

6 Results, Conclusions, Future Work

Consider again the “factory of the future” which was presented in the introduction. Specifically, consider the requirements of such a factory (reiterated below).

- Reprogrammable parts manipulator
- Flexible parts feeders
- Modular, exchangeable hardware
- Generic parts transporter
- Rapidly exchangeable grippers
- Vision system
- Modular, object oriented software
- Products designed for agile assembly systems

A dichotomous theme encompasses these requirements: Encapsulate product specific elements of the system; Generalize permanent elements of the workcell. How, then, has each chapter of this work contributed to the goal of a flexible factory? Re-examining the results of each chapter in this light should provide a more thorough understanding of their contribution to the whole. Chapters 2 and 3 are examples of this dichotomy. Chapter 2 dealt with flexible feeding systems which are a generalized solution to the problem of presenting parts to a workcell for assembly. Chapter 3 presented the application of homogeneous transforms to the problem of encapsulating product specific assembly hardware and grippers into quickly exchangeable packages. Chapters 4 and 5, in contrast, presented methods and techniques to improve the reliability, productivity, and functionality of agile workcells. Chapter 5 dealt specifically with the unique requirements of parts designed for assembly in an agile workcell while Chapter 6 examined the design of grippers for use in the workcell. While not directly related to encapsulating workcell hardware or generalizing hardware (although one could argue that it is an encapsulation of the gripping system), they are none-the-less crucial to the successful implementation of a factory of agile manufacturing workcells. Together, a better grasp on possible physical realizations of the generalized requirements can be deduced.

6.1 Flexible Parts Feeder

Flexible feeders are generalized workcell components. Without the ability to feed a wide variety of parts with no change in physical hardware, the goal of a multi-purpose flexible manufacturing cell is difficult to achieve. It is therefore essential to fully understand the underlying principals in flexible feeders so that they may be effectively applied to the problem of generalized parts presentation.

6.1.1 Results

After extensively testing the CWRU designed feeder system, results were generated in two areas: system throughput and statistical properties. System throughput dealt with determining the ability of the system to present parts to the workcell and with constructing a new method of specifying throughput as a function of the capabilities of feeder sub-systems. Statistical properties of the system were analyzed to determine underlying principals of the system so that a better prediction of system performance could be realized.

6.1.1.1 System Throughput

Reporting results on the throughput of a flexible parts feeder requires a redefinition of the standard parameters used previously to qualify feeders. Unlike a bowl feeder, a typical flexible feeder is composed of several major components (a mechanism to present quasi-singulated parts, a vision system to determine the location of graspable parts, and a mechanism for removing those parts from the system). Simply stating a number as the throughput of the feeder does not indicate the relative speed of each sub-system or pinpoint possible bottlenecks.

To report on the throughput of the feeder the following four different parameters were be used.

1. Overall throughput
2. Throughput of the parts presentation system
3. Throughput of the vision system
4. Throughput of the parts removal system

The overall throughput is the standard feeder parameter. This is a measure of how many parts are removed from the system in a certain amount of time. The throughput of the parts presentation system is a measure of the physical capability of the system to present singulated parts to the workcell. The throughput of the vision system is an indication of the speed of the system in locating candidate parts. The throughput of the part removal system is an indication of, physically, how fast the parts can be removed from the feeder. Examining these four values, as a group and individually, allows a greater understanding of the capabilities of the feeder than would be possible using just the overall system throughput.

The system was tested with a variety of different parts to determine its throughput capabilities. The system was shown to feed parts at rates from 10 to over 30 parts per minute, depending on part size and geometry. It was found that, in general, the larger the part the lower the throughput. When feeding $\frac{3}{8}$ inch and $\frac{5}{16}$ inch hex nuts in the same feeder at the same time, it was found that the relative throughput of each individual part differed. Since there were an equal number of parts placed in the bin, it was expected that the average feed rate for each part would be the same. However, the throughput data showed otherwise. The $\frac{3}{8}$ inch nuts fed at approximately 10 PPM while the $\frac{5}{16}$ inch nuts fed at approximately 11½ PPM. The relative static stability of each part was suggested as a possible explanation of this phenomenon. Therefore, a third test was conducted with the addition of a pause programmed into the controller to halt the system after each part was retrieved. This allowed the number of parts on the horizontal conveyor and the number of parts retrieved to be manually counted.

From this test, it was clear that while approximately the same number of parts were being spilled onto the horizontal conveyor from the inclined conveyor, the percentages of parts fed during the test correlated well with the previous test. Therefore, the differences in the throughput of each size nut could be attributed to their relative stability.

The throughput of the system using four different angles (32°-38°) of the inclined conveyor were conducted. It was apparent from the data that small changes in the angle of the inclined conveyor had little impact on overall system throughput, but did affect the throughput of the conveyor sub-system. Since the limiting factor in overall system throughput (for this test) was the robot, this result is not surprising.

It was also shown that simulating the use of a different robot (by operating the current robot at a greatly reduced speed, 10% of nominal) did affect the overall system throughput and robot sub-system throughput but did not affect the throughput of the vision or conveyor sub-systems.

Lastly, an endurance test was performed to determine the ability of the system to feed parts for a long period of time without jamming or human intervention. A mixture of nuts and plastic sockets was fed. Total run time for the test was about 3 days 9 hours. During that time the system fed over 150,000 parts without intervention and demonstrated the ability to operate without jamming. In addition, a major improvement (about a 50% increase) in the throughput of the system was obtained by altering system parameters and control code.

Several other interesting phenomena were discovered when analyzing the collected data. The amplitude of variation in individual part throughput when feeding multiple parts exhibited changes in size. These jumps in variation occur without warning and are a characteristic of a nonlinear system. It is important to understand the dynamics behind this behavior so that it may be minimized thereby making the system throughput more uniform. In addition to jump phenomena, interesting oscillations in part throughput were noticed. The variation of throughput for each part would change in both amplitude and phase relative to one another as the system operated. This is another indication that the system is nonlinear.

6.1.1.2 *Statistical Properties*

The Poisson distribution is a common model of discrete arrival processes. Hence, it (shifted from 0 by the minimum part retrieval time) appeared a logical choice for modeling the overall system throughput. To test for a Poisson distribution, the fit of an exponential distribution to the part retrieval times was examined. It was clear that the exponential distribution fit the data, which can therefore be modeled by a Poisson process. However, after converting the data from time per part to parts per minute, the feeder and its sub-systems were modeled by a normal distribution, as described in the Central Limit Theorem.

Secondly, it was shown that the average throughput and 1st order interarrival times could be determined from knowing the properties of the sub-systems of the feeder. However, the variances of the average throughput and 1st order interarrival times could not be determined from knowing those properties.

Finally, by examining the correlation between the various feeder sub-systems, it was determined that the conveyor and vision sub-systems are inter-related while the robot is mostly independent of other sub-systems. This result is unique to the physical feeder design and the tested mode of operation (serial). It may not hold for all flexible feeders in all modes of operation.

6.1.2 *Future Work*

Three main thrusts are needed in future work: hardware, testing, and theory.

6.1.2.1 *Hardware*

Several hardware related areas of the current design require further work. First, the mounting hardware needs to be redesigned for ease of adjustment. Changing the angle of the current inclined conveyor is time consuming, difficult, and limited to angles between 30° and 40°. The second area for hardware improvement is in flexible feeding of rolling parts. Current flexible feeder technology (including the CWRU design) lacks the ability to easily feed rolling parts. Some initial work in experimenting with roughly

textured belts has shown promising results, but further testing and work is required. Another area for future work entails examining alternate methods of spilling parts onto the horizontal conveyor. The current inclined conveyor could be replaced by another means of transferring parts from a bulk hopper to an underlit conveyor. For example, a possible solution is to use a simple feeder bowl to scatter parts onto the horizontal conveyor. Lastly, changes in the design and layout of the system which could improve system throughput need to be examined. The use of multiple robots or a new vision system are examples.

6.1.2.2 Testing

The system should be run for long periods of time while data is collected about system throughput. This data should be comprehensive, measuring all aspects of the system, including the time duration for all tasks of the feeding cycle (time to get a part into the vision window, time to determine the pose of a part, and time to retrieve the part), the total run time, the number of parts fed, and (when multiple parts were being fed at once) the type of part retrieved. To further aid in the examination of the data, the testing should generally establish a base (i.e. feed a certain type of part with a specific set of system parameters) and then alter various parts of the system (parameters, part fed, feeder used, etc.) while performing the same test. Using this methodology will allow the effect of each parameter to be seen. In general there are two classes of parameters that have an effect on throughput.

The first is system parameters of which there are two varieties: those that are programmable and those that are fixed as a result of the physical design of the system. Parameters which are programmable, such as the motion of the conveyor belts or the angle of the inclined conveyor, are of highest importance because they are the variables that can be manipulated by an adaptive control scheme to increase and maximize system throughput during operation for any given part. All physical system parameters, such as the width of the conveyor or the kinematic configuration of the part manipulator, taken

as a set, define the “design space” of feeder systems. They are important in the design of new feeders, but cannot be used in the control of the system during operation. Hence, the only way to study the effects of the physical parameters of the system is to construct several different feeders and conduct the same tests with the same parts on each. Such studies are important because the physical design of a feeder may be better suited for feeding one type or style of parts over another.

The second group of parameters that affect throughput are those of the parts being fed. Obviously, the throughput of the feeder is strongly dependent on the part which is currently being fed. Understanding how the part affects the system parameters is important for control. If the feeder behaves differently with one type of part versus another, then it is important to know which parameters the control system needs to manipulate in each case to maximize throughput.

After testing the system, it will become clear which system parameters are most critical and have the most effect on throughput and which do not. From this, groups of programmable system parameters, the styles of parts to which they apply, and the physical design of feeders to which they apply will become perceivable. This multi-level parameterization of the system (programmable parameters associated with styles of parts and physical feeder designs) is another important step in ultimately realizing the goal of an intelligent feeder controller. For example, it would be important to know that parameters a , b , and c are important when feeding thin, flat parts while parameters d , e , and f are important when feeding more block-like, cube-shaped parts.

Finally, long term testing needs to be performed. In an industrial setting, the feeder would be expected to run indefinitely with little intervention from the operator (other than loading parts). It is currently unknown how the feeder will perform over long periods of time. Questions such as the following need to be answered: Does the throughput remain constant, or does it begin to falter as the components of the system wear out? How robust is the system as its components begin to wear? The only way to

determine the answers to these question is to run the system for extended periods and observe the results.

6.1.2.3 Theory

Further work needs to be done in examining the theoretical processes underlying the operation of the feeder. A thorough understanding of the feeding system cannot be obtained until the properties and processes governing the system are determined.

The statistical distributions which describe the feeder and its sub-systems need to be determined. Currently, only the robot sub-system has been fitted to a distribution (normal) that can be explained physically. While the gamma distribution did fit the vision processing data rather well, the physical significance of that distribution and why it applies in this case is not known. Understanding the component distributions is a necessary part of understanding the complete feeding system.

Another important step in system understanding is explaining the observable phenomena. For example, during initial testing, the throughput of the system was observed to oscillate over a wide range of values. It also was observed, when feeding several parts at once, that two of the parts' throughputs displayed an anti-phasal relationship. Over time, this relationship varied. It is important to understand the underlying forces which are causing this phenomena to occur so that it can be controlled. As a second example, the throughput of the system during the extended test showed jumps in the variation of the throughput. In a real world setting, it would be advantageous to control and minimize this variation so that the system would perform more reliably and consistently. As the testing and data collection would proceed, other interesting and currently unknown phenomena would arise.

Next, and perhaps the most ambitious goal, is to determine the throughput and operating parameters of the system given only a CAD model of the part. A design tool such as this would allow designers to quickly try many different component concepts and know immediately how well the design would perform in a flexible feeder. One could even

envision a system which could refine the design of a component based on its feedability. The user would give the design tool a candidate design and request that the design be refined to improve feedability. The system would then test and alter the design automatically. An added feature of the design tool could be the ability to determine the relative throughputs of individual part types when multiple parts are fed with one feeder. The output of such a program would be a CAD based model of the optimized part design, the anticipated throughput of the part in a feeder, and the initial settings for the parameters of the feeding system.

Lastly, as the system operates, throughput results that are different than expected may be seen. Even if system models and optimization predict good nominal parameter settings, the randomness of part orientation in bulk storage and after conveyor advances will inevitably lead to variations in throughput. To deal with each of these situations, a control scheme which employed on-line tuning of programmable parameters would be beneficial. Such a system would ensure that the feeder was always operating at near optimal performance, even when the output of the system design tool produced less than ideal results.

6.1.3 Final Word

The design, construction, and understanding of flexible feeding systems is obviously important to the ultimate goal of an agile manufacturing cell. This chapter of the dissertation laid the foundations toward that ultimate goal, however, much work needs to be done before it is reached. It has been clearly shown that flexible feeders are complex, nonlinear systems which cannot be understood using simple models. If the ultimate goal of throughput prediction is to be realized, further study is required.

6.2 System Offsets

In contrast to the generalization of flexible feeders, system offsets are required to encapsulate product specific hardware so that agility is not hampered. In any given

assembly, it is often advantageous (and sometimes required) to use a dedicated, part specific mechanism to perform an action more quickly and more reliably than would be possible using the robot. In such a case, agility dictates that the dedicated equipment be self contained and readily exchangeable. System offsets, in the form of homogeneous coordinate transforms, allow a mathematical definition of the respective geometric configurations of the general workcell and the specialized hardware so that exchangeability is enabled.

6.2.1 Results

There are many ways to specify offsets in a manufacturing workcell, however, if they are to encapsulate the hardware and enable agility they must be defined with care.

After examining different methods of defining offsets, one method was chosen as the most appropriate for agile manufacturing. In this method all modular table locations and pallet locations are programmed per print and multiple tool offsets are used to account for any inaccuracies in system assembly. For each specific tool offset, two physical offsets are used. The first offset is used to align the tool coordinate frame with the coordinate system on the part or fixture, the second offset is used to translate from the quick change master plate mounted on the flange of the robot to the tool tip.

Next, a procedure was developed and specified which allows the systematic teaching of offsets such that they allow encapsulated hardware to be used at any workcell without reteaching. The offsets themselves were separated into two groups: those describing the geometry of the workcell itself and those describing the geometry of specialized assembly hardware. This grouping enables offsets taught at one workcell to be usable at another.

Lastly, a program was created to automate the calculation of the offsets. This program takes as input geometric information (as coordinate transforms) about the workcell and a part of the specialized assembly hardware and returns the corresponding tool offset.

To test the offsets, an example assembly was constructed using the CWRU workcell. One of the workstations with an Adept550 was designated the “setup” assembly station and the other workstation with an Adept550 was designated the “generic” assembly station. An example assembly containing three parts, a portion of the headcap from a commercially available flashlight, was chosen as the test case. After teaching all workcell specific offsets with respect to both workcells, assembly specific offsets were determined at the setup workcell. Then, 100 assemblies were run through the setup workcell without failure. Next, the assembly hardware was transferred to the generic workcell and 100 more assemblies were performed. New tool offsets were not taught at the generic workcell, those determined at the setup cell were used. Several errors (all the same) were seen at the second workcell; however, they were most likely due to wear on the parts rather than errors in the offset.

One of the most important results of Chapter 3 was the dependence of the offsets on the vision system. Vision allows the workcell to determine the location of encapsulated assembly hardware at system start-up. If the calibration between the camera and the robot’s WCS contains errors, then no matter how well the offsets are defined, the system will fail. It is then of the greatest importance to ensure that cameras are properly calibrated at each workcell to ensure successful system operation.

6.2.2 Future Work

While promising results have been obtained thus far, much further testing needs to be performed. Several key areas need to be studied to improve the confidence in the applicability of the offset method presented here to any generic assembly cell.

- Testing with SCARA robots other than an Adept550
- Testing with non-SCARA robots
- Testing with a workcell where the modular table and pallet are not in the plane of the robot’s world coordinate system
- Testing with a workcell with a different geometric configuration
- Testing with other assemblies

Testing needs to be performed with a SCARA robot other than an Adept550. Since an Adept550 was used in both the setup and generic workcells, it is possible that small errors could have gone undetected due to the geometric similarities of the robots.

Using the same arguments, testing the system at a generic workcell using a robot which does not have a SCARA geometry would also further validate the offsets. Any SCARA robot has a similar geometry that makes some of the offsets extraneous (i.e. the z axis of the robot is always pointing vertically, therefore, it is uncoupled from the x - y plane). Employing a robot that is kinematically different will further validate the offset method by examining the cases where the z axis is not always vertically oriented.

Currently, the CWRU workcell is constructed such that the x - y plane of the modular table is always aligned with the x - y plane of the robot's world coordinate system. To test the most general case, a generic workcell needs to be constructed in which the modular table is not mounted in the x - y plane of the robot. This would allow the testing of the full three degrees of rotation associated with the offsets to be exercised.

While the previous suggestions for further testing deal with exercising the full complexities of the offsets, testing the system using a different geometric workcell configuration would verify the applicability of the offsets to any generic workstation. This is simply another variation of altering the physical system to test that the method of offset determination is valid.

Lastly, testing the system using different assemblies would further test the interaction of the workcell specific and assembly specific offsets. Since the overall method of offsets presented in this chapter is completely dependent on this interaction, it is important that it be thoroughly tested.

6.2.3 Final Word

Just as flexible parts feeding was an element of an agile manufacturing system, an equally important element is the layout, methods, and implementation of workcell offsets. Chapter 3 of the dissertation has defined an implementation of offsets and a

method of teaching those offsets such that reconfigurability is possible. However, further testing and refinement of the offsets and the procedures to determine the offsets needs to be accomplished before they can be used in all circumstances with confidence.

6.3 Design for Manufacture and Assembly

While the design of the physical agile manufacturing workcell is important, an equally important part of a successful workcell is the design of the parts which are assembled in that cell. Designing parts for use in a flexible automation system can have profound results on the overall effectiveness of the system. Often, the root of many of the problems in a workcell 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.

6.3.1 Results

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 benefit from better designed parts. These areas are assembly, feeding, and vision.

Guidelines for automated assembly deal with altering parts design to enhance the reliability of the assembly process, the speed of the assembly process, and the expense required to construct product specific hardware and grippers. The seven guidelines dealing with assembly are the following:

- Use snap fits rather than threads
- Minimize assembly forces
- Design generous tolerances
- Design for smooth gripping surfaces
- Design for vertical assembly
- Minimize components in the assembly
- Design parts and grippers concurrently

When comparing the finding on assembly guidelines to previously published cases, there is good agreement. A good indication of the importance of the rules listed is

the fact that the 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 differently (economic justification, for example). Therefore it can be confidently stated that applying design rules for assembly to products can produce an all-around better situation, including assembly, system reliability, system throughput, and cost.

Guidelines which are applicable to design for flexible feeding are concerned with features which increase the probability that a part on a feeder is usable to the system. They are also concerned with ensuring the parts and feeder will not damage each other. The following guidelines were determined:

- Minimize the number of stable poses (ideally to 1)
- Design parts with stable orientations consistent with assembly
- Design parts to prevent tangling
- Design parts that will not be damaged by the feeder
- Design parts that will not damage the feeder

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 sense to design a part to be easily fed and handled by a human if it is going to be assembled exclusively by automated equipment.

Design guidelines to enhance the ability of a part to be seen by a vision system are concerned with adding features to the parts to enable easy and efficient part and pose determination. The following guidelines were determined:

- Design parts with rotational invariance
- Design parts with asymmetry if rotationally variant
- Avoid translucent parts

Previously, designing with regards to vision recognition had not been done. 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.

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.

6.3.2 Future Work

While the guidelines determined thus far have been beneficial, the formulation of design guidelines needs to be an ongoing process. Current guidelines need to be employed in new designs and new guidelines need to be added as unique products and design goals are encountered.

Secondly, metric could be devised which would be based on the guidelines, but allow a mathematical application of each guideline to a particular part design. This would be a required step before the guidelines could be applied in an automated manor, such as by a computer program.

Lastly, the metric form of the guidelines could be incorporated into one of the many CAD based design tools currently available. In this case, they would be used to gauge the applicability of current designs to agile manufacturing as well as make suggestions for product improvements based on programmed guidelines.

6.3.3 Final Word

As Chapter 2 and 3 emphasized the importance of system design, Chapter 4 has shown the importance of parts design in overall system functionality. While the design of the system and the parts should be separate (the system could have been running for years before the current part design was made), it is nonetheless crucial to the efficient

and reliable functioning of the workcell to properly design parts which are to be assembled in an agile manufacturing cell.

6.4 Gripper Design

Chapter 5, like Chapter 4, was concerned with the design of a part of the workcell which would help to improve the throughput and reliability of the system. Specifically, the problem of designing grippers for use in an agile manufacturing workcell was examined. While grippers and fixtures have always been used in automation systems, an agile workcell places additional expectations and requirements on the grippers. In general an agile workcell is less accurate than a similarly hard-tooled cell. The accuracy and repeatability of the robot, the vision system, the robot-camera calibration, and the tool offsets are examples of additional sources of uncertainty in a flexible manufacturing cell. Properly designed grippers can help compensate for these unknowns.

6.4.1 Results

First, gripper footprint, an important concept in the design of grippers for vision based, flexible parts feeders, was defined. Secondly, guidelines to aid gripper design were presented. These design guidelines were separated into three categories, guidelines to increase system throughput, guidelines to increase system reliability, and guidelines to save cost. Lastly, a review of the approximately 20 grippers designed for use in the CWRU and Eaton RAC workcells was presented.

6.4.1.1 Gripper Footprint

The first result is the definition of the footprint of the gripper. This is an important quantity to understand because it directly affects the ability of the gripper to retrieve parts from a flexible parts feeder. The simple concept of the vertical projection of the gripper fingers is not applicable, as was shown by example. A final definition, which better describes the term, is the following:

The three dimensional space which must be free of obstructions for a gripper to successfully grasp a part.

6.4.1.2 Design Guidelines

Next, gripper design guidelines were listed and explained. The first set of guidelines, listed below, were specifically directed toward increasing the throughput of the system. This was usually accomplished by increasing the sureness of the grasp which the gripper had on the part.

- Minimize interference measure
- Chamfer the exterior surfaces of gripper fingers
- Minimize weight
- Ensure a secure grasp of the part
- Avoid tool changes
- Grasp multiple parts with a single gripper
- Use multiple grippers on a single rotary wrist
- Design functionality into gripper jaws

The next guidelines helped to increase the reliability of the system by encouraging gripper designs which work well in the presence of location uncertainty. The guidelines are listed below.

- Ensure a secure grasp of the part
- Minimize finger length
- Design necessary approach clearances
- Design chamfers on approach surfaces of gripper fingers
- Design gripper to align parts as they are grasped
- Design gripping surface to complement frictional coefficient
- Design fingers to encompass actuator mounting points
- Do not rely on parts added to the assembly for location
- Design lead-in chamfers on assembly grippers
- Design functionality in gripper jaws

The last design guidelines sought to decrease the overall cost of the system by intelligent gripper design. The guidelines are listed below.

- Use less expensive parallel or rotary-jaw actuators
- Use off-the-shelf components for designing gripping systems
- Favor designs which handle multiple parts with a single gripper rather than designs which use multiple grippers on a rotary wrist

6.4.1.3 *Gripper Review*

The remainder of the chapter examined the design of approximately 20 grippers. The strengths and weaknesses of each design, the trade-offs made in each design, and the assembly actions performed by each gripper were examined. In addition to grippers designed for specific parts, the design of a generic rotary jaw gripper was presented. This gripper performs the unique task of retrieving parts from statically stable orientations on a flexible feeder and rotating them into favorable assembly orientations as the robot moves from the feeder to the assembly area. The gripper was designed to minimize size and weight for use on small, tabletop, assembly robots.

6.4.2 Future Work

As with Chapter 4, the guidelines developed have proven useful in the design of grippers for use in flexible manufacturing cells. However, there are constantly new challenges in gripper design that often provide another unique guideline that may be applied to additional grippers. Therefore, the future work for gripper design guidelines needs to include the constant updating of the current guidelines with additional guidelines as they become known.

In addition, the guidelines need to be added to current gripper design tools such that they become more automated. To accomplish this, the guidelines need to be transformed into metrics which can be analytically applied to candidate designs. By programming the metrics, which represent the knowledge contained in the guidelines, into a gripper design tool, the user could simply give the tool the description of the part or parts that are to be manipulated and the program would construct the best gripper design.

6.4.3 Final Word

Gripper design is an often overlooked step in the design of a functional and reliable workcell. If the grippers are not capable of accurately, securely, and rapidly grasping parts and assembling them, then no amount of agility in the rest of the system

will make any difference. Following and respecting a simple set of rules and guidelines during the design of the grippers can have a profound affect on their overall effectiveness.

6.5 Summary

This dissertation has presented 4 separate elements of a successful agile manufacturing workcell: flexible feeding, hardware encapsulation, parts design, and gripper design. There are many other required elements, software design for example, necessary for a completely functional system. If the ultimate goal of a general assembly cell is to be realized, all the elements are necessary. Work must continue to not only improve the procedures, methods, and designs presented here, but to also further develop additional elements of an agile workcell.

