Effects of Uncertainty on Closed Loop Shape Control in Stretch Forming

by

Alexander Pi

B.S., Mechanical Engineering (2000)
Massachusetts Institute of Technology

Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

September 2002

© Massachusetts Institute of Technology
All rights reserved

Signature of Author......

Department of Mechanical Engineering
August 1, 2002

Certified by.................................................. David E. Hardt
Professor of Mechanical Engineering and Engineering Systems
Thesis Supervisor

Accepted by.......................................................... Ain A. Sonin
Chairman, Mechanical Engineering Committee on Graduate Students

OCT 25 2002
DISCLAIMER OF QUALITY

Due to the condition of the original material, there are unavoidable flaws in this reproduction. We have made every effort possible to provide you with the best copy available. If you are dissatisfied with this product and find it unusable, please contact Document Services as soon as possible.

Thank you.

The images contained in this document are of the best quality available.
Effects of Uncertainty on Closed Loop Shape Control in Stretch Forming

by

Alexander Pi

Submitted to the Department of Mechanical Engineering on August 1, 2002 in partial fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

ABSTRACT

The stretch forming process is used extensively in forming airframe parts. There has been constant pressure in the aerospace industry to reduce costs and changeover times, decrease the number of cycles necessary to form a desired part, and minimize part variation. The development of a reconfigurable tool for stretch forming has allowed a reduction in costs and changeover times. Different shape control algorithms have reduced the number of runs necessary to produce a desired part. Using the reconfigurable die, together with a closed loop shape control algorithm results in less costs, fewer cycles, but possibly increased part variation.

Two particular shape control algorithms, the Deformation Transfer Function (DTF) and the Spatial Coordinate Algorithm (SCA) were examined in this research. These algorithms were applied to parts formed experimentally on a reconfigurable stretch forming tool in the lab, and via finite element simulation. Simulations examining the effects of noise on the stretch forming process were also performed.

The shape control algorithm was applied for a greater number of forming cycles than in previous work, and resulted in behavior that had not yet been observed. In particular, shape error did not continue to monotonically decrease, and in fact, often increased. This result was confirmed in simulation as well. This emphasizes the need for as much reduction in process uncertainty as possible. Further simulations also illustrated the suitability of the SCA as the preferred algorithm for application in a manufacturing environment and provided loose guidelines for guaranteeing part convergence within two closed loop cycles.

Thesis Supervisor: David E. Hardt

Title: Professor of Mechanical Engineering and Engineering Systems
Acknowledgements

I’d like to thank Professor David Hardt for his patience and support throughout this research. His suggestions and discussions often opened doors to possibilities that I would not have thought of on my own. I am also grateful for the lesson that good things often result from adversity.

I thank John Papazian and all of his colleagues at Northrop Grumman for the opportunity to contribute to this project. I have enjoyed our meetings and discussions that have shown me the bridge between what I do in the laboratory and what can be done in the real world.

I’d also like to thank my labmate, Adam Rzepniewski, for his assistance on the experimental apparatus, and for lively theoretical debates.

Lastly, I’d like to thank my friends and family for their support throughout the past two years.
“Education is an admirable thing, but it is well to remember that nothing that is worth knowing can be taught.”

--Oscar Wilde
# Table of Contents

ABSTRACT ......................................................................................................................... 3

ACKNOWLEDGEMENTS ......................................................................................................... 5

TABLE OF CONTENTS .......................................................................................................... 9

TABLE OF FIGURES ............................................................................................................. 11

CHAPTER 1 ........................................................................................................................................ 15

INTRODUCTION ..................................................................................................................... 15

1.1 MOTIVATION FOR STUDY ................................................................................................. 15
1.2 BACKGROUND INFORMATION ......................................................................................... 17
1.3 CONTRIBUTIONS OF THIS WORK .................................................................................. 19

CHAPTER 2 ........................................................................................................................................ 21

OVERVIEW OF STRETCH FORMING ...................................................................................... 21

2.1 STRETCH FORMING MECHANICS FOR SIMPLE CURVATURE SHAPES ............................... 21
2.1.1 Springback Quantification .......................................................................................... 27
2.2 SUMMARY ....................................................................................................................... 27

CHAPTER 3 ........................................................................................................................................ 29

PRIOR PROBLEMS AND RESEARCH IN STRETCH FORMING .................................................. 29

3.1 HIGH CAPITAL COSTS .................................................................................................... 29
3.2 SHAPE PREDICTION ISSUES .......................................................................................... 34
3.3 VARIATION IN STRETCH FORMING ............................................................................... 35
   3.3.1 Cycle to Cycle Shape Control ................................................................................ 37
3.4 SUMMARY ....................................................................................................................... 39

CHAPTER 4 ........................................................................................................................................ 41

OVERVIEW OF CYCLE TO CYCLE SHAPE CONTROL ............................................................. 41

4.1 MODELING STRETCH FORMING ..................................................................................... 41
4.2 STRETCH FORMING SHAPE CONTROL ......................................................................... 42
4.3 ESTIMATING THE PROCESS GAIN ............................................................................... 44
4.4 SYSTEM RESPONSE PERFORMANCE ........................................................................... 44
4.5 ERROR PERFORMANCE ................................................................................................. 47
4.6 DISTURBANCE RESPONSE AND MODELING ............................................................... 49
4.7 PART OUTPUT VARIATION ............................................................................................. 52
4.8 SUMMARY ....................................................................................................................... 55

CHAPTER 5 ........................................................................................................................................ 57

IMPLEMENTATION OF SHAPE CONTROL ALGORITHMS ......................................................... 57

5.1 PART REPRESENTATION ................................................................................................. 57
5.2 CALCULATION OF PART ERROR ................................................................................... 59
5.3 ALGORITHM STOPPING CRITERIA .................................................................................. 61
5.4 SUMMARY ....................................................................................................................... 62
Table of Figures

Figure 1: Illustration of stretch forming process on die of constant curvature ($K_f$) ........... 22
Figure 2: Stress and strain distribution in workpieces during pre-stretch ........................................... 23
Figure 3: Strain distribution of material in simple bending ................................................................. 24
Figure 4: Stress distribution for elastic-perfectly plastic material in simple bending ........... 24
Figure 5: Total strain distribution in piece during wrap phase ............................................................. 25
Figure 6: Total stress distribution in piece during wrap phase ............................................................. 25
Figure 7: Strain distribution with all strain values above yield ............................................................. 25
Figure 8: Stress distribution in piece with all strain values above yield [Hardt, 2002] ............. 26
Figure 9: Solid die used in manufacturing leading edge airplane parts ............................................. 29
Figure 10: MIT Reconfigurable Die ........................................................................................................ 31
Figure 11: Northrop Grumman Reconfigurable Tool ................................................................. 31
Figure 12: Illustration of interpolator [Norfleet, 2001] ................................................................. 33
Figure 13: Variations of different control methods in stretch forming [Parris, 1996] .................... 36
Figure 14: Stress Variation and its effect on strain [Hardt et al., 2001] .............................................. 37
Figure 15: Block diagram for cycle to cycle shape control [Hardt et al., 2002] ............................... 38
Figure 16: Block diagram model of the stretch forming process ......................................................... 41
Figure 17: Root Locus for stretch forming closed loop cycle to cycle control in the z plane .................................................................................................................................................. 45
Figure 18: Graphs of system step responses at different loop gain values ........................................ 46
Figure 19: Block diagram with disturbance modeled at part output .................................................. 49
Figure 20: Block diagram modeling disturbance at die setup ............................................................. 51
Figure 21: Variance Amplification for random noise in CL systems [Siu, 2001] .................................. 53
Figure 22: Variance Amplification for correlated noise in CL systems [Siu, 2001] ........................... 54
Figure 23: Figure of a part representation [Norfleet, 2001] ................................................................. 57
Figure 24: Sample error plot for a part ................................................................................................. 60
Figure 25: Table of different algorithms used for shape control [Norfleet, 2001] ........................... 63
Figure 26: Block diagram representing algorithm 1 ............................................................................ 64
Figure 27: Block diagram for Algorithm 2 - DTF .............................................................................. 66
Figure 28: Assumption of periodicity ................................................................................................. 69
Figure 29: Illustration of issues with periodicity assumptions ............................................................ 70
Figure 30: Sample windowing function .............................................................................................. 71
Figure 31: Effect of windowing function ............................................................................................. 71
Figure 32: Comparison of different point spread functions [Norfleet, 2001] .................................... 73
Figure 33: Parameters used for stretch forming by [Valjavec, 1999] .................................................. 75
Figure 34: Typical results of the DTF used in stretch forming [Valjavec, 1999] ............................ 76
Figure 35: Block diagram for Algorithm 3 – SCA ........................................................................... 78
Figure 36: Effect of values near zero on system identification of Algorithm 3 [Norfleet, 2001] .......... 80
Figure 37: Illustration of 3-sigma shift used for the SCA [Norfleet, 2001] ......................................... 82
Figure 38: Flowchart of Abaqus simulations [Norfleet, 2001] ......................................................... 83
Figure 39: Example of die and part mesh formed in Abaqus .............................................................. 84
Figure 40: Softened Contact model used during Abaqus simulation ................................................. 85
Figure 41: Comparison of experimental and simulated cylinders [Norfleet, 2001] ........................... 87
Figure 42: Comparison of experimental and simulated spheres [Norfleet, 2001] ........................... 88
Figure 43: Abaqus Algorithm comparisons for formed cylinders [Norfleet, 2001] ........................................ 89
Figure 44: Noise Amplification with noisy ID [Norfleet, 2001] ................................................... 91
Figure 45: Noise Amplification with pure ID [Norfleet, 2001] .................................................. 92
Figure 46: Table of experimental parameters .................................................................................. 95
Figure 47: Figure of reconfigurable tool used for stretch forming experiments .......................... 96
Figure 48: Explanation of trial sequences in Fig. 49 ........................................................................... 97
Figure 49: Experimental results for cylindrical forming trials .................................................... 97
Figure 50: Maximum part error for extended cylindrical forming trials using DTF ............................... 99
Figure 51: RMS part error for extended cylindrical forming trials using DTF ................................. 100
Figure 52: Plot of average part error vs. cycle number for extended trials ........................................ 101
Figure 53: Figure of process model including all relevant disturbances ........................................... 103
Figure 54: Descriptions of trial sequences with systematic error in die setup .................................. 105
Figure 55: Abaqus simulations of various shifts in pin locations ..................................................... 106
Figure 56: Trial conditions run in Fig. 57 and Fig. 58 ................................................................. 109
Figure 57: Standard deviation of parts with noise inserted into die setup ........................................ 109
Figure 58: Figure of average maximum errors for different noise levels ........................................ 110
Figure 59: Abaqus simulations of the DTF with .008” noise level .................................................... 111
Figure 60: Abaqus simulations of the SCA with .008” noise level .................................................... 112
Figure 61: Abaqus simulations of the DTF with .015” noise level .................................................... 113
Figure 62: Abaqus simulations of the SCA with .015” noise level .................................................... 114
Figure 63: Table summarizing error behavior of Abaqus simulations ............................................. 115
Figure 64: Comparison of noise simulations with noisy and pure ID ............................................. 116
Figure 65: Comparison of effects of different noise sources at cycle 3. (Pure ID) .................. 117
Figure 66: Comparison of part errors for different forming cases .................................................... 119
Figure 67: Part error variation for Abaqus simulations with noise at part output ............................. 120
Figure 68: Plots of Abaqus simulations with noise at part output (DTF – Pure ID) ...................... 121
Figure 69: Plots of Abaqus simulations with noise at part output (SCA – Pure ID) ................. 122
Figure 70: Plots of Abaqus simulations with noise at part output (DTF – Noisy ID) ...................... 123
Figure 71: Plots of Abaqus simulations with noise at part output (SCA – Noisy ID) ...................... 124
Figure 72: Plot of grand error with noise at part output after interpolation ...................................... 127
Figure 73: Variance ratios for parts formed with noise at output .................................................... 128
Figure 74: Open loop formed part (10.15” radius cylinder) showing slight twisting ......................... 138
Figure 75: Figure with significant twisting (5th part, 3rd closed loop part) ....................................... 139
Figure 76: Figure of Part 1 and die 2 resulting from part 1 ............................................................. 140
Figure 77: Part 2 and die 3 resulting from part 2 for 10.65” cylinder ............................................. 141
Figure 78: Part 3 and die 4 resulting from part 3 for 10.65” cylinder ............................................. 142
Figure 79: Part 8 and die 9 resulting from part 8 for a 10.65” cylinder ............................................ 143
Figure 80: Part 1 and die 2 resulting from part 1 for toroid ............................................................ 144
Figure 81: Part 2 and die 3 resulting from part 2 for toroid ............................................................ 145
Figure 82: Part 3 and die 4 resulting from part 3 for toroid ............................................................ 146
Figure 83: Sequence done under standard conditions with first die of 10.15” radius .................. 147
Figure 84: Sequence run with a first die of 13” done under “dual side tangency angle” calculation ............................................................................................................................................ 148
Figure 85: Sequence run with a first die of 13” done under “dual side tangency angle” calculation with an extra travel distance of 1” .................................................................................. 149
Figure 86: Figure of reconfigurable tool used for stretch forming experiments .......................... 150
Figure 87: Computer and associated electronic components and switches [Valentin, 1999]........................................................................................................................ 151
Figure 88: Die pressure Gage and Valve illustration [Valentin, 1999].................. 152
Figure 89: Aluminum jigs and jaw clamps used while inserting sheet metal. [Valentin, 1999]........................................................................................................................ 153
Figure 90: Interface window for stretch forming under force control .................. 154
Figure 91: CMM used for measurement in LMP machine shop................................. 155
Chapter 1

Introduction

This research focuses on the effects of uncertainty in closed loop cycle to cycle shape control. In particular, it focuses on how closed loop cycle to cycle shape control can be effective in achieving desired part shapes using stretch forming. It also focuses on the effect of uncertainty in the process on the part shapes formed. Some uncertainty can be tolerated and is dealt with well by the algorithms described herein. However, some uncertainty, in the form of an inaccurate process identification, or random noise cannot be completely dealt with by applying cycle to cycle shape control. Cycle to cycle shape control may even amplify these uncertainty levels. An identification of the process, or process ID, is typically an estimate of how the process output will respond to different inputs. More details on performing and using system identification techniques will be covered later in this research.

1.1 Motivation for Study

Stretch forming is a process used extensively for forming structural components in airplanes. Unfortunately, stretch forming is a difficult process to quantify analytically. The nonlinear form of the stress strain curve of some materials causes difficulty in developing an analytical method for predicting a desired forming die shape for a desired reference part shape during the stretch forming process.

Also contributing to this difficulty is that the exact form of the stress strain curve for a given material is sometimes not exactly known. Because of these factors, predicting a desired die shape for a given reference shape in industry is often based on operator expertise. In the absence of such expertise, forming a desired shape can be a truly arduous endeavor, requiring countless different stretch forming trials to achieve the desired part.
Prior examination of shape control methods by Webb, [1987] Valjavec, [1999], and Norfleeet [2001], have yielded 2 algorithms that reduce the part shape error to an acceptable level within a minimum number of iterations, or cycles, typically 2 or less. The Deformation Transfer Function (DTF) and Spatial Coordinate Algorithm (SCA) are two different shape control algorithms that take somewhat different approaches to shape error reduction.

The main difference between the DTF and the SCA is that the DTF partially accounts for coupling while the SCA does not. In the case of stretch forming, coupling is the effect that a change in die shape in one particular location has on the part shape in another location. For instance, a change of shape in the center of the die not only affects the part shape in the center, but in neighboring regions up to a couple of inches away as well. The DTF accounts for the effect that a change in a particular die location has on every other part location. A change in the die shape on one side of a 5”x5” part has an effect on the other side of the part, 5 inches away, as well as all closer part locations. Coupling also makes it more difficult to predict a correct die shape. Changing one location on a die may make that single part location more accurate, but it may also have a detrimental effect on the rest of the part. The process identification performed using the DTF accounts for this coupling effect while the SCA does not. The SCA assumes that each change in the die location only has an effect on the part at that same part location.

Valjavec, [1999], has previously shown that the DTF does result in a monotonic reduction of part error during experimental runs of different shapes, including cylindrical, and toroidal shapes. These experiments were performed on a lab scale reconfigurable die at MIT. A reconfigurable die is different from a traditional die in that it is made up of discrete, movable pins, as opposed to one solid die shape. More details on the reconfigurable die will be discussed later. The DTF results in part error reduction at a faster rate than other methods available. The developer of the Spatial Coordinate Algorithm, [Norfleeet, 2001] demonstrated via simulation that the SCA resulted in similar part error reduction as the DTF, with the added benefit of decreased complexity.
Northrop Grumman Corporation has attempted to apply the DTF in a true manufacturing environment. From their experiments, it appears that parts formed after using the DTF can sometimes result in part errors that increase after application of the DTF. It was hypothesized that the system identification of the algorithm was not accurate, or that process noise dominated so much that it caused excessive error.

This research attempts to quantify some of the necessary conditions to guarantee that an acceptable part shape can be formed. In particular, attempts to quantify the amount of uncertainty that can be tolerated in the process and other parts of the control loop, (e.g., measurement, part handling, etc.) were performed in this research. Experiments were performed on the lab scale reconfigurable tool and in Abaqus finite element simulations to determine the suitability of different algorithms for use in a manufacturing environment.

1.2 Background Information

Although stretch forming has been widely used in the aerospace industry for many years, there are still many problems inherent in the stretch forming process. In particular, stretch formed parts sometimes have high variation, and still require high changeover times when switching between different part dies. Although the concepts of lean manufacturing have reduced setup times in aerospace production, parts are still produced in batch sizes that supply enough parts for a few months because of changeover times. Also, the process of producing a desired die for a given part shape can be more of a “trial and error” approach than a rigorous scientific method.

A reconfigurable stretch-forming tool with movable discrete pins, as opposed to a solid die, was designed in an attempt to alleviate the above problems. [Robinson, 1987, Ousterhout, 1991, Valentin, 1999, Valjavec, 1999] A compliant layer, or interpolator, placed over the discrete pins prevents pin dimpling and acts as a “damper” to variations in die pin locations. A further discussion of the effect of the interpolator will be discussed later. The stretch forming tool itself allows for a reduction of setup times
between different parts. As a result, the reconfigurable tool makes it easier to form many different types of parts in a short period of time.

Although the costs associated with a trial and error approach have been reduced, it is still desirable to have a scientific method to determine a desirable die shape. A shape control algorithm that is robust in a manufacturing environment, and also requires only a minimum number of forming trials is ideal. An examination into a shape control algorithm that involves a system identification of the process in the frequency domain was initially developed by Webb, [1981] and implemented on a 3D reconfigurable die by Ousterhout [1991]. Valjavec [1999] showed that the DTF shape control algorithm allowed the user to form a desired part shape that fell below a threshold level within 4 iterations. However, two of these iterations, or cycles were used to perform a system identification, and 2 of these iterations were done while applying shape control. If the system identification is known, only 2 closed loop iterations were necessary to form the desired part. No more than 2 closed loop iterations were performed because the part usually reached the threshold level by this point. It was shown by Valjavec [1999] experimentally that the DTF converged more quickly than an approach where an untrained user “guessed” or changed the next die shape by the error of the part formed in the prior trial.

The forming trials were performed on a reconfigurable tool jointly developed by MIT and Northrop Grumman. A lab scale version was built in the early 1980's at MIT, and has been continually under development. [Olsen, 1980], [Walczyk,1981, 1999, 1999], [Goh, 1984], [Robinson, 1987], [Knapke, 1988], [Ousterhout, 1991], [Eigen, 1992], [Boas, 1997] More recently, a full scale version of the reconfigurable die has been built and used by Northrop Grumman. [Papazian et al., 1999]

Although the shape control algorithm developed by Webb [1987], Ousterhout [1991], and Valjavec [1999] reduced the number of iterations necessary to reach a desired shape, the algorithm developed, the DTF, was more difficult to implement and added complexity to
the forming process. It also proved to be more sensitive to noise than other discrete control methods.

Norfleet [2001] developed a shape control algorithm that used system identification techniques, but was also less sensitive to process variation than the DTF, the Spatial Coordinate Algorithm. Norfleet used a quarter symmetry finite element simulation in Abaqus developed by Socrates [2000] to examine convergence of this algorithm (SCA) as compared to the DTF. Norfleet [2001] used Monte Carlo simulations to study the effect of process noise while implementing these two algorithms. However, no parts were actually formed by Norfleet using either shape control algorithm.

Norfleet determined that although the DTF performed better than the SCA under noise-free situations, the DTF actually performed worse when noise was accounted for. The DTF also has the drawback of being more complex and more difficult to implement. Details of these issues will be discussed later in this work.

Despite the prior examination of these shape control algorithms, all attempts to quantify the necessary conditions for shape convergence while using these shape control algorithms have been unsuccessful.

1.3 Contributions of This Work

The work in this thesis attempted to confirm the suitability of the SCA as a candidate algorithm for closed loop shape control in stretch forming. Experimental results for the DTF and the SCA were both performed under similar conditions to the ones that Valjavec performed.

An examination into the effect of noise was performed using the same finite element simulations used by Norfleet. This research attempted to answer the following questions:
How much noise can the system and process tolerate to guarantee monotonic error convergence?
What level of noise will cause the part shape to not converge within 2 cycles?
Which algorithm, the DTF or the SCA, is more suited for application in a manufacturing environment?

Experiments were performed via the lab scale reconfigurable press to confirm the experiments that Norfleet [2001] simulated with the SCA and the DTF. Traditionally, only 4 iterations were necessary to guarantee algorithm convergence. However, more than 4 iterations were performed on the lab scale press, and via simulation to fully examine the convergence limits of each shape control algorithm. Noise simulations via Abaqus were also performed where process uncertainty was inserted into the forming and system identification process.
Chapter 2

Overview of Stretch Forming

An overview of the stretch forming process is presented in this chapter. The physics of sheet metal forming are also examined. Stretch forming involves pulling sheet metal over a shaped die. In stretch forming, as with any sheet forming process, the part shape does not match the die shape. When the part is in contact with the die, the die and part shapes match. However, once the part is released from the machine, the part shape is altered as a result of residual moments and stresses on the part experienced during the stretch forming process. This change in part shape after the stretch forming process is called springback. It is difficult to determine the springback of an arbitrarily shaped piece of sheet metal. This leads to the difficulty in predicting a correct die shape to form a desired part shape. Stretch forming is done as an attempt to form a desired shape contour while minimizing springback. In order to understand the nature of springback, it is necessary to understand the physics of the stretch forming process.

2.1 Stretch Forming Mechanics for Simple Curvature Shapes

Stretch forming involves a pre-stretch phase, a forming phase, and a post-stretch phase. Any of the phases, except forming, can be excluded from this process. Typically, a sheet metal piece is formed by first stretching the piece along one direction. The piece is then wrapped, or bent across a die. Stretching the piece minimizes the amount of springback that occurs after the stretch forming process. Once the piece is bent across the die and released, the piece usually springs back as a result of residual moments within the piece.

Figure 1 below illustrates the three phases of the stretch forming process. After the sheet metal blank has been loaded into the machine, an initial strain ($\varepsilon_{pre}$), is applied to the material. The strain level can be increased or decreased by controlling the amount of force applied to the sheet. The trajectory during the forming phase can also be controlled via a variety of means, e.g. jaw position. Different control modes, such as force, strain or
displacement control can also be used for the stretch forming process. Regardless of the control method used, the strain level is kept constant during the forming, or wrap phase.

Figure 1: Illustration of stretch forming process on die of constant curvature ($K_i$)

For arbitrary shapes, a curvature value is replaced with an arc-length equivalent curvature. The analysis below is valid only for shapes with constant curvatures. For the purposes of this analysis, the die is assumed to have a cylindrical curvature ($K_i$), where $K_i$ is the inverse of the die radius ($1/R_i$).
During the pre-stretch phase, the sheet is stretched uniformly along the length of the piece until the desired level of strain is reached. The strain state throughout the material thickness, \( \varepsilon(y) \), is defined through any cross section by Eqn. 1:

\[
\varepsilon(y) = \varepsilon_{pre}
\]

Where:

- \( \varepsilon \) = strain state
- \( y \) = position from neutral axis
- \( \varepsilon_{pre} \) = pre-stretch strain value

The resulting stress and strain states are shown in Fig. 2 below. During the pre-stretch phase, both the stress and strain are uniform across the width of the piece.

![Diagram showing stress and strain distribution](image)

**Figure 2: Stress and strain distribution in workpieces during pre-stretch**

To simplify the analysis, the material is assumed to be elastic-perfectly plastic. Equations 2 and 3 below illustrate the stress function for this type of material. For purposes of this analysis, it is a reasonable approximation of materials commonly used during the stretch forming process.

\[
\sigma = E\varepsilon \quad \varepsilon < \varepsilon_{yield} \quad \text{Equation 2}
\]

\[
\sigma = \sigma_{yield} \quad \varepsilon \geq \varepsilon_{yield} \quad \text{Equation 3}
\]
Where:

\[ \sigma = \text{stress state} \]
\[ \varepsilon = \text{strain state} \]
\[ \varepsilon_{\text{yield}} = \text{strain value at yield stress} \]
\[ \sigma_{\text{yield}} = \text{yield stress value} \]

During the wrap phase, the piece is bent across the die. The piece can be treated as being under simple bending for the purposes of this analysis. The stress and strain distributions for simple bending (no pre-stretch) are shown in Fig. 3 and Fig. 4 below.

![Figure 3: Strain distribution of material in simple bending](image)

Note that the outer fibers have stress values that are in yield as a result of elastic-perfectly plastic behavior and high strain levels.

In stretch forming, the total stress and strain experienced by the piece during the wrap phase is the sum of the stress and strain contribution from the pre-stretch and wrap phases. Adding Fig. 2 to Fig. 3 and Fig. 4 result in Fig. 5 and Fig. 6 shown below.
For an elastic-perfectly plastic material, if the lowest value of strain in the piece is above yield, then a perfectly uniform stress state will result in the workpiece across its width. With sufficient pre-stretch strain, Fig. 5 can result in Fig. 7, where all strain values in the piece are above the yield strain value.

The stress states for an elastic-perfectly plastic material will be the same for all strain values that are above yield. The sheet with a strain distribution as shown in Fig. 7 will have a uniform stress distribution as shown in Fig. 8 below if the material is elastic-perfectly plastic.
A uniform stress distribution will result in no springback of the workpiece. The reason behind this is shown in Eqn. 4, which is the level moment $M_I$ given a stress distribution $\sigma(y)$.

\[
M_I = \int_{-h/2}^{h/2} \sigma(y) y w dy
\]

(*Equation 4*)

Where:

- $M_I = \text{moment in workpiece}$
- $w = \text{piece thickness}$
- $h = \text{piece width}$

For a uniform stress distribution, the result of Eqn. 4 is zero. As a result, for a sufficiently large pre-stretch strain, there will be no residual moment, and no springback in the piece. Unfortunately, most materials are not elastic perfectly-plastic, otherwise, there would be no difficulties in stretch forming. Materials such as 2024-O aluminum, that are commonly used in stretch forming are almost elastic-perfectly plastic, so the results from this analysis are still informative. Although the final stress distribution during stretch forming will not be exactly uniform for materials such as 2024-O aluminum, the stress distribution will be close to uniform, resulting in a low amount of springback. However, if no pre-stretch strain is applied, and the material is not close to the elastic-perfectly plastic model, then a greater amount of springback will occur. The results from this analysis illustrate the benefit of stretch forming, as opposed to merely bending a piece without any pre-stretch.
2.1.1 Springback Quantification

The term “springback” refers to the curvature change that occurs after relaxation of the stretch forces. It is a shape difference between the curvature of the loaded piece \((K_i)\) and the curvature of the unloaded piece \((K_u)\). The springback ratio \((\Delta K)\) defines the relationship between the loaded and unloaded curvatures of the piece. For shapes of constant curvatures, the springback ratio can be analytically defined by:

\[
\Delta K = \frac{K_i - K_u}{K_u} \quad \text{Equation 5}
\]

Where:

\(\Delta K\) = Springback ratio

\(K_i\) = Curvature of piece when loaded

\(K_u\) = Curvature of piece when released

Although not all shapes formed are of constant radius, the cylindrical shape illustrates the key concept of stretch forming. In particular, it is a convenient shape to examine in understanding springback.

Analytical solutions that relate the amount of springback of the piece and other relevant parameters, such as material properties, are readily available and easily proven for constant curvature shapes. Springback analyses for non-constant curvature parts have also been developed for some parts. Parris [1996] developed one such analysis for springback. However, the application of such an equation was limited to two-dimensional shapes where the curvature of interest lies along one plane. Springback analyses for three-dimensional parts are more complex and difficult to perform.

2.2 Summary

This section covered the basic concepts of stretch forming. The physics of the stretch forming process were discussed, and the causes of springback were examined. Although springback quantification is difficult for most shapes, an analysis of the springback in constant curvature shapes allows an examination of the issues involved in stretch
forming. Furthermore, it illustrates the complexity involved in forming a correct part shape using stretch forming.
Chapter 3

Prior Problems and Research in Stretch Forming

Traditionally, stretch forming is a capital and time intensive process. In the aerospace industry, the stretch forming process is heavily dependent on operator expertise, and delays are prevalent because of a trial and error approach. High levels of part error are common. Current methods used to control the stretch forming process result in high levels of variation. This chapter will discuss what the issues are in stretch forming, and how prior research has dealt with these issues.

3.1 High Capital Costs

In the aerospace industry, stretch forming is traditionally performed using solid dies such as the one shown in Fig. 9 below. The die is typically composed of a soft metal, or even a polymer, or polymer composite.

Figure 9: Solid die used in manufacturing leading edge airplane parts

(Photograph Courtesy of Northrop Grumman)
Making a die such as the one shown in Fig. 9 above can take several weeks, and alterations to the same die typically take a few weeks, and at least several thousands of dollars. The die in Fig. 9 is approximately 2 feet x 6 feet x 1 feet. However, these dies can range from small wing tip sizes to a large Boeing 747 fuselage section. Each airplane is composed of many different stretch formed parts. Hundreds of dies can be necessary to form parts for a single aircraft, and these dies have an inventory and maintenance cost associated with them.

Stretch formed parts in the aerospace industry are typically formed in small batch or lot sizes. Changeovers are common as a result of this, and although improvements have reduced the changeover time of dies to approximately an hour, this is still significant time devoted to a non-value adding process. This does not account for costs associated with retrieving or tracking a die as well.

To address this issue, research at MIT over the past two decades has been aimed at developing a flexible reconfigurable tool. The die is approximately 1 ft x 1 ft in area, and is composed of 552 discrete pins. The tool, designed by Robinson [1987] and refitted by Valjavec, [1999] is shown in Fig. 10. Northrop Grumman, [Papazian et al, 1999] in a joint project with MIT and Cyril Bath Inc. designed and manufactured a production scale tool of approximately 35 ft x 6 ft with over 2000 pins. The purpose of a reconfigurable tool was to reduce the changeover times and costs associated with the traditional stretch forming process. Both reconfigurable tools are composed of discrete, spherical tipped pins. These pins can be moved independently, altering the part shape as desired.

---

1 Internal communication with Boeing Manufacturing Engineer
Figure 10: MIT Reconfigurable Die
Composed of 552 pins (23 x 24). Each pin is .5” in width. Positioned with 8 servos

Figure 11: Northrop Grumman Reconfigurable Tool
Made up of 2000+ discrete pins of 1 1/8” width, positioned by 2000+ servos
Although there are differences between the MIT and Northrop Grumman tools, the overall functionality is not significantly different. The size of each of the discrete pins determines the minimum curvature that can be formed by the tool. Northrop Grumman determined that for typical aircraft parts, a pin size of $1\frac{1}{8}''$ would suffice, whereas the MIT tool has $\frac{1}{2}''$ pins. Smaller pin sizes allow larger part curvatures. Stretch formed parts in the aerospace industry typically have slight curvatures.

An interpolator, usually a rubber or plastic of some sort, (typically Ethylene Vinyl Acetate, Polyurethane, Elvax, or some other material with favorable compliant material properties) is used to avoid the “dimpling” effects of the discrete pins on the sheet metal. The interpolator distributes the contact pressure of the pins evenly onto the sheet metal. This also results in no dimpling on the piece. The surface of the interpolator is typically treated in some manner to reduce the frictional effects between the sheet metal and interpolator. Coating the interpolator with a lubricant, or using a thin Teflon sheet are among the preferred methods. In general the thickness of the interpolator is determined by the thickness of the pins. It has been found that for optimal performance, the thickness of the interpolator and pin width should be approximately equal.\(^2\)

\(^2\) Internal communication within Northrop Grumman
Figure 12: Illustration of interpolator [Norfleet, 2001]

Pin and interpolator thicknesses are approximately equal. There is a smooth contact surface for the sheet metal piece, which results in no dimpling.

One of the greatest benefits of using a reconfigurable tool is the reduction in changeover times. Added benefits also include a reduction in the number of overall dies, and the associated costs of maintaining those dies.

The reconfigurable tool also lends itself remarkably well to “emergency” or “priority” orders. A significant portion of part orders for stretch formed parts goes towards repairing grounded planes. The parts required are highly variable and will be in extremely small batch and lot sizes, and often, only one unit of a particular part will be required. However, even with the reconfigurable tool, some means of determining the correct die shape for a desired part shape is required.

As discussed in the previous chapter, die prediction is difficult because of the springback effect. The analysis in the previous chapter was limited to constant shape curvatures. The shape of the discrete die is not of a constant curvature, and compounds the shape prediction problem. The addition of the interpolator prevents dimpling, but is another
unknown in an already difficult problem. The properties and physics of the interpolator are not exactly known, and cannot be predicted. Although the reconfigurable tool reduces the changeover time necessary in stretch forming, it makes shape prediction more difficult. Effective shape control is even more important with the reconfigurable tool as a result of these additional issues.

### 3.2 Shape prediction Issues

As previously discussed, springback is difficult to predict for all but the simplest cases. Finite element simulations are a viable method, but variations of the material properties, and uncertainty about the interpolator behavior limit the accuracy and usefulness of analytical methods in precisely estimating springback. In the manufacturing environment, a finite element simulation may first be used for an initial die guess. However, after this first guess, a “look and see” approach has been commonly used for successive iterations based on operator expertise. A result of this “eyeballing” approach is increased part variation and decreased part quality that results from human error. Even with the added benefits of finite element analysis, this iterative cycle could still take weeks if a fixed tool required modification. With a reconfigurable tool, it can still take several iterations to form an acceptable part. To minimize production time and material waste, it is desirable to minimize the number of forming trials needed.

The development of sophisticated finite element analysis (FEA) techniques has allowed much improvement in estimation of die shapes, but they still require significant computational time and other engineering resources. Although it may be possible for the estimates of process parameters to be accurate within simulation, variations can severely alter the values of these parameters in a manufacturing environment. It has been found and observed in our lab that material properties can vary 10-20\% between different batches. Material handling in a manufacturing environment may also not be done with as much care as in a laboratory environment. Other variations in a manufacturing environment, such as temperature variations, the opening and closing of doors, etc. will also cause process variation.
Taking advantage of the availability of a reconfigurable tool would be ideal in dealing with the above issues. An appropriate shape control algorithm in conjunction with the reconfigurable tool would be able to optimize the stretch forming process. This was some of the primary motivation that led Webb, [1981,1987] Osterhout, [1991] and Valjavec [1999] to develop and examine different closed loop shape control algorithms. These shape control algorithms will be covered in more detail in the next chapter.

3.3 Variation in Stretch Forming

Research has also been done in reducing the variation of parts formed using the stretch forming process. The control method used during the stretch forming process has a strong effect on variation. Parris [1996] and Valentin [1999] have shown that the implementation of standard operating procedures with strain control is the best control method in reducing process variation. Figure 14 below illustrates the effect that each control method has on process variation. Strain control usually requires strain gauges, and much time and calibration to implement. It is also very prone to being implemented inaccurately. Displacement control is sometimes performed, as it can be easily correlated to the strain the sheet experiences. However, the displacement of the sheet is usually measured by measuring the jaw position. If the machine is exactly rigid, and there is no backlash in the machine, displacement control can be performed accurately. Unfortunately, Parris [1996] found that the amount of flexing and backlash in the machine could be on the same order of magnitude as the sheet displacement. However, since the jaw displacement would be measured, any backlash or flexing in the machine would affect the displacement measurement, and as a result, the true displacement of the sheet would not be measured. The flexing of the machine and backlash cannot be easily accounted for, and as a result, displacement control is often not a suitable choice for a control method. Force control is the easiest control method to implement, but as illustrated in Fig. 13, it also allows the most process variation.
Understanding the physics of the stress strain curve will illustrate why strain control is the best control method. Hardt et al. [2001] illustrated that a small variation in stress results in a large strain variation. This is a direct result of the shape of the stress strain curve shown in Fig. 14. On the other hand, a small variation in strain results in an even smaller variation in stress. From Eqn. 4, it can be seen that by reducing the variation in stress levels, the springback variation is reduced, and therefore, the variation in part output, is minimized.
A small stress (force) variation results in a correspondingly large strain variation. Hence, controlling strain will result in less stress, less springback, and less part variation.

3.3.1 Cycle to Cycle Shape Control

To fully understand possible variations in stretch forming, it is necessary to introduce the generic form of the shape control algorithms used. Control processes can be sampled at a variety of intervals. In-process control involves feeding back the appropriate process variable, and then altering the process states to achieve the desired output, while the process is still occurring. Examples of in-process control include position placement of a robot arm, or a machine, as well as stretch forces during the stretch forming process. Changes are made to the system while the operation is still occurring. This is the preferred situation to apply closed loop control.
However, in some processes, the appropriate variable cannot be fed back while in-process. Stretch forming is one of these processes. In the case of stretch forming, the part shape is the output and feedback variable of interest. Unfortunately, it is not possible to measure part shape while it is being formed. Even if it were possible, springback would render this measurement inaccurate. The best case possible is to measure each part after it is formed, and then feed back the appropriate variable to the system for the next cycle, and adjust it accordingly. This control method is called cycle to cycle control, since the information is fed back into the system after each iteration, or cycle, so that it can be used in the next cycle. Cycle to cycle shape control is the best shape control method that can be used for stretch forming.

A generic cycle to cycle block diagram is shown below in Fig. 15. There is a delay of one cycle in the block diagram because the information used for the current cycle is taken from the previous cycle.

![Block diagram for cycle to cycle shape control](image)

Figure 15: Block diagram for cycle to cycle shape control [Hardt et al., 2002]

$G_c$ is the controller gain, determined by the user, $K_p$ is the plant or process gain, which represents the behavior of the process. $R(z)$ is the reference input, $Y(z)$ is the output, and $D(z)$ is the disturbance.

The disturbance in Fig. 15 can represent any unmodelled disturbance. For the purposes of this research, “noise” and “disturbance” will be used interchangeably. The process noise in stretch forming can represent mishandling of the part after it has been formed, or a variety of other unmodelled effects that are not captured in the process gain.
Zero-mean, random noise will contribute to part variation. Random noise is an effect that is always present in manufacturing. This will result in a part output that will also be randomly distributed. Reducing the part variation as a result of disturbances is desirable. Siu [2001] performed some research examining the effects of cycle to cycle control on part output variation. Details of Siu’s research will be covered in the next chapter along with a thorough examination of cycle to cycle control.

3.4 Summary

There are three major issues associated with stretch forming. They include the costs associated with manufacturing and maintaining a large number of different dies, the methodology used in shape prediction, and the process variation. These issues have been partially addressed through a reconfigurable tool jointly developed by MIT and Northrop Grumman. The benefits of this tool have also been increased through application of research involving closed loop cycle to cycle shape control algorithms that feed back the part error. This research focuses particularly on the effects of noise on different closed loop shape control algorithms.
Chapter 4

Overview of Cycle to Cycle Shape Control

This chapter more closely examines cycle to cycle shape control algorithms discussed in the prior chapter. Analysis of the performance of cycle to cycle shape control is also performed.

4.1 Modeling Stretch Forming

As previously discussed, cycle to cycle shape control can be expressed as a block diagram. The block diagram in Fig. 16 below is similar to that of Fig.15 except that it is more applicable to stretch forming. The desired reference part \( (p_{\text{ref}}) \) is input into the system. The error \( (e_{i-1}) \) from the prior part \( (p_{i-1}) \) is calculated, and then input into the controller \( (g_C) \). A change in die shape \( (\Delta d_i) \) is calculated, and then added to the prior die value \( (d_{i-1}) \). The part is then formed. The plant matrix \( (g_P) \) represents the forming process. The plant matrix is also referred to as the process gain. In this case, the process gain is a representation of the effect of die shape on part shape. Once the part is formed, the cycle is repeated until an acceptable part has been formed.

![Figure 16: Block diagram model of the stretch forming process](image)

41
4.2 Stretch Forming Shape Control

The shape control model has been developed over the past 15 years. The underlying structure of the control algorithm has not changed, but the algorithm has been refined and applied to different processes. (Webb, [1981, 1987] Osterhout, [1991] and Valjavec [1999]) In all cases, the goal has been to find a die shape that will yield the correct desired part shape, based on measurement of the part shape after each forming cycle.

A “best guess” for the correct die shape that will yield the correct shape is first done. Although a “good” first guess helps the algorithm to determine the “correct” shape more quickly, this is sometimes not necessary. Typically, a good first guess is done using FEA, from prior historical results, or through operator intuition. Once this first part is formed and measured, it is then compared to the desired part shape (or reference part shape). If the first guess is an acceptable shape, there is no further need to continue.

A more likely occurrence is that the part error is not within acceptable limits, and the die shape is adjusted by some proportion of the part error. This proportional gain, or controller gain is set to a value that yields desirable system performance. The algorithms examined in this research include gains that are determined using classical system identification techniques. After an initial part is formed, the next part is formed using a new die estimate based on the algorithm used. The new part is then formed and the errors compared again. The algorithm is continually repeated until an acceptable part is made.

The generic algorithm can be expressed as an equation shown below in Eqn. 6. An equivalent matrix form is expressed in Eqn. 7:

\[ d_i = d_{i-1} + G_c (p_{\text{ref}} - p_{i-1}) \]

Equation 6
The matrix form of the algorithm in Eqn. 7 is useful because the controller matrix can illustrate the relative influence among the different die and part locations. For the purposes of this research, the die is considered to be a grid of M by N pins where M=9, N=10 in the region of interest, also known as the active region. Only the active region is measured and considered during the forming process. On the lab scale tool at MIT, this corresponds to an active region area of approximately 4.5” x 5”. However, it is sometimes desirable to view the parts and dies with finer spacing than those of the die pins in the actual active region. When measuring and representing the die and part for system identification, a grid of M=46, N=51 points is used. This is much finer than the physical die, but the points that correspond to the physical die can be determined using common interpolation techniques.

The controller gain values are therefore, a (MN)x(MN) matrix. This is because a gain value is needed to relate every location on the part to every location on the die. The diagonal of this gain matrix would correspond to the effect that each point on the die had on the corresponding part location. The off diagonal terms are a measure of “coupling” between different die and part locations.
4.3 **Estimating the Process Gain**

The plant matrix, or process gain in Fig. 16 is estimated using Eqn. 8 below:

\[
G_p = \frac{P_2 - P_1}{D_2 - D_1}
\]

*Equation 8*

Where:

- \(P_1\) = First part formed
- \(P_2\) = Second part formed
- \(D_1\) = First die used
- \(D_2\) = Second die used

The process gain \(G_p\), shown in Eqn. 8 will be of size MNxMN where M, and N are the number of points taken along the x and y axes in the Cartesian coordinate plane. The process gain will have diagonal terms that illustrate the influence that each pin has on the corresponding part location. The off diagonal terms will be a measure of the degree of coupling between different die and part locations.

4.4 **System Response Performance**

Minimizing the number of iterations needed to form a desired part is a necessary condition for any control algorithm used in a manufacturing environment. Root locus methods can be a useful tool in analyzing the closed loop system response. The root locus method is based on examining the open loop transfer function of the system. The open-loop transfer function for the process is derived from the block diagram of the overall system shown in Fig. 16, and is defined by Eqn. 9:

\[
\frac{P_i}{P_{ref}} = \frac{g_cg_p z}{z(z-1)}
\]

*Equation 9*

The open loop transfer function has two poles, and one zero. The zero is on the real axis, and the poles are located at 0 and 1 as can be seen from Eqn. 9. The pole at 0 is “cancelled” by the zero on the real axis. As a result, the function can be approximated by
a pole located at 1 on the real axis. The root locus plot for this system is illustrated in Fig. 17.

For Eqn. 9, the root locus is a line extending to negative infinity on the real axis. It is assumed that $g_c$ and $g_p$ are constant gain values. The gain values are the same for each cycle where the closed loop shape algorithm is applied.

The results of the root locus analysis implies that for loop gains $K$ such that $0<K<1$, the response will be that of an over damped system. As the value of $K$ approaches 1, the
system response will be quicker, requiring fewer cycles, or time steps to reach the steady state value.

Figure 18: Graphs of system step responses at different loop gain values
Loop gain values <1 result in overdamped system behavior while loop gain values of >1, but less than 2 result in oscillatory behavior. A loop gain value of 1 is ideal, as the system settles in one cycle under this condition.
Figure 18 illustrates the different loop gain operating conditions. The condition where the loop gain is unity is also referred to as a deadbeat controller. From this analysis, it can be seen that in order for the part shape to settle to the desired part shape as quickly as possible, the overall loop gain value should be unity. The controller in the cycle to cycle control algorithms used is set so that the overall loop gain value is 1. Any loop gain value greater than 2 will result in a part shape that will gradually become worse in successive cycles.

The analysis done here is only valid for a single input, single output system (SISO). For stretch forming with a discrete die, each pin and part location can be regarded as an input and output, resulting in a multi input, multi output system (MIMO). An extension for the analysis done in this section and the rest of the chapter from SISO to MIMO systems can be done.\(^3\)

### 4.5 Error Performance

Ideally, the error of the system in the steady state should be 0. This would imply that the part shape error goes to 0, and that the ideal part is formed. Repeated application of the shape control algorithm should eventually result in the correct reference part. To determine the steady state error of the system, the closed loop transfer function is examined. Equations 10, 11, and 12 below represent the closed loop transfer function of the block diagram in Fig. 16.

\[
\frac{P_i}{P_{ref}} = \frac{g_c g_p}{1 - z^{-1}} \quad \text{Equation 10}
\]

\[
\frac{P_i}{P_{ref}} = \frac{g_c g_p}{1 - z^{-1} + g_c g_p z^{-1}} \quad \text{Equation 11}
\]

\(^3\) Unpublished work by Rzepniewski, A. at MIT
\[ \frac{P_i}{P_{ref}} = \frac{g_c g_p z}{z - 1 + g_c g_p} \quad \text{Equation 12} \]

Where:
- \( p_i \): part shape for the \( i^{th} \) iteration
- \( P_{ref} \): reference part shape
- \( g_p \): plant matrix
- \( g_c \): controller matrix

The response of the closed loop transfer function in the steady state to a unit step can be calculated by multiplying the transfer function by \((z-1)\) (a step input), and taking the value of the closed loop transfer function as \( z \) approaches unity. This can be represented by Eqn. 13 below.

\[ \lim_{z \to 1} \left( \frac{g_c g_p z}{z - 1 + g_c g_p} \right) \left( \frac{z}{z - 1} \right) = 1 \quad \text{Equation 13} \]

The value of Eqn. 13 approaches unity, meaning the part shape will approach the desired shape, resulting in no steady state error. This is possible because the algorithm accounts for the errors in all the previous parts formed. This controller is in effect, an “integrator” that allows for convergence to zero steady state error. This controller integrates the part errors and accounts for them in successive iterations.

Prior research [Siu, 2001] has shown that that closed loop cycle to cycle shape control can amplify process noise. An effort to minimize this noise and disturbance is necessary. The next section will discuss the disturbance rejection capabilities of cycle to cycle control while section 4.7 will discuss noise amplification when using cycle to cycle shape control. [Siu, 2001]
4.6 Disturbance Response and Modeling

Another important measure of system performance is its response to noise, or unwanted and unmodelled disturbances. Disturbances are usually modeled as additive as shown in Fig. 19 below, with the disturbance modeled at the part output.

![Block diagram with disturbance modeled at part output](image)

Figure 19: Block diagram with disturbance modeled at part output

Note that disturbances can also occur in different areas with a summation junction. A disturbance at the part output could be in the form of a measurement error or alteration to the part as a result of mishandling after it has been stretch formed. Disturbances can also occur during the forming process itself, or during die setup.

Disturbances can be of different types (random, systematic, and periodic). Step, or constant disturbances are the easiest to model. These could be constant offsets in die pin locations, or constant measurement errors. To calculate the effect of a step disturbance, the limit of the closed loop disturbance transfer function is calculated. The limit as \( z \) approaches unity is determined. This value will define the ratio between the output and the disturbance. A value of 0 is desired, as this would imply that the disturbance has no effect on the output. Equations 14, 15, and 16 are different representations of the
disturbance transfer function. Equation 17 is the effect of a step disturbance (constant offset), on the output of the system.

\[
\frac{p_i}{\text{dist}} = \frac{1}{1 + g_c g_p z^{-1}} \\
\text{Equation 14}
\]

Where:

\(\text{dist} = \text{value of constant, step disturbance}\)

\(p_i = \text{part shape for the } i^{th} \text{ iteration}\)

\(g_p = \text{plant matrix}\)

\(g_c = \text{controller matrix}\)

\[
\frac{p_i}{\text{dist}} = \frac{1 - z^{-1}}{1 - z^{-1} + g_c g_p z^{-1}} \\
\text{Equation 15}
\]

\[
\frac{p_i}{\text{dist}} = \frac{z - 1}{z - 1 + g_c g_p} \\
\text{Equation 16}
\]

\[
\lim_{z \to 1} (z - 1) \left( \frac{z - 1}{z - 1 + g_c g_p} \right) \left( \frac{z}{z - 1} \right) = 0 \\\n\text{Equation 17}
\]

Where:

\(\left( \frac{z}{z - 1} \right) = \text{step disturbance}\)

Equation 17 indicates that a constant, step disturbance will not have an effect on the steady state value of the system output.
Correspondingly, the system may have a disturbance during die setup. The analysis in this case is somewhat similar to that of the case where a disturbance is added to the part output. Equations 18, 19, and 20 are the disturbance transfer function for the system with a disturbance modeled at the die setup. Equation 21 is the effect at the part output to a step disturbance.

\[
\frac{p_{i,\text{dist}}}{\text{dist}} = \frac{1}{1 + \frac{g_c z^{-1}}{1-z^{-1}}}
\]

Equation 18

\[
\frac{p_{i,\text{dist}}}{\text{dist}} = \frac{1-z^{-1}}{1-z^{-1} + g_c z^{-1}}
\]

Equation 19

\[
\frac{p_{i,\text{dist}}}{\text{dist}} = \frac{z^{-1}}{z^{-1} + g_c}
\]

Equation 20

\[
\lim_{z \to 1} \left( \frac{z^{-1}}{z^{-1} + g_c} \right) \left( \frac{z}{z-1} \right) = 0
\]

Equation 21
Equation 21 illustrates that the system output will not be affected by a step disturbance during die setup.

A system with step disturbances at both the part output, and the die setup will not have its system steady state output affected. Since the disturbances are additive, and they individually do not affect the system output, they will not affect the system output in combination either.

The effect of a disturbance or error in the plant matrix, $g_p$, in Fig. 20 is not easily quantified, especially for a full rank matrix. The estimate of the process gain can be incorrect because of variation in the part and die, as can be seen by Eqn. 8. If the controller gain is set so that the overall loop gain is 1, a misidentification of the process gain will result in an overall loop gain that is not unity. This will result in slower convergence, and perhaps some oscillations in part error. If the process gain is grossly incorrect, the overall loop gain could be over 2, resulting in a part output with monotonically increasing error.

4.7 Part Output Variation

Siu [2001] performed some analysis of variation effects of closed loop cycle to control algorithms. He examined the effects of uncorrelated and correlated noise with respect to variation at the output when using cycle to cycle control algorithms. He illustrated that the application of these algorithms could increase output variation in the presence of uncorrelated noise. In other words, the effect of disturbances can be amplified as a result of using cycle to cycle control. In the presence of correlated noise, the process variation is generally reduced. The variance amplification plots shown in Fig. 21 and Fig. 22 below illustrate the effect of different controller gain values on the variation at the output.
Figure 21: Variance Amplification for random noise in CL systems [Siu, 2001]

Effect of different controller gains on variance at system output. Lower gain values result in less variance amplification. The variance ratio is the variance of the output divided by the variance of the input.
If there is correlated noise in the system, it appears that having a controller gain value of 1 is ideal in reducing the effect of variance on the output. Consistent mishandling or other disturbances can be accounted for with cycle to cycle control. Figure 22 illustrates the effect of 80% correlated noise on variation at the output. Knowing the prior values of noise will help in estimating future values. The stronger the correlation, the more accurate the estimate will be. Figure 22 illustrates that even with the presence of an unmodelled, but somewhat random disturbance, cycle to cycle shape control can account for this and reduce the part output variation. However, this will not affect the average steady state value of the part output. If the noise has a mean of zero, then the average error value in the steady state will be zero, although the part variation may be increased. If the noise is random, but if the mean value of the noise is not zero, the analysis in the prior section holds, and the part output will approach the desired part shape, although with possibly increased part output variation. In stretch forming, correlated noise can include twisting the part the same way after it has been formed, or it
can be a result of bias in measurement. However, with correct controller gains, the effect of these correlated disturbances can be reduced. Unfortunately, if the process noise is completely random, cycle to cycle control will increase the part output variation, although the mean steady state error will still be zero.

4.8 Summary

All shape control algorithms discussed in this research fall under the framework and conditions discussed in this chapter. Any shape control algorithm will use the same set of equations and block diagrams. Using certain tools from discrete control theory, the performance of the algorithm can be analyzed. Any step disturbance will not result in a steady state error. However, although zero mean, random, uncorrelated step disturbances do not affect the steady state output level, they can cause misidentification of the process gain, which means the process will take more than 1 cycle to settle to the desired value. Cycle to cycle control can also cause greater variation in the system output than in the presence of no cycle to cycle shape control.
Chapter 5  
Implementation of Shape Control Algorithms

Regardless of the specific algorithm used, there are certain issues that are common to all implementations of shape control algorithms in this work. This includes the mathematical representation of the die and part, and other parameters relevant for the stretch forming process.

5.1 Part Representation

For shapes of constant curvatures, the \( i \)th iteration of the die and part, \( d_i \) and \( p_i \) are the curvatures that correspond to the \( i \)th die, and part. However, for shapes of non-constant curvatures, different definitions of part measurement are necessary. For these shapes, the vertical locations of the points on a surface of the part represent the part, as illustrated in Fig. 23 below.

![Figure 23: Figure of a part representation [Norfleet, 2001]](image)
Points corresponding to a die are evenly spaced along both the X and Y axes.
The formed parts are measured using a coordinate measurement machine (CMM), although any device that can measure surfaces accurately in the XYZ coordinate system is acceptable. The CMM data is represented as a cloud of points in the Cartesian coordinate system. The CMM can measure the part on any grid that is identically spaced within its accuracy and resolution. However, it is very unlikely that the data points taken are identical to those on the die or reference part. As a result, some interpolation is necessary to determine the points that can be compared appropriately. A variety of interpolation methods have been used in the past, including bi-cubic spline interpolation, and linear interpolation. The benefit of some of the more elaborate forms of surface fitting includes “smoothing” the data. However, different surface fitting techniques do not alter the part representation significantly. Advances in measurement techniques (such as AFI) allow quicker and more accurate measurement of the part. They may also allow better surface fitting techniques and estimation.

In Fig. 23 above, it is assumed that the part has been oriented and aligned properly to a standard. This process is called registration. Each part formed is marked with at least one reference point during the forming process. This mark allows the part to be oriented with respect to the die and the reference part. The parts formed at MIT by Valjavec [1999] and this author have one reference point that is close to the center of the surface. The Z coordinate values are all shifted after the part has been measured so that the “center” of the reference part and formed part match.

The registration method used in this research includes an iterative approach to part registration. This is done by adjusting the part along the Z axis, and then rotating the part along the X,Y, and Z axes until the (RMS) error is at a minimum. Once the angles of rotation along different axes have been determined, the points on the grid of the part are then calculated and reformed in the new configuration. This new part is then considered registered, with respect to the die, and the reference part. Further details can be viewed in Valjavec’s research. [1999]
Other implementations of the part registration involve 2 or even 3 reference points. Each reference point limits more degrees of freedom, and allows a quicker and potentially more accurate registration routine. [Papazian et al., 1999]

### 5.2 Calculation of Part Error

The part must first be registered with respect to the reference part, as discussed in the previous section. The “center” point of the formed part is matched with the center point of the reference part, so the error value there is always zero. The overall part error is calculated by comparing the difference in the z coordinate values between the ith part formed and the reference part. This is represented by Eqns. 22 and 23 below:

\[ e_i = P_{ref} - P_i \]  \hspace{1cm} \text{Equation 22}

\[
\begin{bmatrix}
1,1 e_i & 1,2 e_i & \cdots & 1,N e_i \\
2,1 e_i & 2,2 e_i & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
M,1 e_i & \cdots & \cdots & M,N e_i
\end{bmatrix}
= 
\begin{bmatrix}
1,1 P_{ref} & 1,2 P_{ref} & \cdots & 1,N P_{ref} \\
2,1 P_{ref} & 2,2 P_{ref} & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
M,1 P_{ref} & \cdots & \cdots & M,N P_{ref}
\end{bmatrix}
- 
\begin{bmatrix}
1,1 P_i & 1,2 P_i & \cdots & 1,N P_i \\
2,1 P_i & 2,2 P_i & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
M,1 P_i & \cdots & \cdots & M,N P_i
\end{bmatrix}
\]  \hspace{1cm} \text{Equation 23}
The error plot above illustrates edge effects in stretch forming. The die used for the next iteration should be the “opposite” of this error plot.

The part error is composed of the same number of grid points as the part. Expressing the part error as a plot can allow for analysis of potential problems in the part and process. Although the surface of the error is sometimes useful, the minimum Root Mean Square (RMS) value is also useful for analysis as a quantitative measure of part quality. The RMS error is defined by Eqn. 24 below:
The RMS error is calculated as follows:

\[
RMS\_Error = \sqrt{\frac{\sum_{m=1}^{M} \sum_{n=1}^{N} (e_{(m,n)})^2}{MN}}
\]  

\[\text{Equation 24}\]

Where:

- \(M\) = number of measured points in the x-direction
- \(N\) = number of measured points in the y-direction
- \(m\) = counter for the x-direction
- \(n\) = counter for the y-direction
- \(e_{(m,n)}\) = error at the point \(x=m, y=n\)

Note that shifting the error surface, the formed part, or the reference part along the Z-axis can influence this RMS value. The RMS error used in this research is the minimum value of RMS, which is defined by Eqn. 25 below.

\[
\text{Minimum RMS Error} = \sqrt{\frac{\sum_{m=1}^{M} \sum_{n=1}^{N} (e_{(m,n)} - \bar{e})^2}{MN}}
\]  

\[\text{Equation 25}\]

Where:

- \(\bar{e}\) = overall average part error

### 5.3 Algorithm Stopping Criteria

This quantification of RMS error is useful in determining overall part quality, but it is not the criteria used to determine when to stop forming further parts. The maximum part error is used as the threshold or stopping criteria. The maximum error is determined by shifting the formed part so that Z coordinate values at the center of the surface coincided with the same point on the reference part. The “maximum” error is the largest magnitude of error calculated by subtracting this part shape from the reference part. Valjavec [1999] stopped forming parts once the maximum part error went below 0.01”. This was designated as the “threshold” level because this was what the process noise was estimated at. Although this maximum part error does not give a measure of the overall part quality,
it is of particular interest in the aerospace industry and other applications where a
threshold level of error must be met for all points on the part surface.

5.4 Summary

All algorithms share a common format for expressing the part shape and error. Part
registration, and techniques used to measure part error are similar between all algorithms.
These standards are necessary to insure proper part comparison. The overall part quality
can be determined either by viewing the surface profile of the part error, or by looking at
the RMS value. The stopping criteria for all parts is based on the maximum part error.
Chapter 6

Discussion of the Algorithms

This chapter will discuss the different shape control algorithms that will be examined in this research. Norfleet [2001] classified the various shape control algorithms with the following table:

<table>
<thead>
<tr>
<th>Algorithm #1</th>
<th>Algorithm #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Coupling</td>
<td>No Identification</td>
</tr>
<tr>
<td>- No System ID</td>
<td>- System ID</td>
</tr>
<tr>
<td>- No Coupling</td>
<td>- No Coupling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Algorithm #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling</td>
</tr>
<tr>
<td>- System ID</td>
</tr>
<tr>
<td>- Coupling via Convolution</td>
</tr>
</tbody>
</table>

| No Identification | Identification |

Figure 25: Table of different algorithms used for shape control [Norfleet, 2001]

Further details regarding these algorithms can be viewed in Norfleet’s thesis, although an overview of the algorithms is covered in this chapter. This research is particularly interested in algorithms two and three.
6.1 Algorithm 1

Algorithm 1 was initially developed by Webb. [1981] Since it does not require a system ID, nor does it account for coupling, it is by far, the simplest algorithm to implement. Because of a lack of a system ID and no accounting of coupling, this algorithm has less desirable characteristics than the other algorithms. This algorithm should result in inaccurate identification, and poor performance, as it does not reflect the reality of the process very well. This algorithm was implemented by taking the error from the prior part, and then incrementing the die by that amount. This can be viewed as a cycle to cycle control algorithm where the controller gain is set to unity. The next die is calculated by moving each pin at location (x,y), by the part error at the same location only. A block diagram for algorithm 1 is shown in Fig. 26 below.

![Figure 26: Block diagram representing algorithm 1](image)

Although there is a process gain in this block diagram, no attempts to identify it were made, so the overall loop gain will not be close to unity. As discussed in the prior chapter, this will result in poor performance.

Equations 26 and 27 are used for calculating dies in the next forming cycle for algorithm 1.
\[ d_i = Id_{i-1} + e_{i-1} \quad \text{Equation 26} \]

\[
\begin{bmatrix}
1d_i \\
2d_i \\
(MN,d_i)
\end{bmatrix} =
\begin{bmatrix}
1d_{i-1} \\
2d_{i-1} \\
(MN,d_{i-1})
\end{bmatrix} +
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\times
\begin{bmatrix}
e_{i-1} \\
2e_{i-1} \\
(MN,e_{i-1})
\end{bmatrix}
\quad \text{Equation 27}
\]

Where:

- \( I \) = Identity matrix
- \( d \) = die for \( i \)th iteration
- \( e \) = part error for \((i-1)\)th iteration

This algorithm would provide acceptable performance if springback did not occur. However, because there is springback, and since this algorithm does not perform a system identification of the process gain, it will not accurately model the process. It makes no attempt to identify or deal with the coupling in the part either. Although this algorithm is simple, Webb [1981] determined that it does not yield the desired performance. If the first guess is far away from the reference part, it will take more cycles to form the correct part. The slow rate of error reduction results in an excessive number of trials that can be costly in terms of both time and money.

### 6.2 Algorithm 2: The Deformation Transfer Function

Algorithm 2 addresses some major areas of weakness inherent in algorithm 1. It accounts for the coupling between different locations on the part and die. It captures this effect of coupling in the form of a system identification, an estimate of the plant matrix. As a result, algorithm 2 requires fewer cycles to reach a desired part shape.

Algorithm 2 involves transforming and viewing the part in the frequency domain, and then transforming the part and die back into the spatial domain via the Fourier transform. The Fourier Transform represents functions in the spatial domain as sine curves of
different magnitudes and frequency. Because of this transformation, algorithm 2 is more commonly referred to as the Deformation Transfer Function (DTF). There has been much examination into the exact details and mechanisms of this algorithm. It has been found that a change to a single frequency in the Fourier domain can affect multiple points of the die and part in the spatial domain. In this manner, the DTF accounts for coupling. Once the estimate of the plant has been performed, the controller values are then set, and also remain unchanged during all successive cycles.

Although this algorithm performs better because it accounts for some degree of coupling, it can be shown that this algorithm is also more sensitive to noise than the prior algorithm. [Valjavec, 1999, Norfleet, 2001] It is also more complicated to implement than algorithm 1.

The block diagram for the DTF can be viewed in Fig. 27 below:

![Block diagram for Algorithm 2 - DTF](image)

**Figure 27: Block diagram for Algorithm 2 - DTF**

The part and die representations are all done in the frequency domain by taking the Fourier transform. The representation in the spatial domain is determined by taking the inverse Fourier Transform. An estimate of the plant matrix is determined, and the controller gains are set so that the overall loop gain is unity.
Equations 28 and 29 below are used to calculate die shapes for the DTF. They correspond to Fig. 27 above.

\[
D_i = D_{i-1} + G_c (P_{\text{ref}} - P_{i-1}) \quad \text{Equation 28}
\]

\[
\begin{bmatrix}
1 D_i \\
2 D_i \\
MN D_i
\end{bmatrix}
= \begin{bmatrix}
1 D_{i-1} \\
2 D_{i-1} \\
MN D_{i-1}
\end{bmatrix}
+ \begin{bmatrix}
G_C & 0 & 0 \\
0 & G_C & 0 \\
0 & 0 & 0
\end{bmatrix}
\times \begin{bmatrix}
P_{\text{ref}} \\
P_{\text{ref}} \\
P_{\text{ref}}
\end{bmatrix}
- \begin{bmatrix}
P_{i-1} \\
P_{i-1} \\
P_{i-1}
\end{bmatrix} \quad \text{Equation 29}
\]

Where:

\( \mathcal{S} = \text{Fourier Transform of} \)

\( D_i = \mathcal{S}(d_i) \)

\( P_i = \mathcal{S}(p_i) \)

\( P_{\text{ref}} = \mathcal{S}(p_{\text{ref}}) \)

All operations in Eqns. 28 and 29 were done in the frequency domain. In order to apply Eqn. 29 and Eqn. 30, it is necessary to come up with an appropriate controller gain. Using Eqn 30 below, an estimate of the process gain was made. Since this equation calculates the ratio of the output (P) and the input (D), in the frequency domain, this system identification in Eqn. 30 is referred to as the Deformation Transfer Function (DTF).

\[
\hat{G}_P = \frac{P_2 - P_1}{D_2 - D_1} \quad \text{Equation 30}
\]

Where:

\( \mathcal{S} = \text{Fourier Transform of} \)

\( D_i = \mathcal{S}(d_i) \)

\( P_i = \mathcal{S}(p_i) \)
The controller gains are determined by Eqn. 31. They are the inverse of the plant matrix, since an overall loop gain value of unity is desired.

\[ G_C = \hat{G}_P^{-1} \]  

\textbf{Equation 31}

All operations in Eqns. 28-31 are multiplication operations in the frequency domain, which corresponds to a convolution in the spatial domain.

Equations 32-34 below represent algorithm 2 in the spatial domain. Viewing the DTF in the spatial domain representation can be useful in understanding the actual effect of the DTF. The multiplication operation in the frequency domain is replaced with a cyclic convolution operation in the spatial domain. The cyclic convolution is equivalent to a matrix multiplication if the controller or plant matrix is replaced with a full circulant matrix. This matrix is of size MNxMN, and each column is composed of the same MN column vector, except each column is “shifted” one location from the other.

[Strang, 1986]. The convolution can be complicated and confusing to perform, hence the preference for performing the transformation to the frequency domain and determining the product in that domain. Equations 32-34 are all equivalent. The controller gains in Eqn. 34 illustrate that there is coupling between different part and die locations.

\[ d_i = d_{i-1} + G_c \otimes (P_{ref} - P_{i-1}) \]  

\textbf{Equation 32}

\[ \otimes = \text{Convolution operator} \]

Equation 33 is the matrix form of Eqn. 32. This is also performed in the spatial domain.

\[
\begin{bmatrix}
1d_i \\
2d_i \\
\vdots \\
MN d_i
\end{bmatrix}_{(MN,1)} +
\begin{bmatrix}
1g_C & 0 & 0 & 0 \\
0 & 2g_C & 0 & 0 \\
0 & 0 & \ddots & 0 \\
0 & 0 & 0 & MN g_C
\end{bmatrix}_{(MN,MN)} \otimes
\begin{bmatrix}
1P_{ref} \\
2P_{ref} \\
\vdots \\
MN P_{ref}
\end{bmatrix}_{(MN,1)} -
\begin{bmatrix}
1P_{i-1} \\
2P_{i-1} \\
\vdots \\
MN P_{i-1}
\end{bmatrix}_{(MN,1)}
\]

\textbf{Equation 33}
Equation 34 is another representation of Eqn. 33. The convolution operation has been replaced with the multiplication operation and a circulant matrix. The circulant matrix takes the values of the gains in the controller matrix in Eqn. 32 and 33, and puts them all into one column. Each successive column shifts all the values of the previous column down one value. Each column contains the same information, just expressed slightly differently. The coupling represented by this circulant matrix is not perfect, but it does partially account for coupling.

\[
\begin{bmatrix}
\begin{array}{c}
1 d_i \\
2 d_i \\
\vdots \\
(MN) d_i \\
\end{array}
\end{bmatrix}
= 
\begin{bmatrix}
\begin{array}{c}
1 d_{i-1} \\
2 d_{i-1} \\
\vdots \\
(MN) d_{i-1} \\
\end{array}
\end{bmatrix}
+ 
\begin{bmatrix}
\begin{array}{cccc}
1 \mathcal{G}_C & \mathcal{M}_N \mathcal{G}_C & \mathcal{G}_C & \mathcal{G}_C \\
2 \mathcal{G}_C & \mathcal{G}_C & \mathcal{M}_N \mathcal{G}_C & \mathcal{G}_C \\
\vdots & \vdots & \vdots & \vdots \\
(MN) \mathcal{G}_C & \mathcal{M}_N \mathcal{G}_C & \mathcal{G}_C & \mathcal{G}_C \\
\end{array}
\end{bmatrix}
\begin{bmatrix}
1 P_{ref} \\
2 P_{ref} \\
\vdots \\
(MN) P_{ref} \\
\end{bmatrix}
\]

\text{Equation 34}

6.2.1 Assumption of Periodicity

Using the convolution operation and the Fourier Transform assumes that the part and die used are of identical infinite lengths and periods. The circulant matrix in Eqn. 34 also leads to this assumption. However, the part and die are clearly not infinite in length, and are not necessarily periodic. An assumption of periodicity of the input and part are similar to that of the image shown below:

```
<table>
<thead>
<tr>
<th>Repeated “Periodic” Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>u(nT)</td>
</tr>
<tr>
<td>Signal</td>
</tr>
</tbody>
</table>
```

**Figure 28: Assumption of periodicity**

The die and part are assumed to have a shape that repeats as shown above. This is clearly not necessarily the case.
This periodicity assumptions leads to the need for windowing. The discontinuities between each cycle in Fig. 28 above can cause problems when transforming the part or die representations between the spatial and frequency domains.

6.2.2 Windowing

As stated earlier, there is an assumption of infinite periodicity made while performing the convolution and the Fourier Transform. Sometimes, the beginning and end of the part representation are not continuous, as represented in Fig. 29 below. When periodicity is assumed, there can be a large “gap” between certain time steps.

![Figure 29: Illustration of issues with periodicity assumptions](image-url)
To reduce these sharp transitions, the system inputs and outputs are “windowed” using a “windowing” function. The effect is to smooth the transitions, but they also alter the signal. In this case, the part and die representations in the frequency domain, and therefore, also the spatial domain, are altered. Correspondingly, the actual dies predicted may be incorrect for the parts and dies observed in the experiments. Typically, the windowing function is multiplied by the input function. One such illustration of the windowing function and its effect are shown below. Although the particular effects of windowing were not studied in depth for this research, it has been determined to have a significant and detrimental effect on the performance of the algorithm. More details can be viewed in Norfleet’s research. [2001] Figures 30 and 31 below illustrate the effect of a windowing function on the sample function shown in Fig. 29.

Figure 30: Sample windowing function

The windowing function eliminates discontinuities between each cycle for the sample function, but significantly alters its representation.

Figure 31: Effect of windowing function
6.2.3 2-Dimensional Convolution

For stretch forming, the $Z$ values along both the $X$ and $Y$ coordinate axes are of interest, so a two-dimensional representation of an “impulse” response is needed, as opposed to a one-dimensional impulse response. The impulse response to this two-dimensional system is called the point spread function (PSF). The mathematical representation for this function is shown in Eqn. 35 below:

$$z(mX, nY) = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} u(iX, jY) h_T[(m-i)X, n-j)Y] = u \otimes h$$  \hspace{1cm} \text{Equation 35}

Where:

- $X =$ distance between points in the $X$ direction
- $Y =$ distance between points in the $Y$ direction
- $M =$ number of points in the $x$ direction
- $N =$ number of points in the $y$ direction
- $m =$ counter in the $x$ direction
- $n =$ counter in the $y$ direction
- $i =$ counter in the $x$ direction
- $j =$ counter in the $y$ direction
- $\otimes =$ convolution operation

The point spread function is a measure of the effect of coupling relative to the influence of the primary pin. It gives a clear visual representation of the coupling in the system. It is also possible to have different types and degrees of system coupling. Figure 32 below illustrates different point spread functions for different possible system types.
6.2.4 Implementation of the DTF

The first two forming cycles are done with predetermined die shapes to determine the local process gain. Once the process gain is estimated, the iterative closed loop shape control algorithm is performed. There is a variety of “first dies” that can be used for system identification, or for algorithm “startup”. In theory, any “first guess” and “second guess” are acceptable. However, some guesses will allow the system to converge to an acceptable level more quickly than others will. Valjavec [1999] used a backward difference approach where the first and second die were both either underformed or overformed. An underformed part is one with a curvature that is lower than the desired part. An overformed part is one with a curvature that is higher than that of the desired part. The same backward difference approach will be used in this research.

The calibration dies used for estimating the plant matrix in this research are shown below. The first die guess radius is usually within 10% of the reference part radius,
although this does not necessarily have to be the case. Valjavec [1999] found that the DTF had better performance when the first die guess radius was within 10% of the reference part. The second die is incremented by the error from the first part. The second part formed from this die is then measured. The first two parts and dies are used to determine the system ID, or the plant gain matrix as discussed in Eqn. 30. Equation 36 is used for determining the first two dies and parts formed.

\[
\begin{align*}
    d_1 &= d_* \\
    d_2 &= d_1 + p_{ref} - p_1
\end{align*}
\]

Equation 36

Where:

\(d_* = \text{first die guess}\)

The parts formed are measured, and registered in the manner previously described. Smoothing and windowing functions are applied prior to transforming the part and die into the frequency domain. This author always used the Kaiser windowing function when implementing the DTF experimentally, as did Valjavec [1999]. The Hamming window was used during Abaqus simulations. Norfleet [2001] also used the Hamming window for his Abaqus simulations when applying the DTF.

There has been some debate regarding how often to perform the system identification. Performing the system identification repeated times after the initial two cycles may result in a more accurate system identification. Also, because the stretch forming process is nonlinear, and the system is assumed to behave linearly, being closer to the ideal operating point will result in a more accurate identification. However, as the increment between the part and die values used to estimate the process gain decrease in Eqn. 30, a disturbance in part and die values will have a large effect on the estimate of the process gain. Valjavec [1999] determined that the system identification should be performed only once, and the dies used for estimating the process gain should not be “too close” to the reference part. The process gain was typically estimated with a first part maximum error of approximately 0.07”, and a second part with a maximum error of approximately 0.02".
6.2.5 Historical Results of the DTF

Valjavec [1999] performed stretch forming experiments of the DTF on MIT’s reconfigurable forming press. The parameters he used are listed below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin size</td>
<td>0.5 inch</td>
</tr>
<tr>
<td>Stretch Force</td>
<td>6125 lbs.</td>
</tr>
<tr>
<td>Blank Material</td>
<td>Al 2024-O, 19.5 x 5.5 x 0.063 inches</td>
</tr>
<tr>
<td>Final part footprint</td>
<td>4.5 x 5.0 inches</td>
</tr>
<tr>
<td>Force trajectory</td>
<td>Pre-stretch, wrap, no post stretch</td>
</tr>
<tr>
<td>Control mode</td>
<td>Force control</td>
</tr>
<tr>
<td>Interpolator</td>
<td>Elvax 360 (0.535 in. thick) covered with two layers of Teflon</td>
</tr>
</tbody>
</table>

**Figure 33: Parameters used for stretch forming by [Valjavec, 1999]**

The laboratory experiments discussed in this research will be done under the same conditions as those used by Valjavec. [1999] Experiments were performed on different part geometries for cylindrical and toroidal parts similar to the ones that Valjavec [1999] used. Typical results of trials performed by Valjavec are listed below:
Figure 34: Typical results of the DTF used in stretch forming [Valjavec, 1999]
Experiments were performed until the maximum error on the part fell below 0.01 inches. This was defined as an acceptable error level based on the process noise level.

6.2.6 Deformation Transfer Function Issues
Although the DTF accounts for coupling, and has been found to have better performance than algorithm 1, the DTF is the most complex of the three algorithms available, although it theoretically has the best performance. There have been problems implementing the algorithm by this author and by others at Northrop Grumman. The part errors have not always decreased as desired. It has been hypothesized that excessive process variation and uncertainty may be the cause of these poor results. Norfleet [2001] also determined that the DTF was the most sensitive to noise out of the three possible shape control algorithms. Utilization of system identification techniques has assumed that the system is linear and that the effects and processes involved in the system are also linear. Aside
from the fact that the behavior of the material is nonlinear, the interpolator also behaves very nonlinearly, and as a result, its behavior will be very difficult to incorporate into the process ID. The interpolator requires an input level higher than a certain level before the die input is registered on the part formed. Valjavec [1999] determined that on 0.535” Elvax, (a material similar to polyurethane and Ethylene Vinyl Acetate) the interpolator used in the experiments, a single pin would need to be raised 0.01 inches above the base level before a change in the part shape is seen. Once this dead band region has passed, the interpolator behaves in a somewhat linear manner. Different interpolators also have different behaviors. [Papazian et al., 1999] This includes different sized dead band regions. As a result of the damping effect, small errors and uncertainties in die pin locations do not have an effect on the part shape.

The system identification and the shape control algorithm include everything that occurs during the stretch forming process, and certain operations outside of it. It accounts for everything from the moment the die is setup, to the part formation, measurement, and processes performed until the next part is setup again. The system identification accounts for all of these factors and attempts to identify the effect of all these factors on the process.

Some of the issues brought up here regarding the DTF are also relevant to algorithm 3. The tradeoff between calibration dies close to the reference point, and noise contaminating the system identification is particularly valid, and common to both algorithms. However, the issue of windowing, and the Fourier transform are unique only to the DTF. The DTF’s sensitivity to noise brings into question its suitability as a candidate algorithm for use in a manufacturing environment.
6.3 Algorithm 3: The Spatial Coordinate Algorithm

Algorithm three, also known as the Spatial Coordinate Algorithm (SCA) has a similar block diagram to the DTF shown in Fig. 27. It uses a system identification technique similar to that of the DTF. The only difference is that there is no Fourier transform operation in the algorithm.

![Diagram](image)

**Figure 35:** Block diagram for Algorithm 3 – SCA

The SCA performs an estimate of the plant gain matrix, and sets the controller gains so that the overall loop gain is unity. All operations are done in the spatial domain.

The spatial coordinate algorithm is implemented by using Eqn. 37 and Eqn. 38 below. They are similar to the equations used for the DTF except all operations are done in the spatial domain.

\[ d_i = d_{i-1} + G_c (p_{\text{ref}} - p_{i-1}) \]  

Equation 37
The system identification is performed in a manner similar to that of Eqn. 30, except it is performed wholly in the spatial domain. Correspondingly, the estimate of the plant matrix is determined by Eqn. 39 below. It is also calculated in the spatial domain.

\[
\begin{bmatrix}
1 d_i \\
2 d_i \\
MN d_i
\end{bmatrix}
= 
\begin{bmatrix}
1 d_{i-1} \\
2 d_{i-1} \\
MN d_{i-1}
\end{bmatrix}
+ 
\begin{bmatrix}
g_C & 0 & 0 & 0 \\
0 & g_C & 0 & 0 \\
0 & 0 & 0 & MN g_C
\end{bmatrix}
\cdot 
\begin{bmatrix}
1 P_{\text{ref}} \\
2 P_{\text{ref}} \\
MN P_{\text{ref}}
\end{bmatrix}
- 
\begin{bmatrix}
1 P_{i-1} \\
2 P_{i-1} \\
MN P_{i-1}
\end{bmatrix}
\]

Equation 38

The controller gain is once again set so that the overall loop gain is unity. As a result, the controller for the spatial coordinate algorithm is set as defined by Eqn. 40 below.

\[
G_C = G_P^{-1} = \frac{D_2 - D_1}{P_2 - P_1}
\]

Equation 40

The relative simplicity of using the spatial coordinate algorithm comes at a price. From Eqn. 38, it can be seen that the controller does not account for any coupling between different part and die locations, although it does account for springback as a result of the stretch forming process.

6.3.1 Spatial Coordinate Algorithm Issues

This algorithm is very sensitive to referencing on the Z-axis. As noted by Eqns. 39 and 40 above, values of \(P_2-P_1\) and \(D_2-D_1\) close to zero can result in unreasonably high and noisy gain values. However, shifting all or some of the Z values by a constant does not affect the part representation, even though it does affect the values of the controller and plant matrices. The stretch forming process itself is not affected by a Z-coordinate shift of the die or part, provided that the same stopping and forming conditions are applied during stretch forming. The stopping condition used is when the angle of tangency of the
part pulled is the same as the angle at the edge of the active region on the die. As long as this condition is maintained, shifting the die or part value representation does not affect the process.

Norfleet [2001] showed that Algorithm 2 was not affected by controller or process gain denominator values near zero because of the transformation into the frequency domain. Figure 36 below illustrates one example of adverse behavior that can result when the denominators of Eqns. 39 or 40 are near zero.

![Figure 36: Effect of values near zero on system identification of Algorithm 3 [Norfleet, 2001]](image)

Note that there are some “spikes” that represent particularly high gain values as a result of a division by values close to zero. The result of these high gain values will most likely result in incorrect and distorted die predictions.

There is no “correct” or incorrect value to shift the denominator along the Z-axis. Shifting the controller denominator by a constant is the same as shifting a part and die
value by a constant at all points. Shifting the numerators and denominators of the plant
and controller matrix values will prevent spikes, but, shifting them by a large value will
drive the gains towards a value of 1, as illustrated in Eqn. 42. In the extreme case, this
would cause the algorithm to revert to algorithm 1. Norfleet [2001] used a “3 sigma”
shift as illustrated in Eqn. 41 below, and Fig. 37, to compensate for this problem.

\[
G_C = \frac{D_2 - D_1 + 3\sigma}{P_2 - P_1 + 3\sigma}
\]

Equation 41

\[
\lim_{\sigma \to \infty} G_C = 1
\]

Equation 42

---

Calculate change in part ‘Δp’ with part shapes arbitrarily referenced.

\[
\Delta p = p_2 - p_1
\]

Find the point \((x_{ref}, y_{ref})\) in ‘Δp’ with the minimum value.

This point is termed the ‘reference point’

Shift all part and die representations such that they have value ‘zero’ at this point

\[
p_i = p_i - p_i(x_{ref}, y_{ref})
\]

\[
d_i = d_i - d_i(x_{ref}, y_{ref})
\]

\[
p_{ref} = p_{ref} - p_{ref}(x_{ref}, y_{ref})
\]
Calculate gain values using the equation below where $\sigma$ is an estimate of the system noise level

$$G_c = \frac{D_2 - D_1 + 3\sigma}{P_2 - P_1 + 3\sigma}$$

Figure 37: Illustration of 3-sigma shift used for the SCA [Norfleet, 2001]

According to the simulations performed by Norfleet, [2001] the “3-sigma” shift was sufficient to prevent “spikes” in the gain matrix. However, noise values in the simulations that he ran were exactly known, because he injected them into the simulation. However, later experimentation by this researcher has determined that a “3 sigma” shift may not be sufficient. It was sometimes necessary to shift the values by as much as 10 times the maximum error to guarantee that there were no “spikes” in the gain matrix. Although a “look and see” approach can be used, a scientific and less arbitrary standard should be used to determine the proper “shift”. After sufficient experimentation, a shift of 10 times the maximum part error for the second part ($P_2$) was sufficient to guarantee that there were no spikes in the gain matrix. However, although this shift value prevents spikes, it still has not been proven to be the optimal shift value.

This algorithm has issues due to the “shift” necessary to drive denominator values away from zero. Any amount of shift used is still somewhat arbitrary since it is based on the maximum part error, which is not deterministic. Furthermore, because of this shift, each point is also affected differently by noise variations. The points with gain denominator values closer to zero will be more affected by noise than the points with gain denominator values further away from zero. Furthermore, any shifting distorts controller and process gains away from the “ideal” values. Lastly, this algorithm ignores the effect of coupling, which should result in poorer performance than the DTF. Details regarding
the Abaqus simulation used by Norfleet [2001] to examine the DTF and SCA are covered in the next section.

6.3.2 Abaqus Finite Element Simulations

The finite element simulation developed by Socrates and Boyce [2000] and used by Norfleet [2001] was a means of evaluating the performance of the SCA and of the other shape control algorithms. A detailed schematic of the simulation characteristics is shown below in Fig. 38.

![Figure 38: Flowchart of Abaqus simulations [Norfleet, 2001]](image)

The pin positions for the die are first determined. This includes the pins in the “active region” of the die, as well as the pins in the passive region. These pins are then input into a Matlab program that forms an “equivalent die” in Abaqus. The interaction point of each pin is then calculated. During forming, the Abaqus simulation determines which part of the pins make contact first, and then the surface is converted to a format that Abaqus can recognize. The program also calculates the angle of tangency, or the pull off
angle of the die. An example of the die and part meshes formed by Abaqus are shown in Fig. 39 below.

![Diagram of die and part mesh](image)

Figure 39: Example of die and part mesh formed in Abaqus
The die and part are modeled, as well as the boundary conditions. The “left” side of the part above is always kept in contact with the die.

The rigid die surface and the pull off angle are the only parameters that are changed between different Abaqus forming cycles. Other parameters such as the stretch forces, the geometry and material properties of the piece, including the stress strain curve behavior, are also included as parameters in the model, but are kept constant between different part cycles.

Although the simulation is only performed for a quarter symmetry part, it can still be a useful tool in comparing algorithm performance. Performing the simulation in quarter symmetry allows less computation than performing a full part simulation. The boundary
conditions of the quarter symmetry forming simulations are similar to that of a full forming simulation.

The interpolator is modeled using a “softened contact” interaction definition between the sheet metal and the die. The pressure at the sheet and die interface is a function as shown in Fig. 40 below. The softened contact model begins when the distance between the sheet and the die is \( \frac{1}{2} \) of the interpolator thickness. If the interpolator is compressed less than half its original thickness, then, the contact pressure will be 0, resulting in no alteration in the part shape. This model of the interpolator is a reasonable approximation of the one used at the MIT lab scale press.

![Exponential Function](image)

**Figure 40: Softened Contact model used during Abaqus simulation**

In simulation, the part is pre-stretched, and then wrapped by translating the part downward until it makes contact with the die. Once the sheet touches the die, the sheet is incrementally wrapped around the die while maintaining the stretch force as a constant. Once the part has been pulled until the edge of the active region of the part and die are tangent, the part is released from the stretch forming process by relaxing the “jaw”
constraints. The sheet is released and allowed to spring back to eliminate any residual moments in the cross section.

Once the above steps are completed, a cloud of points representing the node positions in the final part is exported to the Matlab program. The part is then quadrupled so that a “full” part is represented before applying the appropriate algorithm.

6.4 Simulated Results of Algorithms

6.4.1 Comparison of Error Performance of Algorithms

Norfleet’s Abaqus simulations were used to compare and contrast the performance of the various algorithms. The same Abaqus simulations described in the prior section were used here. Norfleet first compared the simulated and experimental parts formed by Valjavec. A comparison of the experimental results formed by Valjavec and typical simulation results for the cylinder (Fig. 41) and sphere (Fig. 42) are shown below.
Figure 41: Comparison of experimental and simulated cylinders [Norfleet, 2001]
A cylinder with 10.65” radius was the reference part, with a first die guess of 8.60”
Figure 42: Comparison of experimental and simulated spheres [Norfleet, 2001]

A sphere with 20” radius was the reference part, with a first die guess of 19.048. The sphere was proven to be unformable on the lab scale press by Valjavec [1999]. The Abaqus simulation confirmed this result.

As can be seen from the above plots, the simulation appears to be a reasonable approximation of the experimental results. Although the error values differ, they can be attributed to variations that are present in the experimental device that aren’t present in simulation. The simulation also converges to a lower error level than the experimental result, most likely as a result of noise in the experimental process.

Norfleet then proceeded to compare the performance of different algorithms under noise free situations. The results of the Abaqus simulation algorithm comparison performed by Norfleet are shown in Fig. 43 below. (Note that Fig. 43 shows the parts’ RMS error, not the parts’ maximum error.)
Figure 43: Abaqus Algorithm comparisons for formed cylinders [Norfleet, 2001]
The reference part was a 10.65” radius cylinder, with an 8.60” radius first die guess. Algorithm 2 without windowing performs very poorly. This is because of the "truncation" present in the input signal. Algorithm 1 performs significantly worse than Algorithm 2 with windowing and Algorithm 3. Unlike Fig. 41 and Fig. 42, the RMS error is shown on the Y-axis. The RMS error and the maximum part error typically follow the same movement trends.

From Fig. 41 and Fig. 42, Norfleet [2001] concluded that the simulation was a reasonable approximation of the experimental process. The data from Fig. 43 shows that algorithm 2 and algorithm 3 resulted in comparable error performance. The final error levels in simulation for Fig. 43 are somewhat unusual since they are much lower than error levels seen in experimental results. The final error level in the experimental data is probably higher because of process noise. This illustrates the need for experimental data to compare algorithm 2 and 3.
After simulating the forming trials, Norfleet decided to examine the noise sensitivity of the algorithms to determine whether Algorithm 2 or 3 was more suitable for use in a manufacturing environment.

6.4.2 Comparison of Noise Performance of Algorithms

Norfleet [2001] performed various “noise simulations” of different algorithms. All parts formed by him were done on the Abaqus simulation developed by Socrates. [2000] Norfleet [2001] performed Monte-Carlo simulations for all three algorithms. This was done by making a first die guess, and then forming a part. After the first die guess, the second and third dies were determined by Eqns. 43 and 44 below. Parts were then formed using those dies.

\[ d_2 = 1.1d_1 \]  \hspace{1cm} \text{Equation 43}

\[ d_3 = 0.9d_1 \]  \hspace{1cm} \text{Equation 44}

Where:

\[ d_1 = \text{initial die shape (array of vertical z-coordinates)} \]

The third part formed was arbitrarily considered the reference part. This was done because it greatly reduced the need for parts to be formed via simulation or experimentation. As a result, the reference die that forms the reference part is exactly known. The information from the first two parts and dies is used to form the third part. The algorithm performance was measured by comparing the estimated third die with the “correct” third die shape. Noise was injected into both part outputs similar to the manner as shown in Fig. 19, only for purposes of calculating the controller gain. The die formed as a result of this controller gain was then compared to the reference die. The process by which Norfleet [2001] performed his noise simulations is detailed in Eqns. 45-48 below.

\[ p_3 = p_{\text{ref}} \]  \hspace{1cm} \text{Equation 45}

\[ d^0_3 = d_{\text{ref}} = d_{\text{correct}} \]  \hspace{1cm} \text{Equation 46}

\[ d^{\text{est}}_3 = (p_{\text{ref}} - p_2)g_c + d_2 \]  \hspace{1cm} \text{Equation 47}
\[ e = d^\text{est}_3 - d^0_3 \]

Equation 48

Where:

\[ d^0_3 = \text{third die that is assumed to be the correct die} \]

\[ d^\text{est}_3 = \text{third die that is estimated} \]

\[ g_c = \text{controller gain} \]

\[ e = \text{error} \]

Norfleet [2001] did mention that his noise simulations probably overstated the amount of noise amplification because it did not fully take the forming process and the effect of the interpolator into account. The result from Norfleet’s [2001] noise simulations are summarized in Fig. 44.

Figure 44: Noise Amplification with noisy ID [Norfleet, 2001]

From this plot, it can be surmised that Algorithm 2, the DTF has high levels of noise amplification while the SCA does not. The Noise Amplification is defined as the ratio of the standard deviation of the part output divided by the standard deviation of the process noise inserted into the system.
For comparison, Norfleet also performed noise simulations where instead of adding noise to the part outputs, and then calculating the controller gain, the controller gains were calculated without any noise, and then the third die was calculated with some noise inserted into the second part error only. As a result, the system identification was not affected by noise, and this second set of simulations measures the effect of noise purely as a result of part error variation. The results of these simulations are summarized in Fig. 45 below.

![Figure 45: Noise Amplification with pure ID [Norfleet, 2001]](image)

The DTF with windowing has the worst noise amplification characteristics with application of a noise-free ID. Algorithm 2 without windowing performs much better than the case of a noisy ID. The Noise Amplification is defined in the same manner as in Fig. 44.

These simulations illustrate that the DTF with windowing, which is the algorithm used in the lab scale setup, has the worst noise sensitivity characteristics. From Fig. 44 and Fig. 45, Algorithm 3, the SCA, appears to have much better noise sensitivity characteristics.
than the DTF with windowing. Since algorithm 3 has the best noise sensitivity characteristics, and it has comparable error performance as the DTF, Norfleet [2001] concluded that algorithm 3 was the best algorithm for use in a manufacturing environment, but recommended that parts be formed experimentally to confirm his conclusions.

6.5 Summary

The theoretical foundation of the shape control algorithms used in this and prior research was examined. Historical results for algorithm 2 (DTF) were examined. Recent research by Norfleet [2001] was also discussed. It appears that the SCA is a better algorithm for use in shape control for stretch forming than the DTF. It has similar error reduction abilities as the DTF, but it is less sensitive to noise. This research uses the Abaqus simulation developed by Socrates [2000] and builds upon the results and theories of Valjavec [1999] and Norfleet. [2001]
Chapter 7

7.0 Data and Analysis of Experiments

An initial attempt to confirm the simulated results of Norfleet, [2001] and the experimental results of Valjavec [1999] were done by performing physical stretch forming experiments. The goal was to examine the effect of the DTF and SCA shape control algorithms on physical parts.

7.1 Experimental Data

The experiments performed were done on the lab scale press at MIT. The experiments were performed under similar conditions as those used by Valjavec [1999]. The experimental parameters are listed in Fig. 46 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin size</td>
<td>0.5 inch</td>
</tr>
<tr>
<td>Stretch Force</td>
<td>6125 lbs.</td>
</tr>
<tr>
<td>Blank Material</td>
<td>Al 2024-O, 19.5 x 5.5 x 0.063 inches</td>
</tr>
<tr>
<td>Final part footprint</td>
<td>4.5 x 5.0 inches</td>
</tr>
<tr>
<td>Force trajectory</td>
<td>Pre-stretch, wrap, no post stretch</td>
</tr>
<tr>
<td>Control mode</td>
<td>Force control</td>
</tr>
<tr>
<td>Interpolator</td>
<td>Elvax 360 (0.535 in. thick) covered with two layers of Teflon</td>
</tr>
<tr>
<td>Shapes</td>
<td>10.65 inch radius reference cylinder</td>
</tr>
</tbody>
</table>

Figure 46: Table of experimental parameters

Valjavec usually formed cylindrical parts with an initial die guess of 8.60” radius.

The experiments were performed on the reconfigurable press shown in the Fig. 47 below.
Figure 47: Figure of reconfigurable tool used for stretch forming experiments

After the die is setup via the die setup mechanism, the sheet metal piece is inserted into the jaws. The jaws can pivot around the jaw pivot to reach the desired contact angle on the die.

Different initial dies were used for different trials, but the same reference die was used for all experiments. All parameters other than the die shape were constant for all experiments. The active region for the part was the only region of the part that was measured. This “active region” is also considered to be the part footprint. In other words, this is the only region that is of interest. The part measurement outside this region is not of interest. The part itself is much larger than the active region. The part is referenced near the “middle” of the active region as described in section 5.1, using a small “punch”. The part is not altered in any way aside from marking this reference point and the stretch forming process itself.

The results for the cylindrical trials done under the conditions listed in Fig. 48 can be summarized by Fig. 49 below.
<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Conditions for trials in Fig. 49</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DTF Sequence 1, $d_1=10.15''$</td>
</tr>
<tr>
<td>2</td>
<td>SCA Sequence 1, $d_1=10.15''$</td>
</tr>
<tr>
<td>3</td>
<td>DTF Sequence 2, $d_1=10.15''$</td>
</tr>
<tr>
<td>4</td>
<td>Experimental from Valjavec’s formed trials (DTF), $d_1=8.60''$</td>
</tr>
<tr>
<td>5</td>
<td>DTF Sequence 3, $d_1=8.60''$</td>
</tr>
</tbody>
</table>

**Figure 48:** Explanation of trial sequences in Fig. 49

Trial 4 is Valjavec’s experimental results, and trial 5 used a starting condition of $8.60''$. Trial 5 was formed, but because of the first part’s low error level, an initial die guess of $10.15''$ was used in trials 1, 2 and 3, instead of a first die of $8.60''$.

**Figure 49:** Experimental results for cylindrical forming trials

Trial 1 and Trial 3 differed only in material batch used. Trial 4 were the experimental results formed by Valjavec. Trial 5 was used with the same first die shape as Valjavec’s experiments in Trial 4.
There are a few points of particular interest in Fig. 49 above. The first set of experiments were performed using an initial die guess with a cylinder of radius 8.60". (Trial 5) The values of maximum error in the first cycle for trials 4) and 5) in the figure above differ by 0.025", which is quite significant for parts formed on this scale. Furthermore, trials 1 and 3, which differ only in the batch of material used, differ in error by approximately 0.02". Trials 4 and 5 were performed under the same conditions, although by different individuals. Although different material batches can partially account for this large difference in part error in the first cycle, it cannot completely account for such a large difference. The causes for this discrepancy between trial 4 and 5 cannot easily be determined. It may be a result of machine aging, but no firm evidence that proves or discounts these theories has been seen. As a note, the first closed loop cycle, or the first cycle where the controller is applied is always cycle 3. Any further reference to the first closed loop cycle will be referred to as run 3 or cycle 3.

Trial 5 is also of particular interest. The first two part cycles in trial 5 have low error values compared to the other trials shown in Fig. 49. The increase in part error between cycle 1 and cycle 2 does not normally occur during open loop stretch forming. The increase in part error between cycle 1 and cycle 2 is possibly a result of process noise. The part error in cycle 3 of trial 5 is marginally worse than that of cycle 2, implying a possible misidentification of the plant gain matrix, but it may also be a result of high process noise.

Although trial 1 and trial 2 both have monotonic error reduction, they do not fall below the error threshold on either trial. The part errors are also quite high compared to traditional error levels. In trial 3, the third part error did fall below the threshold level of 0.01", which would usually have ended that trial sequence. Part 4 for that trial sequence was formed, and it was discovered that the part error actually increased after cycle 3, even though it had already fallen beneath the threshold level. This illustrates that it is possible that even though the part error may be reduced beneath the threshold, the part error may not remain below the threshold. This behavior may not have been observed.
previously because of low process noise, and the fact that if the part error fell beneath the threshold level, the forming trials were stopped.

It was then determined that running an experimental sequence beyond four total cycles might be informative. Correspondingly, two different trial sequences using the DTF and two different initial die guesses were performed. The parameters used were the same as listed in Fig. 46. The system identification was done only once using the first two calibration dies. The same system ID was used for each successive trial, in keeping with the same system identification process as previously used by Valjavec. The extended trial results are shown in Fig. 50 below:

**Figure 50: Maximum part error for extended cylindrical forming trials using DTF**

Extended trials with 2 different initial dies were performed. Part 3 of trial 1 was the best part formed. It has a maximum part error below the threshold level of .01". However, after the 3rd trial, the part error almost monotonically increases. Trial 2 involved a “first guess” that was further away from the desired reference part.
Examination of the RMS error for the same trials is shown in Fig. 51.

Figure 51: RMS part error for extended cylindrical forming trials using DTF

Although this plot shows the RMS error instead of the maximum part error, the trend is very similar to the one shown in Fig. 50.

Trial 2 appears to mostly oscillate between a steady state value, although it never dips below the error threshold level of 0.01". It is difficult to determine whether this is because of the poor "initial guess", and a result of an inaccurate system identification, or of the high process noise. It is likely that this effect is a result of a combination of these two factors.

For trial 1, the part error falls beneath the error threshold in cycle 3. However, each successive cycle gets worse. Whether this is due to a systematic uncertainty, random
uncertainty, or an uncontrollable part of the process is uncertain. However, all of the above possibilities probably contributed to this oscillation and increase in error over subsequent trials. An examination of the average part error in the trials shown in Fig. 50 and Fig. 51 also illustrates that although the part error initially gets better, the part quality in later parts is inconclusive.

![Average Part Error vs. Cycle Number](image)

**Figure 52: Plot of average part error vs. cycle number for extended trials.**
The average error initially implies an underformed part, but after cycle 3, the part appears to be slightly overformed.

The surprising part about both trials in Fig. 52 is that the steady state error of the part does not go to zero, although cycle to cycle control theory says it should. This implies that either a grossly inadequate system identification was performed, or that there is
something in the process that is not behaving properly. More details regarding possible issues in the process will be discussed in Appendix B.

The observations from the above do illustrate some points not dealt with in prior research:

a) Although a sequence appears to converge in 4 trials, it may not monotonically converge for all time.

b) In the presence of noise, even though the part error may go below a threshold level, subsequent trials may yield parts that are worse than prior parts.

This discovery could be important in manufacturing environments. Although oscillations in part error are less than desirable, it does not necessarily imply that the part error will not settle down to a steady state value. However, in a manufacturing environment, this is not a desirable phenomenon because it can result in excess “wasted” parts.

As discussed in Chapter 4, in order for the system to go “unstable” as Figs. 50-52 suggest, it is necessary to have the system closed loop value be greater than 2. The likelihood of this occurrence is low, although gross misidentification can result in a closed loop gain far away from one. A slight misidentification resulting in a closed loop gain either slightly larger or smaller than unity would be insufficient to explain the increase in error of this magnitude, and for this length of time.

Although the noise level of the overall process was previously estimated to be 0.01”, it may actually be higher because of the natural aging process of the machine. Further investigation into this process, and the effects of noise are difficult to perform on the experimental apparatus due to the relatively long cycle time it takes to manufacture and measure a part. It takes approximately 1/10th the time to form a part in simulation as it does to form the physical part. Furthermore, it is possible to exactly control the noise level of the process in the Abaqus simulation. Further examination of the effect of noise...
was done via Abaqus simulations. A more detailed examination into the process variation on the experimental apparatus is performed in Appendix A.

### 7.2 Simulation Results

After the extended experimental trials were performed, noise simulations involving formed parts in Abaqus were performed. Although Norfleet [2001] performed Monte Carlo simulations, as detailed in Chapter 6, they involved only 1 set of formed parts in Abaqus for each algorithm examined. This author performed simulations that involved disturbances both at the part output and during the die setup, although not simultaneously. The full block diagram for all disturbances is shown in Fig. 53 below.

![Figure 53: Figure of process model including all relevant disturbances](image)

The stretch forces in the experimental apparatus are measured and well controlled during the process. The position of other parts on the machine such as the hydraulic cylinders are also well controlled and measured during the forming process. The pin positions are the only inputs not directly measured during the forming process, and were hypothesized to be the variables of most uncertainty during the forming process.
It was initially desired to see how systematic disturbances in the die positions could affect
the part output. Different types of systematic errors in the die pin positions were
assumed. Some constant shifts were examined, as well as other systematic shifts. A
linear shift is one that assumes for a given pin position value, there is an error in the pin
position where \( a \) is an arbitrary constant, and \( x \) is the \( Z \) axis position value of the pin.
This shift is deterministic, and attempts to model a “bent” die setup mechanism, or servo
bias. This methodology is the same for a quadratic shift. The case of constant shifts
assumed that each pin had an offset or error that was the same for all forming cycles.
Prior to the first cycle, a random number generator was used to determine the pin
positions errors. These errors were added to nominal die positions. The mean value of
the constant offset over all pins was 0, but the standard deviation of the pin position
errors was random and normally distributed.

Figure 54 lists the different types of systematic uncertainties examined while Fig. 55
summarizes the results of these systematic disturbances on different forming trials. All
forming trials in Fig. 54 and Fig. 55 were done using the DTF.

Based on the prior analysis of cycle to cycle control systems, a constant bias can be
treated as a step disturbance, which has previously been shown not to have an effect on
the steady state output of the system. A linear, deterministic shift should be accounted
for during the system identification phase of the process. Since this deterministic shift is
a behavior of the system during the forming process, the plant matrix estimate should
account for it. A quadratic shift that is deterministic during the process should also be
accounted for, although the estimate of the behavior will not be as accurate since it is not
linear. One would expect the part shape to approach the desired part shape in the steady
state for all cases shown in Fig. 55. The linear and constant shifts should converge to the
desired part shape almost immediately while the quadratic shift may require more
forming cycles to converge to the desired shape.
<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Conditions for trials in Fig. 55</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline trial, no systematic error</td>
</tr>
<tr>
<td>2</td>
<td>.001x.</td>
</tr>
<tr>
<td>3</td>
<td>.01x</td>
</tr>
<tr>
<td>4</td>
<td>.1x</td>
</tr>
<tr>
<td>5</td>
<td>.5x</td>
</tr>
<tr>
<td>6</td>
<td>(.001)x^2</td>
</tr>
<tr>
<td>7</td>
<td>(.01)x^2</td>
</tr>
<tr>
<td>8</td>
<td>(.1)x^2</td>
</tr>
<tr>
<td>9</td>
<td>(.5)x^2</td>
</tr>
<tr>
<td>10</td>
<td>Constant error, σ=0.025”</td>
</tr>
<tr>
<td>11</td>
<td>Constant error, σ=0.05”</td>
</tr>
<tr>
<td>12</td>
<td>Constant error, σ=0.1”</td>
</tr>
<tr>
<td>13</td>
<td>Constant error, σ=0.25”</td>
</tr>
</tbody>
</table>

**Figure 54: Descriptions of trial sequences with systematic error in die setup**
Generally, systematic errors are accounted for within 2 closed loop cycles, and don’t significantly affect the part error. Large levels of systematic errors may require more than 2 cycles to converge to an acceptable level.

The results shown in Fig. 55 above illustrate that for shifts of 0.5x, 0.5x^2, and 0.05" and greater normally distributed systematic errors, there is significant deviation in the part error of the fourth cycle part. However, for any shifts and biases under the specified levels, the final part error does not differ significantly. Also relevant is the issue of how detectable any of these shifts would be. If the standard deviation of a constant, normally distributed bias is 0.05", this indicates that the entire range of error could be up to +/- 0.15", an overall range of 0.3". A shift this large would be easily detectable, even by visual inspection. It appears that unless there is a large systematic error, the DTF will account for this systematic bias within 2 closed loop cycles. It is possible that these larger systematic biases just take more cycles to settle to a desired level. A large systematic or step disturbance could possibly distort the system identification so that the ideal loop gain of unity is not achieved. However, this misidentification should still...
allow the system to eventually converge. Zero-mean randomly distributed noise will also not affect the steady state error, although the output variation may be higher than the process noise. However, it is possible that a sufficiently high level of random, normally distributed process noise can account for the oscillatory behavior in part error seen in Figs. 50 and 51.

7.2.1 Noise Modeled in Die Setup

After the examination of Figs. 50 and 51, and the analysis performed in the prior section, it was determined that further study of the effects of zero mean, randomly distributed noise could be informative. Does process noise cause oscillations and variations in part error for successive cycles? Can it possibly cause behavior where the part error does not monotonically reduce? Different randomly distributed noise levels were added to the die positions and used in noise simulations. (Any further reference to “noise level” herein will mean the standard deviation of the process noise. For example a process noise level of 0.01” would mean that the standard deviation of the process noise was 0.01”).

10 simulation sequences, under each condition were run. The same initial die guess was used for each set of 10 simulations, and a random normally distributed noise was added to each of the pin positions for each forming cycle. The same initial dies were used for the system identification for each sequence, but with noise injected during the die setup. Because noise was injected into the system during every die setup, each trial will have a different system identification as a result of the different parts and dies used during the first two cycles. The results of these trials would include the effect of a noisy process ID as well as process uncertainty in the die pin locations.

Part1a, part1b, part1c, etc. were all formed, followed by part2a, part2b, part2c, etc. Each cycle had 10 replicates. In other words, there were 10 “cycle 1” parts, and 10 “cycle 2” parts formed by using the data from the corresponding part in cycle 1. As a result, parts (1a-4a), and parts (1b-4b), etc. were formed. Each lettered “set” of parts was considered a sequence. A trial is considered to be all parts run under the same condition. For
example, all parts formed with a noise level of 0.01” would be considered a trial, while all parts formed with a noise level of 0.008” would be considered another trial. In the examples above, each run, or cycle number corresponds to the part number. Each sequence corresponds to the letter. There was no interaction between different sequences or trials during forming. This convention will be used throughout the research.

Figure 56 lists the different noise levels that were inserted into simulation in Figs. 57 and 58. Figure 57 is a plot of the part error variations, and Fig. 58 is a plot of the average maximum error. To clarify, the maximum errors of each part were compared to the other parts formed under the same condition. The “average maximum error” illustrates how close all the parts of a particular cycle in a trial sequence were to the traditional threshold level of 0.01”. Each point in Figs. 57 and 58 represent 10 parts formed under the same conditions, during the same cycle. Extended trials of greater than 4 cycles were only done for the conditions where if not all parts formed under that trial did not monotonically converge towards the correct part shape. If even one sequence showed oscillatory behavior of the part error, then further cycles were run for all sequences. In particular, if any single sequence under one condition exhibited behavior similar to trial 3 in Fig. 49, all 10 sequences for that particular condition were run to a total of 8 cycles. It turned out that only trials 9-12 had non-monotonic part convergence. This meant that for both the DTF and SCA, if the die pin uncertainty is 0.005” or less, then the part will settle to the threshold level within 2 closed loop cycles. The same guarantee cannot be applied to higher noise levels.

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Conditions for trials in Fig. 57 and Fig. 58</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DTF – μ=0, σ=0.0005”</td>
</tr>
<tr>
<td>2</td>
<td>SCA – μ=0, σ=0.0005”</td>
</tr>
<tr>
<td>3</td>
<td>DTF – μ=0, σ=0.001”</td>
</tr>
<tr>
<td>4</td>
<td>SCA – μ=0, σ=0.001”</td>
</tr>
<tr>
<td>5</td>
<td>DTF – μ=0, σ=0.0025”</td>
</tr>
<tr>
<td>6</td>
<td>SCA – μ=0, σ=0.0025”</td>
</tr>
</tbody>
</table>
peak level at cycle 3, for the 0.008” noise level. However, this trend was not the same for the 0.015” noise level.

These results do clearly illustrate that the SCA is less sensitive to die position variations than the DTF. As can be seen from Fig. 57, the noise level of the part output error of the DTF is anywhere from 2-4 times the part output error of the SCA, depending on the cycle. The average maximum part errors are shown below in Fig. 58.

![Average Maximum Error vs. Iteration Number for Different Noise Levels](image)

**Figure 58: Figure of average maximum errors for different noise levels**

Trials 1-8 appear to converge to similar error levels in 4 cycles. In all extended trials under the same condition, the SCA, on average, had a lower error value than the DTF. It appears that with uncertainty in die positions, the SCA performs better in the long run.

The average values of the maximum part error appear to converge during the first four iterations for all trials. All trials except for the case where the noise level was 0.015” had an average maximum part error that was below 0.01” by the fourth trial. Although the
Figure 56: Trial conditions run in Fig. 57 and Fig. 58

<table>
<thead>
<tr>
<th>Trial</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>DTF - $\mu=0$, $\sigma=0.005''$</td>
</tr>
<tr>
<td>8</td>
<td>SCA - $\mu=0$, $\sigma=0.005''$</td>
</tr>
<tr>
<td>9</td>
<td>DTF - $\mu=0$, $\sigma=0.008''$</td>
</tr>
<tr>
<td>10</td>
<td>SCA - $\mu=0$, $\sigma=0.008''$</td>
</tr>
<tr>
<td>11</td>
<td>DTF - $\mu=0$, $\sigma=0.015''$</td>
</tr>
<tr>
<td>12</td>
<td>SCA - $\mu=0$, $\sigma=0.015''$</td>
</tr>
</tbody>
</table>

Figure 57: Standard deviation of parts with noise inserted into die setup

Trials 9-12 were run up to 8 cycles. The DTF always has a higher part error variation than the SCA under the same noise condition.

Under the same conditions, the DTF part error variation was larger than that of the SCA part error variation. Successive part error variations for all other cycles decreased from a
average maximum error of the SCA appears to decrease for all trials, the average maximum error value of the DTF does not appear to monotonically decrease for 0.008” or higher noise levels. In other words, it is possible to guarantee that the “average” maximum part error will decrease for the SCA for up to 0.015” noise levels. The same cannot be said for the DTF. However, just because the average maximum error value monotonically decreases does not mean that any particular sequence will have monotonic error reduction. It is more important to guarantee that all sequences formed will have monotonic error reduction than to have the average error value of all parts decrease. A wasted trial sequence as a result of poor performance in a manufacturing environment would result in unnecessary and undesirable waste.

Figures 59-62 illustrates all 10 sequences of parts formed under the conditions that were discussed in Fig. 57 and Fig. 58 above.

---

Figure 59: Abaqus simulations of the DTF with .008” noise level
Figure 60: Abaqus simulations of the SCA with .008" noise level
Figure 61: Abaqus simulations of the DTF with .015" noise level
Examining individual sequences in Figs. 59-62 above is useful in noting the behavior of individual sequences. Figure 61 illustrates that there were 2 trials out of 10 under the specified forming conditions for which the error continually increases. This is the worst case possible from a manufacturing standpoint, as the part error not only does not reach a steady state error, but will continue to increase with repeated application of the control algorithm. Fortunately, it appears that for the same noise level, the SCA does not have the same problem.

From the above data in Figs. 57-62, it appears that although the part error may monotonically decrease for four cycles, extended application of the control algorithm does not guarantee that the part error will monotonically converge to 0. For a 0.008” noise level, although the part error may oscillate after the fourth cycle, it appears to stay beneath the error threshold. However, for high noise levels (>0.015”), it does appear that repeated application of the DTF shape control algorithm will make the part error worse in
successive cycles. It is desirable to guarantee error convergence beneath the threshold level in two cycles or less, as has been traditionally the case.

<table>
<thead>
<tr>
<th>Monotonic Error Reduction (4 cycles)</th>
<th>.008” noise DTF</th>
<th>.008” Noise SCA</th>
<th>.015” Noise DTF</th>
<th>.015” Noise SCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below noise level @ cycle 4</td>
<td>70%</td>
<td>100%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>Below noise level @ cycle 3</td>
<td>30%</td>
<td>0%</td>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>Below .01” @ cycle 4</td>
<td>80%</td>
<td>100%</td>
<td>20%</td>
<td>10%</td>
</tr>
</tbody>
</table>

**Figure 63:** Table summarizing error behavior of Abaqus simulations

It is possible to guarantee convergence beneath the threshold level if the die pin uncertainty is 0.008” or less, and the SCA control algorithm is used. All successive cycles of the SCA under this noise condition also remained beneath the threshold level.

Figure 63 implies that the SCA appears to be the better shape control algorithm. It has lower average maximum part error than the DTF, does not amplify process noise as much, and it is possible to guarantee convergence of part error beneath the threshold level. The data from Fig. 63 above is a result of both a misidentification of the process gain, as well as the process noise. As a result, simulations where a “pure identification” was taken were also run. It was desirable to “separate out” the effects of a noisy identification and process noise on the part error output. The results of these simulations should illustrate the relative effects of a noisy identification and a noisy process.

Another set of 10 simulations was run for both the SCA and DTF with the 0.008” noise level. Dies 1 and 2, and parts 1 and 2 were formed once without any noise. In other words, the same system ID was taken for all 10 sequences performed under the same noise condition. Random, normally distributed noise with a 0.008” standard deviation was inserted into the third die as a standard normally distributed noise after the system identification had been performed. The results of the parts formed in the third cycle here
were compared to the third cycle parts previously discussed in Figs. 57-62. The purpose was to compare how misidentification affected the part error variation and the average maximum part errors.

<table>
<thead>
<tr>
<th></th>
<th>DTF -.008&quot;</th>
<th>SCA -.008&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Max. Error</td>
<td>0.0099</td>
<td>0.0122</td>
</tr>
<tr>
<td>(pure ID)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. Value of Max.</td>
<td>0.0134</td>
<td>0.0142</td>
</tr>
<tr>
<td>Error (noisy ID)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std. Dev. Of Max.</td>
<td>0.0022</td>
<td>0.0020</td>
</tr>
<tr>
<td>Error (pure ID)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std. Dev. Of Max.</td>
<td>0.0083</td>
<td>0.0027</td>
</tr>
<tr>
<td>Error (noisy ID)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 64: Comparison of noise simulations with noisy and pure ID.**

A pure identification performs much better than a noisy identification. The DTF is affected much more by an inaccurate system identification than the SCA. The coupling terms in the DTF are very susceptible to noise, and apparently can result in greater misidentification than the SCA.

With a “pure” ID, the DTF performs better than the SCA in cycle 3. This result makes intuitive sense because the “pure” DTF ID should be better than the “pure” SCA ID, since the DTF accounts for coupling, and in itself, is a more accurate system identification. The additional increase in maximum error between the noisy and “pure” identification can be attributed to misidentification. For comparison to the above data, simulations were run with noise added to the system at the part output. Comparing the simulations with noise at the part output and die setup will be informative in understanding how the interpolator and process can affect the part output variations and part error.
7.2.2 Noise Modeled in Part Output

After examination of the effect of process noise in the die setup apparatus, simulations were performed in order to examine the effect of process noise at the part output. This was done by adding a random, normally distributed noise to the part output. The noise level inserted into the part output had a standard deviation of 0.008". Once again, a “pure” ID of the process was taken. No noise was inserted into the part output for the first two cycles. The random noise was inserted into the part output starting at the third cycle. A comparison of the two cases where a pure ID was taken, but with noise inserted at the die setup and part output was performed. The results are shown in Fig. 65 below.

<table>
<thead>
<tr>
<th></th>
<th>DTF −0.008&quot;</th>
<th>SCA −0.008&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Max Error</td>
<td>0.0099</td>
<td>0.0122</td>
</tr>
<tr>
<td>Noise inserted at die</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Max Error</td>
<td>0.0364</td>
<td>0.0308</td>
</tr>
<tr>
<td>Noise inserted at part</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std. Dev. Of Max Error</td>
<td>0.0022</td>
<td>0.0020</td>
</tr>
<tr>
<td>Noise inserted at die</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std. Dev. Of Max Error</td>
<td>0.0067</td>
<td>0.0051</td>
</tr>
<tr>
<td>Noise inserted at part</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 65: Comparison of effects of different noise sources at cycle 3. (Pure ID)

Noise at the part output affects the part more greatly than the noise during the die setup by approximately three times. This is most likely a result of the interpolator damping effects. It does illustrate that great care must be made in handling and measuring the piece after it has been formed.

The variation and average maximum part error are both higher by approximately three times when the noise is modeled at the part output, as opposed to the die setup. The implication here is that although die uncertainty may be the largest unknown during the process, any deviation in part output uncertainty in the form of measurement error, or poor part handling has a much larger impact on part variation and part error than die
setup uncertainty. As a result, implementation of standard operating procedures is necessary, and great care must be taken with part handling, after part formation.

Figures 66-71 below are summaries of the extended trials with noise injected into the part output. 10 sequences were run under each set of conditions. Only a 0.008” noise level was used, but one pure identification (where there was no noise inserted into the first two part outputs), and one noisy identification (where noise was inserted into the first two part outputs once), were performed. From the third cycle on, 10 replicates under the same set of conditions was done for each cycle. This study was done to compare and contrast the effect of a single noisy identification with a single pure identification. The results are summarized in Figs. 66-71.
Figure 66: Comparison of part errors for different forming cases

The behavior under any of the conditions listed above are not significantly different. The error levels are much higher than the case where noise was inserted into the die setup, and do not come close to falling beneath the threshold level. The maximum error levels are similar to some of the error levels found during the extended experimental trials. (Fig. 50) This could imply a high “process output” noise level in the experimental apparatus.

The variations in maximum part error were examined in Fig. 67.
Figure 67: Part error variation for Abaqus simulations with noise at part output.

The standard deviations of these part errors appear to all be similar, and do not follow a definitive trend. The open loop cycles (Runs 1 and 2) are not shown because for the case of a Pure ID, there will be no part variation. We are particularly interested in closed loop behavior.

Similar to the results in Fig. 66, the results in Fig. 67 are ambiguous as to the effect of a noisy system identification as opposed to a “pure” identification. Comparison of Fig. 67 to cycle 3 of Fig. 57 illustrate that these part error variation values are slightly higher than the parts formed under the same conditions in trial 9 and trial 10 in Fig. 57. The variations in Fig. 67 are higher most likely because of the lack of a damping effect of the interpolator. The individual sequences for each condition are shown in Figs. 68-71 below.
Figure 68: Plots of Abaqus simulations with noise at part output (DTF – Pure ID)
Figure 69: Plots of Abaqus simulations with noise at part output (SCA – Pure ID)
Figure 70: Plots of Abaqus simulations with noise at part output (DTF – Noisy ID)
As can be seen by Figs. 68-71 above, simulations run with noise at the part output result in more part error variation than the case with noise modeled during die setup. No significant difference was seen between the effect of a "pure" and "noisy" identification in this case. Cycle to cycle control theory says that in the long run, there shouldn’t be a significant difference in steady state behavior for slight differences in process identification.

One interesting fact is that the variation in part output at trial 3 in Fig. 67 should be equal to the variation added, since noise was only added to the part output at part 3. However, this does not appear to be the case. This is because after the part is measured, it is often necessary to perform interpolation while registering the part, so that all the points on the
part correspond to the points on the die. Interpolation was done on the part after it was formed in Abaqus, and after noise was added to the part output. It appears that the effect of interpolation and registration reduces the apparent part variation. This effect was not previously noticed in the experimental process. Fortunately, the shape control algorithm would account for any correlated biases that the interpolation may cause.

Although the above data yield valuable information on the part variation and part error performance, they are not necessarily good measures of whether these closed loop shape control algorithms conform to the cycle to cycle control results from Siu. [2001] For example, as shown in Fig. 21, Siu [2001] plotted variance amplification vs. loop gain for uncorrelated process noise. However, this was done for the single variable case. There is ongoing research regarding appropriate comparisons for cycle to cycle control theory for the multivariable case, but it has not been completed yet. In the absence of a reliable multivariable analysis for cycle to cycle control, an appropriate single variable must be found to perform an accurate comparison to Siu’s [2001] results. To this point, the maximum error has been used as the variable of interest to compare these results with Siu’s [2001]. However, the maximum error may not be a good measure of the overall part quality because it accounts for the worst point on the part. A better measure may be the RMS error, since it is a measure of overall part quality, but it weights certain part locations more than others, so that it may not be a fair measurement of overall controller performance. Hardt et al. [2002] used the matrix norm to compare the results of a cycle to cycle controller for the multivariable case to Siu’s [2002] results. However, the matrix norm also weights different part locations differently.

Instead of calculating the maximum part error, the RMS error, or the matrix norm, an alternative variable of comparison is the grand error and the grand variance. The grand error and the grand variance weight all locations evenly and are a measure of overall part quality. This is first done by determining the mean value of the part at each location. The mean value at each location is then compared to the corresponding locations on the reference part. The difference between these values will be the “mean error”. The average of these error values taken over all points is the grand error. Correspondingly, a
variance for each point can be calculated, and averaging the variances across all points results in the “grand” variance. Equations 49-52 mathematically represent these values.

\[
\bar{e}_{ij} = \frac{\sum_{k=1}^{n}(x_{ij} - x_r)}{n}
\]

*Equation 49*

Where:

- \( e_{ij} \) = average error of parts at point \((i,j)\)
- \( n \) = number of part repetitions
- \( x_r \) = reference part value for point \((i,j)\)
- \( m \) = number of points on part

Equation 49 above represents the mean error. It is a matrix of average part errors at each part location over all parts made under the same condition. Equation 50 below is the grand mean error of all the parts. It is the mean of all elements in the error matrix of Eqn. 49.

\[
e = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} e_{ij}}{mn}
\]

*Equation 50*

Equation 51 is the standard equation used for calculating the variance. In this case, it is the variance of the z coordinate values of all parts at a particular location.

\[
\sigma^2 = \frac{\sum_{k=1}^{n}(x_{ij} - x_r)^2}{n}
\]

*Equation 51*

Taking the mean values of all the elements of the variance in Eqn. 51 yields Eqn. 52, the grand variance.

\[
\bar{\sigma}^2 = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \sigma^2}{mn}
\]

*Equation 52*
Simulations were run where noise was modeled at the part output after any necessary part interpolation had been performed. This was done to ensure that a proper comparison between these results and Siu’s [2001] results could be performed. A 0.008” standard deviation, normally distributed random noise was inserted into the part output. The parts formed here were made by performing a noise free ID once, and then inserting the noise for all cycles at the part output starting with the third cycle. The grand errors and variance ratios (or variance amplification) of these simulations are shown in Figs. 72 and 73 below respectively.

Figure 72: Plot of grand error with noise at part output after interpolation
The grand error appears to be varying about a mean value of 0. Cycle to cycle control theory predicts that the mean value of the error should approach 0 in the steady state for this controller.
Figure 73: Variance ratios for parts formed with noise at output

These values are close to the ones predicted by Siu [2001] in Fig. 21. The variance ratio is calculated by taking the ratio of the grand variance of the part outputs divided by the variance of the process noise. In this case, the variance ratio is a known value since the process noise was inserted into the part output by this author. The variance ratio value for the DTF is approximately 2, which is approximately where Siu [2001] predicted it to be in Fig. 21 for an overall loop gain value of 1 with uncorrelated noise. The SCA has a significantly lower variance ratio than estimated. This low estimate for the variance ratio could be a result of the inaccuracy of the plant identification. The SCA does not include coupling in its model, and clearly, that is an inaccurate assumption. As a result, the overall loop gain could be slightly underestimated, leading to lower loop gain and lower variance amplification. Note that these noise amplification figures differ from Norfleet’s [2001] shown in Figs. 44 and 45.
In particular, Norfleet's estimates of noise amplification for the DTF appear to be quite high for a "pure" identification. As he stated, this is likely because he did not form parts for his noise simulation. As a result, his simulations did not account for the damping effect of the interpolator.

7.3 Summary

The results in this chapter illustrate that although traditional results by Valjavec [1999] have yielded desirable reductions in part error within four cycles, there is a possibility that further application of the DTF and SCA after the first 2 closed loop cycles will result in parts that do not monotonically converge to the desired part shape. The overall long-term trend is inconclusive, but has shown that there exists the possibility that the part error does not necessarily converge to a desirable level in the long run.

The noise simulations reinforce the fact that the SCA is a more robust algorithm in the presence of noise. It appears that some of the detrimental effects of noise are a result of an inaccurate system ID, as well as process noise. The quantification of coupling of the DTF appears to be both a blessing and a curse. It may yield better results in an ideal manufacturing environment, but for the noise levels that appear to be present in the experimental apparatus and other manufacturing environments, the SCA is clearly the better choice. The part variation levels conform to the theories and trends that have been previously established. [Siu, 2001] It appears that when using the SCA, the loop gain is underestimated, which may result in slightly slower error convergence. Furthermore, the variance amplification of the SCA is not as large as the DTF as a result of the misidentification. All the results in this and prior research point to the SCA as the algorithm of choice in a manufacturing environment.
Chapter 8

8.0 Conclusions and Guidelines for Further Work

The original goal of this research was to answer the following questions:

How much noise can the system and process tolerate to guarantee monotonic error convergence?
What level of noise will cause the part shape to not converge within 2 cycles?
Which manufacturing algorithm, the DTF or the SCA, is more suited for application in a manufacturing environment?

This research has answered these questions although some clarification and confirmation is still necessary. The system appears to be able to tolerate up to a 0.008” noise level of die setup in order to guarantee monotonic error convergence. The DTF will not converge to the desired error level within 2 closed loop cycles if the standard deviation of the die process noise is 0.008” or higher, while the SCA will still converge under this condition. Both algorithms are even more sensitive to noise at the part output, by approximately three times, as illustrated in Fig. 65. Correspondingly, the criteria for guaranteeing monotonic error convergence within 2 cycles to the threshold level of 0.01” can be roughly defined by Eqn 53.

Equation 53 is based on the data and observation of Figs. 58, and 63-65 as well as data from all Abaqus simulations. From the data and the simulations run, it is possible to guarantee convergence below the threshold level of 0.01” within 4 total cycles if the die setup noise level is below 0.005” when the DTF is used and 0.008” when the SCA is used. It was shown in simulation that part output noise causes approximately three times the part output variation as compared to noise during die setup. Since the noise model used in this research is linear and additive, it is possible to assume that the effects of these noise are additive. It was based on the above data that Eqn. 53 was formulated.

\[ \sigma_{\text{die setup}} + 3\sigma_{\text{part output}} \leq C \]  

Equation 53
Where:

\[ \sigma_{\text{diesetup}} = \text{standard deviation of process uncertainty at die setup} \]

\[ \sigma_{\text{partoutput}} = \text{standard deviation of process uncertainty at part output} \]

\[ C = \text{convergence level: } C=0.008'' \text{ for SCA, 0.005'' for DTF} \]

The standard for guaranteeing convergence in Eqn. 53 may be somewhat strict, and is only a lower bound for guaranteeing error convergence within 2 closed loop cycles. More research to confirm Eqn 53 is necessary. More tests to confirm that the SCA is the better algorithm for use in the manufacturing environment are also recommended. The tests and experiments performed in this research are summarized below.

The first experimental results were designed to replicate the conditions and results that were discussed in Valjavec’s thesis. [1999] Initial attempts to do so were unsuccessful. Part errors in the formed parts did not follow traditional behavior that Valjavec [1999] observed. Initial hypotheses for this unusual behavior included the consideration of procedural inconsistencies, and high process uncertainty. Quantification of uncertainty levels in the experimental apparatus was performed and it was then determined that the process noise level (0.01") was approximately the same as when Valjavec [1999] performed his experiments.

Valjavec [1999] had previously concluded that a bigger “spacing” between the two calibration dies resulted in more favorable algorithm performance. However, in the absence of noise, it has been shown that two calibration dies that are “spaced” more closely to the “correct” die will result in better and faster error convergence.

Improvements in process uncertainty on the machine were done, but the parts still did not have desirable error convergence. As a result, simulations for the purpose of studying the effects of noise on closed loop shape control algorithms were performed.

There was some debate with regard to what an acceptable level of error “convergence” was. Valjavec selected 0.01” as the “threshold” because that was what the noise level of
the process was estimated to be. On the other hand, it is more convenient to be able to
guarantee error convergence to a certain arbitrary level. Furthermore, the noise level of
the process may not always be known.

Extended experimental trials of the DTF and SCA were run. The DTF and the SCA have
traditionally been stopped after 4 total cycles. (2 calibration dies, and then 2 closed loop
cycles) This was usually sufficient to guarantee error convergence. A larger number of
cycles were run than previously had been done. Two sets of trials with 10 cycles were run. They were both done under different initial calibration dies. One was done with a
“first guess” die that was far away from the correct die shape. (20”) The other “first die”
shape was done using a die that resulted in a part that had an initial error level of 0.05”.
The results illustrated that the part error values may oscillate towards a steady state value,
and possibly, continually get worse after the application of closed loop shape control.

Simulations were done examining the effects of uncertainty in die pin positions and part
output. The results indicate that variations after part formation have a greater adverse
effect on part error and part error variations than uncertainty in the die pin locations. The
effect of a misidentification in the process gain also has a larger effect on part error and
part error variation than the process noise. The simulation results also conform well to
the variance output levels that Siu [2001] had predicted.

It can be concluded that for sufficiently high noise levels, particularly for process noise
levels in the die setup or part output of 0.008” or higher, there will be nonoptimal
behavior observed in the DTF or SCA. This nonoptimal behavior includes error values
that do not monotonically decrease, as well as gradually increasing values of error for a
sufficiently high process noise level.

The damping effect of the interpolator allows more uncertainty to be tolerated during the
die setup as opposed to the part output. As a result, careful control and procedures for
part forming, part handling, and measurement are critical in reducing part variation.
Experimental results have illustrated that although part shapes will reach acceptable levels within 3 or 4 cycles, remaining below the threshold level is not guaranteed. The extended trials formed on the experimental device illustrate that although the overall process error may be below the threshold level of 0.01”, gross mishandling of the part, and large measurement error may contribute to some undesirable results. There are also some machine issues that may have contributed to some undesirable behavior as well. The experimental results do not conform well to cycle to cycle control theory, and further examination as to causes of this deviation in behavior should be taken. System misidentification can contribute to a large portion of the part error and part error variation. As a result, great care to identify the system accurately must also be taken.

Experimental and simulated evidence for which algorithm performs better within the first four cycles is ambiguous for arbitrary conditions. The DTF accounts for coupling, but is more sensitive to noise. However, for extended trials requiring more than 4 cycles, and for noise levels that may be more representative of those in a manufacturing environment, the SCA is clearly the better algorithm. The average part that the SCA formed has less error than the DTF. The SCA is more likely to have parts that will settle down to an acceptable level than the DTF. The SCA is also more likely to fall below the traditional error level of 0.01”. The SCA is also less likely to have run sequences where the error will increase.

As a result of this study, it is recommended that the noise level for the die setup and part output be kept to the recommended level as indicated in Eqn. 53. The SCA is the algorithm that should be used in a manufacturing environment. Further experiments should be done to form parts on a machine for extended periods to confirm the suitability of the SCA as the algorithm of choice to be used for the stretch forming process. An examination into what causes can result in deviation from cycle to cycle shape control theory should also be performed.
Appendix A: Experimental Process Variation

After examining the results in Fig. 49, it was hypothesized that the divergence of part error in trial 5 of Fig. 49 could be caused by excessive process noise. Because of these unusual data, an examination of the process noise was performed. The measurement noise over all points was first determined for a single part three separate times. The same part, tips, and CMM were used. The part was removed from its fixture, and then refixed, as if the part were remeasured from “scratch”. The grand standard deviation of the uncertainty including mishandling, measurement and registration noise was measured to be 0.0015”, which is much lower than the threshold level of 0.01” as previously indicated. This measurement variation was only slightly higher than the CMM’s listed standard deviation of 0.001”. As a result, it can be concluded that the measurement and registration routine have a combined noise standard deviation of 0.0015”, which should not contribute significantly to the overall noise levels.

The repeatability in forming the same part was also determined. This included the entire process from die and pin setup, forming, measurement, and registration. Three parts were formed. The parts were formed on different days, with the die being reset at least once each time. The grand standard deviation for the entire process turned out to be 0.003”. These variations appear to be within the traditionally acceptable error levels as defined previously by Valjavec. Although these noise levels appear to be acceptable, the undesirable behavior in error performance may be a result of uncontrollable modes on the experimental device. Further examination of the device would be needed to confirm this hypothesis. The above data would correspond to a “C” value of 0.006”, as described in Eqn. 53. This would imply that the SCA would converge to the desired level within 2 closed loop cycles, while the DTF would not. However, Fig. 49 shows that the DTF and the SCA both do not converge to the desired level within two time steps for any of the trials formed by this author. A discussion of some possible problems in the experimental apparatus is discussed in Appendix B.

There are also a few points of ambiguity that need to be briefly discussed. It is unclear what Valjavec meant when he stated that “the noise level of the overall system is
estimated to be 0.01” or less”. It could refer to a “3 sigma” standard, a “1 sigma” standard, or that the noise never exceeded that given level. It is unlikely that the overall noise level adopted a “3 sigma” standard, as the measurement “noise” (standard deviation), itself appeared to be +/- 0.0015”. In any case, it is more desirable to reduce part errors beneath a specific arbitrary level. For the purposes of this research, “noise level” has been assumed to represent the standard deviation of the process uncertainty.
Appendix B: Machine Controllability Issues

After determining the process uncertainty in Appendix A, the part contours were more closely examined. The process uncertainty appears to be below the level that Valjavec recommended. As a result, the machine was hypothesized to have some controllability issues. An examination of the part contours showed that parts formed on the machine appeared to have some “twisting” in the part. The cause of this behavior has not been determined, but has been speculated as a problem with the machine design itself. In particular, the jaws on the press may not allow sufficient contact of the part on the die. Also at issue is that perhaps the jaws themselves are somehow misaligned during the process. The jaws themselves have been determined to be in good alignment prior to the initiation of a forming process. A typical part formed by the machine can be seen in Fig. 74 below.
Figure 74: Open loop formed part (10.15” radius cylinder) showing slight twisting. It is difficult to see in this figure, but there is a small amount of twist on the right side of the part.

The above part (Fig. 74) is shown from a side view. There is a slight, but not an overly pronounced amount of twisting. An example of a more “twisted” part is shown in Fig. 75 below.
Figure 75: Figure with significant twisting (5th part, 3rd closed loop part)

There is significant twist on the right side of the figure above. It is the 5th part of a sequence. The formed part above should be close to a 10.65" radius cylinder.

Figure 75 above is a result of repeated application of closed loop shape control. Note that not only is the part twisted, but that the profile of the part is slightly slanted. An examination of the part and die contours over repeated iterations are also telling. The profiles were taken across the center of the piece along the dimension where the Z-coordinate values should be constant, the Y-axis, also known as the transverse direction.
There is possibly slight twisting in the part and die even in this open loop iteration. This can be viewed by examining the left side of the figure. The part should be a straight horizontal line.
Figure 77: Part 2 and die 3 resulting from part 2 for 10.65" cylinder
The part is slightly worse than that in Fig. 76.
Figure 78: Part 3 and die 4 resulting from part 3 for 10.65” cylinder

Part 3 is the first closed loop part, and is the “best” part formed in this particular sequence. However, it is clearly not symmetric, and shows signs of future problems.
Figure 79: Part 8 and die 9 resulting from part 8 for a 10.65" cylinder

Both the part and the die are a mess. The die attempts to compensate for the part shape, but it does not appear to have a significant effect. In fact, it appears to make the part shape worse.

In each of the images above, (Figs. 75-79), the concave down curve represents the part, and the concave up part represents the die. Although the parts and dies look reasonable in the early cycles, later cycles of the part and die look unreasonable. It appears that the die is compensating for the incorrect part shape, yet, the part shape does not appear to be responding in the manner as expected. The appearance of the twist in these contour plots leads to the conclusion that the machine possibly may not be controllable for these problem areas. However, this is merely conjecture, and further examination into the phenomena should be done. Similar results can be seen from an attempted formation of a toroidal (R=33", r=45") shape.
Figure 80: Part 1 and die 2 resulting from part 1 for toroid
Once again, there is slight twisting and some asymmetry even in the first open loop part.
Figure 81: Part 2 and die 3 resulting from part 2 for toroid

The asymmetry is slightly greater than that of Fig. 80.
It is clear from Figs. 76-82 that there is something wrong. It was hypothesized that perhaps the part was not making good contact with the die. During stretch forming, the part is formed so that the sheet metal is tangent to the die at the edge of the active region. This point of tangency is normally calculated by calculating the tangency location on one side of the die. This calculation is valid when the part is symmetric. However, it was observed that the part was not necessarily pulled symmetrically, and that after the first open loop trial, the die was not symmetric. It was observed that since the same “side” of the part was always “underformed”, the part should be pulled so that it is tangent to the side with a steeper angle. An additional overwrap can also be applied to ensure that good contact is made between the part and die. The results of these trials with different tangency angle calculations and overwrap are shown in Figs. 83-85 below. Two open
loop parts (Part 1 and Part 2) and one closed loop part using the DTF (Part 3) were formed under each set of conditions.

Figure 83: Sequence done under standard conditions with first die of 10.15" radius. The part "center" appears to shift slightly into the negative direction. There is some asymmetry also present similar to that in Figs. 76-82.
Figure 84: Sequence run with a first die of 13" done under "dual side tangency angle" calculation

Forcing the die to pull to the side with the steeper angle of tangency does not appear to alleviate the asymmetrical twist. The "peak" of the part also appears to shift more than under normal conditions in Fig. 83.
Figure 85: Sequence run with a first die of 13” done under “dual side tangency angle” calculation with an extra travel distance of 1”

Overpulling the part does not appear to solve the asymmetry problem. Poor part and die contact does not appear to be the cause of the undesirable experimental results.

After determining that poor part-die contact was not the source of the asymmetrical twist, some examination into the accuracy of the die positions themselves were taken. It was found that the die pin positions at the interface between the die and the interpolator could vary up to 0.02”, with a slight bias towards one side. Furthermore, the die pins are cantilevered. The die pins extend outwards approximately 2 feet from their base. The pins cannot be treated as a perfectly bundled set of pins, and as a result, some pins may have large forces exerted on them during forming. Since the pins are extended outwards by approximately 2 feet from their base, an analysis of a cantilevered beam under simple bending can be performed. Depending on how well bundled the pins are, and the forces
that are applied to the die pins during forming, the deflection can be on the order of hundredths to tenths of an inch. It may not sound like much, but when the threshold level is 0.01", deflections of up to 0.1" could cause significant part variations. Furthermore, because of a different die shape during each forming cycle, any forces applied to the die could be highly variable, and cause high levels of process variation.

As a result, any asymmetrical force applied to the die could result in an alteration and bias that is quite large. Redesigning the die so that an asymmetrical load does not affect the pins during forming is required.

Figure 86: Figure of reconfigurable tool used for stretch forming experiments

This is the same figure as Fig. 47. Note that the die is not supported on any side, and extends outwards by approximately 2 feet.

Further examination into the causes of asymmetrical behavior are needed, although redesigning the die so that it is not vulnerable to asymmetrical forces and conditions during forming is first necessary.
Appendix C: Brief Experimental Procedures

A detailed set of experimental procedures can be viewed in Valentin’s [1999] thesis.

The computer used to control the stretch forming process is located next to the stretch forming machine. The computer, and the associated electronic components are mounted on a shelf shown in Fig. 87 below.

Figure 87: Computer and associated electronic components and switches [Valentin, 1999]

Turn on the electronic circuit switches shown in Fig. 87 above.
Make sure all switches on the die setup apparatus are in the on position.
Make sure all kill switches are raised, and all switches on the die setup mechanism are in the “on” position.

Turn on the cooling pump (water), on the blue hydraulic source in the back of the room.

Turn on the hydraulic source to the machine by pressing the green “on” button as shown in Fig. 87 above.

The program used for pin setup is called rev11.exe.

Reset all boards, and click the [servo here] button, after turning on all boards and switches.

Make sure that the round valve behind the computer is in the closed position. The pressure valve clamps the die pins to ensure that they don’t move during forming. It is a round knob located next to the die pressure gage. This valve should be “closed”, turned all the way clockwise, during die setup.

**Die Pressure Gage**

![Die Pressure Gage](image)

**Figure 88: Die pressure Gage and Valve illustration [Valentin, 1999]**

Click [home setup-3D] to home the pin setup mechanism.
If the machine does not set up correctly, or does not set up, press abort, then:
Into the command line on the left box, type PRX=20000, then BG to push the hydraulic cylinder 20000 counts. 19125 counts = 1 inch.
Into the command line on the left, type PRH=-50000 to move the H-axis towards the door.

After the homing sequence is complete, push the pin-setup 3-d button, specify the die setup file and then let the setup sequence proceed.

If the setup sequence freezes, or proceeds incorrectly, press abort, and then type PRX=-50000 to retract the setup pins.

After setup is complete, turn off the hydraulic pump, put all the switches on the die setup mechanism in the “off” position and then open the die clamp valve behind the computer.

Place the black metal clamps onto the pins. The clamp is indicated in Fig. 86

Place the interpolator in front of the pins.

Place the die clamps onto the die.

Place the jaw brackets on the jaws to keep them in place while inserting the piece of sheet metal.

Figure 89: Aluminum jigs and jaw clamps used while inserting sheet metal. [Valentin, 1999]

Tighten the set screws on each jaw as evenly as possible.
Release the fixtures by pushing gently on the metallic portions of the jaw cylinders slightly.

The program used to form the piece under force control is setup.exe. Pick the force control menu option.

![Message Window](image)

*Figure 90: Interface window for stretch forming under force control*

Press reset and press and servo here before inputting the stretch force parameters.

Input the force control parameters. The travel speed should be no greater than 500 c/s.

After the parameters are input, turn on the cooling pump and the hydraulic press.

Form the part by pressing the wrap button. Once the wrap phase is complete, use the reference punch to mark the reference point on the part. It is located in the back of the main press. The machine should still be on.
Press return carriage to return the main carriage to its original position.

Turn off the hydraulic press.

Carefully remove the part from the jaws by unscrewing the set screws.

After removing the interpolator, release the clamp used to hold the pins during die setup, close the valve behind the computer, and home the press and pins by using the [home press] and [home pins] pin setup program.

Take the part upstairs to the CMM and measure it.

Boot up the CMM and type mm4 at the login prompt (no password).

![Figure 91: CMM used for measurement in LMP machine shop](image)

Press the 2nd option on the left column to start the CMM, and follow the instructions as they come up.

Under program file, select a new program name, type in the name, then press confirm.
Load a qualified tip, or qualify one, by pressing the qualify option. The tip used by this author is labeled alex_demo, tip 1.

Fixture the part by placing the vacuum cups on either side of the “top” and bottom of the piece. The movable stops should be placed at the edge of the long ends of the piece.

Designate and determine the reference point as (0,0) by any method desired.

Specify the part grid by using the surface profile option on the CMM. Make sure to sample at the appropriate grid spacing (of 0.2” or finer).

When finished, go to the file options, and click backup. Insert a floppy disk, and select the file desired.

The file will be saved in a “tar” format that will need to be converted from Athena. The appropriate command on Athena is: gtar xvf /vol/dev/aliases/floppy0.

The first 3 columns of points will be the relevant part points in this file. All other points will be irrelevant.

Use the cmm2xyz.m file to “unwrap” the part coordinates

Use the reg_fin2.m file to register the part. Make sure that the reference part is accurately defined within the reg_fin2.m file. Leave the reference point offset as y=-0.125”, x=0.02”. This will insure that the correct point will be designated (0,0).

Use the appropriate file to make the next part (dtfc#.m, sca#.m etc.)

Use auto2b.m to determine pin locations outside of the active region, and the appropriate stretch parameters. The maximum pin length, and Y-travel distance should be recorded and input into the stretch force window when forming.

Use any desired method to determine maximum part error. Generally, zeroing all reference points to each other after registration is sufficient

Repeat the first step to form the next part.

The W and Z axes on board 1000 control the hydraulic jaw cylinders.

The Y axis on board 1000 controls the main travel cylinder.

The H axis controls the movement of the die setup mechanism

The X axis extends and retracts the die setup mechanisms.

The G axis moves the other 8 setup servos up and down.
Board 900 controls the 8 axes for the servos used for die setup.

The DMC files that control the servos are located in C:\wsdk1000 directory. Only alter these servo files if absolutely necessary.

The visual basic source files can be found in C:\vb. Only alter these when absolutely necessary.

More details on machine operations can be viewed in Valjavec’s [1999] and Valentin’s [1999] thesis.
Appendix D: Simulation Procedures

The following steps are necessary in order to perform the Abaqus forming simulations described in this research.

Form the equivalent die using the ka1.m-ke1.m, as86a1.m-es86a1.m (for iterations 1-5 respectively). The output dimensions from these files must be kept constant. They are in SI units, so be careful.

Make sure that an appropriate mkdie.x and mkdie.f file is in the directory used for the simulation.

Recompile the file if necessary using the “f77 --o mkdie.x mkdie.f” command.

Use the a86kl.m or asal.m file to form the Abaqus equivalent of the file. The file will be output as die.dat. Record the relevant stretch parameter values. If they differ, take the average value of these two parameters.

Use the BASE1.INP file as a template.

Insert the die.dat file using either cut and paste, or ctrl-x I in emacs.

In the section labeled “Wrapping Sheet Linearly” towards the end of the file, replace the 0.12 in that section with the relevant stretch forming parameter.

Use the scp command: scp file username@cosmic.mit.edu:~/directory to transfer the file to cosmic, the Abaqus server.

On cosmic, in the appropriate directory, type Abaqus, then the .inp file without the filename extension.

A status of the job can be seen by typing “more file.sta”. The job is complete when step 7 is completed.

When the job is completed, use the scp command to transport the file back to Athena:
Scp username@cosmic.mit.edu:~/directory/file.dat file.dat

The lines of interest in this file are nodes 10-595 in column 1 near the end of the file. The 2nd, 3rd and 4th columns are the X, Y, and Z coordinates of the formed part.

Insert the cleaned .dat file into the appropriate locations in the kb1.m, bs86a1.m file. Repeat the process as needed.

It will sometimes be necessary to remove the part files from the cosmic server, as well as the Athena account. They are quite large (1 MB).
Make sure to convert the die into meters before inputting all values into Abaqus, and convert back to English units after Abaqus processing is complete.
References


Hardt, D. E. “Sheet Metal Forming: Simple Bending Notes”, Introduction to Manufacturing Class Notes, Department of Mechanical Engineer, MIT, April, 2002.


Parris, Andrew, “Precision Stretch forming for Precision Assembly”, Ph.D. Thesis, Department of Mechanical Engineering, MIT, 1996.


