed on Eaton’s RAC. This assembly was different from the tire valve cap packages in that the first robot assembled the product while the second robot disassembled the item. Since the workcell is a demonstration cell, it is easier to have one of the robots disassemble the valve rather than have to do it by hand. Figure 5-27 shows the completed water valve assembly.

The assembly sequence at the first robot proceeds as follows. First, a body is retrieved, the bodies are fed using a tray feeder. A tray of parts in known locations is presented to the robot for retrieval. When the tray is empty, an automated mechanism switches an empty tray for a full one. The body is then placed in a fixture on a pallet. Next a brass fitting is retrieved and inserted into the hole in the front of the body. The brass fittings are fed using a Genex flexible feeder. Next a guide is grasped and then a spin ring is picked up. The guide is then inserted into one of the two pockets near the back of the body. After that, the spin ring is dropped over the top of the guide. Another
guide and spin ring are then retrieved and placed in the other pocket near the back of the body. The completed assembly is then sent to the disassembly robot.

![Completed Water Valve Assembly](image)

**Figure 5-27: Completed Water Valve Assembly**

Disassembly at the second robot proceeds as follows. First the robot removes a guide and spin ring. By grasping the guide and lifting, the spin ring is lifted as well. This subassembly is then dropped through a hole on an inclined slide. The hole is large enough for the guide to drop through, but not for the spin ring. This separates the guide from the spin ring allowing the parts to fall into separate hoppers. Next, the brass fitting is lifted from the body and is dropped into a hopper. Finally, the body is lifted from the pallet and placed back onto an empty tray. Two identical tray feeders are used in the cell, one loads parts at the first robot; the second unloads parts at the second robot. By swapping the trays, no handling of the bodies is necessary.

At the first robot, four parts must be handled (the body, the brass fitting, the guide, the spin ring). The body is retrieved from a tray feeder, so its clearance requirements are constant, however, the body is relatively large and a sure grasp must
be maintained on it during robot motions. The brass fittings are retrieved from a flexible feeder, so gripper clearance is important. The fittings are retrieved from their sides and need to be rotated 90° before insertion. They are relatively heavy parts and care must be taken so that a solid grip is maintained. The guides are retrieved from an RPM vibratory feeder which presents parts to the robot in a “V” groove. Since the guides are retrieved on their sides, they must also be rotated 90° before use. The spin rings are fed using an RPM brush feeder and are retrieved from a flat carpet type surface. Clearance is important since the parts are densely packed as they travel through the vision window. The first gripper must retrieve both the guides and the brass fittings. It must be capable of rotating both parts through 90°. The second gripper must grasp a body as well as grasp spin rings. The footprint of the gripper needs to be small so that the spin rings may be retrieved from a crowded feeder.

The disassembly gripper needs to be able to handle three parts (the guide, the brass fitting, the body). By grasping the guide, the spin ring comes along for free. The clearance of the gripper is not as constrained as the ones at the first robot since parts are always being picked from the same position. For economy, it is desirable to have one gripper handle all three parts.

<table>
<thead>
<tr>
<th>First Robot</th>
<th>Second Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Grasp a body from the tray feeder</td>
<td>1. Remove the guide / spin ring</td>
</tr>
<tr>
<td>2. Place the body on a pallet</td>
<td>2. Drop the guide through a hole, spin ring slides down ramp</td>
</tr>
<tr>
<td>3. Grasp a brass fitting</td>
<td>3. Remove the brass fitting from the body</td>
</tr>
<tr>
<td>4. Place the fitting on the body</td>
<td>4. Remove the body from the pallet</td>
</tr>
<tr>
<td>5. Grasp a guide and spin ring</td>
<td>5. Place the body in the empty tray feeder</td>
</tr>
<tr>
<td>6. Place the guide on the body</td>
<td></td>
</tr>
<tr>
<td>7. Place the spin ring over the guide</td>
<td></td>
</tr>
<tr>
<td>8. Repeat 5 - 7 above for the second guide / spin ring</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-5: N86 Water Valve Assembly / Disassembly Steps

5.4.2.5 Miscellaneous Other Parts

The remaining parts were only used for feeder testing, not for any assembly. This led to a different gripper design. Usually, a less sophisticated design was possible since
there was not a constraint on accurately gripping the parts. Since they were only being dropped in hoppers or returned to the feeding system, the accuracy needed for assembly was not required. Minimizing the gripper footprint was, however, important since the footprint of the gripper can have a serious effect on the throughput of the feeder.

The first gripper was designed to retrieve nuts from a hydraulic fitting assembly produced by the Parker Hannifin Corporation. It needed to pick the nuts from the pose where they are sitting on their sides on one of the flats. The other gripper was used to pick both 5/16 inch and 3/8 inch hex nuts, the plastic sockets (from the headcap assembly), and fittings from the Parker hydraulic fitting assembly. The 5/16 inch and 3/8 inch hex nuts were retrieved from a pose in which they were lying flat (i.e. the threaded hole in a vertical orientation) whereas the plastic sockets were retrieved while lying on their sides. The fittings were retrieved while lying on their sides on the feeder. Since the fittings were round, it was a challenge to keep the fitting from rolling on the feeder. All four parts were needed to be grasped by the same gripper because it was desired to test the throughput of the system when feeding multiple dissimilar parts.

5.4.3 Generic Rotary Jaw Gripper

Flexible workcells present some new and interesting problems to the system designer. One such problem is in parts feeding and handling. In a conventional system, a specialized feeder would be designed for each part. This feeder would present the part in the correct assembly orientation where it could be retrieved. In flexible workcells however, conventional feeding methods, such as vibratory bowl feeders, are not practical because of their specialized nature. When a new or different assembly is being performed, the parts relative to the new assembly need to be fed without spending time designing, tuning, and installing a new feeding system. Flexible feeders fill this need, but at a price.

Since parts are usually fed randomly onto a presentation conveyor, a vision system is used to determine their exact pose (position and orientation). This information
is fed to the controller of the robotic arm so as to guide the arm to a suitable pickup location. Lacking any fixturing specially designed to a specific part, parts settle onto the presentation conveyor in statically stable orientations. Often it is necessary to design the parts so that their stable orientations are in positions which are advantageous to a given assembly. For example, if a part needs to be inserted into an assembly with side A down, then it is advantageous for the part to have a statically stable rest orientation with side A down. This can lead to many difficulties during the design. In other situations, it is impossible to satisfy the above criterion. Consider a long, slender pin which needs to be inserted into a vertical hole. In function, it would be impossible to design the pin to have a stable orientation standing upright.

Solutions to the stated situation include: 1) dedicated hardware for rotating parts in conjunction with multiple grippers for grasping the parts in various orientations, or 2) a gripper capable of rotating the part while also grasping it. A rotating jaw gripper would greatly enhance the flexible feeding in several respects. First, it would allow designers more leeway in designing parts since the part would not necessarily have to have a stable orientation which corresponds to the desired assembly direction. Second, it would, in some instances, increase the throughput of the feeder by allowing the robotic manipulator to acquire parts not only in poses which are advantageous to assembly, but in other poses which could be rotated into a usable orientation.

Several rotary jaw grippers are commercially available, Techno Sommer, for example has a family of rotary jaw grippers. These grippers, however, are heavy, weighing between 2½ and 15 pounds. They also do not have a link between the two jaws which forces the fingers to rotate at the same rate. Since they are driven by rotary pneumatic actuators, it is possible for the finger pads to rotate at different speeds. This could cause the object being gripped to be dropped. A servo rotary jaw gripper is also available, but a controller would be necessary for its operation. Cost would become significant in such a case. A passive pivoting gripper has been presented previously
[115], however, it only uses gravity to rotate parts and has limited (and unreliable) usability.

5.4.3.1 Design Goals

Some of the desired features in the design of this gripper are listed below.

• Operate on a wide variety of readily available parallel motion actuators and provide an additional degree of freedom in the form of rotating pads at the end of the gripper fingers.
• Light weight permitting the gripper to be used on small, inexpensive manipulator arms.
• Utilize a double acting cylinder to positively drive the rotary motion in both directions and operate it from two pneumatic lines so that a single 3-way solenoid valve and two air hoses can operate the device.
• Mechanically link the rotation of the finger pads such that the two pads maintain zero relative motion and such that both pads can be driven from a single pneumatic actuator.
• Independent operation of the open/close motion and rotary motion.
• Fingers of the device should be easily exchanged or replaced without replacing the entire rotary mechanism.
• Adjustable stops and proximity sensors at either end of travel of the rotary motion.

In light of the above goals, a novel, light weight (7oz.), pneumatically actuated, mechanically linked, rotary jaw gripper was designed. From this initial design, a prototype gripper was constructed. This is the Bulb/Bulb Retainer gripper described in Section 5.4.4.7. This design will be discussed in the following section. The gripper design was revised and two additional rotary jaws grippers constructed for use in Eaton’s reconfigurable assembly cell (described in Sections 5.4.4.9 and 5.4.4.13). This design is described in Section 5.4.3.3.

5.4.3.2 First Generation Design

The first generation design lacked some features which were specified in the design goals, but it, never-the-less, proved to be a reliable and functional gripper and is still being used to manipulate the bulbs and bulb retainers. Figure 5-28 shows a CAD
A typical parallel motion manipulator (1) (a Schunk model KTG50 in this case) is the base to which the rotary fingers attach. By redesigning the mounting surface of the fingers, any parallel motion gripper could be used as a base for the rotating jaws.

The left (7) and right (8) fingers of the gripper form the base to which the rest of the mechanism is attached. They serve as a mounting base for the pneumatic actuator (2) as well as for the rotating finger pads (9), (10). The pneumatic actuator mounts to the left finger when the mechanism is viewed from behind.

The solid pneumatic cylinder mounting bracket (4) is attached to the left finger by three 6-32 flathead screws. The mount fits into a slot milled into the finger which locates the bracket relative to the finger and which provides the correct left to right placement of the actuator (a Bimba model 007½ cylinder in this case). The solid mount provides a pivot point for the pivoting pneumatic cylinder mounting bracket (5). The pivot point is required to be in this location for several important reasons. First, the
geometric size of the four bar mechanism must be maintained if the desired motion is to be achieved. Second, by moving the pivot point to a location behind the center line of the fingers, the cylinder may be mounted at a more horizontal angle, allowing for a shorter overall height. Last, by moving the pivot to its current location, an improvement in the transmission angle of the four bar mechanism was realized over initial designs.

The pivoting pneumatic cylinder mounting bracket is composed of two parts. The main part is an “L” shaped bracket (5) which has a tapped hole into which the cylinder mounts. The top of the “L” bracket has a hole machined in it into which the cylinder pivot axle (18), a $\frac{3}{16}$ inch OD (outside diameter) ground steel shaft, is mounted. This is accomplished by means of a press fit. A bronze bushing (20) (Berg B7-8 in this case) completes the interface between the solid pneumatic cylinder mounting bracket and the pivoting pneumatic cylinder mounting bracket. The bushing allows for a rigid, low friction connection, while being lighter and smaller than a comparable roller bearing. A retainer (12), press fit onto the $\frac{3}{16}$ inch shaft, locks the mounting brackets together.

The cylinder terminates in a clevis (3) (Bimba model D-26690 in this case) which mounts to the left linkage arm (6). An $\frac{1}{8}$ inch OD ground steel shaft, called the mechanical rotary linkage (15), connects the clevis and linkage arm together. The shaft also is the mechanical connection between the left finger pad (9) and the right finger pad (10). A roll pin, driven thorough the linkage arm and shaft at assembly, locks them together.

The left linkage arm attaches to the left finger pad axle (16), an $\frac{1}{8}$ inch OD ground steel shaft. The left finger pad is attached to the left finger pad axle. The cylinder, acting through the linkage arm causes the left finger pad axle to rotate, thus moving the finger pad through the desired range of motion. A roll pin, inserted at assembly, is used to lock the left linkage arm to the left finger pad axle.

Two bronze bushings (19) provide a low friction junction between the left finger and the left finger pad axle. The left finger pad is attached to the end of the left finger
pad axle by means of a set screw and a roll pin. A retainer, locked in place by a roll pin during assembly, is used to prevent the left finger pad from moving in an axial direction. Double sided tape is used to attach a rubber pad to the gripping surface of the left finger pad.

The right finger (8) serves as a base to which the right finger pad (10) and the right linkage arm (13) are attached. The mechanical rotary linkage interfaces the right linkage arm through an \( \frac{1}{8} \) inch ID linear bearing (14) (Berg LMB-125SS in this case). The linear bearing allows the mechanical rotary linkage to slide relative to the right linkage arm during the open/close action of the parallel motion actuator. Its low friction interface prevents the mechanical rotary linkage and the right linkage arm from binding or seizing during operation.

The linear bearing is press fit into the right linkage arm. It is necessary to undercut some area of the right finger to provide clearance for the linear bearing. The right linkage arm attaches to the right finger pad axle (17), an \( \frac{1}{8} \) inch OD ground steel shaft, by means of a press fit and a roll pin, the latter of which is inserted during assembly. The right finger pad, being a mirror image of the left, is attached to the right finger pad axle in a similar manner as described in the case of the left finger pad above.

Bronze bushings (19) provide a low friction junction between the right finger and the right finger pad axle. A retainer is not required (as in the case above of the left finger pad) because the right linkage arm prevents axial movement of the right finger pad.

Figure 5-29, below, shows a side view of the first generation design retrieving a bulb retainer and rotating it into a vertical orientation.

While functioning adequately, many small problems were seen with the gripper as it was used. While the problems were not bad enough to make the design non-functional, they did make the design a bit less reliable. The second generation design addressed many of these concerns which are described below.
The first problem was the lack of sensing on the gripper. There were no provisions made for including sensors to determine the location of the finger pads. This made the design less reliable since there was no guarantee that the fingers had actually rotated. This was especially important in the un-rotate action since it was driven by a spring rather than pneumatically. This also makes the system slower since a hard coded time delay had to be included in the program every time the jaws rotated. This delay was necessary to allow sufficient time for the rotation to occur. With sensors, the assembly could take place as soon as the rotation operation had completed rather than waiting a predetermined amount of time.
The second problem was the lack of stops on the rotational motion of the fingers. The un-rotated position was determined by the location of the clevis on the piston rod and the rotated stop was determined by the end of the piston stroke. It would be much better if the fingers had adjustable hard stops to control the range of motion so that as parts began to wear, adjustments could be made to maintain the proper operation of the gripper.

The third problem was the use of a single acting cylinder. Pneumatic pressure is used to drive the jaws into the rotated position. A spring in the cylinder would cause the finger pads to return to the un-rotated state. The spring, however, is weak compared to the pneumatic force and was marginally able to return the jaws. If the mechanism were slightly out of alignment or were worn or dirty, the spring would begin to fail to return the jaws. The lack of sensing made the problem especially dangerous because there was no way to know if the un-rotate operation had completed. Attempting to pick a part with the jaws in the rotated position could damage the gripper.

The fourth problem was discovered when assembling the gripper. The design called for the finger pads to be locked to their respective axles by a rollpin inserted at assembly. A set screw was also provided to temporarily lock the fingers in place while the hole for the rollpin was being drilled. It was found, however, that properly aligning the jaws and holding that alignment during the drilling operation was difficult. A way of positively aligning the finger pads before assembly would be much better.

The fifth problem arises from the design of the mechanical rotary linkage which locks the right and left jaws together. This linkage is a \( \frac{3}{8} \) inch diameter rod which is over 3 inches long. Any small amount of rotational play in the junction of the left linkage arm and clevis and the mechanical rotary linkage is magnified by this length. This is manifest as a noticeable amount of rotational play in the right jaw of the gripper. This could cause the fingers to drop parts because the fingers are not firmly mechanically linked.
The final problem was the footprint of the gripper. In its original design, the finger pads did not extend much past the bottom of the left and right fingers of the gripper body. This caused the gripper to have a large footprint. This was especially noticeable when feeding the bulb retainers. Many of the separated retainers were not retrieved because the gripper was simply too big. A second set of fingers was made and mounted on the gripper (Figure 5-48) to alleviate this problem, but the solution was not satisfactory for two reasons. First, the extra length of the finger pads simply made the rotational play in the right finger pad (described above) more obvious. Secondly, this extra length made the joint between the finger pad and the axles subject to much higher stress. While no failure of this joint was seen, a much better design could be realized by altering the way the finger pads mounted to the fingers of the gripper.

Several design goals were not achieved in the initial design. Some of them have appeared in the description of the problems. The following is a complete list of the objectives not realized in this design. A single acting cylinder was used in place of a double acting because of size constraints. This decision, however, led to the fingers not reliably returning to the vertical position. The fingers of the gripper are not as easily exchanged as would be liked. Currently, the rollpins must be removed from the fingers, the fingers removed from the axles, new fingers placed over the axles and aligned, temporarily locked in place with set screws, new rollpin holes drilled and rollpins inserted. This procedure also damages the axles as the rollpin holes are drilled multiple times. Finally, no provisions for sensing or mechanical stops were included in the design.

**5.4.3.3 Second Generation Design**

After being approached by the Eaton Corporation to design grippers for use in their RAC, the opportunity arose to redesign the rotary gripper. While retaining the overall size and functionality of the original design, the redesign addressed many of the problems seen in the initial design as well as simplified the overall mechanism. Figure 5-30 shows a CAD view of the gripper with labeled components.
The gripper is composed of several parts. The left (6) and right (16) finger bases serve as the main body onto which the gripper is built. The solid (17) and pivoting (5) cylinder mounts attach the cylinder (2) to the left finger base. Left (11) and right (12) fingers, which actually handle the parts, are attached to the finger bases. The piston rod attaches to the driving rod (8) which moves the fingers. While the design changed significantly, the kinematics of the four bar linkage driving the mechanism did not change. This was kept the same to maintain the desired range of rotary motion.

The left and right finger bases mount to the pneumatic actuator (1) in the same manner as the first design. The pneumatic actuator provides the open and close actions of the gripper. The cylinder which provides the rotary motion to the gripper is attached to the right finger base when viewed from behind.

The solid pneumatic cylinder mounting bracket (17) attaches to the right finger base by two flat head machine screws. This bracket provides the mounting point for the pivoting pneumatic cylinder bracket. This mounting point is offset to the rear of the gripper, behind the centerline of the fingers, to shorten the overall height of the gripper.
The cylinder is mounted between the left and right finger bases, in contrast to the initial design where the cylinder was mounted to one side. This movement of the cylinder to a central location had two benefits, first it made the overall gripper less wide, second, it made the connecting rod (8) between the left and right fingers shorter, which corrected the problem of the rotational play in the fingers. The pivoting pneumatic cylinder mounting bracket (5) is “L” shaped. One end of the bracket has a 3/16 inch diameter axle (13) press fit into it. The axle fits through an oil-light bushing (14) in the solid mounting bracket and is secured by a bushing (15) press fit onto the pivot axle. The other end of the pivoting bracket has two tapped holes in it. The cylinder (2) is screwed into the larger hole. The smaller hole is used to mount a proximity sensor (4) for sensing when the jaws are in the un-rotated state.

The cylinder end bracket (not shown in Figure 5-30) connects the cylinder rod to the driving rod. The cylinder end bracket contacts the driving rod through an oil-light bronze bushing to minimize wear and friction. The driving shaft is attached directly to the left and right fingers. The rod is press fit into the right finger and rotates with the finger (hence, there is motion between the driving rod and the cylinder end bracket and the need for the bushing). The driving rod connects with the left finger through a linear bearing (7) which is press fit into the finger.

The right and left fingers attach to the finger bases by means of axles (labeled as (9) but hidden from view). A yoke is machined in the end of each finger base. One side of the yoke has a hole reamed through it that matches the diameter of the axle. The other side of the yoke has a hole in it slightly less than the diameter of the axle. The axle passes through one side of the yoke, through the finger, and is pressed into the other side of the yoke. The finger contains two oil-light bronze bushings (10) which provide a compact, low friction interface between the finger and axle. The bushings also position the finger side-to-side in the yoke. This yoke arrangement is much stronger that the initial design of the finger cantilevered from a small axle. The driving rod is offset from
the axle by about $\frac{1}{2}$ of an inch. By driving the cylinder, the fingers are driven about the axles in tandem. The fingers are locked rotationally by the driving rod while the linear bearing allows the open and close actions to occur independently.

Figure 5-31 shows a back-view of the rotary mechanism of the second generation design in the closed and open positions. Figure 5-32 shows the same from the front side. Figure 5-33 shows two views of the gripper in the rotated state. Figure 5-34 shows several CAD views of the design in the un-rotated and rotated states.

Figure 5-31: 2nd Generation Rotary Mechanism - Back View

While vastly improving in reliability over the original design, there were still a few details that could be improved. In particular, several problems were noted during the use of the grippers. The extended use of the grippers in the Eaton RAC also revealed a few additional subtle problems.

The first problem, as in the initial design, deals with the sensing on the gripper. A sensor was added to the design to determine when the gripper was in its un-rotated
position, however no sensor is present to detect the rotated position. An increase in throughput and reliability could be realized by including a sensor at the rotated position as well as the un-rotated position.

Figure 5-32: 2nd Generation Rotary Mechanism - Front View

The second problem is the lack of hard stops on the rotational motion of the fingers. The design of the finger bases and fingers limits together create the un-rotated stop. The position of the cylinder end bracket with respect to the end of the cylinder’s stroke determines the rotated position. As before, stops would increase the functionality of the design by allowing the range of motion to be fine tuned and adjusted as the gripper’s components wear.

The third problem was the use of a single acting cylinder. Due to size constraints, a single acting cylinder was chosen. The problem of crashing the grippers because the un-rotate motion did not occur was fixed by the sensor, but a quicker rotational action would be better. Also, moving the cylinder to a position between the finger bases seemed to slightly increase the required return force. Since the cylinder spring was only
marginally strong enough previously, the fingers were observed to stick more often than with the initial design.

Figure 5-33: 2nd Generation Rotary Mechanism - Rotated View

Another problem observed when using a single acting cylinder is in regulating the speed of the rotary motion. Trouble appeared when handling the fitting for the Eaton RAC project. If the gripper jaws rotated too quickly, the gripper would drop the part due to the inertia of the part. When the jaw would hit the fully rotated position, the rotational inertia of the part would pull it out of the gripper jaws. With only a single air line, the speed of the gripper cannot be properly regulated. To properly regulate the movement of a pneumatic device, the exhaust port of the cylinder must be controlled. However, with a single sided cylinder, the exhaust port is a hole drilled in the side of the cylinder and it is difficult to regulate the air exiting the hole. A flow regulator was placed on the input port of the cylinder, and while slowing the motion, it also made the motion jerky and erratic.

The final problem seen when using the gripper was a result of the extended operation at Eaton. It was noticed that the driving rod began to show signs of wear at its interface with the linear bearing. This was most likely a result of the stainless steel
driving rod not being heat treated or hardened. Changing the driving rod to a case hardened rod should alleviate the problem.

Figure 5-34: CAD Views of the 2nd Generation Design

Again, in this design, several design goals, described below, were not met. This was mostly due to size constraints of the parts involved. A second sensor needs to be added to sense the rotated position. Adjustable hard stops need to be added to regulate the rotational range of motion. The cylinder needs to be replaced with one that is double acting. Finally, a method which allows the fingers to be quickly exchanged needs to be implemented.
5.4.4 Gripper Descriptions

The following section is a discussion of the grippers developed over the past three and a half years. Many lessons have been learned during this time and the following will hopefully further explain and clarify some of the design guidelines presented.

5.4.4.1 Bottom Cap Gripper

The bottomcap gripper was the first gripper designed for the project. It has undergone more revisions and changes than any other gripper. The same part has always been handled by the gripper, namely the bottomcap. The requirement was to handle the bottomcap in both the open end up and closed end up configuration. Another requirement was to handle the bottomcap in multiple configurations, with no parts attached, with a bail attached, or with a spare bulb holder and spring inserted. During the assembly, the gripper was used for moving the bottomcap. No direct assembly was performed by the gripper. At the first robot, the gripper was used to retrieve the bottomcap from a flexible feeder and place it into a fixture. It then was used to place the bottomcap, with the bail attached, into the pallet. At the second robot, the gripper was used to retrieve the bottomcap from the pallet and place it on the staging area, it then had to lift the inverted bottomcap from the table fixture and place it back into the pallet. In both cases, the gripper was one of two at the robot. In the case of the first robot, the other gripper was used for the bails, at the second, the other gripper was used for the spare bulb holders and springs. The clearance required for the first robot was mostly dictated by the flexible feeder. Since the parts were being retrieved from the flexible feeder, it was necessary to keep the footprint to a minimum. The fixture location had plenty of clearance. The pallet drop locations were more crowded, but it was consistent and not changing as were the clearance requirements on the feeder. At the second robot, the pallet had the same clearance requirements; the staging area and the table fixture were not crowded.
The bottomcap gripper went through four revisions since it was originally designed. The first design used two large jaws. The inside of each jaw was contoured to fit the bottomcap, the outside of the jaws had an octagonal shape. The jaws were made of delrin and were approximately $\frac{1}{2}$ of an inch thick. These grippers were designed to work with a Robotech actuator. This design was never used on the workcell. The first revision was a complete redesign of the gripper. The design had four $\frac{3}{4}$ inch diameter rods extending from the actuator. $\frac{1}{4}$ of an inch of the bottom of each rod had a flat machined in it. Figure 5-35 shows this design.

![Figure 5-35: Bottom Cap Gripper - 2nd Revision](image)

This flat was designed to help hold the bottomcap more securely. Two rods were mounted on each side of the parallel motion gripper. The distance between the rods on each half and between the two halves when closed would match the outside diameter of the bottomcap. The rods were chosen as a design to minimize the footprint of the gripper. Using this design, the gripper could retrieve a bottomcap when it was in its most crowded situation on the feeder.
In the third revision of the gripper, a more usable design was achieved. The actuator mechanism was changed to a Schunk model RH907. This change was made to accommodate the new pneumatic rotary wrist added during Phase II of the Agile Manufacturing project and because it was much smaller and lighter than the Robotech design. The gripper jaws consisted of two smaller aluminum fingers approximately 1 inch wide by 1½ inches long. The inside of the jaws matched the outside diameter of the bottomcap. The outside of the jaws were also turned round to minimize the footprint. Each jaw was about 9/32 of an inch thick. The jaw located the bottomcap using the shoulder of the cap when picking the cap from the feeder and used the top of the bail for location after the bail had been placed, rotated into position and seated using the press.

![Figure 5-36: Bottom Cap Gripper - 4th Revision](image)

The bottom edge of the gripper jaws included a generous chamfer to allow the bottomcap to self center as the gripper approached the final pick location from above. The final redesign of the gripper fingers was essentially the same as the third with the alteration that the gripper located on the top of bottomcap at all times. Figure 5-36 shows this design.
The footprint of the initial design was large. Besides the gripper fingers themselves being almost 1\(\frac{1}{2}\) of an inch thick, mounting brackets which connected the fingers to the actuator added an extra 1\(\frac{1}{2}\) of an inch to the back of each finger. The second design of the gripper was the complete opposite of the first, it had a minimal footprint consisting of only the four 1\(\frac{3}{4}\) inch diameter posts. The design was such that even if a bottomcap had other caps touching it (the maximum crowded situation), the gripper could still retrieve the cap. The third and fourth designs had identical footprints. It was a relatively small footprint consisting of the size of the thin fingers plus the amount of travel of the actuator. Because of their one inch width, most parts were retrievable simply by rotating the gripping angle until there was clear area in which to descend with the fingers.

The first gripper design was only a prototype and was actually not used for assembly. It picked and dropped the bottomcaps in a test setting, but lacked any features to vertically locate the caps. It also had a much too large footprint to be useful.

The second gripper was used successfully during the first phase of the project. It had a small footprint, which was good for feeding and for reaching constrained locations, but it had other problems that affected its performance. Its four rods provided too little surface area over which to develop a solid grasp. The rods themselves were also rather frail and would bend easily in a collision. The design of the actuator made it difficult to align the fingers properly, therefore it was difficult to get all four rods to maintain a solid contact on the bottomcap. The small shoulder where the flats were machined at the end of each rod was too small to reliability transmit the vertical force of the robot to the cap. This was most noticeable when trying to insert the cap into the pocket on the table fixture.

The third gripper design worked much better for grasping and manipulating the bottomcap. Its wider jaws distributed the gripping force over a much larger area which reduced part deformation. While the footprint was slightly larger that the second design,
it was still sufficiently small to not be a problem. One problem with the gripper was the method of vertical registration. A step was machined in the surface of the jaws which was used to vertically locate the cap. Without a bail, the step would rest on the shoulder of the cap, when a bail was present, the shoulder would rest on the top of the bail. The first inconvenience was that different heights had to be taught for placing the endcap on the fixture and picking it up after a bail was added. Since the same part was being handled by the same gripper at the same physical position, it was confusing to have a different location defined for removing the part. The main problem, however, was vertically locating the cap on the bail. Seating the bail was a problematic step of the assembly and any errors in that step would translate into a bad or missed grasp of the bottomcap. Sometimes the bail would be seated, but would be resting at an angle rather than resting on the shoulder, at other times, the bail would not be properly seated. On a few occasions, the bail would fly off on the way to the press and would not be present at all. These errors were magnified by the gripper design since they would usually cause the part retrieval operation to fail.

The current (and fourth) design of the gripper is similar to the third, the only difference being the removal of the shoulder. Instead of vertically locating the part on the shoulder and the bail, the part is located on the top of the cap. This is a surface that is constant even if the bail is improperly seated or missing. This has greatly increased the reliability of the gripper removing the part from the fixture.

The endcap gripper embodies many of the design guidelines presented in the previous section. It has, in fact, been the catalyst of many of the guidelines. There was an effort to minimize the footprint of the gripper as the design progressed. While the footprint did grow slightly between the second and subsequent designs, it was still kept small. It was clear from the second gripper’s performance that a more positive grasp of the part was required. That was the reason for designing a set of jaws that matched the shape of the bottomcap. Another guideline that was followed was to not squeeze the part.
It became evident during the operation of the second design (phase I of the project) that squeezing the part too tightly would cause it to deform to the extent that it would no longer fit into the fixture. The third design of the jaws was such that the diameter of the cap was reached when the actuator was almost entirely closed. This left a little compression for holding, but not so much as to deform the part. The fingers were also designed to center the part as they closed. This was done by chamfering the parting line of the jaws. The serrated outside of the bottomcap made it difficult to center since the gripper fingers would catch on the serrations. The final design corrected the problem of locating vertically using the bail. This was embodied in the guideline which says to not rely on added parts for location. Finally for economy, an inexpensive, pneumatic actuator was used.

While the gripper works well in its current configuration, several important improvements could be made. The first has to do with aligning the fingers on the actuator. Currently, the fingers mount to the actuator using only the screw holes for location. More accurate location on the actuator would help align the fingers better. The second improvement would be to make the gripper jaws wider. This would allow for a larger chamfer on the exterior surfaces of the fingers which would help them in aligning the part as the gripper jaws were closing.

During the first phase of the project, the gripper was mounted together with the gripper which handled bails and the gripper which handled lamp holders and springs (discussed in the following sections). The entire assembly was mounted on the fifth axis of an AdeptOne robot which allowed all the grippers to be immediately accessible and allowed the single robot to perform the entire assembly. Figure 5-37 shows the complete gripping system. During subsequent phases of the project, the gripper was mounted on a pneumatic, rotary wrist with the bail gripper. Figure 5-38 shows this gripping system.
5.4.4.2 Bail Gripper

The bail gripper was the second gripper constructed for use in the workcell. In contrast to the bottomcap gripper however, it has had no design changes. The gripper was required to retrieve and assemble a bail onto a bottomcap. The bails are fed on a flexible feeder so the gripper had to pick a bail from a flat surface. The stable pose of a bail is lying on its side on the feeder so a clever design was required to lift the bail from this position. The second task of the gripper was to spread the ends of the bail and
position it over the mounting holes on the mounting block of the bottomcap. It then had to release the bail and leave it attached to the bottomcap. In the original assembly plan, the gripper was also used to rotate the bail into position over the shoulder of the bottomcap before pressing. It became apparent however, that it was more efficient and reliable to use a dedicated mechanism to flip the bails. A copper tube was fashioned into an appropriate shape for this task.

The gripper is used at the first robot during the bottomcap assembly. It is used on the same rotary wrist as the bottomcap gripper. The gripper was remade during Phase II because a different actuator was required for use with the rotary wrist (Schunk RH907 in place of a Robotech model 1610, used during Phase I), it was not redesigned. This gripper has a unique requirement on footprint. Since the gripper grasped the bail from the inside using an opening action of the gripper fingers, it had to fit inside the bail as it laid on the flexible feeder. After the bail was grasped, it was taken to the bottomcap fixture and attached to the cap. In this location there was plenty of clearance. Figure 5-39 shows the gripper retrieving a bail from the flexible feeder.

![Bail Gripper Retrieving a Bail](image)

Figure 5-39: Bail Gripper Retrieving a Bail

The design of the gripper is unique in that it grasps a part when the actuator is open instead of when the actuator is closed. This is necessary since the bail must be
flexed open to be attached to the bottomcap. The fingers are about 1 inch wide and 1 inch long. They are about \( \frac{3}{4} \) of an inch thick. The exterior surface of the grippers are turned to a diameter that approximates the diameter of the inside of the bail. At the end of each finger a round groove is machined. The radial diameter is the same as the cross sectional diameter of the bail. As the gripper opens, the bail is lifted from the surface by the grooves. This opening action of the gripper also spreads the ends of the bail. The corners of the groove are chamfered to help the bail align in the groove. The lower portion of the groove runs out at the end of the fingers which leaves an angled surface which helps lift the bail from the feeder. The back of each finger is machined flat. Figure 5-40 shows a closer view of the end of the bail gripper.

The fingerprint restrictions on this gripper are relatively relaxed. To function properly, the gripper must fit inside the bail. For a bail to be graspable, it needs to be singulated on the conveyor, which means there will be nothing in the middle of the bail. Therefore, by designing the gripper to function properly guarantees that it has sufficient clearance.

![Figure 5-40: Bail Gripper Finger Detail](image)

This gripper has been used successfully for the past four years. It has been reliable in retrieving the bails from the feeder. It has been mostly reliable in placing the
bails on the bottomcap. Some of the problems with reliability stem from the bail rotating on the gripper fingers as they are opened. Because the bail is split at one end, as it is spread open, it tends to rotate both sides of the bail from a point located at the mid-section of the bail (the side directly opposite the split). Since the gripper jaws open in a linear fashion, the bail needs to slide on the gripper jaws as it spreads. Variations in the surface finish of the bail and how well the gripper is aligned with the bail before opening affect how evenly this sliding takes place. If this sliding action does not happen evenly, then the bail will end up rotated on the gripper. There is no mechanism for accurately locating the bails rotationally on the fingers. Since the split end of the bail is placed over the mounting block on the bottomcap, the rotation of the bail on the gripper jaws is important if it is to be repeatable.

Some of the guidelines followed when designing this gripper include a secure grasp of the part, chamfers on approach surfaces, and gripper fingers that complement part shape. The fingers were designed to use the elastic flex of the bail as the source of force holding the bail on the gripper. By machining a groove in the gripper fingers in which the bail sits, when the bail is flexed open it rests in the groove. To fall off the gripper, the bail would have to flex open even further than it is when being held. Chamfers were provided on the bottom edge of the fingers and on the edges of the groove to help guide the bail into the groove when it is being retrieved. The gripper fingers themselves are contoured to match the shape of the bail. The outside diameter of the jaws match the inside diameter of the bail and the diameter of the groove matches the cross sectional diameter of the bail. This helps to establish a more secure grasp on the bail. A guideline which was not included in the design was to align parts on the gripper as they are being grasped. This is indicated by the problem mentioned earlier of the bail not being consistently rotationally positioned on the gripper fingers.

A future revision is to design the motion of the gripper to better match the motion of the bail as it is spread open. To accomplish this a rotary motion gripper would
be used in place of the parallel motion gripper. This rotary motion actuator would be mounted on its side with the gripper jaws extending sideways from the mounting posts below the gripper. The bail would be retrieved by lowering the jaws into the middle of the bail and opening the jaws rotationally. This rotational motion would better match the motion of the bail and would reduce the amount of sliding of the bail on the gripper fingers. This reduction in sliding should make the location of the part on the gripper more consistent and repeatable.

5.4.4.3 Lamp Holder / Spring Gripper

The lamp holder / spring gripper was the last gripper made during Phase I of the project. It was the first gripper designed to handle multiple parts. It originally was mounted on the three gripper mechanism used on the AdeptOne robot used during the first phase of the project. The gripper is used to handle the spare lamp holder and the spring. It can not handle both parts simultaneously. During Phase I, both parts were retrieved from a vertical orientation. The spare lamp holders were fed using a special grate which held them in a vertical pose with the grasping tab pointed straight upward. The springs were fed standing upright with the large coils pointing down. After Phase I, the lamp holders were fed resting on the flexible feeder lying on the flat belt surface. This required the gripper to approach the lamp holder at an angle equal to its static rest angle. Figure 5-41 shows the lamp holders being retrieved from the grated surface and the flat surface. The springs are still fed upright. The gripper is used for both part retrieval and for assembly. In the case of the lamp holder, the gripper has to retrieve one from the flexible feeder and then place it into the bottom of the bottomcap. It must have sufficient clearance to reach the bottom of the cap. In the case of the springs, it must be capable of grasping a spring from above. There is a large tolerance in the size of the springs and the gripper must be capable of dealing with this. After grasping a spring, the gripper must then seat the spring in the bottom of the bottomcap. To do this, it drives the spring through the spring funnel which guides the spring into location. The gripper must
fit through the spring funnel in its open position as well as its closed position. The gripper is used on the same wrist unit as the bottomcap gripper. This gripper is unique in that it uses the angular degree of freedom in the wrist unit to align itself with the lamp holder for pickup. By limiting the range of rotation of the wrist, the lamp holder gripper extends at the correct angle to pick the lamp holders from the flexible feeder. A special mounting block was produced to allow the bottomcap gripper to be vertically orientated when the wrist is at this angle. By rotating the wrist to its other stop, the lamp holder is in a vertical oriented, ready for insertion into the bottomcap.

![Figure 5-41: Lamp Holder Retrieval During Phase I and Phase II](image)

The gripper fingers themselves are made of two parts. The first part is an extender to which the actual fingers are attached. This extender is used since the original fingers, used during Phase I, are still being used. During Phase I a Robohand actuator was used. A Schunk RH907 has been used since Phase II (to mate with the rotary wrist) and so an adapter was needed to attach the fingers to the new actuator. A redesign of the spring funnel adapter also required the fingers to be a bit longer to reach the bottom of the bottomcap. The finger extender has a rectangular cross section and is about 1 inch long. The fingers themselves are each a half round cross section. The outside diameter is about 5/8 of an inch in diameter and about 1 inch long. At the end of the finger is a smaller diameter post. On the inside of the post a slot is cut and is used to pick the lamp holder. The width of the slot is slightly less than the width of the tab which provides a secure hold on the lamp holder. The exterior of the post has a chamfered end.
to help guide the spring over the post. For most of its length there is a reverse taper designed to hold the spring after it has been grasped. The shoulder between the post and the larger diameter is used to drive the spring through the spring funnel. The gripper is rotated 90° from the standard mounting orientation. This was done to align the direction of motion of the actuator with the orientation of the lamp holder as it sits on the feeder. Figure 5-42 shows the fingers of the gripper holding a lamp holder and spring.

![Figure 5-42: Gripper Holding a Lamp Holder and Spring](image)

The gripper can have a unique footprint depending on the orientation of the wrist. In the case of retrieving springs, the gripper grasps springs from within the top coil of the spring. So as in the case of the bail, the gripper's footprint is smaller than the size of the part that is being picked. This mean by its very design, the gripper will reach the part if it is singulated on the feeder's conveyor. The footprint of the gripper in the lamp holder orientation is not as obvious. There are two components which may collide with other parts on the feeder. The first part is the gripper fingers and actuator. Since the gripper is approaching at an angle, there is the possibility of the bottom edge of the actuator hitting parts. The second (and not so obvious) part to watch is the bottomcap gripper. Since the bottomcap gripper is in a vertical orientation when the lamp holder gripper is at an angle, it may also hit other lamp holders. These two parts of the gripper give it an odd shaped footprint. Its footprint resembles an oval directly in front of the
lamp holder with a circular area, separate from the oval, a greater distance away from the face of the lamp holder being retrieved. The resulting footprint of the gripper is rather large.

The design has been fairly successful for both the lamp holder and spring. The lamp holder has been mostly reliable. It usually picks the lamp holder from the flex feeder cleanly and places it in the bottomcap with no problems. Some of the problems seen have been with the lateral positioning of the lamp holder in the gripper. Since a flat slot is being used for gripping, there is nothing to properly align the lamp holder sideways in the gripper. This causes problems when trying to insert the holder into the bottomcap because the lamp holder can catch on the threaded inside of the cap and get stuck sideways in the cap. The other problem is seen after extended testing using the same lamp holders. After a while the bulb holding posts on the holder tend to get bent and the holder ends up sitting at a different angle than the one for which the gripper was designed. This can cause the lamp holder to slide in the gripper as it is being closed which produces an unreliable positioning of the holder in the gripper jaws.

The spring gripper works well. It usually picks parts and inserts them into the bottomcap without error. The problems seen when using this gripper can usually be attributed to the variations of the springs being fed. The first problem is in the size of the top coil of the spring. If there is not enough room to physically fit the gripper through the top coil, problems can be experienced. The second problem has to do with the alignment of the top coil with the bottom coil. If the coils are not nearly concentric, when the gripper attempts to place the spring in the bottomcap using the spring funnel, the spring will hang-up on the top of the funnel. The last problem has to do with worn springs. Over time, the height of the spring decreases since its coils get compressed each time it is placed in the bottomcap. Eventually the spring is too short to reach all the way through the spring funnel and it is left stuck inside the funnel rather than being seated properly in the bottomcap. All these problems, however, are attributed to the spring and not the
design of the gripper. A better gripper design would perhaps help to correct some of these problems from happening, but a better solution is to fix the part rather than try to patch the problem with an overly complex gripper.

Several guidelines were important in the design of this gripper. This gripper also demonstrates a situation where it is impossible to satisfy all the guidelines, and trade-offs must be made as to what guidelines are more important. The gripper itself is designed to grasp two different parts which helps the throughput of the system by allowing the assembly to take place without a tool change. The gripper fingers had to be designed longer than recommended because of the need to reach through the spring funnel with the spring and because of the angle at which the lamp holder is retrieved from the flexible feeder. The junction between the extensions and the fingers was designed to properly align the two components. The junction between the extensions and the actuator only relied on the screw holes for alignment. The lamp holder gripper was compromised in several ways at the expense of grasping multiple parts. The guideline which stipulates that the gripper align the part as it is being grasped and the guideline that says to fully encompass the part being grasped had to be forgone so that the same gripper could pick both the lamp holder and spring. Since the tab on the lamp holder is much larger than the top coil of the spring, it was impossible to provide lateral positioning to the lamp holder as it was being grasped. This caused the variation in the lateral position of the lamp holder in the gripper jaws as discussed in the previous section. The spring gripper had chamfers on the exterior surfaces which helped center the spring on the gripper as the spring was approached. It has a reverse taper on the exterior of the post to ensure a secure grasp of the spring. The circular shape of the post helped to align and hold the spring.

If the design were to be revised, there would be several areas for improvement. The first is in the junction between the actuator and the fingers. This junction needs to encompass the mounting posts so that the gripper fingers are properly aligned. Another
improvement would be to design a feature into the fingers which would properly align the lamp holder laterally in the fingers. It would also be better to design the fingers as a single unit rather than use an extender as is currently being done. This would save weight and make the fingers more compact.

The lamp holder / spring gripper was mounted on a pneumatic, rotary wrist with a second bottom cap gripper (nearly identical to the one previously discussed, made of a nylon material rather than aluminum). It was used at the second robot to perform the second half of the bottom cap assembly sequence. Figure 5-43 shows the gripping system.

![Image of Lamp Holder / Spring / Bottom Cap Gripping System](image)

Figure 5-43: Lamp Holder / Spring / Bottom Cap Gripping System

5.4.4.4 Lens Ring Gripper

The lens ring gripper was originally designed to only handle the lens ring. The redesign of the gripper to hold both the lens ring and reflector is discussed in the next section. The original assembly sequence of the headcap called for the lens ring to be placed in the assembly last. This gripper was tested on the robot, but was never used for assembly. The assembly sequence was altered and a new gripper was constructed before the assembly commenced.
This lens ring was to be handled in the open end down configuration. The parts were to be fed using the flexible parts feeder, so the footprint of the gripper was of concern. The gripper was required to retrieve a part from the flexible feeder and place it into a fixture on the modular worktable for a subsequent pressing operation. It then needed to lift the completed headcap assembly from the fixture and place it in the pallet. Since the lens ring formed the outside of the assembly, the same gripper should be used. The only concern was that the gripper could handle the added weight of the full assembly.

The gripper was constructed from delrin (a nylon type material) to save weight. It was about 1\(\frac{1}{2}\) inches wide and 1 inch tall. The insides of the jaws were contoured to match the outside diameter of the headcap. The jaws themselves were about \(\frac{3}{16}\) of an inch thick. The outside of the jaws were turned to a diameter to minimize the footprint. The jaws were sufficiently chamfered to help center the parts in the jaws during both the approach and closure. The footprint of the gripper is the size of the gripper fingers plus the amount the actuator opens.

The gripper worked well in testing and handled the lens rings without error. Several guidelines were followed in the design of the gripper. The first guideline followed was to minimize footprint. Since parts were being retrieved from the flexible feeder, the footprint was an important criterion. Gripper weight was minimized by using delrin material for construction rather than a heavier metal material. The gripper jaws were designed to fit the contour of the parts being handled to provide a secure grasp of the lens ring. The jaws were designed to not overly squeeze the parts so that there would be no problem in inserting the parts into the fixture because of a deformed part.

While the gripper jaws were functional, there were two areas of the design which could be improved. The first is with the chamfers on the jaws. A larger chamfer on the leading edge and parting line of the fingers would make the grippers more reliable. The second improvement was to design the fingers to encompass the mounting points of the
actuator. This would help alignment and positioning of the fingers on the actuator. Since the gripper was redesigned into a combined lens ring / reflector gripper, these improvements were able to be made.

5.4.4.5 Lens Ring / Reflector Gripper

After the assembly sequence was redesigned (to that listed in Section 5.4.2.2), it was determined that a gripper was needed which would handle both the lens ring and the reflector. This was necessary because three parts were being handled at the first robot. Since the lens was much different geometrically compared to the lens ring and reflector (flat disk in contrast to a more circular shape), it made sense to design the lens ring and reflector into a single gripper. The design criterion of the gripper was fairly restrictive. It was required to retrieve a lens ring from the flexible feeder and place it into a fixture on the modular table. It was also required to retrieve a reflector from the flexible feeder and place it into the lens ring. Finally, it had to remove the lens ring / lens / reflector assembly from the fixture and place it into a pallet. The lens rings were handled in an open end up orientation while the reflectors were handled in an open end down orientation. The reflectors were also fed using a flexible feeder. The gripper was used on a rotating wrist system with the lens gripper.

The footprint of the gripper was a concern during the design since both parts were being fed using a flexible feeder. To keep the footprint to a minimum, the jaws were made as thin as possible. Clearance for approaching parts was also kept small. The clearance around the lens ring, however was bigger than absolutely necessary to accommodate the reflector portion of the gripper. Since both parts are rotationally invariant, a suitably clear area for grasping could be found by simply rotating the pickup angle until a clear area was found. Figure 5-44 shows a close up of one jaw of the gripper and also shows the gripper holding each part.

The gripper fingers are approximately 1 inch thick by 1 inch wide by 1 1/2 inches long. The top of the fingers have a square pocket milled in them which encompasses the
mounting point on the actuator to ensure the jaws are aligned properly. The fingers themselves have a circular inside and outside diameters. The first inside diameter is designed to match the outside diameter of the open end of the lens rings. It is approximately $\frac{1}{2}$ of an inch long and terminates at a shoulder. The shoulder is used to vertically align the lens ring in the gripper fingers. A second diameter, not used for gripping, begins at the shoulder and continues for another $\frac{1}{2}$ of an inch. A bore with a tapered top and a flat lip on its bottom is used to grasp the reflectors. The reflectors are grasped using the metal conductive shield on the back of the reflector. This shield fit into the bore of the gripper jaws. The taper on the top of the bore matches the angle on the top of the metal shield. The reflector is held in the gripper by being constrained in the bore rather than by friction alone.

Figure 5-44: Lens Ring / Reflector Gripper
Care was taken when designing the various diameters of the fingers to ensure that collisions would not occur during assembly. This was particularly critical when inserting the reflector in the lens ring. The sizes of the fingers had to be designed such that the surface which usually held the lens ring would be held at a larger diameter when holding a reflector so that the reflector could be placed in the lens ring without the gripper colliding with the lens ring. The vertical heights of the gripper had to be carefully designed so that the gripper could grasp a reflector without hitting the feeder’s belt and could grasp a complete sub-assembly without hitting the metal shield of the reflector.

The design worked well. After a slight modification to the amount of clearance on the approach to the lamp holders, the gripper fingers worked without problems. Lens rings or completed assemblies were never mishandled. The only problem with the grippers, seen rarely, was in the release of the reflector. Occasionally, a reflector would hang up in the bore and not be released cleanly. This usually caused the reflector to be left sitting in the lens ring at an odd angle. The press none-the-less usually seated the reflector correctly.

The gripper used many of the guidelines previously discussed for its design. The footprint of the gripper was kept to a minimum, since parts were being grasped from a flexible feeder. The footprint did, however, become a little bigger so that both the reflector and lens ring could be handled. This was seen as an acceptable compromise, since handling both parts was more important than simply minimizing the footprint. By designing the shape of the gripper jaws to match the lens ring, a secure grasp was obtained. By designing the reflector to be held in a groove, an even more secure grasp was obtained since more than just friction alone is used to hold the part. The guideline which suggests using a single gripper to handle multiple parts was also followed. This saved a tool change operation and helped to reduce the cycle time. The gripper fully encompasses the reflector when its being held. This helps to increase reliability by reducing the possibility of the part being dropped. The gripping surface for the lens ring
was designed so that the ring would not be squeezed to the point that it would not fit into
the fixture. The circular shape of the fingers which complement the shape of the part
allows the gripper to center the parts as they are being grasped even if the parts are not
exactly at the pick location (as returned by the vision system) before the gripper begins to
close.

![Figure 5-45: Lens Ring / Reflector / Lens Gripping System](image)

The gripper has been successful and only two areas could be improved. The first
is the weight of the gripper. If the gripper were made of a plastic material, it would be
lighter and could possibly allow for faster robot motions. The second area of
improvement, if a revised gripper were being designed, would be to make the release of
the reflector more reliable.

The gripper was mounted on a pneumatic, rotary wrist with the lens gripper
(discussed below) and used at the first robot for the first half of the headcap assembly.
Figure 5-45 shows the complete gripping system.
5.4.4.6 Lens Gripper

The lens gripper was the second gripper constructed for the headcap assembly. It was the first gripper which used suction as the means of holding the parts. It was designed to lift a lens from the flexible parts feeder and place it into the lens ring. As stated previously, the lens is a unique part in that it is a flat plastic disk and is translucent. Because of the darkened ring around the perimeter of the lens, it appears to the vision system as a circle. To successfully pick up a lens, the gripper must be capable of lifting it from the flexible feeder. Since the disk is thin, about $\frac{1}{10}$ of an inch, a parallel jaw gripper would be inappropriate. After retrieving the lens, the gripper had to place the lens inside the lens ring. It had to place the lens far enough into the lens ring to allow room for the reflector to be placed into the ring on top of it. Since the lens is nearly the diameter of the lens ring, it would have been difficult to insert the lens using a gripper which held the lens by its perimeter. The gripper was used at the first robot on a rotary wrist with the lens ring / reflector gripper.

The footprint of the gripper is not a concern for this design because of the method of gripping of the part. Since the gripper is using suction and approaches the part from above, no additional clearance around the part is required. If the vision system has identified the part as valid for retrieval, then there is sufficient clearance for the gripper.

The gripper is an arrangement of three suction cups in a triangular pattern. The gripper mounts to the rotary wrist using a circular disk of aluminum about $\frac{3}{8}$ of an inch thick. The suction cups mount on three posts which extend from the aluminum disk. The posts are about $1\frac{1}{4}$ inches long. The three suction lines run from each post serially. A single venturi type vacuum generator is mounted to the quick connector and provides the suction for the gripper. The suction cup itself has a base of hard rubber and is mounted on a brass barb fitting. This provides the force necessary to push the lens into the lens ring. The vacuum lines enter the posts which hold the gripper from the side approximately one inch from the end of the suction cup. Figure 5-46 shows the design.
The design has worked well and has been reliable at retrieving the lens. After the proper tool offset was taught, there have been no problems inserting the lens into the lens rings. One minor reliability problem was noticed while using the gripper.

Figure 5-46: Lens Gripper

The problem seen is the durability of the suction cups. Since the cups are being used to press the lens into position, they can develop tears in the bellows section which causes a loss of suction. After about 3 months of intermittent testing, one of the suction cups developed a tear. This was not a major issue since the rubber cup can be replaced in about 10 seconds and the replacement part only costs pennies.

Since many of the guidelines deal with parallel and rotary motion actuators and their gripper fingers, not many of them were applied to the design of the lens gripper. The entire gripper was made from aluminum to save weight and was constructed using standard suction cups to save cost. Providing features to laterally align the parts was not included in this design. The compliance of the rubber suction cups, however, allowed the
part to line up with the lens ring as it was being inserted. Since the gripper is used for assembly (and not just pick and place), another guideline suggests to design chamfers on the gripper to help align the parts before insertion. Designing a feature such as this into the gripper would have made the gripper cost much higher and the gripper more complex. Again, the compliance provided by the suction cups offsets the lack of features to pre-align the parts.

The only part of the gripper that could be improved if a revision were made would be the suction delivery system. In its current configuration, if one of the suction cups fails, then the gripper will drop the part because all the cups receive their vacuum from a common supply line. It would be more fail-safe to design the gripper such that the failure of one suction cup would not cause the part to be dropped.

5.4.4.7 Bulb / Bulb Retainer Gripper

The gripper which handles the bulbs and bulb retainers is unique in that it rotates parts through 90° after acquiring the part. This type of motion is often needed for use with flexible parts feeders. Since flexible feeders present parts to a vision system in their stable poses (at least marginally stable, i.e., rolling parts), it is often necessary to rotate the parts before using them for assembly. It became apparent during the design of the assembly sequence for the headcap that feeding the bulb retainers and bulbs was going to be challenging. The statically stable pose of the bulbs is lying on their sides and while a few of the bulb retainers stand upright, most end up lying on their sides. However, in both cases, the parts were required to be in a vertical orientation for assembly. After a search of commercially available components turn up no valid gripping solution, a rotary jaw gripper was designed. The rotary jaw gripping mechanism has been revised and is now rather generic in nature. It is discussed in detail in Section 5.4.3. Refer to that section for details about the design of the rotary mechanism, this section will deal primary with the gripper used specifically for the bulbs and bulb retainers.
Both the bulbs and bulb retainers are fed using the flexible parts feeder. Gripper footprint is a concern, especially in the case of the bulb retainers which tend to lie in close proximity to one another on the feeder belt. Another design challenge was the shape of the parts. While the bulb has a circular shape to it, the bulb retainer has an almost square shape. This meant that the design of the gripper fingers must accommodate both round and square parts. After grasping the parts and rotating them 90° the gripper then had to place the bulbs directly in the back of the reflector. The bulb retainers were placed into a temporary fixture before being placed into the reflector by another gripper. The table fixture was such that there was a restricted amount of room in which to position the gripper for dropping the parts. To make a successful assembly, the gripper was used to lift a bulb from the flexible feeder, rotate it 90°, and place the bulb in the hole in the back of the reflector. It also was used to lift a bulb retainer from the flexible feeder and place it into the table fixture. The gripper is mounted on a rotary wrist with the bulb retainer assembly gripper. The two grippers allow the second robot to perform the second half of the headcap assembly without a tool change. Figure 5-47 shows the gripper handling both a bulb and bulb retainer.

Figure 5-47: Bulb / Bulb Retainer Gripper
The footprint of the gripper is small. Its fingers are \( \frac{1}{8} \) of an inch thick by \( \frac{1}{2} \) of an inch wide. This allows the gripper to retrieve bulb retainers from the feeder when they are in close proximity to one another. While the rotary mechanism is much larger than the gripper fingers themselves, the fingers are long enough to keep the mechanism at a height where it will not interfere with the other parts on the feeder.

The design of the gripper is unique. A linkage drives both fingers of the gripper from the single cylinder. The fingers are mounted on axles and are driven by the axles. The fingers extend below the rotary mechanism when in the un-rotated state and point behind the rotary mechanism when rotated. The fingers themselves are flat plates to which a layer of rubber and cellophane tape is applied. This allowed the gripper jaws to have a compliant surface which greatly increased the secureness of the grasp of both parts. The gripper fingers including the rotary mechanism is mounted on a Schunk KTG 50 actuator. The first design of the gripper had stubby fingers, which did not extend very far past the rotary mechanism. This caused problems since it greatly increased the footprint of the gripper. A severe reduction in feeder throughput was seen because of the size of the gripper’s footprint. To fix the problem, a new set of fingers were designed which were much longer than the first. These fingers greatly reduced the footprint of the gripper and improved the feeder throughput.

The gripper has been used in the workcell for over a year with much success. As previously stated, the first design had stubby fingers which caused feeder problems. After extending the fingers, much greater feeder throughput was observed. Other problems were encountered at first. The gripper jaws were originally left as flat aluminum plates. This greatly reduced the quality of the grasp and some mishandling of parts was observed. Next, the layer of rubber was added. This improved the grasp of the gripper by increasing the friction between the gripper fingers and the parts and by increasing the surface area of the fingers which were in contact with the parts, but other problems were evident. After grasping and rotating the part, the gripper would move to
the drop location and open its jaws. However, the part would stick in the gripper because of the compliant nature of the rubber. To fix this situation, a layer of cellophane tape was applied to the gripper fingers over the rubber. This kept the parts from sticking to the rubber when the gripper jaws opened. The friction between the gripper jaws and the parts were lowered by the use of the tape. However, there were no problems maintaining a solid grasp on the parts as they were being moved. After correcting the length of the fingers and the surface material of the fingers, the gripper has performed without problem. Figure 5-48 shows the original design with short fingers and a close up of the lengthened fingers.

![Figure 5-48: Bulb / Bulb Retainer Gripper with Short and Long Fingers](image)

Many guidelines were followed during the design of the rotating jaw gripper. Several of the guidelines were actually created directly because of lessons learned during the design and testing of the gripper. Minimizing the footprint of the gripper was a priority after the first tests of the gripper were conducted. By extending the fingers beyond the rotary mechanism, a much smaller footprint was realized. Chamfering the outside of the gripper fingers was also done to help the gripper push parts out of the way as it approached a different part. Minimizing the weight of the gripper was important so that it could be used on a rotary wrist with another gripper. Both of the commercially available grippers were far too heavy to be used on the robot in the workcell. A secure grasp of the part was ensured by adding the compliant rubber material to the gripper
fingers. Since the jaws were simple flat plates and contained no features with which to orient the parts as they were retrieved, this compliance did not affect the precision of the gripper. Tool changes were avoided by designing the gripper to be used on a rotary wrist mechanism and by designing the gripper to handle multiple parts.

Figure 5-49: Bulb / Bulb Retainer Gripper / Assembly System

Cycle time and reliability were also enhanced by designing the rotary motion in the gripper and avoiding an external flipping mechanism. Several guidelines had to be ignored, however, to allow the gripper to handle multiple parts. Since the parts have different shapes (circular and square), the gripper fingers were not made to complement the shape of the parts being grasped. Also, to decrease the footprint of the gripper, the gripper fingers had to be lengthened a little beyond the maximum length recommended by the actuator manufacturer.
The bulb / bulb retainer gripper is mounted on a pneumatic, rotary wrist with the bulb retainer assembly gripper. It is used at the second robot to perform the second half of the headcap assembly. Figure 5-49 shows the gripping system.

5.4.4.8 Bulb Retainer Assembler

The bulb retainer assembly gripper was designed to complement the rotary jaw gripper for the second half of the headcap assembly. While the rotary jaw gripper had the ability to grasp the bulb retainer and rotate it 90°, it lacked the ability to press the retainer into the back of the reflector. The pressing operation takes some amount of force and the rotary jaw gripper was not capable of generating that force for several reasons. First, the jaws were parallel flat plates and had no features to transmit the vertical force of the robot to the part. Secondly, the rotary mechanism was not strong enough to take the repeated torque generated by the pressing operation. Lastly, there were no features in the jaws to accurately align the parts as they are being inserted. To alleviate this problem, a dedicated gripper was designed to press the bulb retainers into the reflectors.

The only parts handled by this gripper are the bulb retainers. The parts are retrieved from the fixture on the table, where they are placed by the rotary jaw gripper, and pressed into the back of the reflectors while they are in the pallet. The footprint of the gripper was not as big a concern as it was for the rotary jaw gripper since the parts are always being retrieved and placed in known locations. The design did have to be built strong enough to withstand the repeated force generated by the pressing operation. The footprint of the gripper was made small by using several features. First, the fingers were designed such that the total stroke of the actuator was limited to about \( \frac{1}{8} \) of an inch. The thickness of the fingers was also made small and extra material was removed to reduce the footprint even further.

The design of the fingers was made as simple and compact as possible to increase the strength and robustness of the design. The fingers are about 1\( \frac{1}{2} \) inches wide by 1 inch long by 1\( \frac{1}{4} \) inches thick. The fingers completely encompass the mounting points on
the actuator to enhance the strength, stiffness, and repeatability of the jaws. The outside of the jaws have an octagonal shape. The corners at a 45° angle to the direction of motion were removed to reduce the weight and footprint of the gripper. The inside of the jaws are square shaped to match the shape of the part being gripped. This allows the parts to be accurately located laterally while being held by the gripper. This is important since there are no features to align the bulb retainer and the reflector before the insertion operation. Generous chamfers are included on the leading edge and parting line of the gripper jaws to help align the parts as they are being grasped. The base of the gripping area is left solid to provide a reliable transmission of vertical force to the parts and to provide positive vertical alignment of the part in the gripper jaws. The jaws themselves are constructed of aluminum for durability and strength. Figure 5-50 shows a side and end-on view of the bulb retainer assembly gripper.

The gripper has undergone no revisions since its design and has performed well in use. The chamfered surfaces help to align parts which are not sitting squarely in the fixture. After a year of use, no wear or bending of the fingers have been observed. Only one problem has been observed during use. On several occasions the bulb retainer stuck in the gripper after its jaws were opened. This was usually attributed to large burrs on the bulb retainer. Making the inside of the gripper fingers slightly larger should alleviate the problem.

Figure 5-50: Bulb Retainer Assembly Gripper
Many of the guidelines were used in designing this gripper. While not a major concern, the footprint was minimized to lessen the chance of a collision when picking or placing a part. The parts were fully encompassed with the gripper fingers when being transported. This helped to align the parts in the jaws, helped to align the parts properly before insertion, and helped to hold the part solidly during the insertion. The finger length was kept to a minimum to lessen the forces seen by the actuator during the pressing operation. Generous chamfers were included in the inside of the jaws to properly align the parts as they were grasped. The fingers themselves fully encompassed the mounting points of the actuator for strength and rigidity.

5.4.4.9 Cap / Container Gripper

This gripper was designed for use in Eaton's reconfigurable assembly cell. The gripper is a rotating jaw gripper similar to the bulb retainer/bulb gripper described in the previous section. It is a second generation design, however, and its rotational mechanism is different than the one on the previous example. The gripper is designed to handle two parts, the cap and the container, both from the tire valve cap package assembly. It was necessary to handle both parts with one gripper to avoid a tool change at the robot. As described in Section 5.4.2.3 the first robot must handle three parts: the cap, the container, and the lid. Since the cap and container must both be rotated through 90°, it seemed logical to use the same gripper for that purpose and to use a different gripper (mounted on a rotary wrist) for picking the lids. The design requires several features. The first, and most obvious, is the ability to rotate the parts 90°. Other requirements include a small footprint (the caps are fed using a flexible feeder) and the ability to handle two different parts. Figure 5-51 shows the gripper holding a cap and container.
The gripper is required to pick a cap from a flexible feeder. The location of the part is random and is returned by the vision system. Clearance is a concern, since the parts may be packed closely on the underlit conveyor. The parts must then be rotated through 90° and placed into a pocket in a pallet. The gripper must also pick the containers from a feeder. The parts are presented to the robot on their sides in a shallow “V” groove. The open end of the container may be forward or backward, but the location of the part is always known. After grasping a container, the gripper rotates it 90° as it travels to the pallet. At the pallet the container is placed into a pocket. After grasping a cap, the gripper also rotates it 90° on its way to the pallet where it is placed in a pocket. The gripper is part of a two gripper system used at the first robot. The other gripper is used to grasp lids. Figure 5-52 shows the gripper system.

The footprint of the gripper is small to accommodate parts being fed using a flexible feeder. To accommodate picking both parts, the footprint for the caps was made slightly larger than it needed to be. This is again a case of one design parameter (handling two parts) being more important than another (minimizing footprint). Chamfers were added to the bottom outside edge of the finger to further minimize the
footprint. The footprint of the gripper was not a concern when picking the containers, since they were always in the same place.

Figure 5-52: Tire Valve Gripper System - Robot 1

The design of the gripper is similar to the bulb / bulb retainer gripper. The rotary mechanism is driven by a single acting pneumatic cylinder. The fingers are mounted on passive axles and are driven by a shaft attached to the end of the cylinder rod. The same shaft drives both of the fingers so they are kinematically linked. Three air lines are needed to operate the gripper, two to open and close the jaws and one to rotate the jaws. Three sensors are also used in the gripper. Two sensors detect the open and close positions of the gripper while a single sensor is used to detect the un-rotated state of the fingers. There is no sensor to detect the rotated state of the fingers. The sensors to detect the open/closed state of the jaws are mounted using a manufacturer supplied bracket to the side of the actuator. Bolts of different lengths extending from one of the finger mounting pads are used to actuate the sensors. The sensor to determine the rotated/un-rotated state of the fingers is mounted in-line underneath the air cylinder. A bolt, extending from the piston rod bracket, is used to actuate the sensor. The fingers themselves are \( \frac{1}{2} \) of an inch wide by \( \frac{3}{8} \) of an inch thick by \( 1\frac{1}{2} \) inches long. The bottom
half of the fingers are hard anodized for wear protection. The fingers were cut using a wire EDM machine to match the contour of the caps. A relief area was also cut to accommodate the containers. The fingers were designed long enough so that the footprint of the gripper would not be affected by the size of the rotary mechanism and would be small. Chamfers were added to the bottom outside edge of the fingers to reduce the footprint further. The entire rotary mechanism was mounted on a parallel motion actuator from Schunk (KTG 50). No revisions of the design have been made. Figure 5-53 shows the detail of the rotary mechanism.

![Figure 5-53: Cap / Container Gripper - Rotary Mechanism](image)

The design has been used for several mouths in a demonstration setting with few errors. No errors have been noticed handling the containers. Those seen when handling the caps have included dropped parts, sticking rotary motion, and worn connector rod (the link which connects the end of the cylinder to the fingers). The dropped parts problem can be attributed to the parts themselves. After checking, it was determined
that many of the parts were undersized, which caused the gripper fingers to close on each other before contact was made with the part. The sticking rotary mechanism and the wear on the connecting shaft are problems with the rotary mechanism and not with the gripper fingers themselves. These problems and their solutions will be discussed in Section 5.4.3.

Several guidelines were important when designing this gripper. The footprint of the gripper was minimized by lengthening the fingers so the rotary mechanism would not collide with anything. Chamfers were added to the outside of the gripper fingers to further minimize the footprint. The entire gripper was made from aluminum and had much material removed for weight savings. To ensure a secure grasp of the part was maintained, the fingers were shaped to complement the shape of the parts. To avoid tool changes, the gripper was mounted on a rotary wrist and the fingers themselves were designed to handle multiple parts. Inherent to the design of the rotary mechanism, functionality was added to the grippers which allowed them to rotate the parts without releasing them. One guideline that was not followed strictly was to not squeeze the parts unnecessarily. Since the caps are smaller than the containers, it was necessary to allow the container to be squeezed when grasped. By picking the container near the open end, the base, which is inserted in the pallet pocket, was not distorted to the point to cause problems.

5.4.4.10 Lid Gripper

This was the second gripper designed for Eaton's reconfigurable workcell. It was designed to handle the container lid. The lid is retrieved from a flexible parts feeder in an open end down orientation. After grasping the lid, it is placed onto a post on the pallet. The actual assembly is performed at the second robot, so the gripper only acts in a pick and place manner. The gripper is used at the first robot on a rotary wrist with the cap/container gripper (Figure 5-52). Since only three components are used at the first robot, this gripper was only required to handle one part, the lid. The gripper was
required to retrieve parts from a flexible parts feeder. The feeder is a model 1224 made by RPM. As the parts pass through the vision window, they are mostly in an open end up (an undesirable) orientation. Gripper footprint is important since most parts are in this incorrect orientation. Any parts which are identified by the vision system need to be grasped so the system throughput is not adversely affected. The gripper needs to leave the bottom of the lid clear of obstructions so that it can be placed onto the post on the pallet. Figure 5-54 shows the gripper holding a cap.

![Image of Lid Gripper]

Figure 5-54: Lid Gripper

The design was simple. The lid is gripped from its rim from above. The gripper fingers have an internal groove into which the rim of the lid fits. This allows the gripper to securely hold the lid without relying on friction between the lid and gripper jaws. The fingers themselves are approximately \( \frac{7}{16} \) of an inch in diameter in two halves. The parts of the jaws which are below the groove are relieved about 45° from each parting line to help prevent the lid from sticking in the gripper. It also allowed the gripper to open less to clear the part on the approach which made the footprint smaller. Sensors are included on the gripper to detect the open and closed position of the fingers. The footprint of the
gripper was kept to a minimum by making the gripper fingers thin. The range of the 
stroke of the actuator was also restricted to further minimize the footprint by reducing 
the amount which the fingers open. No revisions of the gripper have been made. It has 
worked without fail in the workcell.

Even though the gripper was of a basic design, many guidelines were followed. As 
previously mentioned, minimizing the footprint was important to the success of the 
design. Weight was kept to a minimum by keeping the fingers short and thin. A secure 
grasp of the part was designed so that the part would not shift during robot motions. 
This was accomplished by grasping the lid using its rim so that the lid was physically 
constrained and not held by friction. By designing the gripper to function as part of the 
gripping system at the first robot on a rotary wrist, tool changes were avoided. By 
grasping the lid from the rim, the part was held without being overly squeezed. The 
necessary approach clearance was maintained without overly opening the gripper jaws 
by relieving part of the bottom of the gripper fingers. Chamfers were included on the 
inside of the gripper jaws to help align the parts as they are being approached by the 
gripper. Chamfers on the edges of the reliefs on the ends of the gripper fingers helped the 
gripper to align parts as they were being grasped. The gripping surface matched the 
shape of the parts which helped secure the grasp. The gripper fingers themselves fully 
encompassed the mounting points of the actuator. This helped to align the jaws on the 
actuator which improved the grasp.

The gripper fingers have proven to be reliable and therefore revisions are not 
necessary.

5.4.4.11 Seal Gripper / Assembler

The seal gripper/assembler was designed as part of the gripping system for use at 
the second robot of Eaton's reconfigurable assembly cell. The gripper is used to assemble 
the tire valve stem caps and place them in a final package. This operation had the 
possibility of being difficult and error prone. First, a seal has to be retrieved from a bowl
feeder. Next, the seal has to be pressed into the bottom of a cap. After the seal is in place, the cap/seal assembly has to be retrieved from the pallet and placed into the container. The caps and containers arrive at the second robot on the pallet in pockets in an open end up orientation. The seals themselves are small and light. They are presented from the bowl feeder in a track with only their tops exposed. Also, the seating operation requires that the gripper hold the part only from the top. The seating operation itself requires some force to be successful and also requires that the cap and seal be in good alignment because the seal has an interference fit with the cap. After the seals are seated, the cap needs to be lifted from its pocket. For efficiency, it would be convenient to use the same gripper to move the cap as well. The cap must be placed into the container. It is acceptable to drop the cap when placed over the end of the container, it does not have to be placed gently. The footprint of the gripper was not of a major concern. All the locations are known, so the necessary clearances can be designed into the gripper. The gripper is mounted on a rotary wrist with the lid gripper/assembler. Figure 5-55 shows the gripper system.

Figure 5-55: Tire Valve Gripper System - Robot 2
The design of the gripper is unique. Suction is used to grasp the seals and pick up the cap/seal assembly. A linear actuator is designed into the gripper and is used to seat the seals without the use of any extra assembly hardware. The design of the gripper is a two chamber cylinder arrangement. The first cylinder is used to drive the linear motion. The second cylinder is used to maintain the vacuum during the motion of the piston. This gripper does not use a commercial pneumatic actuator. The outside diameter of the gripper housing is about 2 inches in diameter for its top half and then steps down to \( \frac{5}{8} \) of an inch in diameter for its lower half. The overall height of the gripper body is 1\( \frac{9}{16} \) inches. In all, the gripper is composed of 6 separate parts. The plunger, the piston rod, the piston, the piston bottom, the housing, and the housing top.

The housing forms the main body of the gripper. The housing top allows the piston and vacuum chamber to be placed into the housing. Internally, the piston shaft goes through the piston bottom. The piston and the plunger are attached to the piston shaft. The piston shaft rests in the housing on a shoulder and is held in place by the housing top. The static joint between the piston bottom and the housing is sealed using an O-ring which sits in a recess in the wall of the housing. An O-ring is also used to seal the piston rod. The top of the housing, which also forms the wall of the piston, is screwed into the housing. The static seal between the housing and housing top is sealed using an O-ring in the housing wall. The top of the plunger is designed to have an O-ring seal with the lower part of the housing to form the vacuum part of the cylinder. Four larger holes extend most of the way through the plunger. Eight small holes are drilled into the end of the plunger, two small holes aligning with a single larger through hole. These holes allow the vacuum to pass through the plunger. No soft seal is necessary on the end of the plunger because the compliance in the part (the seal) is used to seal the vacuum. A small nub extends from the end of the plunger which is used to align the seal on the plunger when it is retrieved.
Three pneumatic ports are in the housing and are used to attach air to the cylinder and vacuum to the plunger. Flow controls are mounted on the ports that go to the air cylinder. During operation, the plunger must retract while holding the seal. If the plunger retracts too rapidly and the vacuum generator cannot draw air out of the vacuum chamber quickly enough, then the seal could be dropped. The flow controls regulates the speed of the plungers so that the seal is not dropped. Parker Hannifin’s O-ring design book was used to size all the dimensions so standard sized O-rings could be used. Figure 5-56 shows a CAD cut-a-way view of the internal details of the gripper. It also shows the gripper holding a seal.

Figure 5-56: Cap / Seal Gripper / Assembler

Operationally, the gripper begins by extending the plunger and approaching the pick location on the bowl feeder. The vacuum is activated and a seal is retrieved. As the robot moves to the cap location on the pallet, the plunger is retracted. The robot lowers the gripper into position over the cap and the plunger is extended, seating the seal into the cap. While still maintaining the vacuum, the gripper departs vertically from the position. The vacuum holds the seal and lifts the cap along with it. The robot then positions the gripper over the container and lowers the cap/seal assembly into the top of the container. The vacuum is then released and the plunger retracted which drops the
cap assembly into the container. Figure 5-57 is an end-on view of the gripper showing the internal linear actuator at its motion extremes.

Figure 5-57: Linear Actuator at Extremes of Motion

The gripper was revised once during the design and testing. The plunger originally had four small holes through its entire length. This had two adverse effects. First, the small holes restricted the vacuum to the extent that the seal was barely held in place. Secondly, the holes were difficult to drill correctly because of their length. The length of the plunger is about \( \frac{3}{4} \) of an inch while the diameter of the holes was 0.040 of an inch (#60 drill).

The gripper has been used in the workcell with mixed success. Several revisions have been proposed and will be discussed later. The first problem observed when using the gripper was the inability to properly seat the seal in the cap. Usually the seal would be left sitting in the top of the cap. Additionally, when the seal would not be seated properly, the gripper would usually fail to pick up the cap/seal assembly. Several reasons were found for this error. First, when designing the gripper, it was specified that 7 pounds of force was required to seat the seal. However, it was later learned that the seals were lubricated when that number was recorded. The gripper was designed to produce
approximately 20 pounds of force. It was thought that this extra force would ensure the operation would be successful. The amount of force produced by the actuator is directly related to the pressure of air being supplied to the gripper and to the diameter of the piston. Apparently, however, without lubricating the seals, much more force is needed than was originally specified.

Another problem was found to be the tolerances of the parts. It was found that many of the caps were smaller than the lower specified tolerance and many of the seals were larger than the upper specified tolerance. This combination made for a difficult insertion operation.

Another problem seen during use was the plugging up of the plunger. It was found that during the insertion operation, particles of the seal were shaved off the exterior of the seal as it was being seated. The threads in the inside of the cap were generally responsible. The vacuum would then pull these pieces of material into the vacuum chamber where they could stick to the inside walls because of the lubrication in the cylinder. After time, this would build up to the point where the actuator would cease functioning. Generally, the plunger would get stuck in the extended position since there is less force to retract the plunger than there is to extend it (due to the reduction in the surface area of the piston due to the piston rod). Occasionally a cap would stick on the end of the plunger after a seal was inserted. It was determined that this was caused by caps whose inside diameters were smaller than the lower tolerance. The plunger would wedge in this smaller diameter due to physical interference. Other than these problems, the gripper worked as planned. Few failures were seen when attempting to retrieve a seal. To circumvent the trouble seating the seals, the plunger was operated three times in rapid succession while positioned over the cap.

Many of the guidelines were employed in making this gripper. In contrast to most of the grippers designed, footprint was not a major concern in this case. It was kept small to minimize weight, but the lack of vision-based feeding during this assembly made the
clearance constant throughout the operation. The gripper was designed to handle multiple parts, the seal and the cap/seal sub-assembly, to help avoid tool changes. The gripper was mounted on a rotary wrist with another gripper so that the entire assembly could occur without a tool change. Functionality was designed into the gripper which helped speed the assembly operation by precluding the need for a dedicated pressing operation. It also helped the reliability of the operation by allowing the gripper to seat the seal in the cap and then place the cap/seal assembly into the container without letting go of the seal. The correct lengths had to be designed into the plunger and the housing so that seals could be retrieved from the bowl feeder, the cap could be approached without hitting the seal, and the cap/seal assembly could be handled. A large chamfer was machined into the bottom inside diameter of the housing to help guide the caps into position before the seal was seated. This chamfer also helped to align the cap and the seal as the seal was seated. This was especially important in this design since the seal was actually larger than the inside diameter of the cap and alignment was critical to the successful operation of the assembly.

Several areas of the gripper could be revised. The first is the diameter of the piston. Increasing the diameter of the piston would increase the force produced by the plunger and make the seal seating operation more reliable and sure. The second revision would be in the vacuum cylinder area. A better design would remove the vacuum chamber completely and route the vacuum line through the center of the plunger. The vacuum line could exit the plunger from its side through a slot in the lower housing. This would keep the vacuum from causing the piston to stick while at the same time allowing the lower housing to be maintained. The lower housing is critical to the operation since its allows the cap and seal to be aligned as the seal is seated.

5.4.4.12 Lid Gripper / Assembler

The lid gripper/assembler was used at the second robot of Eaton’s RAC. It was used to insert the lid into the container of the tire valve assembly after the tire valves
had been placed in the container. This operation also had the potential to be problematic. The lid is held on the container by friction, therefore, there is no clearance between the parts. There is a small lead-in taper on the lid to help guide it into position, but it is small (approximately 0.015 of an inch on a side by \(\frac{3}{8}\) of an inch long). The gripper was designed to handle two different parts. First, the gripper handled the lid. Second, the gripper was used to retrieve a completed assembly (four tire valves in a container with a lid) from the pallet and drop it into a hopper. A successful assembly was defined as a lid being pressed into a container. It was necessary for the gripper to retrieve the part from the pallet and press it into top of the container. Secondly, the container had to be removed from the pallet. The footprint of the gripper was not a concern since all the parts were being retrieved and placed into known locations. The necessary clearances could be included in the design of the gripper. The gripper was mounted on a rotary wrist with the seal gripper assembler (Figure 5-55). This gripping system allowed the robot to do the second half of the tire valve cap assembly with a tool change.

The design of the gripper was a simple one. It has a circular cross section divided into two halves. The gripper has a rectangular shape where it mates with the actuator. Below that, the fingers have a circular shape for the rest of their length. The inside of the jaws are also a circular shape. A groove in the jaws is used to securely hold the lid. The gripper fingers extend for approximately \(\frac{1}{2}\) of an inch below the point where the lid is held. This extra length is composed of a long taper which is used to align the container as it is being approached. The end of the fingers terminate in a large chamfer. Simple inductive proximity sensors are included to sense the open and closed positions of the jaws. Figure 5-58 shows a CAD drawing of the internal finger detail and the gripper holding a finished assembly.

No revisions of the gripper have been made. The gripper has been used without error. It has successfully assembled many parts and has always worked well. Only one small problem has been noted. On several occasions, the gripper failed to drop a
completed assembly after opening its jaws over the output hopper. Upon examination, it was determined that a large amount of flash on the lid was the culprit. This made the lid much larger than it should be, which caused it to wedge in the jaws.

![Lid Gripper / Assembler](image)

Figure 5-58: Lid Gripper / Assembler

Even in this simple design, many guidelines were followed which help make the gripper successful. A secure grasp of the part was assured by several features. First, the shape of the fingers complement the shape of the part; second, the gripper fingers fully encompass the part; and third, a groove is used to hold the part. Multiple parts are manipulated using the gripper. The gripper is used on a rotary wrist which allows the robot to perform its job without a tool change. Generous chamfers are used on approach surfaces so that lids may be retrieved without error. Large chamfers on the parting lines of the two jaws align the lids as the jaws close. The fingers fully encompass the mounting points of the actuator. This helps to align the fingers when they are mounted on the actuator. A long lead-in chamfer was designed in this gripper to help align the lid and container before the insertion operation which made the operation reliable. One last thing that helped this design was the alteration of the pallet to allow a much simpler and reliable gripper. As stated in the introduction to this chapter, much better gripper
designs can be realized by designing the grippers and the rest of the assembly system concurrently. Originally, the lid was to be carried in a pocket in the pallet and grasped solely from above. Changing the method of transportation of the lid from a pocket to a post allowed the gripper to be designed with a long lead-in chamfer. Without this lead-in chamfer, the insertion operation would have been more difficult because the accuracy and repeatability of the robot would be used to align the parts rather than the gripper.

There are no future revisions planned for this gripper. It has worked without fail and no revision is needed.

5.4.4.13 Fitting / Guide Gripper

The fitting/guide gripper was another gripper designed for use in Eaton’s RAC. It is also a second generation rotary jaw gripper identical to the container/cap gripper described in Section 5.4.4.9 except for the fingers. The gripper is used to handle the guide and fitting of the water valve assembly described in Section 5.4.2.4. It was necessary to handle both parts using a single gripper so a tool change could be avoided. The gripper is used at the first robot of the workcell. Four parts are handled at the robot: the guide, the fitting, the body, and the spin ring. Since both the guide and fitting needed to be rotated by 90° before assembly, both parts were handled by a single gripper. The body / spin ring gripper is described in the following section. The guides are fed using the same flexible feeder used for the containers discussed previously. The guide is presented on its side in a shallow “V”-groove. Gripper footprint is not as important for this operation since the parts always appear in the same location and with the same clearance. The fittings are fed using a Genex flex feeder and tool footprint needed to be minimized for this part. The rotated fittings are placed into pockets in the body. The fitting is also placed into a pocket on the body. The gripper is part of a gripping system used at the first robot. It is mounted on a rotary wrist with the body spin ring gripper described in the next section. Figure 5-59 shows the gripper system.
The design of this gripper is identical to the container/cap gripper except for the fingers. Refer to Section 5.4.4.9 for a discussion of the cap/container gripper or Section 5.4.3 for a discussion of the generic rotary jaw gripper. The remainder of this section will discuss the design of the fingers used which are mounted to the rotary jaw mechanism on fixed axles. The fingers themselves are \( \frac{3}{8} \) of an inch wide by \( \frac{3}{8} \) of an inch thick by \( 1 \frac{1}{2} \) inches long. The bottom half of the fingers are hard anodized for wear protection. The fingers were cut using a wire EDM machine to match the contour of the guides and fittings. Since the guide and fitting are different diameters, the gripper contacts each part at differing amounts of closure. Circular contours which match the fitting are machined shallower in the fingers than the smaller diameter contour which fits the guide. The fitting contacts the fingers on at four surfaces around its perimeter. The guide is contacted on two surfaces opposite one another. The fingers were designed to be long enough that the footprint of the gripper would not be affected by the size of the rotary mechanism and would be small. Chamfers were added to the bottom outside edge of the fingers to reduce the footprint further. Several problems, discussed in Section 5.4.4.9,
have been observed. No problems, however, have occurred due to the fingers themselves. Figure 5-60 shows the gripper holding the guide in both un-rotated and rotated states. Figure 5-61 shows the gripper holding a fitting and shows a CAD detail of the gripper fingers.

Figure 5-60: Fitting / Guide Gripper with Guide

Figure 5-61: Fitting / Guide Gripper with Fitting and Finger Detail

The gripper design guidelines that were followed will be discussed below. The length of the fingers was designed so that the rotary mechanism would not increase the gripper’s footprint. Chamfers were added to the exterior of the fingers to further reduce the footprint. The shape of the fingers was designed to complement the shape of the parts so that a secure grasp would be maintained. Multiple parts are grasped using a single
gripper and the gripper is used on a rotary wrist mechanism to avoid tool changes. Care was taken to ensure the gripper had sufficient clearance to approach the fitting. Since the guide and fitting are of differing diameters, extra care had to be taken in designing this dimension. The surfaces used for grasping the fitting acted as large chamfers when grasping the guide and helped align the guide with the gripper jaws as the gripper closed. This was especially important since, while sitting in the “V”-groove, the guide rests at a slight angle relative to the gripper jaws. The added functionality of the rotary motion also helped improve the reliability and throughput of the system.

The gripper fingers do not need revision, they work well in their current state. Revisions to the rotary mechanism will be discussed in Section 5.4.3.

5.4.4.14 Body / Spin Ring Gripper

The body/spin ring gripper was used to handle two of the four parts of the water valve assembly at the first robot of Eaton’s reconfigurable assembly cell. The gripper was mounted on a rotary wrist with the guide/fitting gripper (Figure 5-59), discussed in the previous section. The gripper was required to grasp the body from a tray feeder and place it into a pocket location on a pallet. The tray feeder presented an array of bodies to the robot at known locations. While the parts were closely packed on the tray, gripper clearance was not a concern since the required clearance was specified and could be designed into the gripper. The spin rings were fed using a flexible parts feeder. The parts were often in close proximity to one another and gripper clearance was important for this part. To avoid tool changes at the robot, the gripper had to be capable of grasping both parts (although not at the same time).

The design of this gripper was unique in that it was the first gripper designed with two separate fingers for picking each part. Since the parts were so dissimilar in shape and size, it was impossible to design a single pair of fingers which could handle both parts. One set of fingers were designed to handle the spin ring. Offset laterally from those fingers were another set of fingers which were used to grasp the bodies. Both sets
of fingers were machined from a single block of material and attached to a single pneumactic actuator. Figure 5-62 shows a CAD drawing of the gripper fingers and the actual gripper.

The fingers used to hold the spin rings had a rectangular exterior for most of their length. The ends of the fingers were turned round to minimize the gripper’s footprint. The entire finger was not machined round because the body fingers were in the way of the machine tool. Due to the low height of the spin rings, this did not adversely affect the footprint. The inside of the gripper fingers were bored round. The end of the fingers contained a groove which was used to grasp the spin rings. Chamfers were placed on the inside edges of the groove and on the leading edge of the fingers.

![Figure 5-62: Body / Spin Ring Gripper](image)

The body fingers were simple rectangular extensions. At the end of each extension was a rectangular nub. The nub was well chamfered to facilitate proper positioning of the body on the fingers. The extensions were lowered into the body and, when the gripper closed, the nubs would engage internal holes which provided a secure grasp. The length of the body fingers was less than the length of the spin ring fingers so that they would not add to the footprint of the spin ring gripper. The spin ring fingers were approximately 1 inch long and \( \frac{3}{4} \) of an inch wide. The body fingers were \( \frac{1}{4} \) of an inch square and \( \frac{5}{8} \) of an inch long. There was approximately \( \frac{1}{2} \) of an inch of clearance
between the body fingers and the spin ring fingers. Inductive proximity sensors are used to sense the open and closed states of the gripper. The sensors are mounted on a bracket supplied by the manufacturer of the actuator and sense two small screws protruding from the mounting posts of the actuator. Figure 5-63 shows the gripper holding a spin ring.

![Figure 5-63: Body / Spin Ring Gripper with Spin Ring](image)

The gripper has worked well during use. No errors have been observed using the gripper and no revisions were made to the gripper during its design and use.

Many guidelines have been applied to this design. The length of the fingers relative to one another were carefully designed so that the footprint of the spin ring gripper would be minimized. The outside of the spin ring jaws were machined round to further reduce the footprint. A secure grasp of the body was ensured by using nubs to mate with internal features. A tool change was avoided by designing the gripper to handle multiple parts and by mounting the gripper on a rotary wrist mechanism. The spin ring grippers fully encompassed the parts by holding the part in the groove of the fingers. This had several benefits. The parts could self center as the gripper closed which helped increase the reliability of the picking operation. This also increases the secureness of the grasp by fully containing the parts rather than relying on friction for holding power. Extra care was needed in designing the necessary approach clearances since there
were two fingers which could collide with things. Chamfers were added to the inside of the spin ring fingers and to the nubs on the body fingers to help align parts as they were being grasped. The mounting points of the actuator were fully encompassed by the fingers to ensure proper alignment of the fingers. No future revisions are planned for the gripper.

5.4.4.15 Water Valve Disassembly Gripper

The water valve disassembly gripper was the last gripper designed for Eaton’s reconfigurable workcell. It was used at the second robot to disassemble the water valve assemblies. The fittings, guides, and spin rings are removed from the body and dropped into bins. The body is removed from the pallet and placed onto a tray. To save money and weight, a single gripper was desired to handle all three parts. (By picking the guide from the body, the spin ring is also removed). The requirements for this design are much less strident than for the other grippers. The footprint of the gripper is not a concern since all the parts are retrieved from the same location and dropped into bins. Also, since the parts are dropped into bins, there is no chance of an error while placing a part. No rotary wrist was used, only the single gripper was used at the robot. A special extender, mounted between the quick connect and the pneumatic actuator, was made to simulate the length of a rotary jaw. This was necessary because of the limited stroke of the robot and the need to also use the second gripping system of the tire valve cap package at the same workstation.

The design of the gripper is similar to the design of the body/spin ring gripper described in the previous section. Two separate sets of fingers are used to manipulate the four different parts. One set of fingers is used to grasp the guides (with the spin ring over the guide) and a second set of fingers is used to handle the body. The fingers used to grasp the guide and fitting have a rectangular outside shape with large chamfers on each corner to reduce weight. The inside of the fingers are bored through at a diameter matching the outside diameter of the guide. The bottom $\frac{5}{16}$ of an inch of the bore has a
larger circular shape machined into it with the center of the large circle being offset from the parting line of the jaw. This allows the gripper to match the shape of the fitting when not closed completely. When completely closed, the diameter matches that of the guide. Only the last $\frac{5}{16}$ of an inch has this secondary diameter since that is the length of the surface of the fitting which is to be grasped. Overall, the fingers are $\frac{3}{4}$ of an inch square and extend $\frac{3}{8}$ of an inch in length. The parting line of the jaws is well chamfered to help align the parts with the gripper as the gripper closes. This ensures a reliable grasp of the part. The fingers used to move the body are identical to those used in the body/spin ring gripper. They have a rectangular shape and are $\frac{1}{4}$ of an inch square and $\frac{5}{8}$ of an inch long. A rectangular nub is used to mate with an internal feature in the body. The nub is well chamfered to help align the body as the gripper is being closed. The lateral spacing between the fingers is approximately $\frac{1}{2}$ of an inch. Figure 5-64 shows the gripper handling each part of the disassembly process.

The gripper has worked well; however, several minor problems have been observed. On several occasions, the gripper failed to release a guide after the gripper opened. It was determined that the guide was slightly oversize and was wedging in the jaws. Increasing the amount of chamfer on the parting line of the bore fixed this problem. The second problem was the gripper occasionally failing to release a body after placing it into the tray. This error was attributed to the position of the tray being incorrect which prevented the gripper from correctly releasing the body. Other than increasing the chamfer on the parting line of the bore, no revisions were made to the gripper during testing.
Many of the guidelines followed in previous gripper designs were not needed in this design since it was such a simple operation. The extra time and effort needed to implement the features would have been wasted since the design would not have been any better, only more costly and complex. The footprint of the gripper was not a concern. The only situation where clearance was critical was in placing the bodies on the tray. The required clearance was constant and could be accounted for in the design. Large vertical chamfers were machined onto the exterior surfaces of the fitting/guide fingers to help reduce weight. By designing the surfaces of the gripper fingers to complement the shape of the parts being retrieved, a secure grasp of the parts was obtained.

The gripper was designed to handle multiple parts so a tool change would be avoided. Also, the added expense of a rotary wrist mechanism was avoided by designing the gripper to handle all the parts. Care had to be taken to ensure there was necessary
clearance to place the bodies in the tray. Chamfers were designed on the fingers to help align the parts as the gripper closed. The fingers themselves encompassed the mounting points of the actuator to ensure they were properly aligned. To save cost, the gripper was designed to handle multiple parts rather than designing two separate grippers and mounting them on a rotary wrist. No future revisions are planned.

5.4.4.16 Hydraulic Fitting Nut Gripper

This gripper was designed to handle nuts from a hydraulic fitting assembly. The nuts were retrieved from the CWRU flexible parts feeder while lying on one of the flats of their hex shape. The gripper was used to test the throughput of the system so minimizing the footprint was important. After retrieving a nut, the part was dropped onto the return conveyor.

The design of the nut gripper was simple. Two flat plates with machined grooves matching the included angle of the hex nut were used. The hex of the nut would fit into the grooves on the finger providing a solid grasp. The fingers themselves were thin to reduce the footprint. They were about \(\frac{1}{4}\) of an inch thick by \(\frac{3}{2}\) of an inch wide by \(\frac{3}{4}\) of an inch tall. The outside and inside leading edge of the fingers were chamfered to further reduce the footprint and help align the parts. The fingers mount to the actuator using
two screws per finger and partially encompass the mounting points. Figure 5-65 shows the gripper holding a nut.

The gripper worked without fail for testing and demonstrated that a simple gripper design can be used for simple, non-precision tasks.

5.4.4.17 Nut / Bulb Retainer / Fitting Gripper

This gripper was also a simple design used for testing the throughput of the feeding system. This gripper needed to handle four different parts. First, two different sizes of hex nuts and plastic sockets were used for testing feeder throughput when feeding different parts at the same time. Secondly, fittings from a hydraulic fitting assembly were fed to test feeder throughput and functionality when feeding round parts which tend to roll. As in the case of the previous gripper, footprint was the most important factor. All the parts manipulated using the gripper were either dropped onto the return conveyor or into a bin. Therefore no precision placement was required.

The design of the gripper was the simplest made: two flat, parallel plates. To minimize footprint, the fingers are small. The top half of the fingers were about \( \frac{3}{4} \) by \( \frac{1}{2} \) of an inch in rectangular cross section. The lower half of the fingers were \( \frac{1}{8} \) of an inch thick by \( \frac{1}{2} \) of an inch wide. The overall finger length was about \( \frac{7}{8} \) of an inch. The junction between the upper and lower portions of the fingers is a steep chamfer to help push parts out of the way. Large chamfers were machined into the leading edges of the fingers to further reduce the footprint. When complete, the gripper had almost a knife edge so that the footprint was only as large as the amount the gripper opened beyond the size of the part. A layer of duct tape was applied to the surface of the gripper to increase the friction between the gripper and the part and to provide a slight amount of compliance to the gripper jaw which allows it conform slightly to the shape of the part. Figure 5-66 shows the gripper holding each size nut, the plastic sockets, and a hydraulic fitting.
Figure 5-66: Feeder Test Gripper with Various Parts

The gripper worked well for testing and provided valuable feeder throughput data. Again, this gripper shows how a simple design can be used when close tolerance is not required.

5.5 Conclusions

As has been clearly demonstrated, the design of grippers and gripping systems is not a trivial task. However, thoughtfully designed grippers can decrease workcell cycle time and increase reliability. Guidelines have been presented which can aid in the design of grippers, but it is impossible to cover all the possible gripper and part configurations. As the seventeen examples above demonstrate, the application of any single guideline does not always manifest itself in the same way in all gripper designs. How then, can
general guidelines be developed to address each unique design? Many grippers, while physically different, share the same general function. For example, most parallel jaw grippers approach from a single direction, and then close to grasp the part. Rotary action grippers, in contrast, move to a position above the part and then rotate their jaws to grasp the object. Having developed guidelines which can be applied to a style of gripping rather than a specific gripper design, they may be applied to a wide variety of grippers.

Table 5-6 presents a concise list of all the design guidelines discussed in Section 5.3.

<table>
<thead>
<tr>
<th>Guidelines to Increase System Throughput</th>
<th>Guidelines to Increase System Reliability</th>
<th>Guidelines to Reduce Gripper Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Minimize Interference Metric</td>
<td>• Ensure a secure grasp of the part</td>
<td>• Use less expensive parallel or rotary jaws actuators</td>
</tr>
<tr>
<td>• Chamfer the exterior surfaces of gripper fingers</td>
<td>• Minimize finger length</td>
<td>• Use off-the-shelf components for designing gripping systems</td>
</tr>
<tr>
<td>• Minimize weight</td>
<td>• Design necessary approach clearances</td>
<td>• Favor designs which handle multiple parts with a single gripper rather than designs which use multiple gripper on a rotary wrist</td>
</tr>
<tr>
<td>• Ensure a secure grasp of the part</td>
<td>• Design chamfers on approach surfaces of gripper fingers</td>
<td></td>
</tr>
<tr>
<td>• Avoid tool changes</td>
<td>• Design gripper to align parts as they are grasped</td>
<td></td>
</tr>
<tr>
<td>• Grasp multiple parts with a single gripper</td>
<td>• Design gripping surface to complement frictional coefficient</td>
<td></td>
</tr>
<tr>
<td>• Use multiple grippers on a single rotary wrist</td>
<td>• Design fingers to encompass actuator mounting points</td>
<td></td>
</tr>
<tr>
<td>• Design functionality in gripper jaws</td>
<td>• Do not rely on parts added to the assembly for location</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Design lead-in chamfers on assembly grippers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Design functionality in gripper jaws</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-6: Gripper Design Guidelines
Using these guidelines, grippers can be designed more quickly and with a higher confidence level. The guidelines may also be used as performance criteria and allow a rapid evaluation of designs.

Grippers designed using the stated guidelines have been constructed and are being successfully used in two different modular workcells. One workcell is in a research setting while the other is in a demonstration setting. The design of these grippers has been reviewed as examples of the application of the guidelines. Although the grippers designed are different, the guidelines applied to both equally well.