

4 Design For Manufacture and Assembly

4.1 Introduction

Designing parts for use in a flexible automation system can have profound results on the overall effectiveness of the system. While simply attempting to automate the assembly of existing designs is possible, the resulting operation is often prone to error and continual failure. More than often, the root of many of the problems can be traced back to the parts and assembly procedures being used. Design for manufacture and assembly (DFMA™) is the process by which designs and assembly sequences and procedures are altered to increase the ease and effectiveness of automated assembly. However, applying this approach to automation requires a paradigm shift in the approach to manufacturing if it is to be effective.

In the past, design and manufacture tasks have been performed independently. In this scenario, the designer designs a product and “tosses it over the wall” to the manufacturer to produce. There is no interaction between the designer and manufacturer and often what results is a design that is difficult to produce using automation. What is required is a collaboration between all aspects of the engineering staff, beginning with product conception all the way through delivery. By tapping into the expertise of all engineering areas (design, automation, manufacturing, ...), an equally functional and high quality design will result, but it will be much easier to reliably manufacture in an automated system. In practice, this approach is often difficult to implement, especially if the product designers are employed by one sub-contractor, the machine builders by another, and the raw components manufactured by a third. However, time spent by all involved parties in mutual consultation at the design phase will far out weigh any inconveniences.

Many times the objections to this approach to manufacturing comes from the designers and those in marketing who have a preconceived idea that they will lose

control. Their preliminary job function is to produce a product that the consumers will desire. However, this notion is often in error. The knowledge gained into the manufacturing process will far outweigh any ill effects. Making a part more manufacturable does not always mean a complete redesign. Alterations in part designs do not have to be drastic. For example, only a slight redistribution of mass may be necessary to improve the probability of a particular stable rest position, thereby improving flexible feeder throughput. Or a slight shifting of a vision registration fiducial can be sufficient to provide an asymmetry which can be used to determine pose. Or a larger chamfer can vastly improve the reliability of an assembly task. These types of small changes to a design can have a major impact on the quality and ease of automated manufacture.

While many guidelines and procedures have been developed in the past (as will be discussed in Section 4.2), many of these guidelines are not directly applicable to flexible robotic assembly. Much of the previous work has been specific to manual assembly. It is the purpose of this chapter to first review the history of DFMA™, to present rules and guidelines specific to flexible robotic assembly, and then to compare and contrast between the previous guidelines and the ones presented here. While there are many ultimate goals of design, ranging from ease of assembly to ease of disassembly and recycling, it is the purpose of this chapter to examine three areas of design which have a direct impact on the success of a flexible assembly system. Namely, design for assembly, feeding, and vision registration.

4.1.1 Assembly

Design for assembly specifically addresses parts of the design that have a direct impact on the ease and reliability of assembly. There are many tasks that, compared to a human, a robot cannot do very well. These include inserting things into holes with little tolerance, compensating for variations in component size, performing assembly requiring a fine touch (or force feedback), and performing actions which require a range of motion

beyond which the robot is capable (i.e. screwing two parts together). By redesigning the components which make up the assembly, many of the problems can be avoided. Rules for improving assembly usually tend toward decreasing the necessary precision of the robot required to successfully complete the assembly and decreasing the chances of parts jamming when being assembled.

4.1.2 Feeding

Design for feeding deals specifically with designing parts to improve their throughput in a vision-based flexible parts feeding system. This is different than designing parts for use in a bowl feeder or some other type of part-specific feeding device. In the case of a vision-based flexible feeding system, the main concern is to present the parts in a singulated fashion to the vision system and robot. Since all flexible feeders tend to work on the principle of randomly distributing parts onto a horizontal surface, the important design criterion is minimizing the number of statically stable rest poses of the component.

4.1.3 Vision

The final design criterion deals with designing the part to be easily recognized by the vision system. The guidelines developed are even more specifically suited to backlit binary vision. This further criterion was specified because the flexible feeders (described in Chapter 2) use an underlit window to present the parts to the vision system. Also, binary vision algorithms are much faster to process and less sensitive to fluctuations in the lighting than gray scale algorithms. In this section, some of the guidelines determined actually contradicted some of the guidelines established previously. This was because many of the previous guidelines did not address vision-based flexible feeding, which has a particular set of unique requirements.

4.2 Survey of Previous Work

In the late 1950's and early 1960's, companies began to realize that the current design methodologies and paradigms were not very applicable to the new style of automated manufacturing. In particular, robotic and reprogrammable manufacturing systems had many different concerns and requirements than those of previous years. From this realization, companies began producing guidelines which could be used to enhance the design of their products in relation to their manufacturability and assemblability. One of the earliest works dealing exclusively with this topic was produced by General Electric and was called the *Manufacturing Producibility Handbook* [82]. Throughout the 1960's and 1970's, a lot of internal research was done independently by many companies that realized the need to streamline their designs and processes for the evolving paradigm in manufacturing. By the 1980's the concept of design for manufacturing and assembly was being embraced by many companies. During this time, many of the previously-determined rules were being quantified and programmed into computers for automated analysis of designs. During the 1990's, more emphasis has been placed on designing not only for manufacture, but for the whole life of the product including: manufacture, service, repair, and, ultimately, disassembly and recyclability. Throughout this entire evolution, however, the basic premise of designing a product for ease of assembly has been constantly updated as the methods and techniques of manufacturing have changed.

There are generally three different methods of employing some type of a design for manufacturability process to a product. The first method described below was the one which was initially used. It is the following of a general set of rules or guidelines. These rules generally are not quantitative in nature and require a human to interpret and apply to each specific and unique case. While this is a much better case than just blindly starting each design from scratch, it does require some skill and knowledge on the part of the designer to correctly interpret and apply the rules.

The second method, forwarded by Boothroyd and Dewhurst [83], employs a quantitative analysis of the design. Each part of the design is rated with a numeric value depending on its manufacturability. The numbers are summed for the entire design and the resulting value is used as a guide to the overall quality of the design. The product is then redesigned, using the numerical values as a goal to be minimized. By concentrating on areas of the design that contribute heavily to the overall score, the effects of the redesign can be maximized. This again, however, requires much insight and knowledge on the part of the designer.

The third, and most recent development in this area, is in the automation of the entire process. By using a computer, quantitative analysis can be applied to the design. Then by building an expert system in the computer employing the general design rules, a system can be developed which can analyze a design and then optimize it by repeatedly applying the rules and evaluating the quality at each iteration. This last approach is still in its infancy, however, as the application of general rules to individual designs is a difficult and inherently qualitative process. It is this type of system that will ultimately allow the designer to conceive of a design, enter it into the computer, and then oversee the evolution of the design as the computer tries many variations in search of the “best” design.

Now that a general history of design for manufacture and an examination of the general process has been presented, the rest of this section will examine a few specific cases of the creation and application of DFMA™. It is, however, difficult to examine all the rules and guidelines previously determined, since they are so numerous. Generally what will be examined is the overall picture of the types of guidelines rather than specific rules themselves.

Boothroyd Dewhurst, Inc. (BDI) was the first company founded whose primary service was design for manufacture. In fact, the now common letters “DFMA” are actually a trademark of the company. Beginning in the early 1970’s, Geoffrey Boothroyd

began work on an analytical tool for reviewing a design. The company was formed in 1982 as a result of the development of the software which would perform the analytical analysis. Since that time, the company has expanded their products to include all sorts of “design for” products. Currently they offer programs to help with the design of circuit boards [84], with manual assembly, with robotic assembly, and with machining. They also do a lot of work examining the economic justification of each design revision. There are many books and articles describing the design guidelines and goals presented [85][86][87]. BDI also teaches many classes on design for manufacture at companies all over the world.

Scarr, Jackson, and McMaster [88], in 1986, compiled a list of over 60 rules and guidelines to be used in the design of products for automated assembly. Many of these rules were gleaned from the ever burgeoning supply of papers and conference proceedings on the subject. The purpose of the paper was to examine the necessary information to present to a designer and to determine an effective method of presenting that information. The paper concentrated on the development of design rules which are appropriate to robotic and automated assembly.

Sprague [89], describes the design for manufacturability studies and endeavors undertaken at NCR during the 1980's. In 1982, NCR began a formal program on implementing design for manufacturability throughout its operation. By 1989, the program had been officially named as Design for Excellence (DFX). The company described DFX as

“Continuous improvement in concurrent product and manufacturing process development to focus developers’ attention from the beginning on all key product lifecycle considerations such as customer requirements, quality, time to market, cost of ownership, and operational complexity.”

As an example of the results of the initiative, the 2760 retail terminal was redesigned and compared with previous versions. The results were an 80% reduction in

parts and assembly time, a complete elimination of screws and assembly tools, and a 69% reduction in parts suppliers.

AT&T [90] has an extensive computer analysis program which analyzes circuit board designs for manufacturability which began in 1985. Since that time, an extensive array of rules (comprising over 30 categories) has been compiled. A computer program has been designed to allow the design engineer to immediately see the application of the rules to his particular design. Beginning with the selection of the actual components the system is used to automatically populate the board according to the design rules. Specialized components may be placed by hand as needed. Throughout the entire process (component selection and placement, interconnection routing, testability, and manufacturability), the software continually monitors the design, flagging any areas that are in violation of design rules. Since the beginning of the DFM program, time for the design and analysis of a circuit board dropped from several weeks to 30-45 minutes.

In an attempt to begin to quantify many of the qualitative design rules, Kim et al. [91] defined a quantitative metric for the feedability of a particular polygonal part being grasped by a simple, parallel jaw gripper. A generic parts feeder was designed in which a flat parallel jaw gripper is used to reorient parts on a horizontal surface. After reorientation, the parts are in known locations on the conveyor belt. A metric, "Feedability", was developed to relate the design of the part with the amount of work required by the feeder to get the part into a known orientation. Using this metric, rules are formulated for part alteration which can increase the feedability, thereby making the part more suitable for use in the feeder.

Another attempt at automating the application of manufacturability design rules was discussed by Kim [92]. In this approach, rather than examining the design from the component to finished product, the proposed design was examined in reverse. First, a completed design was specified and then taken apart in the computer. Candidate assembly schemes were then created by reversing the taking apart process. A computer

program, called “REV-ENGE” was created which could compute possible disassembly sequences. After determining problem location in the design, a possible redesign is suggested. One of the shortcomings of this approach, however, is the inability to analyze a design as it is being constructed. A complete design is required as the starting point of the process.

There have been several publications [93][94][95] produced by the agile manufacturing team at Case Western Reserve University which also describe design guidelines. These guidelines have been determined over several years of working with actual parts on a flexible manufacturing system. They have been centered on three main areas, design for feeding, vision, and assembly. It is from these initial ideas that this chapter was written.

4.3 Guidelines, Rules, Experience

This section is divided into 3 sub-divisions. The first examines design guidelines for assembly, the second guidelines for feeding, and the third, guidelines for vision enhancement. Many of the guidelines have appeared previously in the literature. However, they are presented here in the context of design for assembly in an agile manufacturing workcell.

4.3.1 Design for Assembly

Many factors can affect the reliability of the assembly operation. Several guidelines have been determined which can improve the reliability and ease of assembly. While some of these guidelines are imposed because of the use of SCARA type robots, most of the guidelines are applicable to any robotic assembly:

4.3.1.1 Use Snap Fits Rather than Threads

Use snap fits rather than threaded fits whenever possible. Threading a nut onto a rod or a screw into a threaded hole can be a tedious process for a robot to accomplish. Without some form of force feedback, the robot can only follow a prescribed path to

accomplish the task. The possibility of cross threading the screw is likely, resulting in a failed operation. Another problem is with the range of motion required to fully insert a screw. Since the robot will not likely be able to perform an unlimited amount of rotations, it will be necessary to release and regrip the screw several times before it is fully seated. This adds time to the operation and increases the possibility of mishandling the part.

In contrast to a screw attachment, a snap fit is much easier for a robot to perform. No rotation is necessary, only a straight line motion is required to make the attachment. It is also possible to design a combination snap/screw fit. By using a shallow thread depth (usually a fine pitch or multi pitch thread), it is possible to snap the components together while still allowing the possibility of subsequently disassembling them using the thread fit. An example of this is the lid on many milk containers. They are designed to be a thread connection which can be snapped together for ease of automated assembly.

4.3.1.2 Minimize Assembly Forces

Design parts to minimize assembly forces. While snap fits are advantageous to robotic assembly, if large forces are required to mate parts then dedicated assembly hardware may be necessary. Robots are only capable of a relatively small amount of force compared to a dedicated press (mostly due to their use of electric motors). This is especially true of smaller, inexpensive, table-top style assembly robots. Designing an assembly which requires a large force for completion will require additional, dedicated hardware. Since this requires the robot to place the parts and then move out of the way while the dedicated hardware is actuated, more time is required for the operation and there are more opportunities for part mis-handling and failure.

4.3.1.3 Design Generous Tolerances

Design generous tolerances into mating components. This demands less precision when assembling, thereby increasing reliability. Robots, in general, are less precise than most dedicated assembly hardware. If parts are designed which require accurate

placement of the parts for mating, then problems are going to occur because of the inaccuracies of the robot. A generous chamfer will allow the robot to “miss” the assembly location by some small amount and still perform a successful assembly.

4.3.1.4 Design Smooth Gripping Surfaces

Design parts with smooth surfaces where the gripper jaws will make contact. This will allow the gripper to more easily self-center the part as it is being acquired. A common problem when retrieving parts (especially from a vision based feeder) is the robot mishandling the pickup because of slight misalignment between the part and gripper. By designing the parts to slide relative to the gripper jaws, the robot can be misaligned with the part and still retrieve it properly. In contrast, parts with serrated edges tend to hang up on the edges of the gripper jaws rather than sliding into proper alignment. This guideline complements the gripper design guideline listed in Section 5.3.2.5

4.3.1.5 Design for Vertical Assembly

Design products for vertical assembly for SCARA type robots. Since the prismatic joint on a SCARA robot is in the vertical direction, it is easier and quicker to assemble components in the vertical direction (stack up) rather than in another direction. Straight line motions (other than z) require the robot's controller to perform coordinated joint motion. These moves are generally slower than only a single axis move. By designing for only straight-line z insertion, an increase in the speed of the assembly can be realized.

4.3.1.6 Minimize Assembly Components

Design assemblies with a minimum number of components to reduce the number of grippers and feeders required. This is a rather obvious guideline and one of the first reported in the literature. By reducing the number of parts being handled, many benefits become evident. Among them, an increase in reliability, a decrease in system cost, an increase in throughput, and a decrease in product cost. These benefits are realized because of the decrease in grippers, feeders, and complexity of assembly.

4.3.1.7 *Design Parts and Grippers Concurrently*

Design parts and end effector tooling concurrently. Concurrent design of parts and tooling allows the gripper to be designed to handle more than one part so that a minimum number of grippers is needed for any given assembly. It also allows for the gripper and component material to be matched (as discussed in Section 5.3.2.5) which can increase the reliability of the system.

4.3.2 Design for Feeding

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

4.3.2.1 *Minimize number of stable poses*

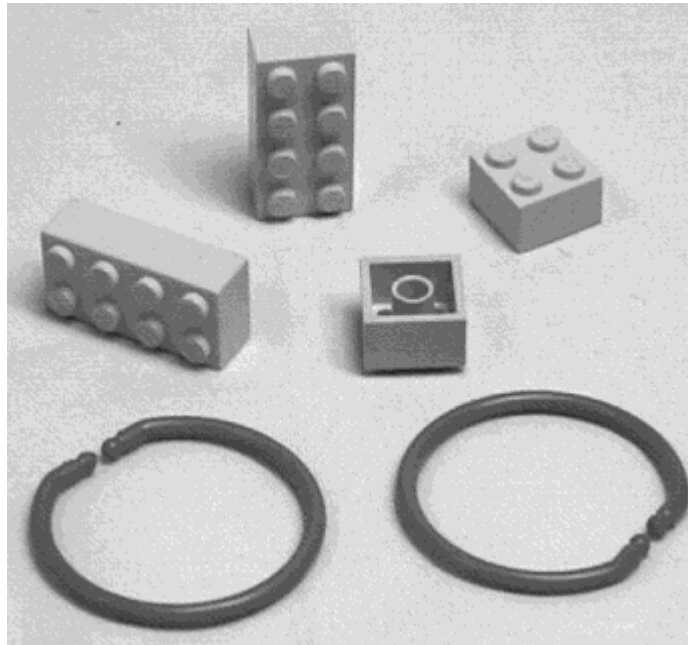


Figure 4-1: Plastic Snap Rings and LEGO™ Blocks

The first guideline is to minimize the number of stable poses of a part. This increases the probability that a part will land in a suitable orientation. Consider, as an example, two test parts shown in Figure 4-1. A snap ring has two stable orientations,

face up and face down, which are identical. Since it does not matter which side is up, all snap rings on the horizontal conveyor which are singulated are potential candidates for assembly. In contrast, LEGO™ blocks have 3 - 4 stable poses; top (or nubs) up, bottom up, side up, and in some instances, end up. A singulated LEGO™ block on the horizontal conveyor has less probability of being in the correct pose for assembly.

4.3.2.2 Design parts with stable orientations consistent with assembly

The second guideline suggests designing parts with stable orientations which are consistent with the given assembly. For example, if a part needs to be inserted into an assembly with side A down, then it is useful for the part to have a statically stable orientation with side A down. This can lead to difficulties during the design. In some situations, it is impossible to satisfy the above criterion. For example, long, slender parts needing to be inserted lengthwise from above (e.g. a pin into a hole) are a problem since it is impossible to design the pin to be stable standing on end. Rotary jaw grippers or specialized hardware may be employed to grasp the part in its stable orientation and then rotate it for assembly.

4.3.2.3 Design parts to prevent tangling

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

4.3.2.4 Design parts to be not damaged by the feeding operation

The fourth guideline is to design parts which are not easily damaged by the feeder. In the bulk hopper, parts tumble and rub against one another; if they are fragile or have an easily marred surface finish, they could be damaged. If they are recirculated during feeding, they must fall from the end of the horizontal conveyor to the

return conveyor, then from the return conveyor back into the bulk hopper. Both these drops have the potential to cause damage. As an example, parts with transparent areas, such as display covers for automotive dashboards, could be scratched.

4.3.2.5 Design parts so as to not damage the feeder

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

4.3.3 Design for Vision

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

4.3.3.1 Design parts with rotational invariance

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

4.3.3.2 Design parts with asymmetry if rotationally variant

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

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

Three nubs may be placed on the inner circumference of a ring or on the outside diameter of a disk at slightly differing relative angles, 116° , 120° , and 124° for example. If the relative angles between nubs are always determined in one direction (i.e. always clockwise or always counter-clockwise) then the order of appearance of each angle creates an orientation signature that can only have two states, if viewed as a circular list. If the list is shifted such that the smallest value is first, then examining the value of the second element reveals the up/down orientation as well as the rotational orientation. Figure 4-2 shows the image of a ring with three internal nubs after vision processing. While not readily apparent to the eye, the vision system easily finds the 4° offset.

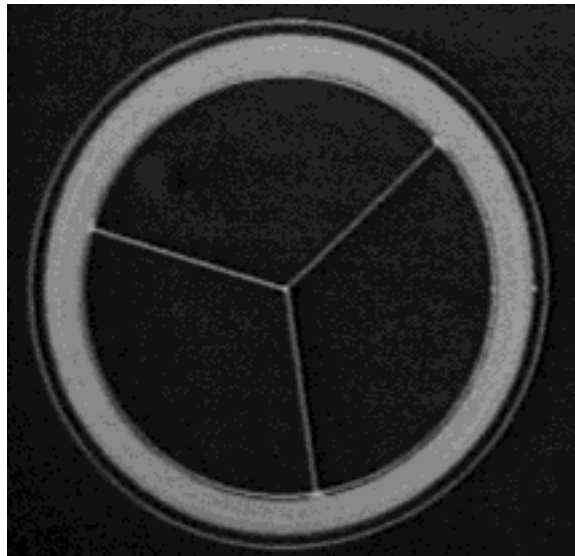


Figure 4-2: Vision Processed Image of 3 Asymmetric Nubs

Two “shoulders” of a part may have slightly different lengths to create an asymmetry. Consider, for instance, a small plastic thumb switch found in many electronic devices. The pose of the switch is easily determined by examining the length of each shoulder relative to the location of the end of the base. After acquiring an image, the major axis of the part is determined. By examining the distance to the edge of the part to

the left and right of the axis, the up/down orientation can be determined. If the smaller distance is to the right of the axis, the part is face up. If, conversely, the smaller distance is to the left of the axis, the part is face down. The unequal “shoulders” presented by the switch’s silhouette make determining its orientation straightforward. Figure 4-3 shows the switch and the corresponding image after vision processing.

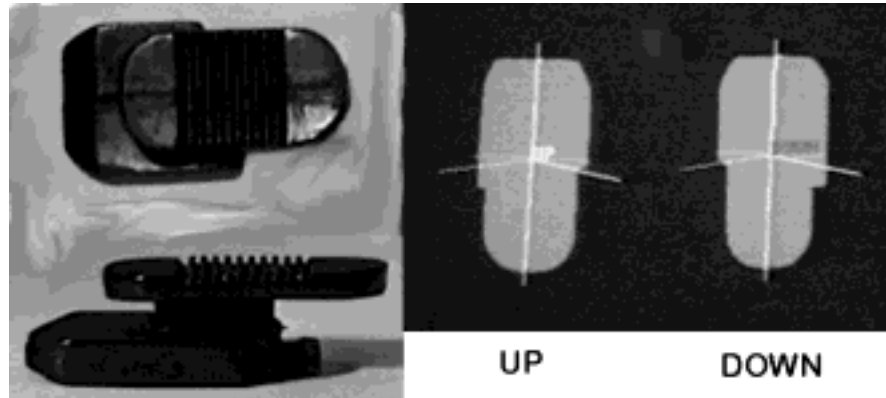


Figure 4-3: Plastic Thumb Switch with Different Shoulder Lengths

4.3.3.3 *Avoid translucent parts*

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

4.4 **Redesign of an Inexpensive Flashlight: An Example**

As mentioned previously, flashlights were chosen as an inexpensive product to use as a test case of light mechanical assembly. Since many of the guidelines previously discussed were developed while the system was being designed and built using the test case, it was decided that a good example of the guidelines would be to redesign a readily

available, off-the-shelf flashlight for assembly in a flexible system. Rogers [96], in 1993, reported on a concept of a modular production system. In that paper, several design guidelines were put forth for parts redesign in a flexible system. In addition, the guidelines were applied to the redesign of a flashlight. However, the guidelines presented were rather general in nature and no physical system was used as a basis for developing the guidelines. In contrast to this, the following redesign of a flashlight was based on rules developed while using an actual, physical system.



Figure 4-4: Generic Mini-Lantern used for Re-Design Exercise

A generic, 2-cell handheld lantern type light was chosen as an example. The original design consisted of nearly 10 parts (not counting the batteries) including a lens, lens ring, switch sub-assembly, conductive spring and strips, case, bulb, and bulb retainer. Emerging manufacturing concepts and tools including Concurrent Engineering, DFMA™, Solid Modeling, Rapid Prototyping, and Rapid Tooling were used to optimize designs, reduce errors, and enhance communications among design team members. Each

part was examined and redesigned to facilitate flexible feeding, vision recognition, manipulation, and assembly.

4.4.1 Lens

The lens itself is inherently difficult to “see” with the vision system because it is transparent. For flexible feeding, however, some definite clues to locate lenses are needed. The solution for the flashlight used for system testing involved applying a dark band around the outer circumference of the lens with a magic marker. This appears as a well-defined ring to the vision system and does not degrade the performance of the flashlight. While reasonable for prototype work, this solution is not cost effective for production situations as it requires a separate operation. One proposed solution is to roughen or “frost” a ring around the outer diameter of the lens. This frosting can be seen in several flashlights currently on the market. This frosting can be done when injection molding the lens, by roughening the respective parts of the mold, so that no extra operations are required. The frosting darkens the image presented to the vision system, allowing the lens to be located. Another proposed solution was to put a promotional sticker on the lens in a known position and orientation. This sticker could be used for pose determination and could then be removed by the consumer. A draw back to this solution would be the extra manufacturing step required to apply the sticker.

An even more innovative solution, however, is to incorporate the lens and the lens ring into one part. This not only solves the problems of “seeing” the lens and determining whether it is up or down, but it also reduces the total number of parts in the assembly, a practice advocated by the Boothroyd and Dewhurst model of DFMA™. This new part could be fabricated with a double-shot injection molding process, allowing for the molding of two different materials in one part: the lens ring will be made of an opaque material and the lens made of a transparent material. This technique has been used for some small consumer electronics (a portable cassette player with a clear window, for example) with impressive results.

4.4.2 Lens Ring

Using the original design as a starting point, many new concepts were generated for the design of the lens ring. Some of the criteria for design included the ease of assembly, the ability of the design to be used in the CWRU flexible parts feeder, and the ease of vision recognition.

Feeding the lens ring presented another set of problems. To make the feeding more reliable, the aspect ratio of the lens ring was kept as small as possible. This was to ensure that the part would be more stable in the desired assembly position than other positions. A raised rim was also included in the design to help protect the lens while it is in the feeder.

The original lens ring design was simply a threaded ring. The problem with such parts is that it is difficult to determine whether the part is facing up or down by a binary image processing system. This is important because they are needed in the face up orientation for assembly. In one concept, triangular protrusions could be placed around the perimeter of the lens ring. By creating the triangles in a saw-tooth pattern, an asymmetry could be introduced into the design which could be used to determine which side was up. Another concept was the use of two concentric feature sets which, when used together, would provide a positive indication of the pose of the lens ring. After examining the various ideas, a rapid-prototype of the last concept was fabricated. In this design two protrusions or “feet” were added to the exterior of the lens ring. These are used as a rotational reference when locating the lens ring. To the consumer, they appear as feet to provide a more stable pose when the flashlight is resting on a flat surface. On the interior of the lens ring are three half-circular nubs separated by 120° . By measuring the relative angle between the exterior protrusions and one of the interior protrusions, the pose can be determined. Figure 4-5 shows the first and second generation concept reflector. Figure 4-6 shows CAD views of the same.

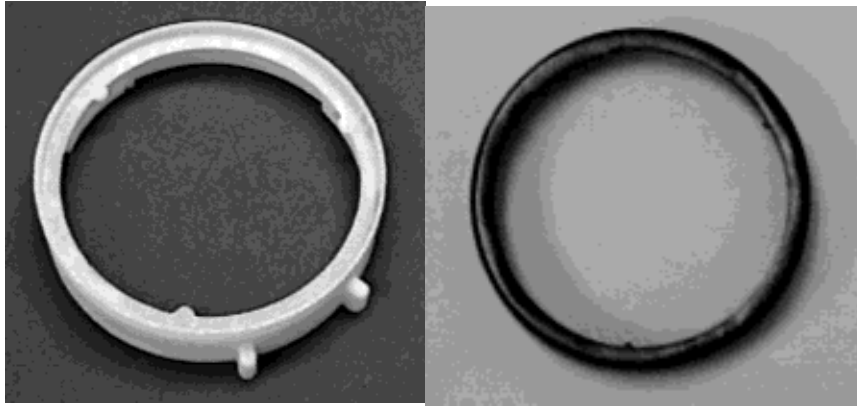


Figure 4-5: First and Second Generation Concept Reflectors



Figure 4-6: CAD Views of the First and Second Generation Concept Reflectors

The feet, however, looked out of place so to create an improved look to the lens ring, the feet were removed and a small angular asymmetry of 4° was introduced in the location of the internal nubs. This small variation is not readily noticed by humans, but the vision system can readily locate it. The asymmetry is then used to determine the up/down orientation of the lens ring. The nubs can also be used to determine the angular orientation of the part.

The Adept 550 robots do not have an infinite degree of motion on joint 4 (i.e. they can only rotate a finite number of degrees) which hampers any design in which the robot must rotate multiple turns to screw parts together. DFMA™ favors snap-together fits over screw together parts because of the slower assembly times and more complicated

motion associated with the latter. As a compromise, a bayonet mount was chosen as a good way to attach the lens ring to the flashlight body. While still requiring some rotation, that motion can be limited to a fraction of one revolution. This comes at the cost of positioning, however. For a standard screw, it is not necessary that the lens ring and body be aligned rotationally for the threads to mesh. Rotating the two parts together will bring the beginnings of both threads in contact. With a bayonet attachment, though, rotational alignment is important. As mentioned, the internal nubs can be used to determine the angular orientation of the lens ring so that the bayonet lock can be engaged.

4.4.3 Reflector

In this flashlight design, the reflector serves two purposes. It first functions as a traditional reflector in that it concentrates and directs the light toward a target. It also functions as a mounting surface on which contact strips are attached which conduct the current from the batteries to the switch and to the lamp. Because of this, the design requires that the contact strips be attached to the back of the reflector. Several concepts were generated to eliminate these parts (which are difficult for robotic manipulation) and subsequent assembly steps from the design.

One concept uses mold interconnect device (MID) technology which molds the contacts into the reflector, thereby reducing the part count and the extra associated assembly steps. Another concept was to plate the contacts onto the back of the reflector at the same time the front coating was being applied. This should not introduce any extra steps into the manufacturing of the reflector, but would make assembly much easier. By plating with chrome, or a similar hard substance, the front of the reflector would also be protected during the feeding. Another concept was to include the switch as an integral part of the reflector. This would eliminate another part from the assembly, but the switch would have to be attached somewhere upstream of the agile workcell.

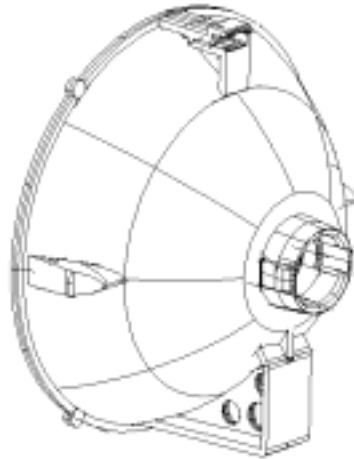


Figure 4-7: Concept Reflector CAD View

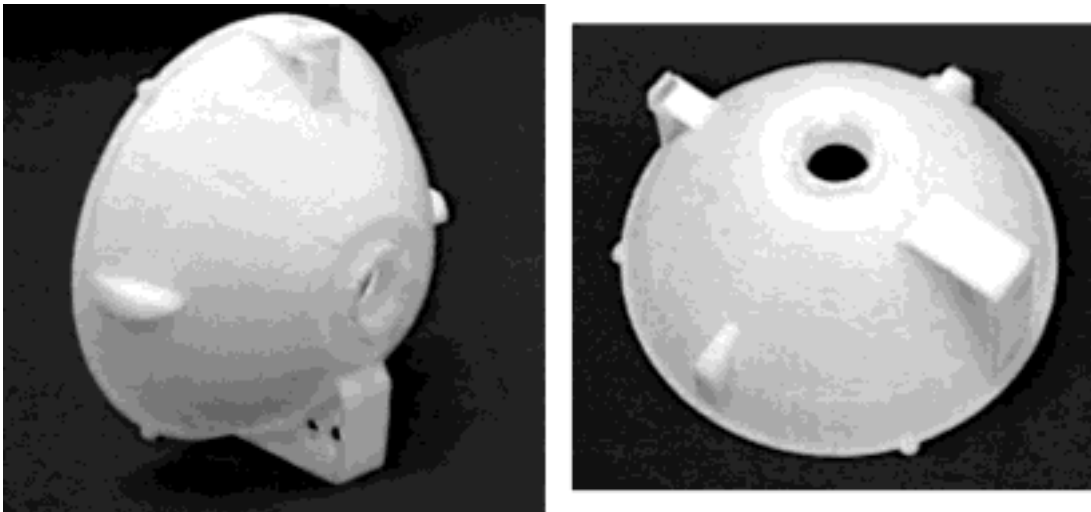


Figure 4-8: Concept Reflector

For vision recognition, three nubs are molded into the exterior of the reflector (similar to those on the interior of the lens ring) so that the up/down orientation can easily be determined by the vision system. Figure 4-7 and Figure 4-8 shows the reflector.

4.4.4 Switch

Several different concepts were generated for the switch: a self-contained push button switch, a sliding block pressing contacts together (original design), or a sliding block with snap together contacts. The advantage of the first concept is that it would be

self-contained. The second two designs offer the advantage that they would interact with the back of the reflector to close the current loop. The second concept would require feeding and manipulation of the thin pieces of copper necessary for completing the circuit. The third concept could be implemented with MID technology in which the conductive components are inserted into the switch during molding, eliminating the copper pieces.

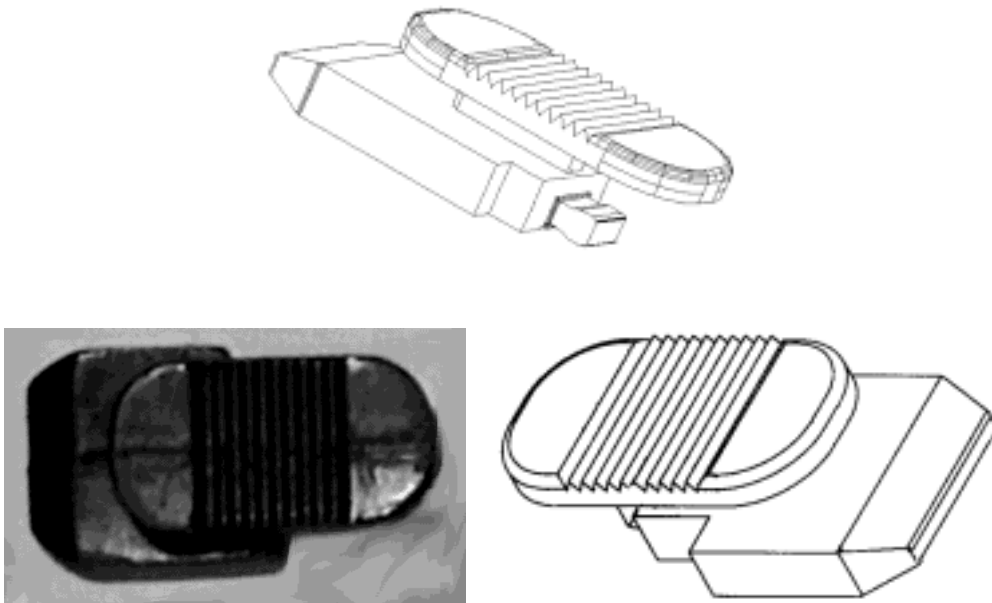


Figure 4-9: Concept Switch - Top View and CAD Views

The assembly method was also considered in deciding which concept to implement. Since the robot works easiest and quickest in vertical moves, it would be advantageous to insert the switch from above. In the original design, the switch is inserted from the side before the two halves of the case are ultrasonically welded. Since the case sides will already be joined before they enter the workcell, a different approach had to be devised. By cutting a slot from the end of the body to the switch location, the switch can be inserted from above. The switch and lens ring must overlap each other in such a way as to cover the slot when the switch is in both the on and off positions. It is simple for the vision system to determine whether the new switch is up or down because

of the asymmetries in its design as discussed in Section 4.3.3.2. Also, the switch has been designed to virtually eliminate stable poses which are not graspable. Figure 4-9 shows a top view and CAD view of the concept switch.

4.4.5 Spring

Since the flashlight uses two batteries, a spring may be used to link the positive terminal of the one battery to the negative terminal of the other battery. This can be accomplished in one end of the flashlight, and does not require a circuit element that runs the length of the flashlight. Several concepts were generated to improve this part for use in the workcell. The first design consisted of two coil springs (as used in the original assembly) linked together so that one spring contacts each battery. Coil springs are perhaps the most difficult part to handle and feed because they tend to tangle. The next concept was a leaf spring made by bending a flat piece of metal. The use of a battery pack was also discussed. This pack would provide a housing for mounting the batteries as well as holding the spring. Battery packs can be seen in many flashlight designs currently on the market. The final concept was the use of a foam spring. This spring would consist of a piece of foam with a conductive coating.

4.4.6 Bulb Retainer

There are several different types of bulb retainers which are currently in use. The retainer could screw on to the back of the reflector, securing the bulb, as in the original design. Another concept is to use a bayonet mount similar to the lens ring to attach the bulb retainer. A third variation is to use a snap fit. The robot would have a difficult time assembling the screw on mount and the use of a bayonet mount would necessitate knowing the rotational position of the retainer to insert it correctly. Several iterations on the design were made, including a bayonet lock, a snap lock, and bayonet-snap hybrids. The current design uses the snap-lock with the added bonus that it may be removed by a slight rotation, a snap / thread hybrid as discussed in Section 4.3.1.1.

Figure 4-10 shows various concepts for the bulb retainer. Figure 4-11 shows CAD views of various concepts.



Figure 4-10: Bulb Retainer Concepts

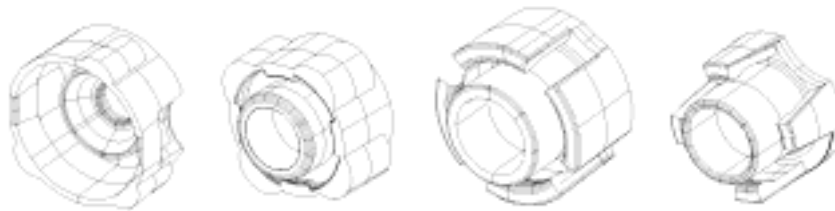


Figure 4-11: CAD Views of the Concept Bulb Retainers

4.4.7 Bulb

The flashlight bulb is one part over which there is little control. Bulbs from many different flashlights are all nearly the same. They are purchased from an outside source (this conclusion was reached by two factors: the bulb had a vendor name printed on it which was not the manufacturer of the flashlight and many flashlights from various vendors used the same bulb from the same vendor) which means the supplier would have to alter the design which is unlikely. Because the rotation of the bulb in the reflector is not important, all that is required is that the end of the bulb which to grasp when lifting it off the presentation conveyor can be determined.

4.5 Conclusions

Guidelines have been developed to assist in the design of parts for assembly in a flexible manufacturing workcell. Three main areas of the workcell have been examined which can benefit from better-designed parts. These areas are assembly, feeding, and vision.

When comparing included assembly guidelines to previously published ones, there is good agreement. A good indication of the importance of the rules listed is the fact that included rules were obtained by examining the system from a strictly physical standpoint. Others who have found the same or similar rules often approached the problem from a different viewpoint (economic justification, manual assembly, or dedicated automatic assembly for example). Therefore, it can be confidently stated that applying design rules for assembly to products can produce a better situation overall, including assembly, system reliability, system throughput, and cost.

Guidelines which are applicable to parts design for feeding are, in comparison to assembly guidelines, more interesting. In the previous literature, feeding guidelines were developed for manual feeding (picking parts from a hopper by hand) and for bowl feeders. Therefore, some of the guidelines which were discovered do not appear in previous rule sets. There is a large difference between designing a part to be fed using a bowl feeder as compared to a vision-based flexible feeder. This shows the importance of applying a proper set of guidelines to any given design. It does not make much sense to design a part to be easily fed and handled by a human if it is going to be assembled exclusively in automated equipment.

Design guidelines to enhance the ability of a part to be seen by a vision system are the newest of the rules. Previously, no one had examined designing for vision. Important rules were discovered and simple but effective techniques to enhance the ability of a part to be recognized by a binary vision system were developed. At times, these rules actually contradicted previous guidelines listed in the literature. For

example, when designing a part for a human to recognize (using vision), the following guideline was determined.

“If complete symmetry is not possible then exaggerate asymmetric features” [97]

An exaggeration of an asymmetric feature, good for human recognition and manual assembly, is not necessary for a vision system and could affect the aesthetic appearance of the part. A slight asymmetry is all that is needed for the vision system to determine the pose of the part.

Finally, the design guidelines determined and presented were used to redesign a handheld flashlight for assembly in a flexible assembly cell. While this was only an exercise, it shows the importance of applying current design guidelines to products to reduce the overall complexity of the design. In the original design (as purchased) there were a total of 14 parts. Through the application of design for manufacture, feeding, and vision principles, the total part count was reduced to 7.

As can be seen when examining the guidelines in comparison to previous rules, it becomes apparent that using guidelines tailored to current manufacturing practices is important. An excellent example being the contradiction between the old rule of exaggerating asymmetry versus the new rule of providing slight asymmetry. Finally, it is important to begin applying rules and guidelines as soon as possible in the design process. The sooner the guidelines are applied, the easier (and less costly) it is to make the necessary design changes. According to Boothroyd Dewhurst Inc.[98], a copier company shipped a product with a defect. The president of the company was quoted as stating that correcting the defect at the design phase would have cost about \$35.00. Instead, it cost the company almost \$600,000.00 to correct. This shows the importance of improving the design as soon as possible.

4.6 Future Work

While the guidelines determined thus far have been beneficial, the formulation of design guidelines needs to be an ongoing process. There are three areas of design for manufacture and assembly in an agile workcell that require further work.

First, as new assemblies with their unique components are introduced into the system, new guidelines will emerge. As these new guidelines become apparent, they need to be incorporated into the existing base of knowledge. Secondly, metrics need to be devised which encapsulate the meaning of the guidelines into a more directly programmable form. Such a metric could then be applied, quantitatively, to various designs to determine their relative goodness. Lastly, the metrics could be incorporated into a CAD type design package which would allow an intelligent, automated evolution of a candidate design into one more suited for agile assembly.

