

## **Abstract**

**HUGHES, ROBERT EUGENE.** Analysis and Redesign of the Brim Forming Manufacturing Process (Under the guidance of Dr. M. K. Ramasubramanian)

The principles of mechatronic design have been further applied to develop a robust brim curling system. The brim curling machine uses integration of mechanical, electrical, and computing systems to form a unique machine that is able to produce quality finished paperboard cups. This research involves the conversion from a PC controller to a stand-alone servo/stepper controller. The controller offers more programming flexibility with improved process control. This research also explores optimization of the brim curling machine to determine the maximum production rate. The rotary and linear servo actuators were tuned using a PID scheme. The machine processes for forming a brim were explored and time for the machine to complete these processes was evaluated. The process that took the most amount of time was the cup shell feeding mechanism. The feeding mechanism was reconfigured and the time required to feed a cup shell was reduced. Analysis was performed on a falling cup shell to determine a theoretical time estimate. This research also investigates the effects of machine turret deflection and the deflection's affect on cup brim thickness. Finite element analysis was used to determine the stresses present in a redesigned coupling. The coupling replaced a previously failed coupling. The brim curling machine was completely reconfigured and the result is an industry ready high speed brim curling machine.

# **Analysis and Redesign of the Brim Forming Manufacturing Process**

by  
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A thesis submitted to the Graduate Faculty of  
North Carolina State University  
in partial fulfillment of the  
requirements for the Degree of

**Master of Science**

**Mechanical and Aerospace Engineering**  
**Raleigh, North Carolina**  
August, 2003

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## **Biography**

I, Robert E. Hughes was born on August 29, 1974 in Burlington, North Carolina. I was raised in rural Alamance County by my parents Dennis and Nancy Hughes. I graduated from Eastern Alamance High School in May of 1992. Upon graduation from high school, I began my Bachelor's degree in mechanical engineering at North Carolina State University. In May of 1997, I completed my Bachelor's degree with a minor in graphic communications. I started work at Gardner Glass Products as a plant supervisor / project engineer. In 1998, I moved to a maintenance / project engineer with Hendrix Batting in High Point.

I later decided I was interested in doing more design / prototype work. In order to achieve this goal it was in my best interest to enroll in the Master's program at North Carolina State University. In the spring of 2001, I began working on my Master's degree. The first semester back in college I became interested in Mechatronics. I was intrigued by the thought of using a small microprocessor to control a machine or robot. Subsequently, I decided to make Mechatronics my thesis concentration. I wanted to work with machines and be able to make them semi-intelligent. Since working on my degree, I have had the opportunity to be a teaching assistant to undergraduate mechanical engineering students in manufacturing their senior design projects. I also gained further experience from this position which allowed me to design and create prototypes for several design other projects.

After completion of my Master's degree, I plan to continue working in the mechatronics field designing and creating machine prototypes.

## Table of Contents

<b>List of Tables .....</b>	<b>v</b>
<b>List of Figures.....</b>	<b>vi</b>
<b>1. Introduction.....</b>	<b>1</b>
1.1 Mechatronics .....	1
1.2 Drawbacks of Traditional Brim Curling Machines .....	2
1.3 Prototype Brim Curling Machine .....	2
1.4 Purpose .....	4
<b>2. Background .....</b>	<b>4</b>
<b>3. Mechatronic Design Considerations .....</b>	<b>5</b>
3.1 Motion Control Software .....	5
3.2 Machine Control and Program Flow .....	6
<b>4. Machine Performance.....</b>	<b>9</b>
4.1 Servo Control Variables .....	9
4.2 Actuator Speeds and Machine Processes .....	11
4.3 Cup Shell Feeding Mechanism .....	13
4.4 Improvements to increase production speeds .....	17
<b>5. Cup Shell Feeding Motion.....</b>	<b>18</b>
5.1 Free Falling Cup Shell.....	18
5.2 Falling Cup Shell with Initial Velocity .....	19
5.3 Effects of Drag Forces on the Cup Shell .....	20
5.4 Theoretical Time Estimate to Feed One Cup & Actual Time Taken .....	21
<b>6. Finite Element Analysis of Machine Turret Plate &amp; Turret Coupling .....</b>	<b>24</b>
6.1 Analysis of Single Load Acting on Machine Turret without Cup Dies .....	26
6.2 Analysis of Double Load Acting on Machine Turret without Cup Dies .....	27
6.3 Analysis of Single Load Acting on Machine Turret with Cup Dies .....	28
6.4 Analysis of Double Load Acting on Machine Turret with Cup Dies .....	29
6.5 Effects of Machine Turret Deflection on Brim Thickness .....	30
6.6 Solution to Prevent Machine Turret Plate Deflection .....	33
6.7 Replacement of mechanical coupling .....	34
<b>7. Conclusions .....</b>	<b>39</b>
7.1 Recommendations for Further Development .....	40
<b>8. References.....</b>	<b>42</b>
<b>9. Appendices.....</b>	<b>43</b>
9.1 Operator's Manual for Start-Up.....	43
9.2 Compumotor 6K8 Onboard Programmable I/O's and Function for Axes 1-4 .....	44
9.3 Compumotor 6K8 Drive Connector.....	44
9.4 Radio Shack RS-232 Cable Pin Assignments.....	45
9.5 Apex 40 Connections to 6K8 Drive Connector.....	45
9.6 Apex 40 Connections to 6K8 Encoder Connector .....	45
9.7 IDC B8001Connections to 6K8 Drive Connector .....	46
9.8 IDC B8001 Connections to 6K8 Encoder Connector .....	46
9.9 S Drive Connections to 6K8 Controller.....	46
9.10 Compumotor 6K8 Triggered I/O Functions for Axes 1-4.....	47

<i>9.11 Compumotor 6K8 Output Functions for Axes 1-4 .....</i>	<i>47</i>
<i>9.12 Brim Curling Machine Assembly Drawing .....</i>	<i>48</i>
<i>9.13 Cup Brim Forming Motion Program .....</i>	<i>48</i>

## List of Tables

Table 6 -1 - List of Maximum Nodal Deflections Per Case .....	31
Table 9-1 - Onboard Programmable I/O's .....	44
Table 9-2 – 6K8 Drive Connector.....	44
Table 9-3 – RS-232 Cable Pin Outs.....	45
Table 9-4 –Apex 40 Servo Drive Connections .....	45
Table 9-5 – Apex 40 Servo Drive Encoder Connections.....	45
Table 9-6 – IDC B8001 Servo Drive Connections .....	46
Table 9-7 – IDC B8001 Servo Drive Encoder Connections .....	46
Table 9-8 – Parker S Drive Stepping Motor Connections .....	46
Table 9-9 - Triggered I/O Functions .....	47
Table 9-10 – Output Functions .....	47

## List of Figures

Figure 1.1 - Mechatronic Relationships .....	1
Figure 1.2 - Mechatronic Prototype Brim Curling Machine .....	3
Figure 3.1 - Motion Planner Programming Software .....	6
Figure 3.2 – Control Schematic of Brim Curling Machine .....	8
Figure 4.1 - Step Response of Turret Servo .....	10
Figure 4.2 – Step Response of IDC Linear Actuators .....	11
Figure 4.3 – Machine Processes to Manufacture a Cup Brim .....	12
Figure 4.4 - Cup Shell Feeding Mechanism .....	14
Figure 4.5 – Solid Model of Cup Shell Feeding Mechanism .....	16
Figure 5.1 - Free Body Diagram of Cup Shell .....	19
Figure 5.2 - Free Body Diagram of Cup Shell and Feed Wheels. ....	20
Figure 5.3 – Overall Free Body Diagram of Cup Shell .....	22
Figure 5.4 – Graphical Solution to Fourth Order Polynomial .....	23
Figure 6.1 – Solid Model of Machine Turret Plate .....	25
Figure 6.2 - Machine Turret Plate with Tetrahedral 4 Meshing .....	26
Figure 6.3 - Nodal Deflection of Machine Turret Plate with Single Load .....	27
Figure 6.4 - Nodal Deflection of Machine Turret Plate with Double Load.....	28
Figure 6.5 - Nodal Deflection of Machine Turret Plate and Cup Holder for Single Load .....	29
Figure 6.6 - Nodal Deflection of Machine Turret Plate and Cup Holder for Double Load.....	30
Figure 6.7 - Relationship between Angles of deflection.....	32
Figure 6.8– Right Side Mounted Ball Transfer Rollers .....	33
Figure 6.9 - Center Mounted Ball Transfer Rollers .....	33
Figure 6.10 - Original Turret Plate Coupling.....	35
Figure 6.11 - New Turret Plate Coupling .....	35
Figure 6.12 - Ansys® Stress Analysis Result for New Turret Coupling, Force Applied to Center Face of Coupling .....	37
Figure 6.13 - Ansys® Stress Analysis Result for New Turret Coupling, Force Applied to Outside Face of Coupling .....	38
Figure 9.1 – Solid Model Representation of Brim Curling Machine .....	48

# 1. Introduction

In the past, industrial paper board machinery used to form drinking cup brims consisted solely of mechanical systems. These machines were controlled from a central main shaft. This main shaft provided the timing for all functions in the formation of paper cups. Branched off of this main shaft were other mechanical elements such as gears, chains, and cams. Therefore all the machine functions were interdependent on one another. As the main shaft spins, the cup shell is moved into the dies and rotated around with each revolution. The main shaft also controls actuation of the brim curling dies that form the cup brim. The finished cup is then indexed around and ejected from the machine.

## 1.1 Mechatronics

The term *Mechatronics* is used to denote a rapidly developing, interdisciplinary field of engineering that deals with the design of products whose function relies on the synergistic integration of mechanical, electrical, and electronic components connected by a control architecture [1].

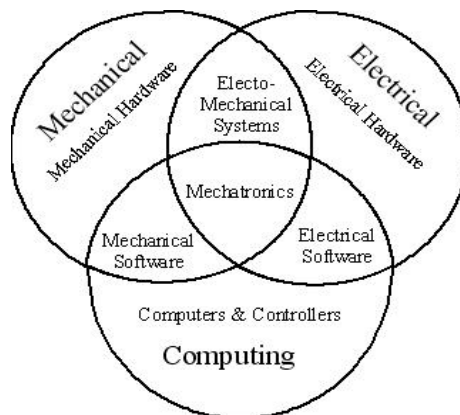


Figure 1.1 - Mechatronic Relationships



Mechatronic systems allow a designer to create not just a machine, but a system within which machine can function. These machines are then able to make simple decisions on their own without human intervention. This decision making process is due to the advancement in microprocessor based controllers. These controllers are stand alone controllers that use analog and digital sensors provide input to make decisions, and use electrical actuators to carry them out. Other advantages to mechatronic systems are; 1) The systems require simplified mechanisms, 2) The systems are more compact, and 3) The systems have higher accuracy due to feedback. Mechatronic products are used in a wide variety of products in today's society. These products range from the automotive industry to production of simple household products.

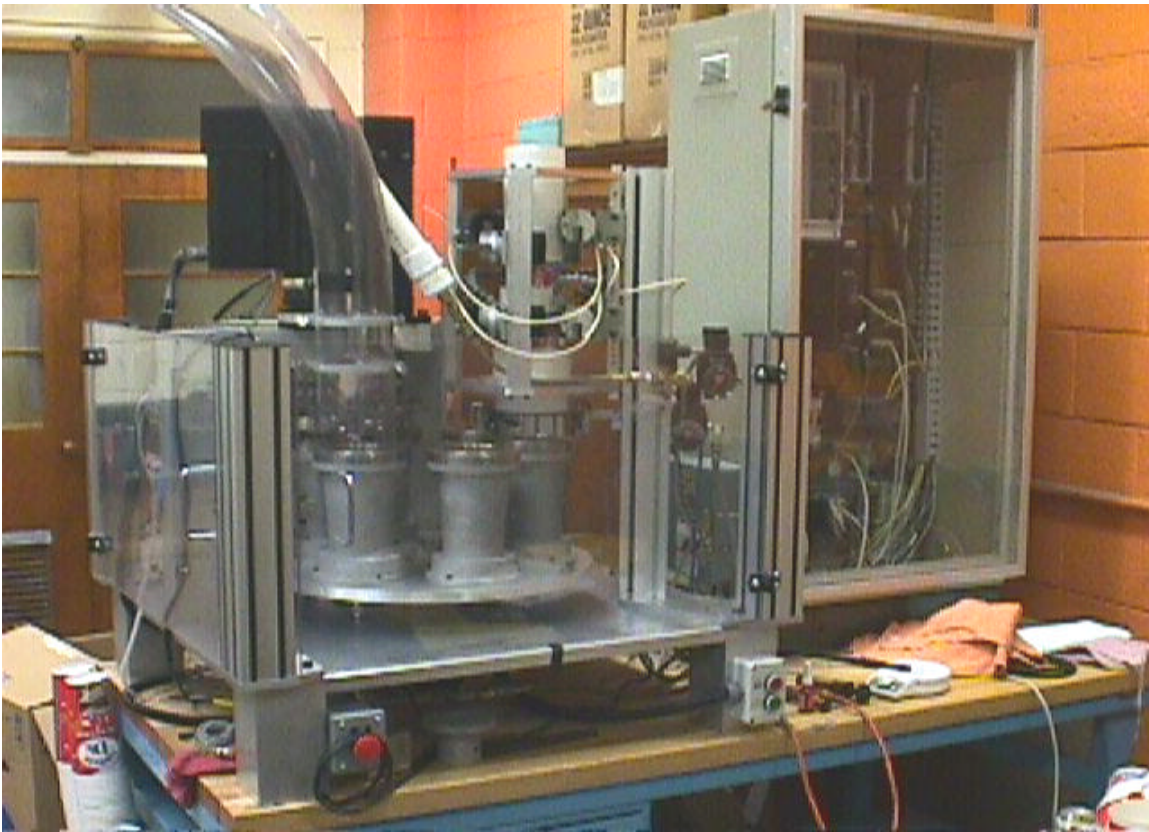
### *1.2 Drawbacks of Traditional Brim Curling Machines*

Traditional brim forming machines have drawbacks due to its mechanical nature. Parts wear over time and cause timing inaccuracies and backlash. This will result in changes in the quality of the products produced and eventually defective products. This results in downtime for the machine and loss of production. Another drawback is the inflexibility of the machine. To change form one product to the next involves complete disassembly and reassembly resulting in weeks of downtime. Large number of custom parts and mechanisms make these machines very expensive to build, run, and maintain.

### *1.3 Prototype Brim Curling Machine*

The prototype brim curling machine was developed at North Carolina State University [2]. This machine is an integration of mechanical and electrical components,

coupled with a Parker Compumotor controller. The machine incorporates servo motors, stepping motors, pneumatics, and other electrical components to form the cup brims. The current machine is completely constructed from 6061 aluminum. The machine is composed of a feeding device, turret that has six cup holders, pre-curl station, final curl station and ejection station. This machine uses a high torque servo and a high precision gear reducer to index the turret. The turret indexes to the appropriate station each function to be performed. Once the cup brim is formed the cup is finally indexed to the ejection station.



**Figure 1.2 - Mechatronic Prototype Brim Curling Machine**

### *1.4 Purpose*

The purpose of this work is to develop a systematic analysis of the performance of the machine. Identify bottlenecks, and improve performance through design changes. This evaluation involves the actual motion of the devices as well as program flow. Further, critical components will be analyzed for stresses and redesigned if necessary to prevent premature failure of mechanical components and improve reliability of the machine. The ultimate goal of this research is to have a brim curling machine that is robust, intelligent and performs optimally.

## **2. Background**

The prototype brim curling machine is a stand-alone system, instrumented to obtain information in real-time. The machine has a rotary turret that holds six cup die holders. This turret can be indexed precisely around to the various work stations. The workstations include the feeding station, the pre-curl station, the final curl stage and the ejection stage. As the turret indexes, a cup shell is fed into the holder. The cup shell is then indexed around until the final product is formed. The machine is continuous production machine. Therefore, as one cup is indexed and formed, another cup is being fed or waiting to be formed. The machine is controlled with a Parker AT6250 servo controller [8]. This controller has four axis control capability. The machine uses a Compumotor rotary servo with a precision Bayside gear reducer to move the turret. The pre-curl and finish curl dies are controlled by two IDC linear actuating servos. The servos use rotary encoders to give position feedback. The servos use hall-effect sensors to determine a home position. This home position is the starting position for the

actuators. The machine also has a cup shell feeding mechanism. This mechanism uses stepping motors and pneumatics to feed the cup shells.

### **3. Mechatronic Design Considerations**

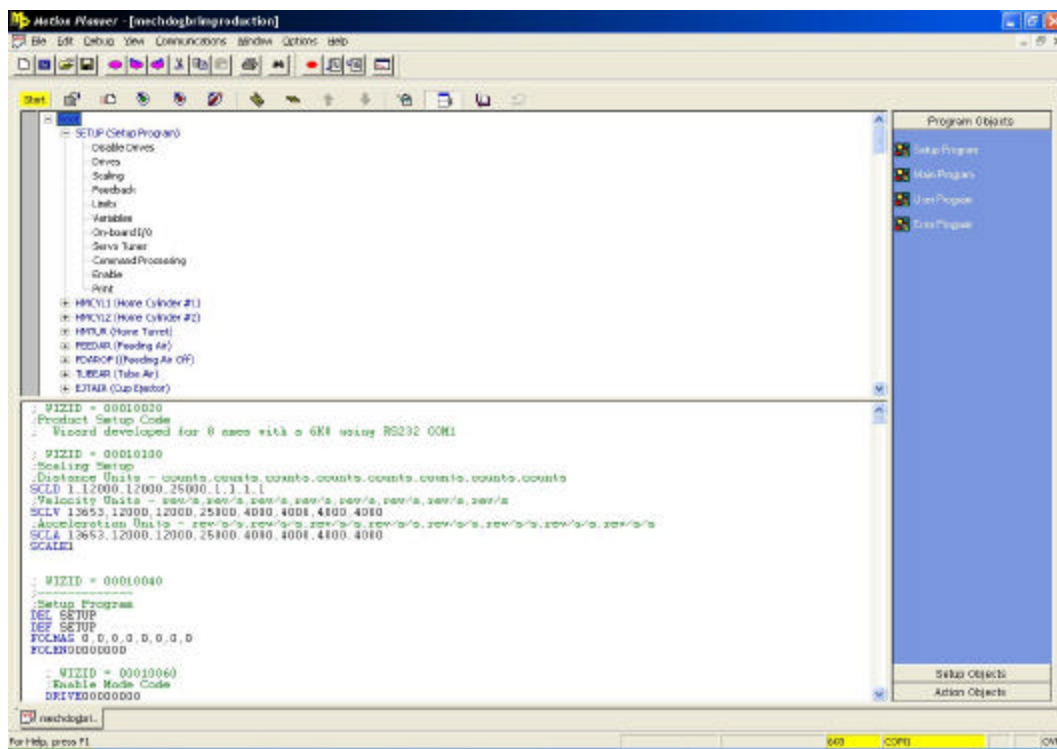
The prototype brim curling machine is an integration of mechanical and electrical components, driven by a central controller. The current prototype brim curling machine was controlled by a PC based controller and control algorithm [2]. The installation of a new controller to the prototype machine allows for greater control and more functionality. The controller selected was a Parker 6K8 Controller [8]. The 6K8 is an eight axis stepper/servo controller with a servo update rate of 62.5 $\mu$ s. The 6K8 controller allows the total machine to be controlled and monitored from one source. This controller is a stand-alone controller. That is, once the program is loaded there is no need of an external PC.

#### *3.1 Motion Control Software*

Programs for the 6K controller were written using the Windows-based programming tool Motion Planner (Figure 3.1). Motion Planner uses Compumotor's 6000 motion control language for programming. This programming language uses ASCII mnemonic commands followed by a command delimiter to provide signals to the controller. As the controller receives commands, the commands are placed in an internal buffer. From the buffer the commands are executed in the order upon which they are received. The programs are downloaded to the controller using a RS-232 interface. The controller utilizes flash memory to store the programs. Therefore, if there is power loss

the operating system and program are not lost. Once the program is downloaded the PC is just used as a terminal to answer feedback questions or to receive machine feedback.

The 6K software has commands to allow a programmer to scale units for motion, home actuators, enable outputs, read digital and analog inputs, perform calculations, multitask, and send feedback to external interface. This gives a system tremendous flexibility to perform a multitude of operations. The system is also expandable for future work.



**Figure 3.1 - Motion Planner Programming Software**

### *3.2 Machine Control and Program Flow*

The 6K8 controller provides a solid platform for superior motion control. The controller enabled the brim curling machine to make precise movement to produce a quality product. The control system utilizes four of the eight axes available. Three of

these axes control the appropriate servos while the other controls the feeder stepping motors.

Once the controller was installed, the appropriate connections to the servo and stepper drives were made. The controller uses an -10 to +10 volt analog signal to control the servos as well as the step and direction signal used to drive the steppers. In return, the controller receives feedback from the encoders on the servos for motion control.

The controller has eight programmable outputs and seventeen programmable triggered inputs. The brim curling machine utilizes three of the outputs and five inputs. The outputs control the pneumatics and the inputs are optical sensors to detect cup positions for feeding and ejection.

The 6K8 also has a bank of limit inputs for each servo motor. These inputs are used to give the system feedback such as home position, positive end of travel limit, and negative end of travel limit. The home inputs were used for the turret servo and for both die actuators.

With the integration of the actuators, pneumatics, sensors, mechanics, and the controller, a highly superior mechatronic system is created.

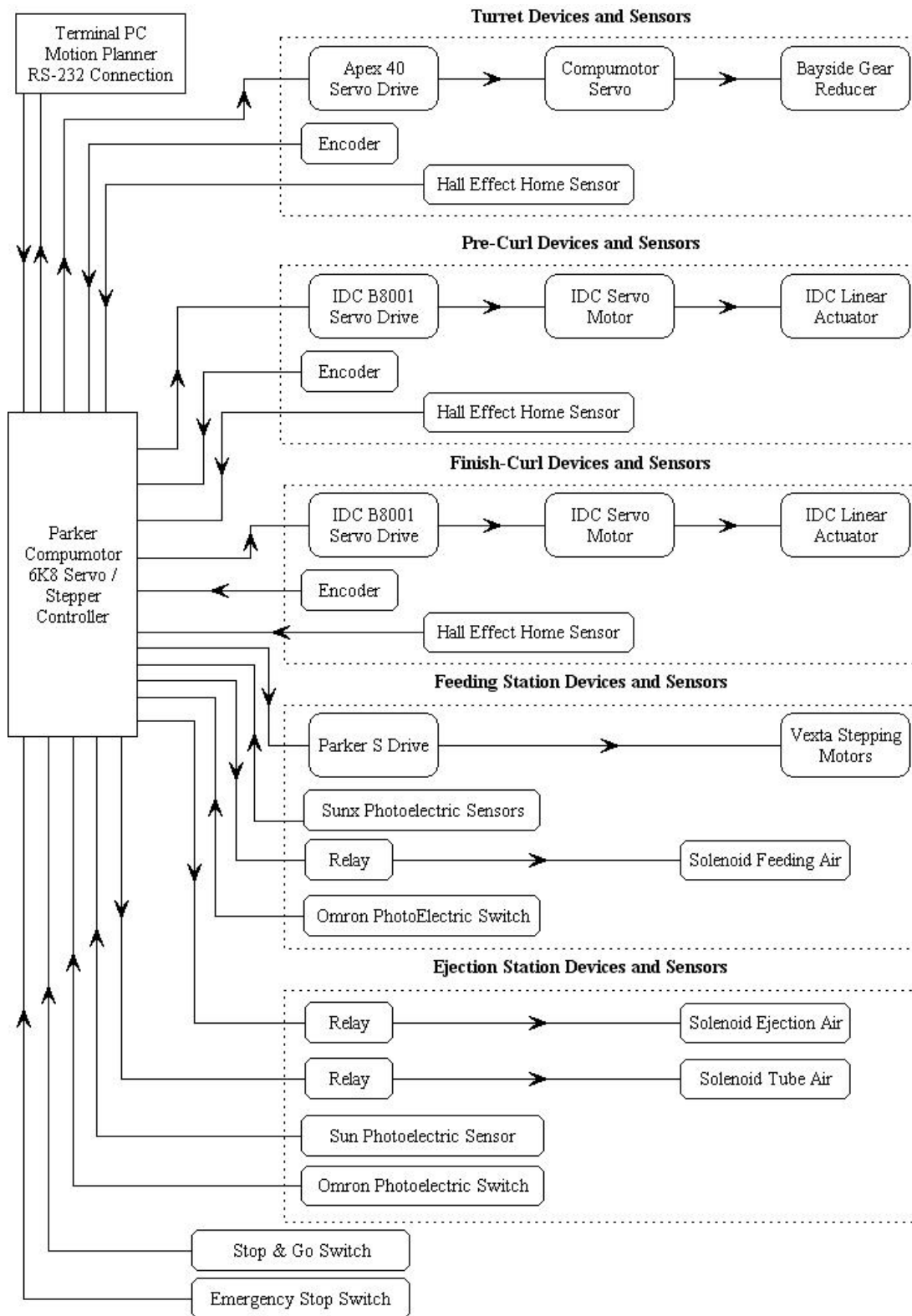


Figure 3.2 – Control Schematic of Brim Curling Machine

## 4. Machine Performance

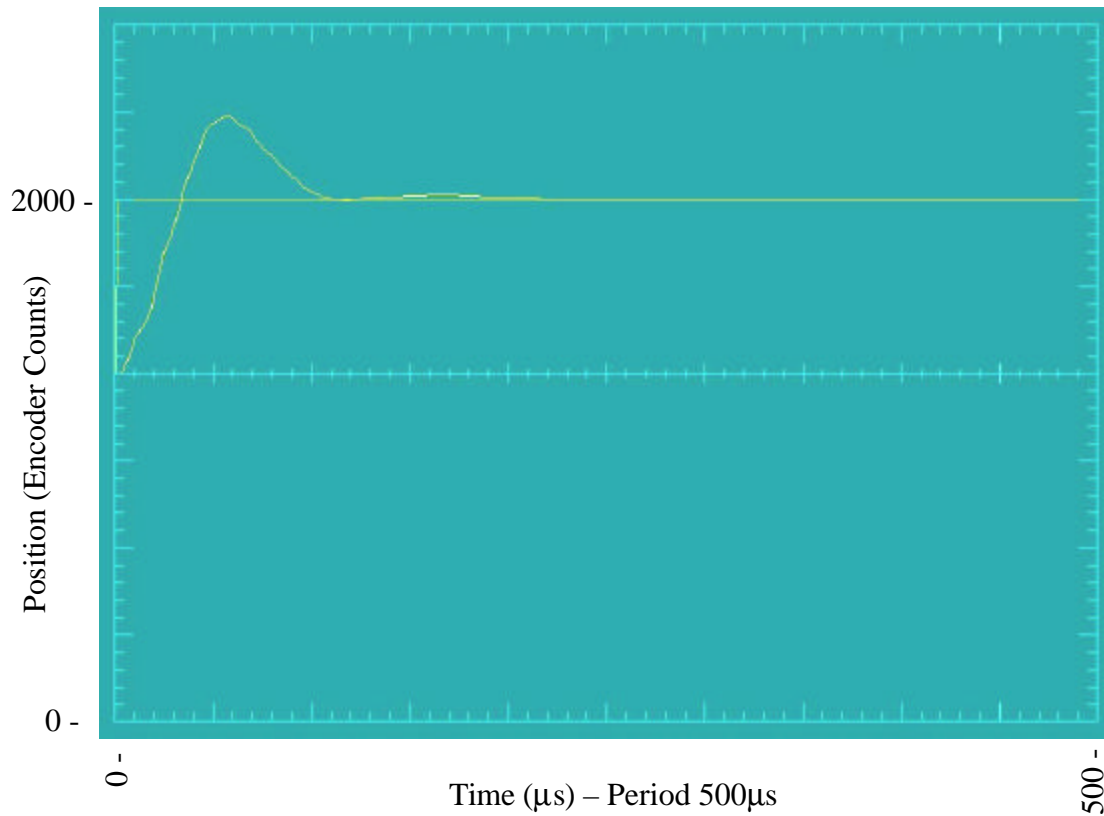
In order to have the machine perform optimally the servos need to be tuned for stable, agile performance. This was done by determining the PID constants by a tuning procedure. The proportional gain (P) was adjusted first to control peak overshoot. Next, derivative gain (D) was added to control settling time while the integral gain (I) was set to control steady state error. Once the indexing servo was tuned optimally, the next step was to tune the actuator servos for optimal performance. The next step was to study the actuator speeds to determine the maximum production rate. Finally, the cup feeding mechanism was critically reviewed, modeled, and improved.

### *4.1 Servo Control Variables*

Initially, the servos were tuned using the Parker controller. Since the servos are closed loop systems, each servo must be configured for optimum performance. After launching the servo tuner software, a first order response can be obtained. The servos on the machine were tuned to a step function. This step is respectively a small step; only 2000 thousand counts on the encoders. The indexer encoder had a resolution of 4096 counts per revolution, and the actuator encoders were 8000 counts per revolution. The encoder then provides feedback to the screen allowing the response to be viewed. The servo is then tuned by systematically adjusting the PID gains as described earlier.

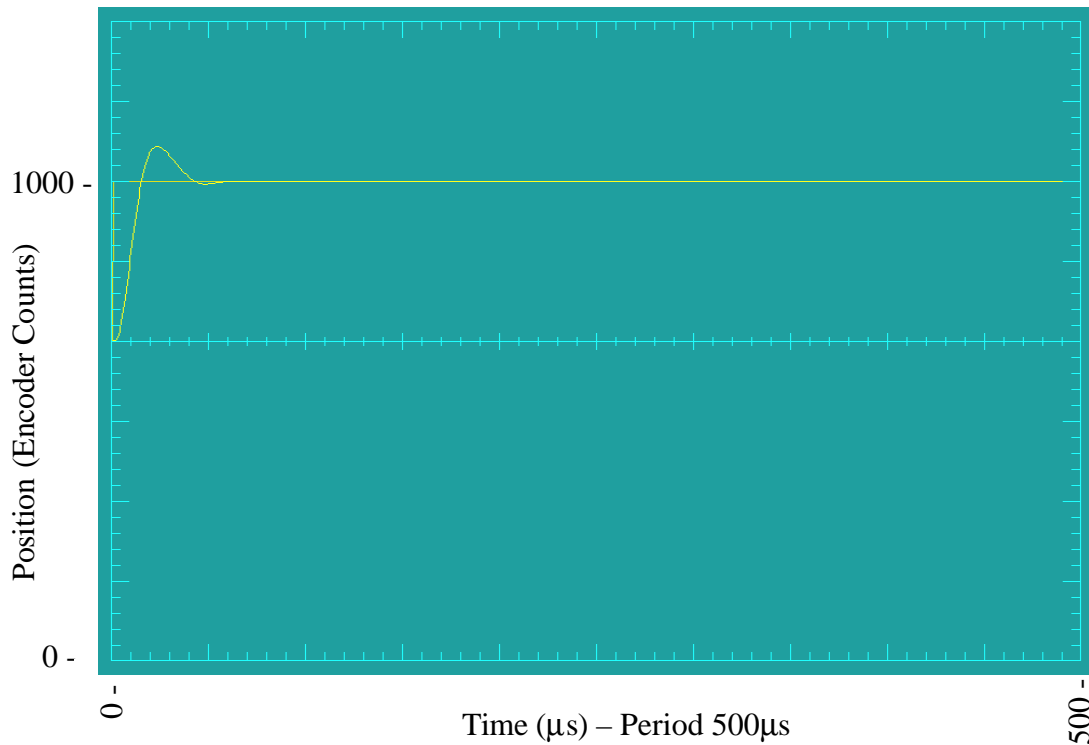
The turret is driven by a Compumotor Servo. The first order step response is shown in Figure 4.1. The tuning gains are:  $P = 10$ ,  $I = 20$ , and  $D = 15$ . Tuning the turret servo proved to difficult. This was due to the small amount of backlash present in the Bayside gear reducer. The effects of the backlash are shown in Figure 4.1.





**Figure 4.1 - Step Response of Turret Servo**

The pre-curl die and finish curl die are actuated by the IDC linear servo. Both dies are actuated by the same type servo motor and both motors were tuned with the same PID parameters. The first order response of the linear actuator is shown in Figure 4.2. The tuning gains are:  $P = 8$ ,  $I = 2$ , and  $D = 5.2$ . The gains gave a response that would rise quickly and then settle to the desired value. It was desirable not to have a lot of overshoot for these actuators so that when the actuator is programmed to move one inch, there is only a few thousands variance from the mark.

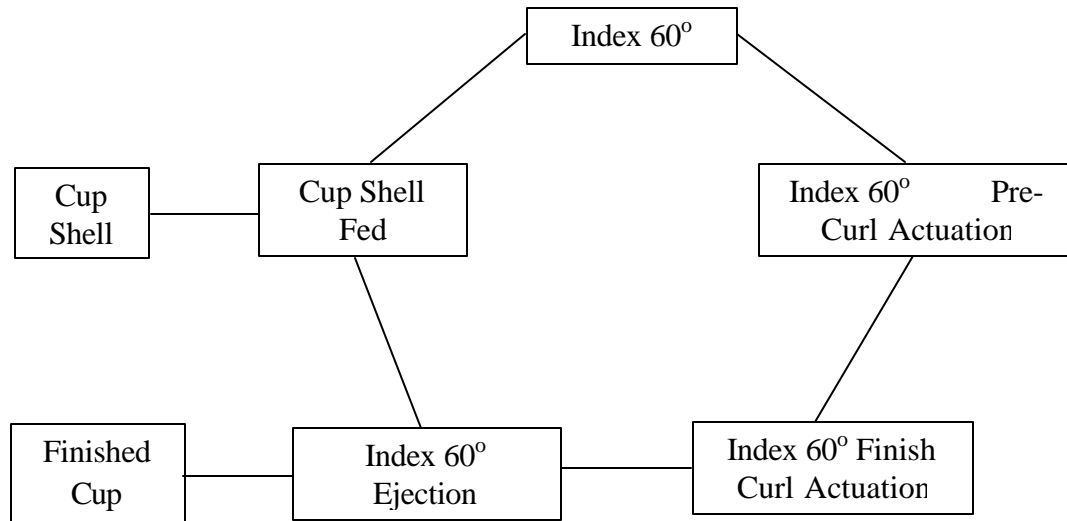


**Figure 4.2 – Step Response of IDC Linear Actuators**

#### *4.2 Actuator Speeds and Machine Processes*

Production rate is defined as the speed at which quality finished cups can be produced. In the earlier design [2], the turret indexing speed was used as the production speed which is incorrect. The brim curling machine production speed is based on cups per minute. The machine processes that the machine must perform to make one cup include (Figure 4.3);

- 1.) Feeding the Cup
- 2.) Index 60° to Open Slot
- 3.) Index 60° to Pre-Curl Station
- 4.) Pre-Curl Actuation
- 5.) Index 60° to Finish-Curl Station
- 6.) Finish Curl Actuation
- 7.) Index 60° to Ejection Station
- 8.) Finished Cup Ejection from the Machine



**Figure 4.3 – Machine Processes to Manufacture a Cup Brim**

In a manufacturing cycle, some of these processes happen simultaneously. Once the program is started and the brim curling machine is in full operation, the production rate is determined from the time the machine can feed a cup shell and index once. The other processes still occur but they are not a limiting factor in determining production rate. Experiments were performed to determine the machine's maximum production rate.

The first test was to determine the maximum production speed without any feeding operation. The result will give a time value in milliseconds for the turret to index 60° and the linear actuator to move down and back to the home position. For this experiment a separate motion program was written to test the time value for this process. In the motion program, the distance, velocity, and acceleration of the actuators are based on the scaled values assigned in the program. For example, the scaled velocity has the units of counts/sec. The linear actuator has a maximum velocity of 20in/s and the turret actuator with gear reducer has a maximum velocity of 112.5 rpm. The minimum time to

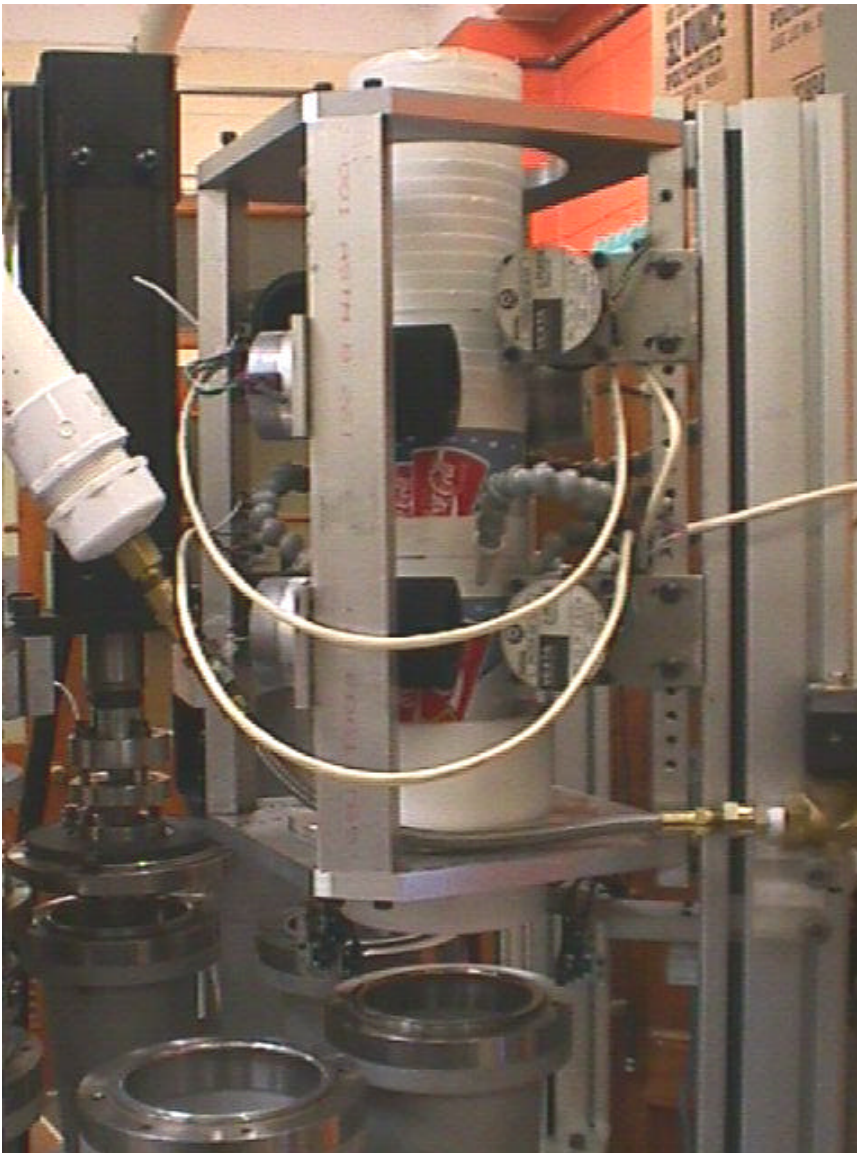
complete this process was 0.45s. This yields a maximum production rate 133 cups per minute.

The final experiment to determine the production rate used the same motion program with the feeding operation included. Using the velocities and accelerations from the previous experiment, the time increased to 0.722s. This yields a maximum production rate of 80 cups per minute. Therefore, it can be concluded that the cup feeding mechanism is the rate limiting step in this process.

#### *4.3 Cup Shell Feeding Mechanism*

Cup shell feeding is an important issue in the production speed of this industrial brim curling machine. A 32oz cup is difficult to feed because of the cups' geometrical shape and the effective stiffness of the cup shell. The cup shell must be fed in the proper orientation and in the shortest amount of time possible. The mass of a 32oz cup shell is 0.0375lb. The feeding mechanism (Figure 4.4) uses eight stepping motors that are driven by a Parker S-series stepping drive. These motors have foam rubber wheels attached to the output shaft providing a friction hold on the cups until feeding is necessary. Compressed air is used to help force the cup down into the holder as the feeding wheels advance. The compressed air is controlled by a solenoid valve. The air is moved through four nozzles that are placed around the cup stack. The cup shells are placed into the feeder in a stack. The advancement of the cup stack is controlled by a series of three photoelectric sensors that detect when a cup needs to be fed. These sensors also do error checking for proper feeding. When a cup shell needs to be fed, the stepper motors and air turn activate simultaneously to start feeding cups. As the stack of

cup shells advance the air pressure blows the cup down through the guide tube and into the cup holder. Photoelectric sensors also control when the steppers and air need to turn off. The machine will remain at the feeding station until the sensors allow the cup shell to index to the forming station.



**Figure 4.4 - Cup Shell Feeding Mechanism**

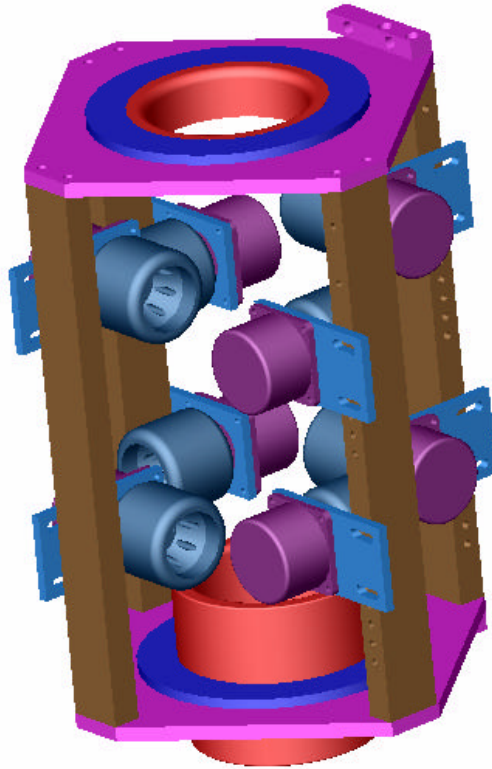
Initially, the cup shell mechanism was very inconsistent in feeding the shells. The stepping motors were controlled by an external step drive that functioned as an

independent unit. Coordination with the rest of the machine was not robust, causing inconsistency. Converting to the Parker S-drive allowed for more robust control due to documentation available, and the ability to integrate into central controller. The S-drive was compatible with the 6K8 controller, which enabled the drives output to the stepping motors to be scaled and worked seamlessly. This allowed for precise speed control and for faster update rates to turn the stepping motors off and on. Due to the difficulty in feeding a cup shell, it was determined that a slower velocity profile for the steppers was far more beneficial than a fast velocity profile. Since the steppers move at 3.35in/s, the air pressure from the nozzles had the biggest affect in properly feeding the cup shells in the shortest amount of time.

Another problem with the cup feeding process is feeding errors. Feeding errors include; 1.) Double feeding cup shells 2.) Partially feeding cup shells 3.) Cup shells hanging between the feeder and the cup holder. These errors require operator intervention to be corrected. As shown in Figure 4.4, the stepping motors can be shifted up or down along the vertical columns. Originally, the spacing of these motor was 9in this allowing the cup shell stack to twist. The upper set of stepping motors were moved together to reduce the spacing. Two of the stepping motors were positioned 6.5in apart while the other two stepping motors were positioned 5.5in apart (Figure 4.5). This change gives the cup shell stack in the feeder more stability. The stepping motors can be adjusted to increase or decrease the tension on the cup shell. The lower set of stepping motors were positioned to have less pressure on the cup shell while the upper set was position to add pressure to the cup shell. This allowed 80 percent of the mass of the cup

stack to be held by the upper set of feeding wheels. This corrected a large percentage of the feeding errors along with the determination of stepper motor velocity.

The biggest error that still plagued the feeding mechanism was the cup hanging between the feeder and the cup holder. This is a problem due to the distance between the feeding mechanism and the cup holder. The cup had to travel a distance of 8in in the air with no guidance. To solve this issue a feeding chute was installed in the bottom of the feeding mechanism (Figure 4.5).



**Figure 4.5 – Solid Model of Cup Shell Feeding Mechanism**

This chute was made from a machinable plastic, Delrin. The inner diameter of the chute was made 0.005in larger than the largest outer diameter of the cup shell. This provided enough guidance to keep the cup in the proper orientation until seated in the cup holder.

The effective distance the cup shell has to travel unguided with the feeding chute installed is 1.75in.

Improvements to the feeding mechanism allow for optimum performance and consistency in feeding cup shells. Initially, the cup feeding mechanism could feed a cup shell in approximately 350ms. After the modifications were complete and the velocity of the stepping motors was set the feeding mechanism was capable of feeding a cup shell in 270ms. From the time the photoelectric sensors detect a cup shell, there is a 125ms time delay to allow the cup to travel into the cup holder. If the cup shell does not clear these sensors in the allotted time, an error message is sent to the terminal for the operator to check. Therefore, the cup shell must travel from the bottom of the cup stack into the cup holder in 125ms. The other time required in feeding the cups is the result of the stepping motors advancing the cup stack. The cup stack must advance approximately 0.4375in in order for a cup to be released. Therefore, the time required for this advancement is 0.147s. These time values were determined experimentally with the use of internal timers available in the 6K8 controller.

#### *4.4 Improvements to increase production speeds*

The brim curling machines is capable of producing up to 80 cups per minute. This production speed is not the maximum capability for the servos. In the optimization stage there is a point where the machine becomes unstable. This instability is not due to poor manufacturing of the machine, but partially due to the environment. The machine needs a suitable base to be mounted upon. The table upon which the machine is placed moves when the machine is running at high productions speeds. Another way to increase



production speeds would be the addition of another set of brim curling stations. In order to increase the production speed for the current brim curling machine the machine would have to increase in size. Another feeding and ejection station would also have to be added. If the machine turret was larger in diameter then the machine speeds could decrease as production speeds increase. Consequently, more cup holders could be installed. This machine is very flexible and is capable of producing a high quality product. This can be considered as an extension of this work.

## **5. Cup Shell Feeding Motion**

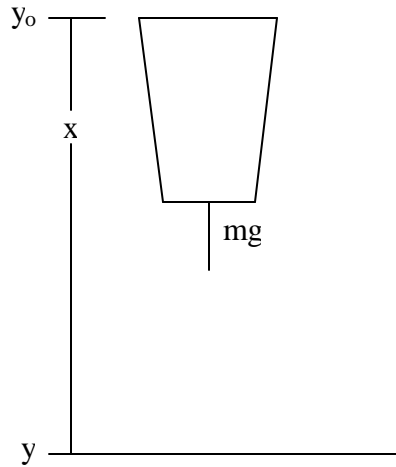
The dynamics of feeding cup shells is important to the production rate of the brim curling machine. The time the cup shell needs to leave the feeder and become seated in the cup holder is important to the production speed of the machine. The following analysis examines some the factors that affect the falling of the cup shell falling.

### *5.1 Free Falling Cup Shell*

The first approach to finding the time taken for the cup to be fed was to consider a freely falling cup (Figure 5.1). This analysis was done in order to get a baseline of how long it took for a cup shell to travel from rest to the final destination. This base line time was done with the assumption that the forces of the surrounding air had no affect on the time for the cup to drop. The distance the cup must travel is 8in. Also the cup is released from rest. Therefore, the initial velocity of the cup shell is zero. In this analysis the only force action on the cup is the force of gravity. Employing classical Newtonian mechanics the equation for a freely falling body is written as [3]:

$$y - y_0 = v_o + \frac{1}{2}gt^2 \quad (7.1)$$

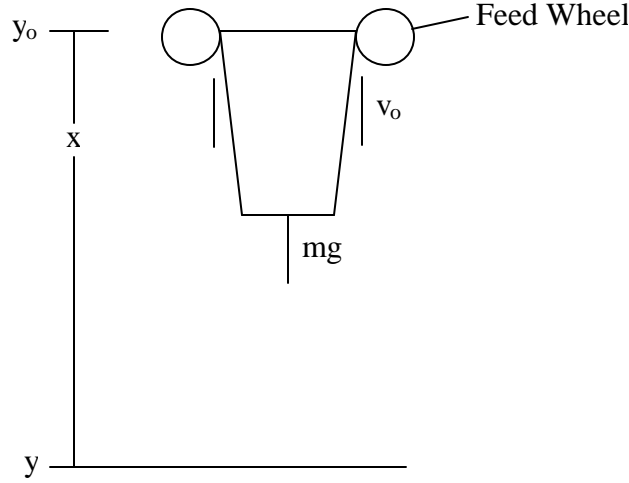
In equation 7.1 ( $y$ ) is the final distance and ( $y_0$ ) is the initial starting point. The acceleration of gravity is denoted as ( $g$ ), the time is give as ( $t$ ), and ( $v_o$ ) is the initial velocity. The time taken for the freely falling cup to reach its destination is 0.2035s. Therefore for a cup shell to travel eight inches takes approximately 200ms. This is the initial base line for determining how a cup shell can be fed.



**Figure 5.1 - Free Body Diagram of Cup Shell**

### *5.2 Falling Cup Shell with Initial Velocity*

Now consider a falling cup shell with an initial velocity induced by the feeding wheels (Figure 5.2). The velocity of the stepper motor was experimentally measured with a tachometer. The feed wheels have a constant velocity of 3.35in/s. The solution yields a time value of 0.1950s. Therefore, the feeding wheels only drop approximately 50ms off the time to feed the cups versus a gravity feed. The speed of the feeding wheels is very important. If the wheels index too far the feeder will double feed a cup shell. This is why the velocity of the feed wheel is relatively slow.



**Figure 5.2 - Free Body Diagram of Cup Shell and Feed Wheels.**

### *5.3 Effects of Drag Forces on the Cup Shell*

The component of the net force parallel to the uniform upstream flow is the drag force [4]. This force acts on the moving cup shell and tries to slow it down. The drag force,  $F_D$ , is a function of the diameter,  $D$ , the fluid velocity,  $V$ , the density of the fluid,  $\rho$ , and the viscosity,  $\mu$ . The drag force can be represented in function form as:

$$F_D = f(D, V, \mathbf{m}, \mathbf{r}) \quad (7.2)$$

Using the Buckingham Pi theorem to evaluate the function the result is:

$$\frac{F_D}{\mathbf{r}V^2A} = f\left(\frac{\mathbf{r}VD}{\mathbf{m}}\right) = f(\text{Re}) \quad (7.3)$$

In equation 7.3 the cross-sectional area of the body is represented as ( $A$ ). This equation is valid for incompressible flow of any body. Next, the drag coefficient is defined as:

$$C_D = \frac{1}{2} \left( \frac{F_D}{\mathbf{r}V^2A} \right) \quad (7.4)$$

From equation 7.3 and 7.4, the coefficient of drag can be shown as:

$$C_D = f(\text{Re}) \quad (7.5)$$

Since the coefficient of drag is a function of Reynolds number, the value for Reynolds number must be determined. If the value for Reynolds number is greater than 1000 the drag coefficient will be independent of this value. For the cup shell, the Reynolds number is around 8200. From Table 9.3 [4], the coefficient of drag for a disk is approximately 1.15. This value is used to later determine the force of drag on the bottom of the cup shell.

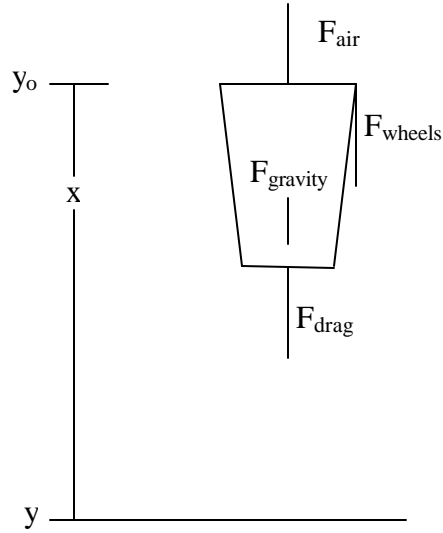
#### *5.4 Theoretical Time Estimate to Feed One Cup & Actual Time Taken*

To determine a theoretical time estimate to feed one cup shell all the forces acting on the cup were considered and some assumptions made. The assumptions are:

- Neglect pressure build up inside the cup holder
- Drag Forces on the sidewalls of the cup shell are negligible
- Forces exerted by roller wheels is negligible compared to force of air nozzles
- Assume incompressible flow
- Assume viscous flow
- Neglect static pressure between the cups in the stack

Figure 5.3 shows the free body diagram of the cup shell. Consider Newton's 2<sup>nd</sup> Law [5]:

$$\sum F = ma = m\ddot{x}(t) \quad (7.6)$$



**Figure 5.3 – Overall Free Body Diagram of Cup Shell**

From Figure 5.3, all of the forces acting on the cup shell can be summed:

$$\sum F = F_{air} + F_{gravity} + F_{wheels} - F_{drag} \quad (7.6)$$

Where  $F_{air}$  is a constant force exerted against the cup,  $F_{gravity}$  is equal to  $mg$ ,  $F_{wheels}$  is negligible and

$$F_D = C_D \frac{1}{2} \rho V^2 A \quad (7.7)$$

The flow velocity is given by:

$$V = v_o + gt \quad (7.8)$$

The final result is:

$$m \ddot{x}(t) = F_{air} + mg - C_D \frac{1}{2} \rho (v_o + gt)^2 A \quad (7.9)$$

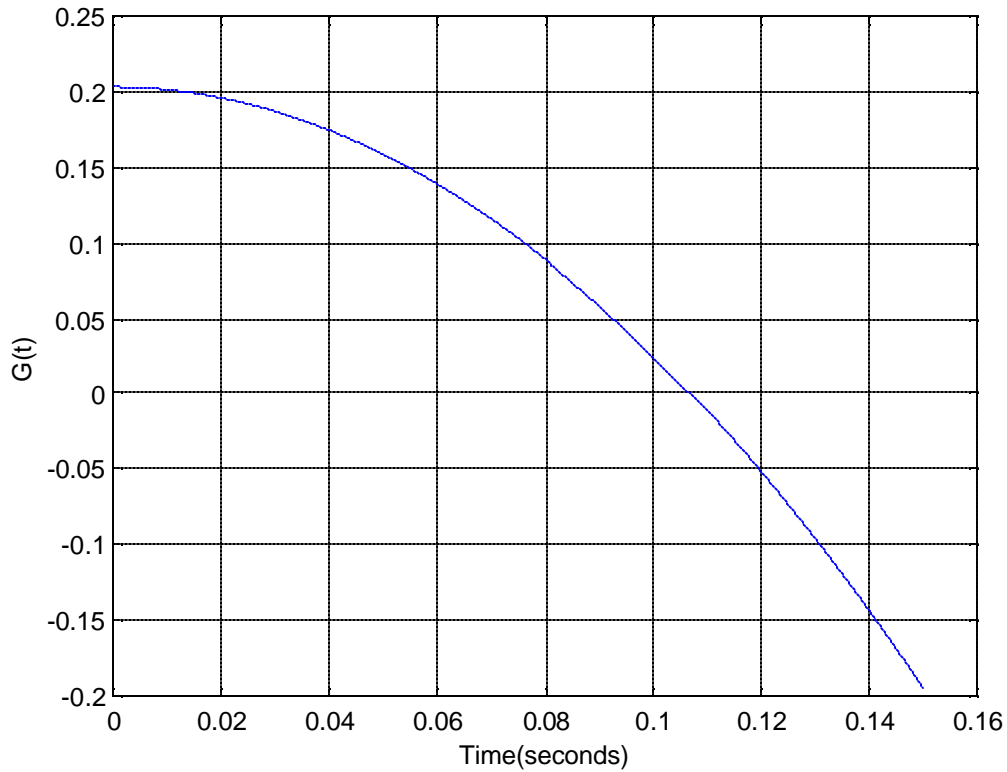
By integrating equation 7.9, displacement for the cup shell drop is a fourth order polynomial in time.

$$x(t) = -\frac{C_D r A g^2}{24m} t^4 - \frac{C_D r A v_o g}{6m} t^3 + \frac{F_{air} + mg - \frac{1}{2} C_D r A v_o^2}{2m} t^2 \quad (7.10)$$

Since  $x(t)$  is a constant, let a function  $G(t)$  be defined as:

$$G(t) = \frac{C_D r A g^2}{24m} t^4 + \frac{C_D r A v_o g}{6m} t^3 - \frac{F_{air} + mg - \frac{1}{2} C_D r A v_o^2}{2m} t^2 + x \quad (7.11)$$

The positive root of function  $G(t)$  is the time required for a cup shell to be fed. Numerical techniques, such as graphical simulations from Matlab, yields a required time of 0.1071s for  $G(t)$  equal to 0 (Figure 5.4).



**Figure 5.4 – Graphical Solution to Fourth Order Polynomial  $G(t)$**

Theoretically, the time needed to feed one cup with the current system is 107ms. Experimentally the time allowed for the system to feed a cup is 270ms. Due to the difficulty in feeding cup shells, this is an acceptable time to feed one cup shell.

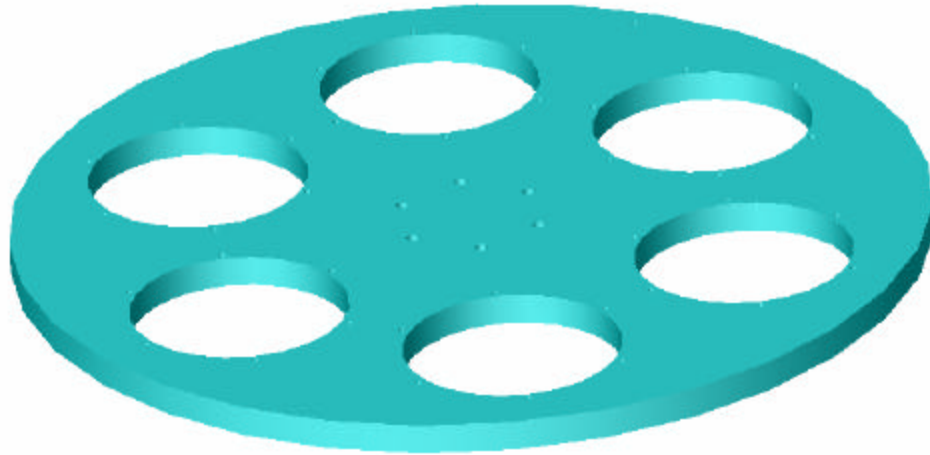
Another issue is pressure build up in the bottom of the cup holder as the cup closes the cavity. This pressure build up can be overcome by pulling a vacuum on the bottom of the cup holder. This will help overcome the drag force present on the cup shell. The drawback to this idea is the cost of the extra compressed air used to create this vacuum. Another way to reduce this pressure build up is to cut holes in the cup holders. This would allow the air to escape out the side of the cup holders. Another benefit of these holes is a mass reduction of the cup holders and a decrease in rotational inertia present on the turret plate.

## **6. Finite Element Analysis of Machine Turret Plate & Turret**

### **Coupling**

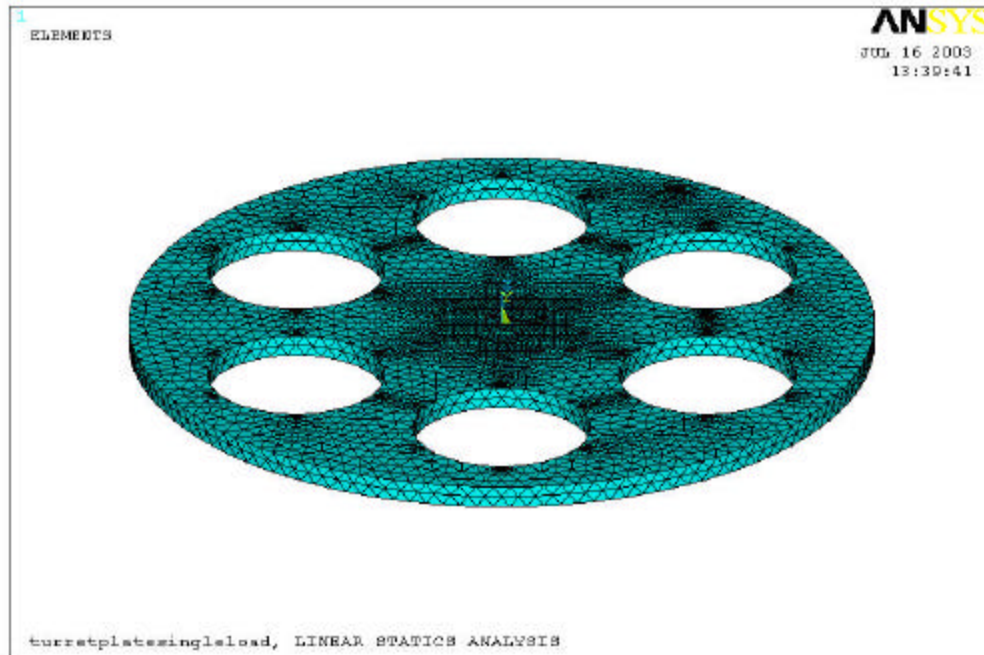
Brim forming requires perfect alignment of curling iron and die for uniform brim diameter. This is a critical attribute for snap lid assembly. If the turret plate deflects downward then the die and iron will be nonparallel causing brim diameter variation. In order to understand the effect of turret plate deflection on die parallelism, finite element analysis was used (Figure 6.1). This plate is constructed of  $\frac{3}{4}$  in thick 6061 Aluminum. The importance of analyzing this component is to determine if there is too much deflection from the linear actuators creating quality issues in forming the cup as well as machine wear issues. The finite element analysis was performed using Unigraphics® and Ansys®. The part file was imported into Unigraphics® as a solid body. The structures

environment in Unigraphics® was used to create a mesh and apply forces. The mesh used was a triangulated mesh, Tetrahedral 4 (Figure 6.2) [6]. Boundary conditions were assigned to rigidly hold the part in position. The points selected for the boundary conditions were where the machine turret bolts to the motor coupling. Force was applied to the machine turret at the location where the cup die is mounted. After the mesh, boundary conditions, and forces were applied, an Ansys® Structural file was created. Ansys® was then used to solve the problem. The nodal solution was examined to determine the maximum deflection of the plate.



**Figure 6.1 – Solid Model of Machine Turret Plate**

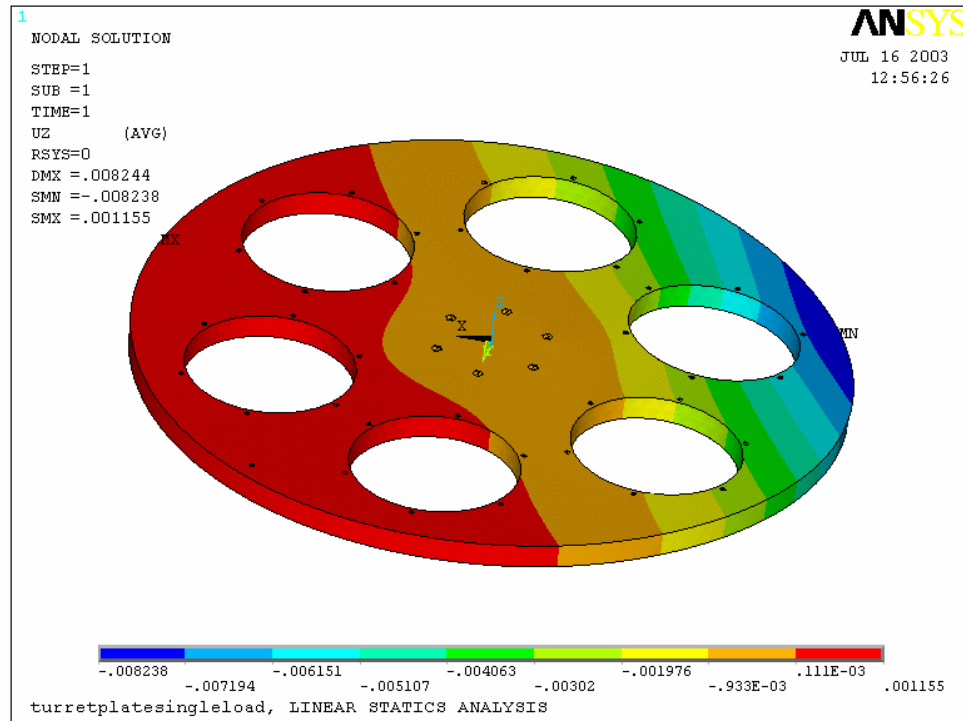




**Figure 6.2 - Machine Turret Plate with Tetrahedral 4 Meshing**

### *6.1 Analysis of Single Load Acting on Machine Turret without Cup Dies*

The first case considered was the machine turret plate with no cup dies attached and a load of 400lb applied to one die hole. In this case, since the cup holder dies are not attached, the plate is more flexible and should have a higher deflection. After running the Ansys® file, the nodal solution was determined.



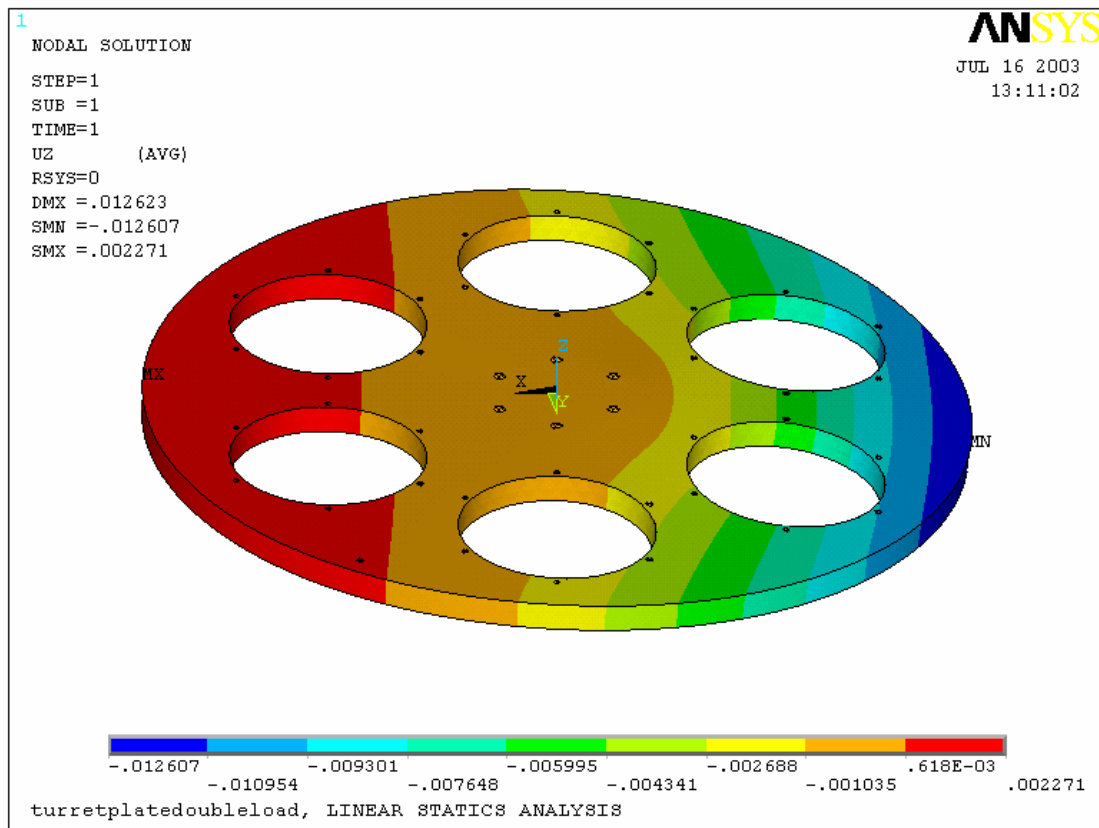
**Figure 6.3 - Nodal Deflection of Machine Turret Plate with Single Load**

Nodal deflections from Figure 6.3 show a maximum deflection of 0.008244in at the tip of the machine turret plate. The bar graph at the bottom of Figure 6.3 shows the deflection distribution across the turret plate. The graph also shows the downward deflection to be positive. That is a result of applying the force as 400lb in the negative direction. This was done in order to show the deflection in the proper orientation.

## 6.2 Analysis of Double Load Acting on Machine Turret without Cup Dies

The second case considered was the machine turret plate with no cup dies attached and a load of 400lb applied to two die holes. This case is a representation of two stage brim forming. Therefore, there was a total load of 800lb applied to the turret plate.

As in the first case, there are no cup holder dies considered and this case should yield the highest deflection. After running the Ansys® file, the nodal solution was determined.



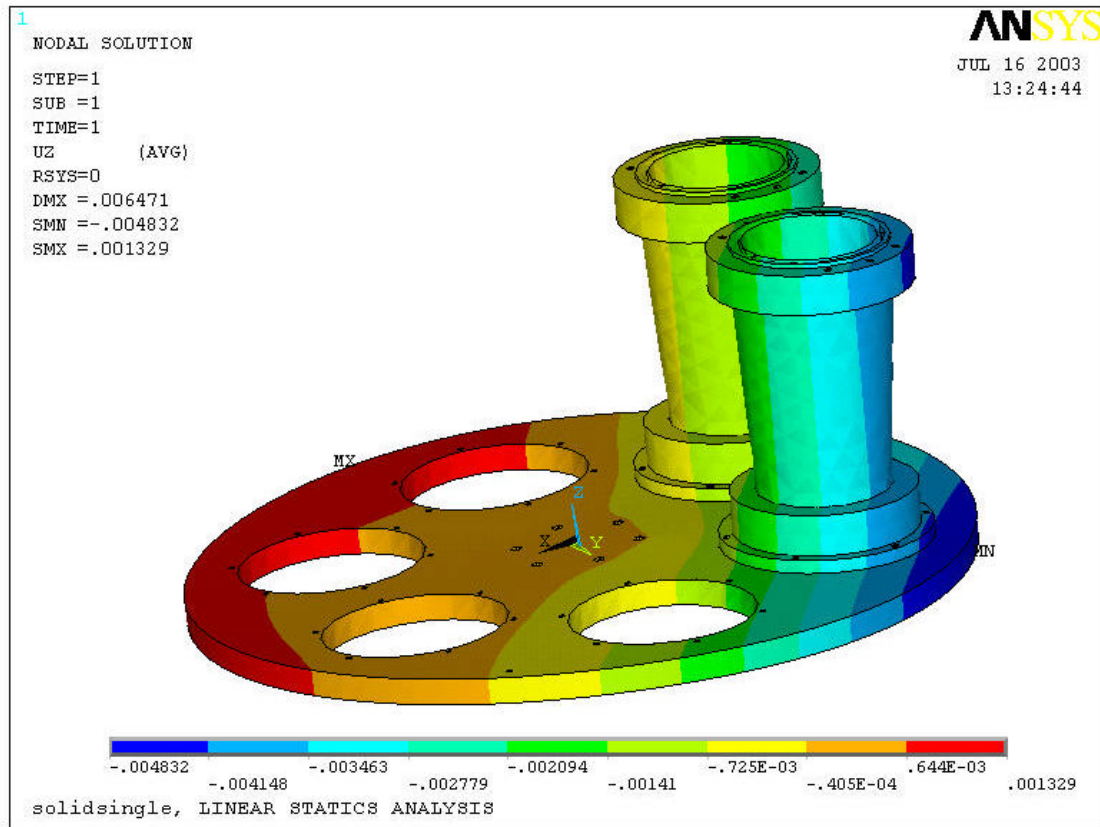
**Figure 6.4 - Nodal Deflection of Machine Turret Plate with Double Load**

The nodal deflections from Figure 6.4 show a maximum deflection of 0.012623in at the tip of the turret plate. There was a increase of approximately 0.004in in deflection from the extra load.

### 6.3 Analysis of Single Load Acting on Machine Turret with Cup Dies

The third case considered was the machine turret plate with the associated cup holders in position. For this case a single load of 400lb was applied to one cup holder. This analysis simulated turret plate deflections from a single stage brim forming process.

For analysis purposes, the turret plate and the cup holder were modeled as one part. This in essence, stiffened the turret plate. Therefore, the maximum nodal deflection should be smaller than the first or second case.

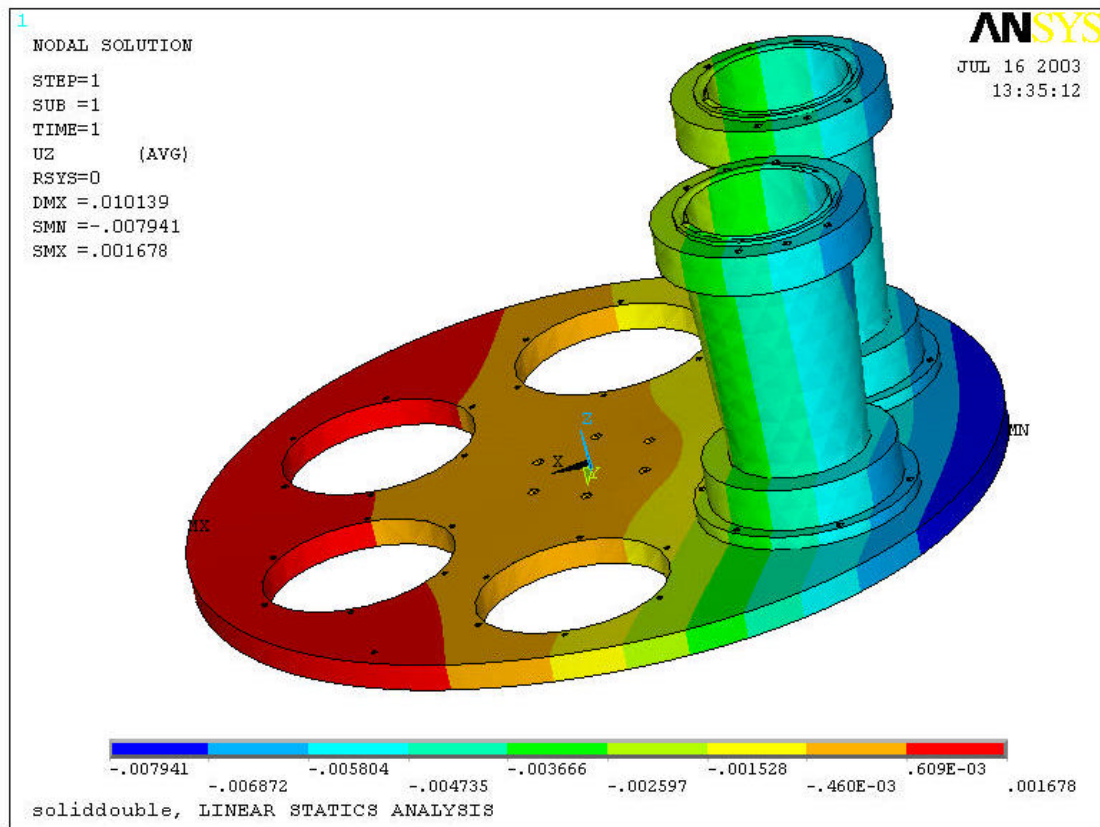


**Figure 6.5 - Nodal Deflection of Machine Turret Plate and Cup Holder for Single Load**

The result of the nodal deflection analysis yielded a maximum deflection of 0.006471in (Figure 6.5). This shows that the cup holder stiffens the turret plate however there is still some noticeable deflection.

#### *6.4 Analysis of Double Load Acting on Machine Turret with Cup Dies*

The final case considered double load acting on two cup holders. The load again was 400lb applied to the top of each cup holder. This case would simulate the turret plate deflection from a two stage brim forming process.



**Figure 6.6 - Nodal Deflection of Machine Turret Plate and Cup Holder for Double Load**

The resultant of the nodal deflection analysis for the double load yielded a maximum deflection of 0.010139in (Figure 6.6). Even with the extra stiffness added by the cup holder to the turret plate, there is only a difference reduction of 0.002in in deflection.

### 6.5 Effects of Machine Turret Deflection on Brim Thickness

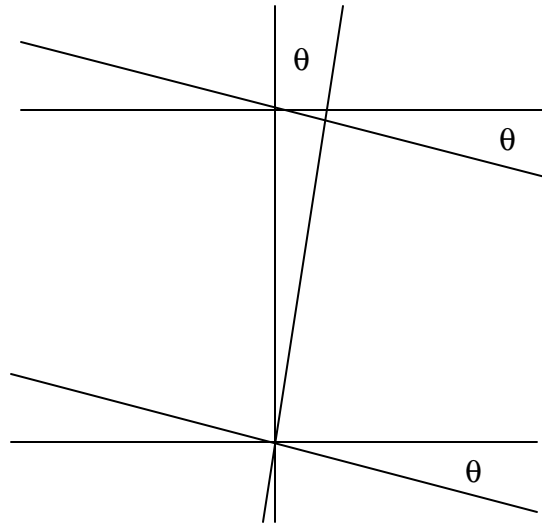
Turret deflection will have effects on the brim thickness of the cup. The cup brim diameter is approximately 0.150in. Small percent changes in this thickness will

drastically change the quality of the brim formed. Based on the finite element analysis performed on the turret, there was noticeable amount of deflection (Table 6 -1).

**Table 6 -1 - List of Maximum Nodal Deflections Per Case**

<b>Deflection Cases</b>	<b>Maximum Nodal Deflection (in)</b>
Turret Plate Single Load	0.008244
Turret Plate Double Load	0.012623
Turret Plate w\ Cup Holders Single Load	0.006471
Turret Plate w\ Cup Holders Double Load	0.010139

To show the percent change in brim thickness, the case for a single load on the machine turret plate was used. A theoretical line was drawn from the center of the turret plate through the center line of the cup holder position. Then, by using the nodal numbers from Ansys®, the nodal deflections could be listed for each node corresponding to the theoretical line drawn. The nodal values were then plotted and a best fit line could be approximated. This, in turn, allowed for a good approximation of the turret plate deflection along the vertical axis of the cup holder. This nodal deflection was calculated to be 0.008in. Next, by assuming small angle approximation for the deflection, an angle of tilt from the horizontal position could be determined. The angle theta ( $\theta$ ) calculated is 0.0873°.



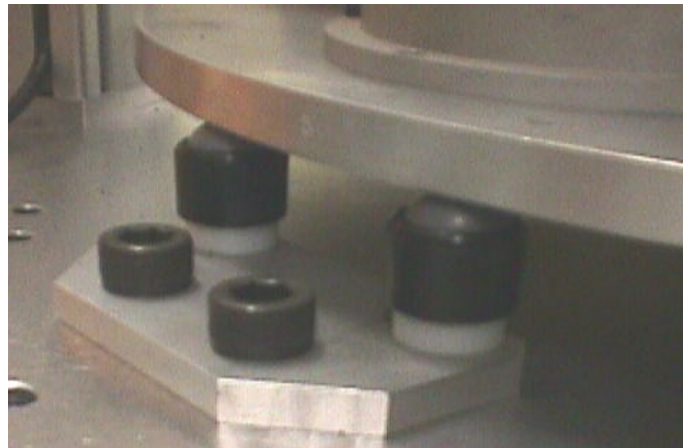
**Figure 6.7 - Relationship between Angles of deflection**

Figure 6.7 shows the relationship between the change in angle of the turret plate and the top of the cup holder. This change in angle from the horizontal makes a 2% change in brim thickness. The result is that the brims are formed with a thick and a thin side; a change of approximately 0.003in.

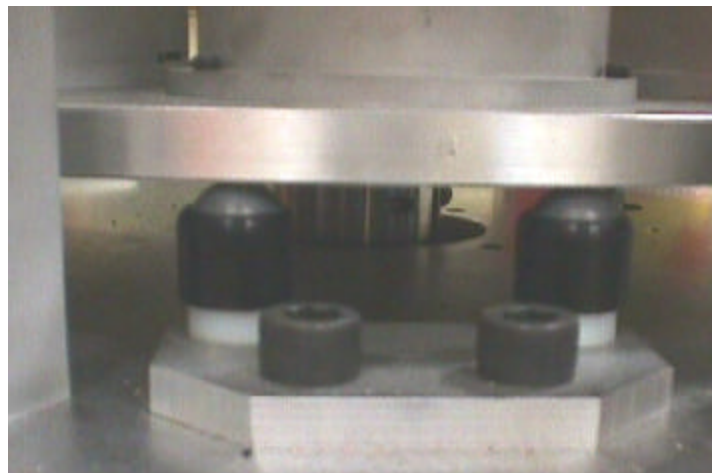
One quality issue associated with the failure to produce a uniform brim could be the inability for the lids to latch properly onto the cup resulting in a recall of the product. Another quality issue is that the brims may not curl properly causing a total loss of the product being produced. A final quality issue is the change in brim thickness would affect the effective stiffness of the cup brim. The turret deflection also created machine hardware problems. This deflection will also cause misalignment of the dies and wear to the brim forming dies. Furthermore, misalignment would cause premature failure of the actuators from shock loads and induced side loading.

### *6.6 Solution to Prevent Machine Turret Plate Deflection*

The solution to prevent turret plate deflections was the addition of six stud-mount ball transfer rollers. These rollers were installed underneath the turret plate to help support the load induced from the brim curling operation (Figure 6.8 & Figure 6.9).



**Figure 6.8– Right Side Mounted Ball Transfer Rollers**



**Figure 6.9 - Center Mounted Ball Transfer Rollers**

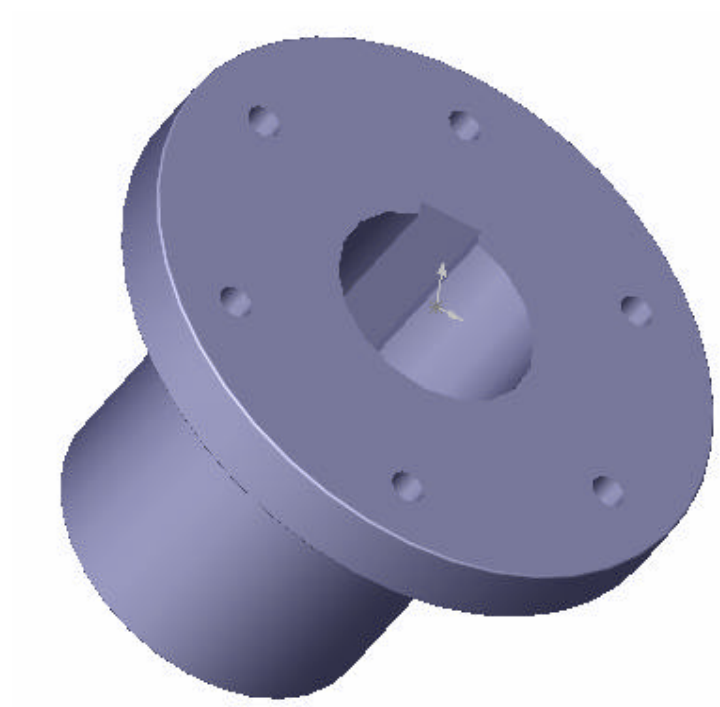
The ball transfer rollers selected have a static load carrying capacity of 25lb each. The composition of the main roller is nylon selected so that there would be minimal amount of wear between the turret plate and the roller. Therefore, as the turret rotates, the balls will rotate as the cups are indexed. When the actuation is performed to curl the brim, the



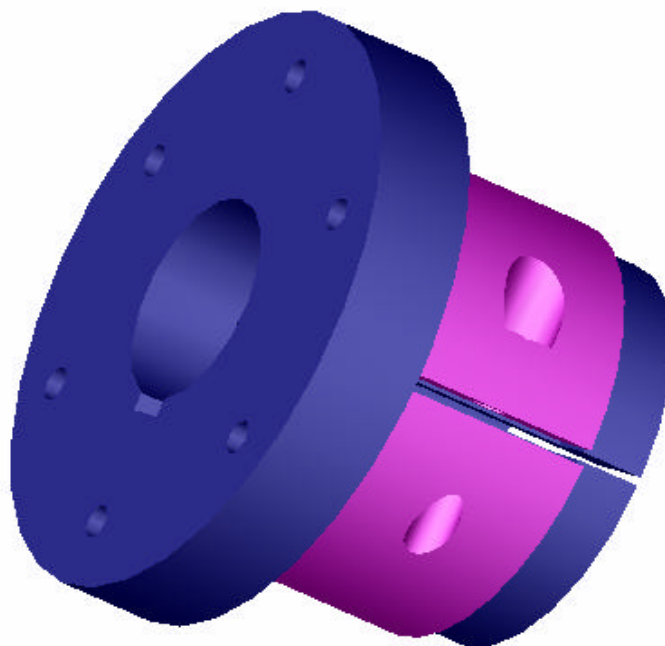
rollers exert a reaction force on the outer edge of the turret plate to prevent unwanted turret plate deflection. As a result, a tight uniform brim is formed.

#### *6.7 Replacement of mechanical coupling*

In order to improve the reliability of the machine further, another component that was analyzed, namely the, mechanical coupling between the turret plate and the main servo gear reducer. The original coupling was composed of 6061 Aluminum. This coupling was designed to slide just over the shaft and be set screwed down to the shaft (Figure 6.10). This coupling caused machine alignment issues. This was a result from the indexing load to which the machine turret is subjected. The turret plate indexes 60 degrees to the next position. In order to achieve this, the main servo must accelerate and decelerate quickly. This operation at maximum production rate happens in about 400ms, at a peak torque rate of 3,485 in-lbs. This shock load requires the old coupling to carry high loads on the key way. Over time, 3 years of intermittent operation, the key way expanded and introduced unacceptable levels of play into the system. This play caused die misalignment and defective brims.



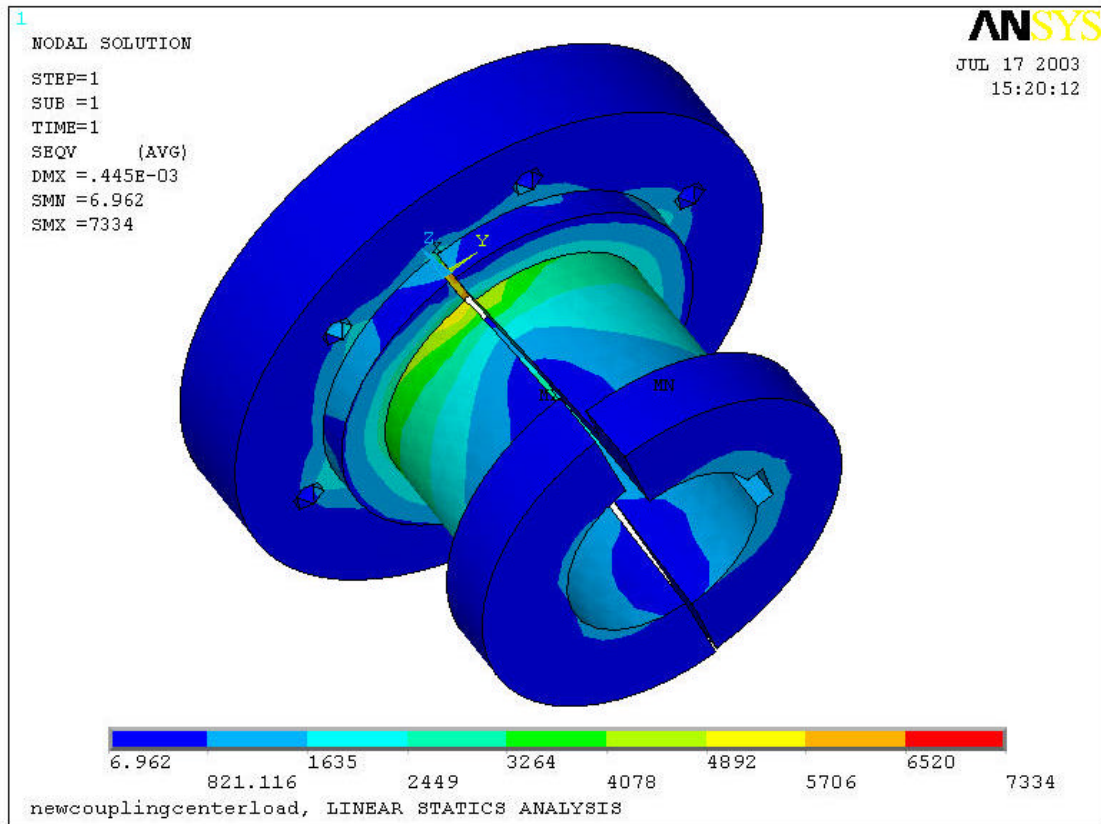
**Figure 6.10 - Original Turret Plate Coupling**



**Figure 6.11 - New Turret Plate Coupling**

To solve this problem a new coupling was designed (Figure 6.11). This coupling is made of steel. The coupling was designed as a split coupling. Therefore the tolerances for the shaft were tighter. The coupling was designed not only to allow the key to carry the load, but also to allow the surface area of the shaft to carry the load due to friction between the output shaft and the collar. The split in the coupling allowed for ease in assembly. Figure 6.11 shows another split collar that is installed on the outside of the coupling. This collar allows the coupling to grip the gear reducer and prevent any slippage.

Ansys® was also used to check the stresses in the new coupling. This analysis was performed excluding the outer coupling. The analysis was first performed considering the maximum torque of the servo. The force was first applied to the inside face of the coupling while the turret bolt holes were fixed. The value for the force applied to this face was distributed load of 5000lb. This gave a simulation as if the turret plate was stalled. Figure 6.12 shows the Von Mises stresses present in the coupling for this case. The bar graph on the bottom of Figure 6.12 gives a stress range from approximately 7psi to 2400psi for this case. The high stress region is located at the bottom of the split.

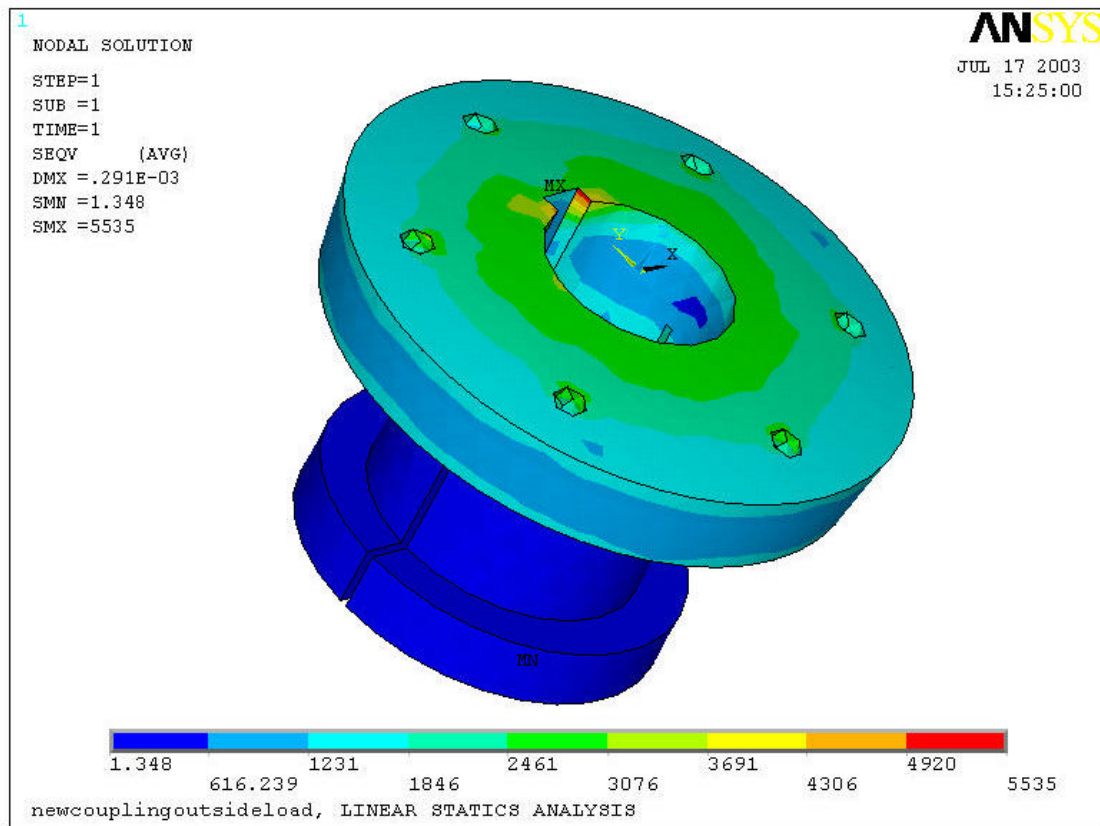


**Figure 6.12 – Von Mises Stresses on the New Coupling, Force Applied to Center Face of Coupling**

In the next analysis, the center of the coupling was fixed. The force was then applied to the outer surface of the coupling.

Figure 6.13 shows the von Mises stresses present in the coupling for this case. The highest area of stress is located at the key way. The bar graph at the bottom of

Figure 6.13 shows the stress values range from 2psi to 5600psi for this case.



**Figure 6.13 – Von Mises Stresses on New Coupling, Force Applied to Outside Face of Coupling**

Both cases show that the stresses are low for the new coupling. The yield stress for machine steel is 50 to 100ksi [7]. The values of stress for the new coupling are much smaller than the minimum value for yield. Therefore, the component is safe. These stresses will be even lower with the addition of the split collar attached to the coupling. The result is a well-designed coupling that will not add any external backlash to the system, other than the inherent gear box backlash.

## 7. Conclusions

Installation of the new controller and optimization of the cup forming processes has shown that the brim curling machine is a robust mechatronic system. The performance of the machine is not based on the timing of mechanical systems working together, as in traditional systems. The machine can be reconfigured by changing the variables and sequences in the source code, without hardware changes. The machine shows intelligent behavior by performing error checking to prevent loss of product or damage to the machine itself. The installation of the 6K8 stand alone controller improved the system's efficiency through faster processing speeds and gave the programmer multiple options to create the motion program. The 6K8 controller provided a more reliable servo tuning software.

The machine can produce up to 80 cups per minute. The machine is able to feed a cup shell and form a brim in 722ms. The turret actuator is capable of indexing to the next station in 450ms with the balance of time used to feed the cup shell. The feeding mechanism is capable of consistently feeding cup shells without errors.

Theoretical work shows that feeding a cup shell is a complex problem. There are a number of factors that affect the falling of a cup shell. These factors limit the time a cup shell can fall. To help speed up this process, air nozzles were used to force the cup shell down into the cup holder. It was determined that a cup shell could be fed in 107ms.

Work was also done to determine the influence of turret plate deflection on the thickness of the brims. Finite element analysis showed that a 400lb load applied to the cup holders would deflect the plate by 0.008in leading to a 2% change in brim thickness.

To resolve this problem, ball transfer rollers were placed under the turret plate to resist the load exerted during the brim forming process.

A redesign of the machine turret coupling allowed the machine to perform at high speeds. This coupling was analyzed by applying a 5000lb load to the outer and inner faces of the coupling, using a finite element model. The tests show that the maximum stress was well below the yield stress of steel. The coupling performed well under production conditions with reduced backlash.

### *7.1 Recommendations for Further Development*

The following list provides suggestions for additional research and product development.

- 1.) Add a pressure sensor to the forming dies. This sensor would be capable of sensing the forming pressure inside of the cup. This would allow the cups to be quality tested before the cups exited the machine, eg. Leak detection on every cup.
- 2.) Increase the size of the machine. This development will allow the machine to have more forming and feeding stations. The result will be an increase in the production rate.
- 3.) Make additions to the machine to complete the cup forming process. Create the cup sealing and bottom forming apparatus. This will make the machine a complete unit. The machine will be able to take a sheet of paperboard, cut the cup shape, and form a completed cup.
- 4.) Make use of the controller's ability to connect via the Ethernet. This will allow machine control and production data to be viewed at remote locations away from the

machine. Therefore, a number of brim curling machines could be monitored and run by one person in a work cell.

- 5.) Design and manufacture components to show that the machine can change production runs in a matter of minutes. Create a feeding mechanism that is capable of feeding any size cup from 8oz to 32oz. This will decrease changeover time and allow the machine to become more flexible. Produce turret plates that can be changed out to allow for production of smaller sized cups. Also, produce the associated dies to complete this process and design a quick coupling to rigidly hold the dies in place after changeover is complete.
- 6.) Add the vacuum station to help decrease the feeding time.



## 8. References

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- [8] Compumotor Motion Control Systems, Catalog 8000-4/USA, Parker Automation. *Parker Hannifin Corporation* [www.compumotor.com](http://www.compumotor.com)

## **9. Appendices**

### *9.1 Operator's Manual for Start-Up*

#### **Start -Up Procedure for Terminal / Programming PC**

1. Turn on the terminal PC.
2. Open Motion Planner Software Program
3. Motion Planner asks for Default Communications. Press OK.
4. Open motion program.
5. If motion program is not already stored in 6K8 then the file can be downloaded. Motion Program cannot be downloaded until the machine is powered.
6. Open terminal Screen
7. To start program type "SETUP"
8. The appropriate axes should initialize, then type in "MAIN"
9. Follow instructions given by motion program on the terminal screen.

#### **Start – Up Procedure for Brim Curling Machine**

1. Attach compressed air line to quick coupling on the wall. Air will flow from the machine until the machine is powered and SETUP from the PC has been run.
2. Check building pressure to ensure the pressure is at least 80psi.
3. Before powering machine, check pre-curl and finish curl actuators to make sure that they are not in any interference with the turret. "This is a machine safety precaution." If the actuators need to be adjusted then set them just above the top of the cup holders.
4. Turn on the 230V 3-phase power disconnect.
5. Turn on the 120V single phase power.
6. At this point the PC and Motion Planner are running, and the program can be downloaded or run.
7. Happy Cup Forming

## 9.2 Compumotor 6K8 Onboard Programmable I/O's and Function for Axes 1-4

**Table 9-1 - Onboard Programmable I/O's**

<b>6K8 Control Function</b>	<b>Bit #</b>	<b>Pin #</b>	<b>Function for Brim Curling Machine</b>
Positive End of Travel Limit, Axis 1	1	23	Not Used
Negative End of Travel Limit, Axis 1	2	21	Not Used
Home Limit, Axis 4	3	19	Home Switch for Turret Actuator
Positive End of Travel Limit, Axis 2	4	17	Not Used
Negative End of Travel Limit, Axis 2	5	15	Not Used
Home Limit, Axis 4	6	13	Home Switch for Linear Actuator
Positive End of Travel Limit, Axis 3	7	11	Not Used
Negative End of Travel Limit, Axis 2	8	9	Not Used
Home Limit, Axis 4	9	7	Home Switch for Linear Actuator
Positive End of Travel Limit, Axis 4	10	5	Not Used
Negative End of Travel Limit, Axis 4	11	3	Not Used
Home Limit, Axis 4	12	1	Not Used

**Note:** All even pin #'s correspond to earth ground (GND)

## 9.3 Compumotor 6K8 Drive Connector

**Table 9-2 – 6K8 Drive Connector**

<b>Pin #</b>	<b>Wire Color</b>	<b>Function</b>
7	Brown	Shtno
14	Yellow	Common
8	Grey	Shtnc
3	Black	CMD+
6	Red	CMD-
5	Green	DRF
13	White	Iso GND
15	Blue	AGND
--	Orange	No Connection
--	Purple	Outside Jacket – No Connection
--	--	Shield Wire

#### 9.4 Radio Shack RS-232 Cable Pin Assignments

**Table 9-3 – RS-232 Cable Pin Outs**

Pin #	Wire Color
1	Black
2	Brown
3	Red
4	Orange
5	Yellow
6	Green
7	Blue
8	Purple
9	Grey

#### 9.5 Apex 40 Connections to 6K8 Drive Connector

**Table 9-4 –Apex 40 Servo Drive Connections**

Apex 40 Signal Name	Compumotor 6K8 Signal Name	Compumotor 6K8 Connector Pin #
Enable In	SHTNO	7
Fault Out	DFT	5
GND	AGND	15
--	COM	14 *
Command +	CMD +	3
Command -	CMD -	6

\* -- For this connection also jump COM pin to AGND

#### 9.6 Apex 40 Connections to 6K8 Encoder Connector

**Table 9-5 – Apex 40 Servo Drive Encoder Connections**

Apex 40 Signal Name	Compumotor 6K8 Signal Name	Compumotor 6K8 Connector Pin	Radio Shack RS-232 Wire Color
CHA +	A+	2	Brown
CHA -	A-	3	Red
CHB +	B+	4	Orange
CHB -	B-	5	Yellow
CHZ +	Z+	6	Green
CHZ -	Z-	7	Blue
GND	GND	9	Grey
--	--	1	No Connection
--	--	8	No Connection

### 9.7 IDC B8001 Connections to 6K8 Drive Connector

**Table 9-6 – IDC B8001 Servo Drive Connections**

<b>IDC B8001 Signal Name</b>	<b>Compumotor 6K8 Signal Name</b>	<b>Compumotor 6K8 Connector Pin #</b>
Enable	SHTNO	7
Fault	DFT	5
Common	AGND	15
--	COM	14 *
Command +	CMD +	3
Command -	CMD -	6

\* -- For this connection also jump COM pin to AGND

### 9.8 IDC B8001 Connections to 6K8 Encoder Connector

**Table 9-7 – IDC B8001 Servo Drive Encoder Connections**

<b>IDC B8001 Signal Name</b>	<b>Compumotor 6K8 Signal Name</b>	<b>Compumotor 6K8 Connector Pin</b>	<b>Radio Shack RS-232 Wire Color</b>
CHA +	A+	2	Brown
CHA -	A-	3	Red
CHB +	B+	4	Orange
CHB -	B-	5	Yellow
CHZ +	Z+	6	Green
CHZ -	Z-	7	Blue
GND	GND	9	Grey
--	--	1	No Connection
--	--	8	No Connection

### 9.9 S Drive Connections to 6K8 Controller

**Table 9-8 – Parker S Drive Stepping Motor Connections**

<b>S-Drive Signal Name</b>	<b>Pin #</b>	<b>Compumotor 6K8 Signal Name</b>	<b>Pin #</b>
Step +	1	Step +	1
Step -	14	Step -	9
Direction +	2	Direction +	2
Direction -	15	Direction -	10
Shutdown +	16	Shutdown +	11
Shutdown -	17	Shutdown -	12
Fault Output	9	Drive Fault	5
Fault Return	21	GND	13

### 9.10 Compumotor 6K8 Triggered I/O Functions for Axes 1-4

**Table 9-9 - Triggered I/O Functions**

Bit #	Pin #	Program Function	Cup Brim Forming Machine Function
1	23	Triggered Input 1 (TRIG-1A)	Sunx Photoelectric Feeding Sensor #1
2	21	Triggered Input 2 (TRIG-1B)	Sunx Photoelectric Feeding Sensor #1
3	19	Triggered Input 3 (TRIG-2A)	Sunx Photoelectric Feeding Sensor #1
4	17	Triggered Input 4 (TRIG-2B)	Sunx Photoelectric Feeding Sensor #1
5	15	Triggered Input 5 (TRIG-3A)	--
6	13	Triggered Input 6 (TRIG-3B)	Production GO Button
7	11	Triggered Input 7 (TRIG-4A)	Production STOP Button
8	9	Triggered Input 8 (TRIG-4B)	Omron Photoelectric Tube Clear Sensor

**Note:** All even pin #'s correspond to earth ground (GND)

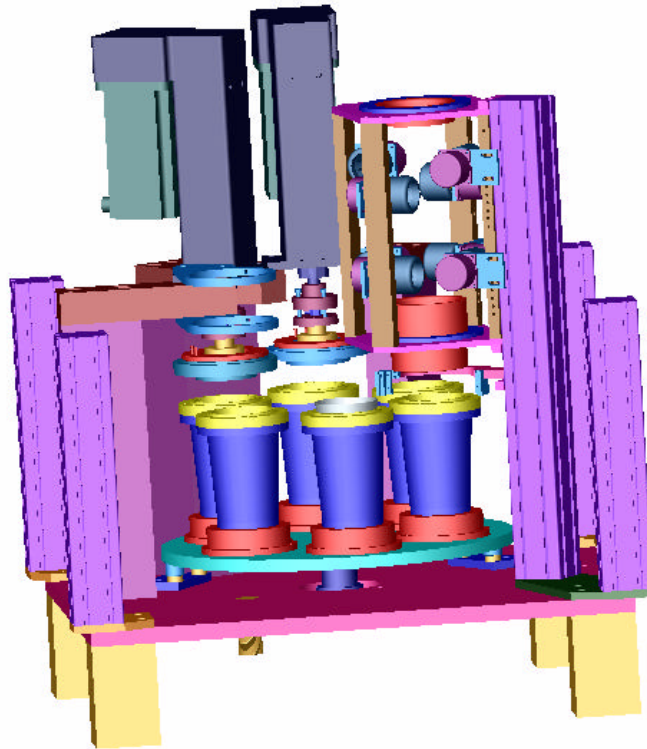
### 9.11 Compumotor 6K8 Output Functions for Axes 1-4

**Table 9-10 – Output Functions**

Bit #	Pin #	Program Function	Cup Brim Forming Machine Function
1	7	Output 1	Ejection Air Solenoid
2	5	Output 2	Feeding Air Solenoid
3	3	Output 3	Tube Air Solenoid
4	1	Output 4	--

**Note:** All even pin #'s correspond to earth ground (GND)

### 9.12 Brim Curling Machine Assembly Drawing



**Figure 9.1 – Solid Model Representation of Brim Curling Machine**

### 9.13 Cup Brim Forming Motion Program

#### **Motion Program file for Brim Curling Machine**

**Written by: Robert Hughes**

**Date: 4/20/03**

```
;Product Setup Code
; Wizard developed for 8 axes with a 6K8 using RS232 COM1

;Scaling Setup
;Distance Units - counts,counts,counts,counts,counts,counts,counts,counts
SCLD 1,12000,12000,25000,1,1,1,1
;Velocity Units - rev/s,rev/s,rev/s,rev/s,rev/s,rev/s,rev/s,rev/s
SCLV 13653,12000,12000,25000,4000,4000,4000,4000
;Acceleration Units - rev/s/s,rev/s/s,rev/s/s,rev/s/s,rev/s/s,rev/s/s,rev/s/s,rev/s/s
SCLA 13653,12000,12000,25000,4000,4000,4000,4000
SCALE1

;-----
```

```
;Setup Program
DEL SETUP
DEF SETUP
FOLMAS 0,0,0,0,0,0,0,0
FOLEN00000000
```

```
;Enable Mode Code
DRIVE00000000
;Drive Setup
;Axis 1, Servo Control, Apex Drive, TURRET
;Axis 2, Servo Control, Other Drive, CYLINDER#2
;Axis 3, Servo Control, Other Drive, CYLINDER#1
;Axis 4, Stepper Control, S Drive, FEEDSTEPPERS
;Axis 5, Servo Control, No Drive
;Axis 6, Servo Control, No Drive
;Axis 7, Servo Control, No Drive
;Axis 8, Servo Control, No Drive
AXSDEF 11101111
DRFLVL 11111111
DRFEN 11110000
KDRIVE 111X0000
DRES,,,25000,,,
PULSE,,,0.3,,,
DSTALL XXX0XXXX
```

```
;Scaling Setup
;Because scaling commands are not allowed in a program,
;the scaling commands will be placed at the beginning
;of the program file. This insures that motion programs
;in subsequent programs will be scaled correctly.
```

```
;Feedback Setup
SFB 1,1,1,,1,1,1,1
ERES 4096,8000,8000,,4000,4000,4000,4000
SMPER 4000,4000,4000,,4000,4000,4000,4000
EFAIL 000X0000
ENCPOL 000X0000
ENCSND 000X0000
ESTALL XXXXXXXX
ESK XXXXXXXX
ENCCNT XXXXXXXX
;Hardware Limit Setup
LH 0,0,0,0,3,3,3,3
LHAD 100,100,100,100,100,100,100,100
LHADA 100,100,100,100,100,100,100,100
```



```
;Software Limit Setup
LS 0,0,0,0,0,0,0,0
LSAD 100,100,100,100,100,100,100,100
LSADA 100,100,100,100,100,100,100,100
LSNEG 0,0,0,0,0,0,0,0
LSPOS 0,0,0,0,0,0,0,0
```

```
;Home Limit Setup
HOMA 10,10,10,10,10,10,10,10
HOMAA 10,10,10,10,10,10,10,10
HOMV 0.25,2,2,1,1,1,1,1
HOMAD 10,10,10,10,10,10,10,10
HOMADA 10,10,10,10,10,10,10,10
HOMBAC 11100000
HOMZ 000xxxxx
HOMDF 100xxxxx
HOMVF 0.1,1,1,0,0,0,0,0
HOMEDG 111xxxxx
```

```
LIMLVL 0000000000000000000000000000
```

```
;Variable Setup
VAR1 = 13653.00000000 ;FSVARR01
VAR2 = -40.00000000 ;FSVARR02
VAR4 = -13653.33300000 ;FSVARR04
VAR5 = 0.98750000 ;FSVARR05
VAR6 = 0.68750000 ;FSVARR06
VAR7 = 0.12500000 ;FSVARR07
VAR8 = 0.00000000 ;FSVARR08
VAR13 = 0.00000000 ;FSVARR13
VAR14 = 0.00000000 ;FSVARR14
VAR15 = 0.00000000 ;FSVARR15
VAR16 = 0.00000000 ;FSVARR16
VAR17 = 0.00000000 ;FSVARR17
VAR18 = 0.00000000 ;FSVARR18
VAR20 = 0.00000000 ;FSVARR20
VARI14 = 0 ;FSVARI14
VARI16 = 0 ;FSVARI16
VARI18 = 0 ;FSVARI18
VAR1 = "0" ;INPUT#OFCUPS
VAR2 = "0" ;SPEEDOFMACHINE
VAR3 = "0" ;ENDPRODUCTION
VAR4 = "0" ;USERERRORINPUT
```

```
INDEB4;
TRGLOT24;
;Onboard Limits
```

LIMFNC 1-1R	;Functions for hardware limit inputs,
LIMFNC 2-1S	;Functions for hardware limit inputs,
LIMFNC 3-1T	;Functions for hardware limit inputs,
LIMFNC 4-2R	;Functions for hardware limit inputs,
LIMFNC 5-2S	;Functions for hardware limit inputs,
LIMFNC 6-2T	;Functions for hardware limit inputs,
LIMFNC 7-3R	;Functions for hardware limit inputs,
LIMFNC 8-3S	;Functions for hardware limit inputs,
LIMFNC 9-3T	;Functions for hardware limit inputs,
LIMFNC 10-4R	;Functions for hardware limit inputs,
LIMFNC 11-4S	;Functions for hardware limit inputs,
LIMFNC 12-4T	;Functions for hardware limit inputs,
LIMFNC 13-5R	;Functions for hardware limit inputs,
LIMFNC 14-5S	;Functions for hardware limit inputs,
LIMFNC 15-5T	;Functions for hardware limit inputs,
LIMFNC 16-6R	;Functions for hardware limit inputs,
LIMFNC 17-6S	;Functions for hardware limit inputs,
LIMFNC 18-6T	;Functions for hardware limit inputs,
LIMFNC 19-7R	;Functions for hardware limit inputs,
LIMFNC 20-7S	;Functions for hardware limit inputs,
LIMFNC 21-7T	;Functions for hardware limit inputs,
LIMFNC 22-8R	;Functions for hardware limit inputs,
LIMFNC 23-8S	;Functions for hardware limit inputs,
LIMFNC 24-8T	;Functions for hardware limit inputs,

LIMLVL 000000000000000000000000

;Onboard Triggers

INFNC 1-A	;Input function assignment
INFNC 2-A	;Input function assignment
INFNC 3-A	;Input function assignment
INFNC 4-A	;Input function assignment
INFNC 5-A	;Input function assignment
INFNC 6-A	;Input function assignment
INFNC 7-A	;Input function assignment
INFNC 8-A	;Input function assignment
INFNC 9-A	;Input function assignment
INFNC 10-A	;Input function assignment
INFNC 11-A	;Input function assignment
INFNC 12-A	;Input function assignment
INFNC 13-A	;Input function assignment
INFNC 14-A	;Input function assignment
INFNC 15-A	;Input function assignment
INFNC 16-A	;Input function assignment
INFNC 17-A	

INLVL 011010110000000000

;Onboard Outputs

OUTFNC 1-A ;Output function assignment, EJECTRELAY  
OUTFNC 2-A ;Output function assignment, FEEDRELAY  
OUTFNC 3-A ;Output function assignment, TUBERELAY  
OUTFNC 4-A ;Output function assignment,  
OUTFNC 5-A ;Output function assignment,  
OUTFNC 6-A ;Output function assignment,  
OUTFNC 7-A ;Output function assignment,  
OUTFNC 8-A ;Output function assignment,

OUTLVL 11100000

;Servo Tuner Setup

SGP 10,8,8,,0.5,0.5,0.5,0.5  
SGI 20,2,2,,0,0,0,0  
SGILIM 75,50,50,,0,0,0,0  
SGV 15,5.2,5.2,,0,0,0,0  
SGVF 0,0,0,,0,0,0,0  
SGAF 0,0,0,,0,0,0,0

;Command Processing Code

;Command Processing During Motion

COMEXC 0

;Enable Mode Code

DRIVE11110000

;Native Code module

WRITE" SETUP COMPLETE"

;Error Setup

;To modify the error bits,

;Please double-click on your Error Program

; Error program setup

ERRORP CRASH ; Error program setup

ERROR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX ; Bits tested

END

;-----

;User Program

;Subroutine to home cylinder one

DEL HMCYL1

DEF HMCYL1

```
;Native Code module  
write"homing cylinder #1"
```

```
;Home Code  
HOM xx1xxxxx
```

```
;Set Position Code  
PSET ,,0,,,,,  
END
```

```
;-----  
;User Program  
;Subroutine to home cylinder 2  
DEL HMCYL2  
DEF HMCYL2
```

```
;Native Code module  
write"homing cylinder #2"
```

```
;Home Code  
HOM x1xxxxxx
```

```
;Set Position Code  
PSET ,0,,,,,  
END
```

```
;-----  
;User Program  
;Subroutine to Home Turret  
DEL HMTUR  
DEF HMTUR
```

```
;Native Code module  
write"homing turret"
```

```
;If Code  
IF(LIM=bx1xxxxx1xx1)  
;Home Code  
HOM 0xxxxxxx
```

```
;Wait Code  
T 1.000
```

```

;Assignment Code
VAR3 = VAR1 +VAR2 ;

;Motion Parameter Code
;Distance
D (VAR3),,,,,,

;Motion Parameter Code
;Velocity
V .25,,,,,,

;Go Code
GO 10000000
;Native Code module
TPE

ELSE
NIF
END

;-----
;User Program
;Subroutine to cut on the feed air
DEL FEEDAR
DEF FEEDAR

;Output Code
OUT x1xxxxxx
END

;-----
;User Program
;Subroutine to turn feeding air off
DEL FDAROF
DEF FDAROF

;Output Code
OUT x0xxxxxx
END

;-----
;User Program
;Subroutine to turn on Tube air
DEL TUBEAR
DEF TUBEAR

```

```
;Output Code
OUT xx1xxxxx
END
```

```
;-----
;User Program
;Subroutine to turn on air to eject cup
DEL EJTAIR
DEF EJTAIR
```

```
;Output Code
OUT 1xxxxxxx
END
```

```
;-----
;User Program
;Subroutine to turn ejection airoff
DEL EJTOFF
DEF EJTOFF
```

```
;Output Code
OUT 0xxxxxxx
END
```

```
;-----
;User Program
;Error subroutine to clear blocked ejection tube
DEL CLRTBE
DEF CLRTBE
```

```
GOSUB AIROFF
;Native Code module
write"***** Error - Ejection Tube Blocked *****\13"
write"*** Make Sure Tube is Clear at Collision End ***\13"
write"***** Press GO Button to Blast Out and Resume *****\13"
```

```
;Wait Code
WAIT(IN=bxxxxx1)
GOSUB EJTAIR
GOSUB TUBEAR
;Wait Code
T 5.000
```

```

;If Code
IF(IN=xxxxxxx1)
;Native Code module
write"***** Failure to Clear Tube -- Still Clogged *****\13"
write"*** Shutting Down -- Manually Clear Tube and Restart ***\13"

```

```

GOSUB CRASH
ELSE
NIF
END

```

```

;-----
;User Program
;Subroutine for sunx 4 sensor at entrance of ejection tube
DEL TUBEIN
DEF TUBEIN

```

```

;Native Code module
TIMST0
;Loop Action
REPEAT
;Assignment Code
VARI9 = VARI9 +1 ;

```

```

;Native Code module
IF (TIM>500)

```

```

write" Tube entrance blocked"
write" ending production"
write" Check air pressure"

```

```

CRASH

```

```

NIF

```

```

UNTIL(IN=xxxx0)
END

```

```

;-----
;User Program
;Cut the freakin air off
DEL AIROFF
DEF AIROFF

```

```

;Output Code

```

```
OUT 000XXXXX  
END
```

```
;-----  
;User Program  
;Subroutine to set feeding steppers motion profile  
DEL STEPS  
DEF STEPS
```

```
;Motion Code  
MA XXX0XXXX  
A ,,100,,,  
AA ,,0,,,  
AD ,,100,,,  
V ,,0.5,,,  
D ,,0.1,,,  
MC XXX0XXXX
```

```
END
```

```
;-----  
;User Program  
;Subroutine to start feeding steppers  
DEL STPSON  
DEF STPSON
```

```
;Go Code  
GO 00010000  
END
```

```
;-----  
;User Program  
;Subroutine to turn stepping motors off  
DEL STPOFF  
DEF STPOFF
```

```
;Native Code module  
k0001
```

```
END
```

```
;-----  
;User Program  
;Subroutine for user stop
```



```

DEL USRSTP
DEF USRSTP

;If Code
IF(IN=xxxxxxx1)

;Native Code module
write" What you stoped me \13"
write" Well ok Initiating User Stop Routine"

;Wait Code
WAIT(IN=xxxxxxx0)
;Native Code module
Write"*** Hit GO button to resume or hit STOP button again to end\13"

;Wait Code
WAIT(IN=xxxxxxx1 OR IN=xxxxxxx1)
;If Code
IF(IN=xxxxxxx1)
;Native Code module
BREAK

; WIZID = 00011560
ELSE
; WIZID = 00011580
;Loop Action
REPEAT
;Native Code module
write" Enter Number For Desired Option -- <!"NUMBER>\13"

write" 1 = Terminate Without Clearing Machine"
write" 2 = Clear Machine and Terminate Production"

VAR4=">"
VARI18 = READ4
WRVARI18

;If Code
IF(VARI18=1)
RUN CRASH
ELSE
NIF

;If Code
IF(VARI18=2)

```

```

;Native Code module
write" Clearing Machine and Terminating Production"

ELSE
NIF

;If Code
IF(VARI18<>1 AND VARI18<>2)
;Native Code module
write" TRY AGAIN, READ INSTRUCTIONS\13"

ELSE
NIF

UNTIL(VARI18=1 OR VARI18=2)
NIF
ELSE
NIF
END

;-----
;User Program
;Subroutine to clear machine
DEL CLRMAC
DEF CLRMAC

;Assignment Code
VARI19 = 3 ;
;Native Code module
write"should do loop"

;Loop Action
REPEAT
;Assignment Code
VARI19 = VARI19 -1 ;

;Motion Code
MA 0XXXXXXX
A 50,,,,,,
AA 0,,,,,,
AD 50,,,,,,
V 5,,,,,,
D (VAR4),,,,,,

```

```

MC 0XXXXXXX

;Go Code
GO 10000000

;Wait Code
T 0.500

GOSUB EJTAIR
UNTIL(VARI19=0)
;Assignment Code
VARI13 = 0 ;

;Assignment Code
VARI18 = 0 ;

END

;-----
;User Program
;Subroutine to read in number of cups to be made
DEL CUPAMT
DEF CUPAMT

;Loop Action
REPEAT
;Native Code module
Write"Input number of cups to be made -- <!\"number>"
VARS1=">"
VARI11 = READ1
WRVARI11

;If Code
IF(VARI11<1)

;Native Code module
Write"YO at least make one cup. Try again.\13"

ELSE
NIF
UNTIL(VARI11>=1)
END

;-----
;User Program

```

```

;Subroutine to set input speeds to make cups
DEL SPEED
DEF SPEED

;Loop Action
REPEAT

;Native Code module
write"Input Machine Speed from 20 cup/min to 100 cups/min"

write"Min. 20 cups/min Max. 100 cups/min"
write"***ONLY INPUT SPEEDS BY INCREMENTS OF 20 CUPS/MIN***"

write"Input Machine Speed -- <!'cups/min>"

VARS2=">"
VAR20 = READ2
WRVAR20

;If Code
IF(VAR20=20)
;Assignment Code
VAR13 = 1 ;

;Assignment Code
VAR14 = 50 ;

;Assignment Code
VAR15 = 5 ;

;Assignment Code
VAR16 = 200 ;

;Assignment Code
VAR17 = 0.5 ;

;Assignment Code
VAR18 = .300 ;

ELSE
NIF
;If Code
IF(VAR20=40)
;Assignment Code

```

VAR13 = 5 ;

;Assignment Code  
VAR14 = 50 ;

;Assignment Code  
VAR15 = 10 ;

;Assignment Code  
VAR16 = 400 ;

;Assignment Code  
VAR17 = 0.2 ;

;Assignment Code  
VAR18 = 0.2 ;

ELSE  
NIF

;If Code  
IF(VAR20=60)

;Assignment Code  
VAR13 = 15 ;

;Assignment Code  
VAR14 = 60 ;

;Assignment Code  
VAR15 = 20 ;

;Assignment Code  
VAR16 = 600 ;

;Assignment Code  
VAR17 = 0.2 ;

;Assignment Code  
VAR18 = 0.100 ;

ELSE  
NIF

;If Code  
IF(VAR20=80)  
;Assignment Code

VAR13 = 100 ;

;Assignment Code

VAR14 = 125 ;

;Assignment Code

VAR15 = 100 ;

;Assignment Code

VAR16 = 800 ;

;Assignment Code

VAR17 = 0.001 ;

;Assignment Code

VAR18 = 0.010 ;

ELSE

NIF

;If Code

IF(VAR20=100)

;Assignment Code

VAR13 = 100 ;

;Assignment Code

VAR14 = 150 ;

;Assignment Code

VAR15 = 100 ;

;Assignment Code

VAR16 = 1000 ;

;Assignment Code

VAR17 = 0.075 ;

;Assignment Code

VAR18 = 0.010 ;

ELSE

NIF

;If Code

IF(VAR20<>20 AND VAR20<>40 AND VAR20<>60 AND VAR20<>80 AND  
VAR20<>100)

```
;Native Code module
write" Hold on buddy! "
write" READ a little closer"
write" Try Again to enter a correct value"
```

```
ELSE
```

```
NIF
```

```
UNTIL(VAR20=20 OR VAR20=40 OR VAR20=60 OR VAR20=80 OR VAR20=100)
END
```

```
;-----
```

```
;User Program
```

```
;Subroutine to feed cups
```

```
DEL FEEDIN
```

```
DEF FEEDIN
```

```
;If Code
```

```
IF(VARI20>VARI14)
```

```
;Loop Action
```

```
REPEAT
```

```
;If Code
```

```
IF(IN=b10)
```

```
; WIZID = 00013480
```

```
RUN STPOFF
```

```
; WIZID = 00013500
```

```
;Command Processing Code
```

```
;Command Processing During Motion
```

```
COMEXC 0
```

```
;Native Code module
```

```
Write" Cup Already There"
```

```
Break
```

```
ELSE
```

```
;Command Processing Code
```

```
;Command Processing During Motion
```

```
COMEXC 1
```

```
RUN STPSON
```

```

RUN FEEDAR
;Native Code module
write"Feeding Cups"

NIF
;If Code
IF(IN=bx1)
  RUN STPOFF
  ;Command Processing Code

  ;Command Processing During Motion
  COMEXC 0
  ;Native Code module
  write" Cup Fed"

  RUN FDAROF

  ;Wait Code
  T 0.125

ELSE

NIF

;If Code
IF(IN=b111)

  ;Native Code module
  write"      ***** Cup Hung *****"
write"    *** DANGER -- Open Door ***"
write" *** Remove or Replace Cup Error ***"
write"***** Press GO Button to Continue *****\13"

  RUN STPOFF

  RUN FDAROF
  ;Command Processing Code

  ;Command Processing During Motion
  COMEXC 0
  ;Wait Code
  WAIT(IN=bxxxxx1)

ELSE
NIF

```



```

;If Code
IF(IN=b11 AND IN=bx0)
;Native Code module
write"***** Double Feed Condition *****"
write"**** Feed Error -- Two Cups in Holder ****"
write"***** or One Not Fully Down *****"
write"***** Initiating Error Sequence *****\13"

RUN STPOFF
RUN FDAROF
;Command Processing Code

;Command Processing During Motion
COMEXC 0
;Wait Code
T 1.000

;Native Code module
write"***** Indexing backwards to Clear *****"

;Motion Code
MA 0XXXXXXXX
A (VAR14),,,,,,
AA 0,,,,,,
AD (VAR14),,,,,,
V (VAR13),,,,,,
D (VAR1),,,,,,
MC 0XXXXXXXX

;Go Code
GO 10000000
;Native Code module
write" ***** DANGER -- Use Caution ***** "
write"***** Open Door and Remove Extra Cup *****"
write"**** or Press Single Cup Down into Die ****"
write"**** Close Door and Press GO Button ****"
write"***** When Ready and All is Clear *****\13"

;If Code
IF(VARI14<>1)
;Assignment Code
VARI14 = VARI14 - 1 ;

ELSE

```

```

NIF
;Wait Code
WAIT(IN=bx0 AND MOV=b0)

ELSE
NIF
;If Code
IF(IN=bx0)
;Native Code module

        Write" Out of Cups "
        Write" Please Feed The Monster"
        RUN STPOFF
        RUN FDAROF
        COMEXC0

        wait(IN=bx0)
        write" Thanks for your support"

ELSE
NIF
UNTIL(IN=b1 AND IN=b0)

ELSE

NIF
END

;-----
;User Program
;Subroutine to loop for cups
DEL MKCUPS
DEF MKCUPS

; WIZID = 00014480
;Loop Action
REPEAT

RUN CUPAMT

RUN SPEED
GOSUB STEPS
;Assignment Code

```

VARI11 = VARI11 +3 ;

;Loop Action  
REPEAT

;Assignment Code  
VARI10 = VARI11 ;

;Assignment Code  
VARI20 = VARI10 -2 ;

;Assignment Code  
VARI14 = 0 ;

; WIZID = 00014660  
;Assignment Code  
VARI16 = 0 ;

; WIZID = 00014680  
;Native Code module  
write" Keep all hands and legs inside the vehicle at all times \13"

WRITE" Now press GO button to start production"

;Wait Code  
WAIT(IN=bxxxxx1)

RUN TUBEAR

;Loop Action  
REPEAT

;Assignment Code  
VARI14 = VARI14 +1 ;

;Assignment Code  
VARI13 = VARI10 -VARI14 ;

;Native Code module  
TIMST0  
RUN TUBEIN

;Loop Action  
REPEAT

```

;If Code
IF(IN=xxxxxxx1)
;Native Code module

write"*** Allowing Tube to Clear ***\13"

IF (TIM>500)

        CLRTBE

NIF

ELSE
NIF

UNTIL(IN=xxxxxxx0)

GOSUB FEEDIN
;If Code
IF(VAR14<2)
;Motion Code
MA 0XXXXXXX
A (VAR14),,,,,,
AA 0,,,,,,
AD (VAR14),,,,,,
V (VAR13),,,,,,
D (VAR4),,,,,,
MC 0XXXXXXX

;Go Code
GO 10000000
ELSE
NIF
;If Code
IF(VAR14=2)
;Motion Code
MA 0XXXXXXX
A (VAR14),,,,,,
AA 0,,,,,,
AD (VAR14),,,,,,
V (VAR13),,,,,,
D (VAR4),,,,,,
MC 0XXXXXXX

;Go Code
GO 10000000

```

```
;Motion Code  
MA XX1XXXXX  
A ,(VAR16),,,,,  
AA ,,0,,,,,  
AD ,(VAR16),,,,,  
V ,(VAR15),,,,,  
D ,(VAR5),,,,,  
MC XX0XXXXX
```

```
;Go Code  
GO 00100000
```

```
;Motion Code  
MA XX1XXXXX  
A ,(VAR16),,,,,  
AA ,,0,,,,,  
AD ,(VAR16),,,,,  
V ,(VAR15),,,,,  
D ,(VAR7),,,,,  
MC XX0XXXXX
```

```
;Go Code  
GO 00100000  
ELSE  
NIF
```

```
;If Code  
IF(VARI14>=3 AND VARI13>1)  
RUN EJTAIR
```

```
;Motion Code  
MA 0XXXXXXXX  
A (VAR14),,,,,,  
AA 0,,,,,,  
AD (VAR14),,,,,,  
V (VAR13),,,,,,  
D (VAR4),,,,,,  
MC 0XXXXXXXX
```

```
;Go Code  
GO 10000000
```

```
;Motion Code  
MA X11XXXXX  
A ,(VAR16),(VAR16),,,,,  
AA ,0,0,,,,,
```

AD ,(VAR16),(VAR16),,,,,  
V ,(VAR15),(VAR15),,,,,  
D ,(VAR6),(VAR5),,,,,  
MC X00XXXXX

;Go Code  
GO 01100000

;Motion Code  
MA X11XXXXX  
A ,(VAR16),(VAR16),,,,,  
AA ,0,0,,,,,  
AD ,(VAR16),(VAR16),,,,,  
V ,(VAR15),(VAR15),,,,,  
D ,(VAR8),(VAR7),,,,,  
MC X00XXXXX

;Go Code  
GO 01100000

RUN EJTOFF

ELSE  
NIF

;If Code  
IF(VARI13=1)

RUN EJTAIR

;Motion Code  
MA 0XXXXXXXX  
A (VAR14),,,,,,  
AA 0,,,,,,  
AD (VAR14),,,,,,  
V (VAR13),,,,,,  
D (VAR4),,,,,,  
MC 0XXXXXXXX

;Go Code  
GO 10000000

;Motion Code  
MA X1XXXXXXXX  
A ,(VAR16),,,,,,  
AA ,0,,,,,

AD ,(VAR16),,,,,,  
V ,(VAR15),,,,,,  
D ,(VAR6),,,,,,  
MC X0XXXXXXX

;Go Code  
GO 01000000

;Motion Code  
MA X1XXXXXXX  
A ,(VAR16),,,,,,  
AA ,0,,,,,  
AD ,(VAR16),,,,,,  
V ,(VAR15),,,,,,  
D ,(VAR8),,,,,,  
MC X0XXXXXXX

;Go Code  
GO 01000000

RUN EJTOFF

ELSE  
NIF

;If Code  
IF(VARI13=0)

RUN EJTAIR

;Motion Code  
MA 0XXXXXXX  
A (VAR14),,,,,,  
AA 0,,,,,  
AD (VAR14),,,,,,  
V (VAR13),,,,,,  
D (VAR4),,,,,,  
MC 0XXXXXXX

;Go Code  
GO 10000000

;Wait Code  
T 1.000

RUN EJTOFF

```

ELSE
NIF

RUN USRSTP

;If Code
IF(VARI18=2 OR VARI18=3 OR VARI18=4)

    RUN CLRMAC

ELSE
NIF

UNTIL(VARI13=0)

;Wait Code
T 2.000

GOSUB AIROFF

;If Code
IF(VARI16=0)

    RUN QUERY

ELSE
NIF

UNTIL(VARI16<>3)
UNTIL(VARI16<>4)

;Native Code module
write" That's All Folks\13"
write" The Program is Finished"

DRIVE000
HALT

END

;-----
;User Program
;Subroutine to ask operator what to do next after production has ended
DEL QUERY

```



DEF QUERY

```
;Native Code module
write"* ***** End of Production Cycle *****\13"
write" ***** Choose End Option *****\13"
```

```
;Loop Action
REPEAT
```

```
;Native Code module
write" Enter Number For Desired Option -- <!'Number>\13"
write" 1 = Terminate Production"
write" 2 = Run Again With Same Parameters"
write" 3 = Run Again With New Parameters"
```

```
VAR3 = ">"
VARI15 = READ3
WRVARI15
```

```
;If Code
IF(VARI15=1)
```

```
;Assignment Code
VARI16 = 2 ;
```

```
;Native Code module
write"Production Terminated"
```

```
ELSE
NIF
```

```
;If Code
IF(VARI15=2)
```

```
;Assignment Code
VARI16 = 3 ;
;Native Code module
write"Here we go again"
```

```
ELSE
NIF
```

```
;If Code
```

```

IF(VARI15=3)

;Assignment Code
VARI16 = 4 ;

;Native Code module
write"OK lets go again with changed parameters"

ELSE
NIF

;If Code
IF(VARI15<>1 AND VARI15<>2 AND VARI15<>3)

;Native Code module
write" YOU HAVE ENTERED A BAD VALUE \13"
write" TRY AGAIN"
ELSE
NIF

UNTIL(VARI15=1 OR VARI15=2 OR VARI15=3)
END

;-----
;Main Program
DEL MAIN
DEF MAIN

RUN SETUP
RUN HMCYL1
RUN HMCYL2
RUN HMTUR
GOSUB MKCUPS
END
STARTP CLR

;-----
;Error Program
DEL CRASH
DEF CRASH

RUN AIROFF

;Enable Mode Code
DRIVE000XXXXX

```

```
;Native Code module  
write"OH NO You Broke MY Machine\13"  
write" Now you can fix it I am just a computer\13"  
write" Therefore after the necessary repairs run setup again and start over"
```

```
Halt
```

```
END
```