Project Number: 11582

PCC AUTOMATED RIVET INSPECTION SYSTEM

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ABSTRACT

The goal of this project was to design and construct an inspection tool to measure and validate critical rivet dimensions in high volumes and consolidate the inspection data for use in a real time statistical control process. The customer, Cherry Aerospace, will use the product to reduce inspection costs and accurately document dimension analysis. The final design needed to be usable by personnel with minimal training and provide a go/no-go indication to the operator.

The inspection system utilized a Keyence High Speed LED/CCD optical micrometer, with a custom LabVIEW program for data capture and analysis. The team furthermore designed and manufactured linear and rotational stages and mounts to ensure that the measurements are taken precisely.

This project is working in conjunction with another project for PCC, P11581. P11581 designed and constructed an automated tool to measure, inspect, and validate critical thread roll die dimensions. Many of the aspects of both projects are shared between the teams.

Through proper design, assembly and testing, this system will meet as many of the required performance specifications as possible.

INTRODUCTION & BACKGROUND

Cherry Aerospace is a member of the SPS Fastener Division of Precision Castparts Corporation (PCC). Cherry is headquartered in Santa Ana, California and is a global leader in the design and manufacture of fastening systems for the aerospace industry.

Cherry manufactures pull-type rivets for aerospace applications that are produced in large batches and need to adhere to the acceptable tolerances allowed. A sample of rivets is taken from the produced lots for inspection. Presently, the key parameters of these rivets are measured manually by technicians through the use of micrometers and other metrology instruments. Cherry has been examining the market for a comparable product that would automatically measure and output the results they require.

The lack of an automated inspection tool has posed some risks for the Cherry Aerospace Facility. The current insufficient inspection capacity prevents Cherry from delivering product on time in accordance with customer demand. The additional necessary utilization of temporary and overtime labor is preventing Cherry from achieving cost reduction goals. Furthermore, the possible failure to satisfy customer demand will jeopardize their ability to sustain and grow its current customer base.

Due to the significance of this project the desired state of the final product is crucial. It will be needed to attain a state of inspecting all of the

critical attributes of a rivet. Cherry would like to be able to increase the inspection capacity and inspect the critical attributes of high volume product lines. Additionally, the ability to track the data analysis output from the program will be essential for Cherry to establish statistical process control.

CUSTOMER NEEDS

The automated rivet inspection system was started to improve the inspection department productivity and reduce the department costs. Depending on the outcome of this project the inspection system could be implemented in numerous PCC facilities throughout the world.

Through several phone conferences and emails with employees from PCC, the team was able to generate three main categories that the design architecture would be focused and ranked by overall importance. The categories were: System Needs, Physical Measurement, and Data Processing. The completed set presented to the customer can be seen in Figure 1.

Customer Need #	Importance	Description
		System Needs
CN1	9	Simple user interface (Go/NoGo) for operators
CN2	9	Available 'technician mode' showing more options & features
CN3	9	Switch between different rivet models with minimal set up
CN4	3	Relatively portable (fits on cart top ~ 1-2 sqft)
CN5	3	Shielding to help withstand manufacturing environment
CN6	9	Training documentation provided with system
CN7	3	Low cost
CN8	1	Tests multiple parts at once
CN9	1	Autoloading
		Physical Measurement
CN10	1	Improved cycle time over hand measurement
CN11	9	Compatable with a variety of rivet models
CN12	9	Holds part without damaging it
CN13	3	Capable of measuring along entire length of rivet
CN14	3	Capable of rotating part 360 deg around main axis
CN15	9	Measures rivet body diameter ("D")
CN16	9	Measures rivet body length ("L")
CN17	9	Measures rivet body roundness
CN18	9	Measures rivet head diameter ("A")
CN19	9	Measures rivet head protrusion ("B")
CN20	3	Measures rivet head land thickness ("0.010 / 0.002")
CN21	9	Measures stem diameter
CN22	9	Measures stem length
CN23	9	Measures mandrel diameter
CN24	1	Measures mandrel roundness
CN25	9	Check that mandrel meets length requirement
CN26	3	Measures concentricity of rivet body to mandrel
CN27	1	Measures undercut angle
CN28	1	Measures undercut round
CN29	1	Checks presence of indented circle
CN30	1	Checks presence of washer
		Data Processing
CN31	9	Analyze data to accurately determine measured values
CN32	9	Veryify conformance of part based on input limits
CN33	3	Local storage of recorded measurements
CN34	1	Able to recall data saved locally
CN35	3	Perform SPC tracking from local data
CN36	9	Capable of transfering data to SQL server
CN37	9	Storage of multiple limit sets and analysis routines

Figure 1: Customer Needs

ENGINEERING SPECIFICATIONS

Once the needs were identified, a set of engineering specs and metrics were assembled. All of the specifications and metrics have marginal and target values along with measureable unit denominations. These specs and metrics were also given rankings of importance. These rankings coincided with the overall importance of the customer needs. Each of the defined metrics were approved with the customer on importance, ideal and marginal values to ensure that the final product would meet their needs.

Upon confirmation from the customer on the specifications the team developed a variety of design ideas to meet the customer needs and specifications.

DESIGN PROCESS

Once the customer needs and engineering specifications were clearly defined and confirmed by the customer the team assembled a functionality diagram to break the task into manageable sub-functions. The main sub-functions were presenting the rivet for measurement, measuring the critical dimensions of the rivet, interpreting the results, and providing structure and protection for the overall system. These were further broken down into another layer of sub-functions to capture and define all of the key processes for the team to develop and capture during the design process.

A morphological analysis was applied to systematically analyze multiple forms of a solution for each of the main sub-functions described above. Measure rivet and interpret results were bundled into one group for solutions. This was due to the various forms of measuring solutions including software for interpreting. The team assembled four possible solutions for each sub-function.

Pugh charts were applied to compare design solutions determined in the morphological analysis against one another. Pugh charts choose a datum, a standard position, and conduct a pair-wise comparison of the solutions. The team performed two analyses using two different datums to ensure that the best solution emerged.

Based on the outcome of the Pugh charts, four design proposals were assembled and

provided to the customer. A listing of the pros and cons were presented along with each of the design solutions. The four solutions presented were a Digital Micrometer with Linear and Rotational Stage Motion System, a 2D Laser Profile Scanner with Linear and Rotational Stage Motion System, a Vision Camera and Rotational Stage and a Coordinate Measurement Machine (CMM). The CMM was used as a base comparison for the best possible measurement tool, however the scope of the project did not allow for the purchase of this machine.

Each design was presented to PCC with the team recommendations and the final design conclusion was further confirmed by the customer. The final design chosen was to use a Digital Micrometer in conjunction with a linear and rotational stage motion system. Figure 2 contains an isometric view of the design system chosen. The various possible risks were considered after choosing an acceptable solution. Each risk was provided an action item to help minimize the risk.
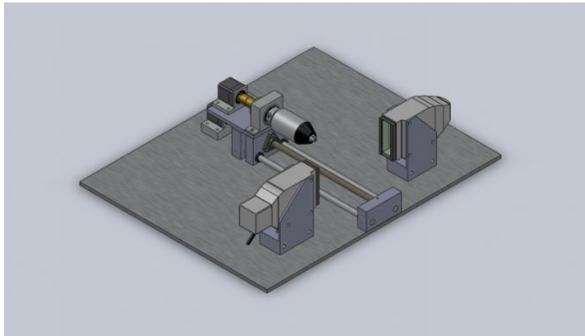

Figure 2: System Isometric View

The assortment of components to complete the project went through a critical design selection process. The components included the linear and rotational stages, the chuck, stepper motors, motion controller, and digital micrometer. Each component went through a design selection process that had to provide a minimum of 3 options for each component in addition to the specifications outlined, and advantages and diadvantages for each option.

FABRICTION

The majority of the components were manually fabricated using RIT's machine shop.

Linear/Rotational Stage

The end blocks for the linear stage were cut roughly to thickness from a 2"x3"x24" piece of aluminum stock using a band saw. The roughly cut blocks were then brought to size using a three-axis mill where the linear guide holes, rail and mounting holes were also added.

The stage blocks themselves were fabricated in similar fashion. Two stage blocks were used to provide more stability and to eliminate vibrations due to the weight and moment produced by the chuck. A large center hole was reamed out to allow mounting and clearance for the anti-backlash drive nut on one block, and clearance on the other block. Mounting holes for the stage plate and linear guide bearings were added to the top and face of the blocks, respectively.

The stage platform was made from a piece of ¼" stock aluminum. The plate was again cut roughly to size using the band saw, and was then finished on the mill. Mounting holes for the stage blocks, motor mount, and spindle block were added.

The lead screw was turned down to ¼" diameter on each end using a lathe to allow it to be coupled to the motor and so that the ball bearings could be mounted to it.

The spindle block was fabricated from the same piece of stock aluminum as the end and stage blocks. Large, precision holes were reamed for the angular contact bearings.

Digital Micrometer Mounts

The digital micrometer mounts are composed of three separate parts: a mounting block on the bottom and two side plates.

The mounting blocks were made from the 2"x3"x24" piece of aluminum stock. They were brought to size using the three-axis mill, where the baseplate mounting holes and side plate mounting holes were added.

The side plates were made from a piece of 1/8" thick stock aluminum. They were cut to size using a stomp shear, and holes were once again added on the mill.

Motor Mounts

The motor mounts are composed of two components: the mounting block and the faceplate.

The mounting blocks were again made from the 2"x3"x24" piece of aluminum stock. The band saw was used to bring them roughly to size and they were finished on the mill.

The faceplates were made from the 1/8" thick piece of stock aluminum, and were again cut to size using the stomp shear. The mounting holes and motor clearance hole were added using the mill.

Shaft couplings also had to be custom made, due to the variance in shaft sizes. These were fabricated from a ¾" piece of aluminum round stock. The different diameter holes were added using the lathe. They were then cut roughly to length using the band saw, before being brought to their final length on the lathe. Set screw holes were then added on the mill.

Arbor

In order for the holding and rotating configuration that we designed to be successful, several modifications needed to be made to the arbor. First, a hard stop needed to be machined and placed onto the front end of the arbor. We bored a hole out of the front end of the arbor and pressed a pin into it. The pin was then turned down in a lathe to the appropriate diameter in order to provide a stop for any rivet placed into the chuck and at the same time have the jaws able to close and clamp down on the rivet and not the stop. Second, the back of the arbor needed to be coupled to the shaft of the motor. In order for this to take place, the back diameter of the arbor needed to be the same as the motor shaft. A hole was bored into the back of the arbor and another pin was pressed into it. Again, the pin was turned down in a lathe to the proper diameter. The final modification needed for the arbor was to thread the back end. Since the arbor was hardened, we were actually unable to thread the arbor itself. To solve this problem, we bored a hole through a set screw with the proper thread sized. We then took the arbor and ground down the back end to a smaller diameter. Finally, we pressed the set screw over the back end of the arbor to bring it

back to the appropriate diameter while still having the necessary threads.

Enclosure

The system's enclosure is made out of 80/20 aluminum and plexi-glass. The 80/20 was roughly cut to size with a band saw and then trimmed to a more accurate size with a mill. The ends of each piece were hand tapped and holes were drilled into the 80/20 at appropriate locations in order to fasten all the pieces together. The plexi-glass was simply cut to needed size with a saw.

PROGRAMMING

Data processing and analysis was performed using a custom built LabVIEW program. LabVIEW was chosen for its versatility and ease of use with regards to device communication and code implementation. As per customer requirements, the system must be simple enough that an operator with minimal experience can use it, but must also provide detailed information to the engineer. To satisfy this, the front panel consists of multiple tabs, including initialization, rivet testing, detailed data viewer, advanced settings, and shutdown.

The initialization sequence consists of four major operations which must be performed prior to actually testing any rivets. These initialization procedures must be run after machine start-up or re-start, in the event of a system malfunction. The first initialization sequence sets up operating parameters of the Keyence optical micrometer. This is done by sending ASCII commands through a serial RS-232 interface between the computer and micrometer controller. The controller receives a setting change command and echoes back the command to confirm the change has been made. Setting changes that can be made include the OUT1 and OUT2 measurement types, OUT1 and OUT2 averaging values, and panel lock. To prevent improper setting, changes must be made from the Advanced Settings tab. Once all commands have been sent and confirmed, the micrometer setup is considered ready. If a setting change is required, this routine can be run anytime. The second portion of initialization is for the motion control hardware. ASCII strings are sent to the motion controller to select each motor and establish the startup and top speeds.

The motor setup sequence also homes both motors. This requires that the linear stage is initially closely in front of the linear homing sensor. In the case that it is not, the operator can run the sequence multiple times until it reaches correct position, or can physically turn the lead screw to put the stage in position. After initializing the motors, the third initialization routine is to simply move the linear stage to its start position, where it can be loaded with a part. This is performed by sending a single command telling the linear motor to move an appropriate number of steps. The final initialization step is the system calibration check. A notched gauge pin is loaded into the chuck, and is then measured by the micrometer as the linear stage is moved in. The measured diameter over the entire length must fall within the limits of the gauge pin. The measured length from the end of the pin to the notch is used to confirm the linear stage constant (change in linear position for one motor step). Finally the known total gauge pin length is used to determine the position of the chuck's hard stop, which located at the end position of the part to be measured. After each initialization sequence is run, it is assigned a status of 'ready' through a light indicator in the program. Only once all four sequences are ready is the system ready for rivet measurement.

The first stage of data analysis interprets data obtained during the linear motion of the rivet. As the rivet is slowly moved through the optical micrometer, a repeating while-loop continually records values of the optical micrometer diameter reading (D) and bottom edge positions (Y), as well as the linear step motor position (X). These values are stored in 1D arrays. An additional array representing the center of the measured part (C) is obtained by adding each element of the X with half of the corresponding D element. A LabVIEW routine was developed to use this data, along with part specs and user inputs, to determine the locations of key features of the rivet. The process begins by reversing the data arrays to start with data from the rivet stem side. The routine then steps through the array data until certain features are found based on search criteria. When this occurs, the array index is stored and used later for position and length calculation. The routine then continues from this position, searching for the next feature. Table X

shows the trigger and error conditions for finding the features of a flush head rivet.

Feature	Trigger	Error Conditions
Start of stem	$D_i > 0$	$D_i > \text{Ddia}_{max}$
Start of sleeve	$D_i > \text{Ddia}_{min}$	$D_i > 1.1 \text{ x Ddia}_{max}$
Start of head	$D_i > \text{Ddia}_{max}$	$D_i > \text{Ddia}_{max}$
Start of land	$D_i < D_{i-1}$	i x LSC x steps/scan < 0.25 x Bref i x LSC x steps/scan > 1.25 x Bref
End of head	$|D_i - D_{i-5}| > 0.04$	i x LSC x steps/scan > LandThickness$_{max}$ + 0.01
End of washer	$|D_i - D_{i-8}| > 0.75$ x (WasherDia - MandrelDia)	i x LSC x steps/scan > HeadToMandrel Length
Start of mandrel serrations	$D_i < 0.98$ x MandrelDia	i x LSC x steps/scan > 1.5 x HeadToMandrel Length
Start of chuck bodies	$D_i > 0.75$	i x LSC x steps/scan > 1.5 x HeadToMandrel Length

D_i is the diameter of the current step, Ddia is the D diameter specification, i is the current step, and LSC is the linear stage constant. A similar sequence is also followed for universal head type rivets. When the array indexes of all the above features are determined, the corresponding step values are gathered from the X array. Length values can be obtained by subtracting step values and multiplying by the linear stage constant.

To ensure the accuracy of the above linear measurements, the hold angle of the part is calculated. Between the start of sleeve and start of head, two values of C and corresponding X are captured and used to calculate the hold angle, Φ, of the part, as follows,

$$\emptyset = \tan^{-1}\left(\frac{C(x_1) - C(x_2)}{(x_1 - x_2) \times LSC}\right)$$

If the hold angle is greater than a set limit, the routine may not be able to accurately find key features. This may occur as the result of a misloaded part or an excessively bent mandrel. If this occurs, an error message will be displayed and the linear stage will return to the start position. For a flush head rivet, the head angle is also calculated. The angle of the bottom edge is calculated by

$$\gamma_1 = \tan^{-1}\left(\frac{Y(x_1) - Y(x_2)}{(x_1 - x_2) \times LSC}\right)$$

The corresponding top edge angle, γ_2, is found similarly, with top edge values in place of the bottom edge values shown in the equation above. The top edge value at an x position is the sum of the bottom edge and diameter values. The

final value for head angle γ is the sum of γ_1 and γ_2.

After the linear analysis sequence is complete, the rotational analysis begins. User inputs on the Advanced Settings tab determine how many rotational scans to perform for each of three segments: stem, sleeve and head. The start and end positions of each feature are already known from the linear analysis. For each segment the total length, in steps, is divided by $N + 1$, in which N is the number of rotational scans for that segment. This yields the total count of steps that the linear motor must be driven before and after rotational scans.

During the rotational scans, diameter and bottom edge measurements are recorded for every 1.8° of rotation. The diameter values may contain information about the roundness of the segment, but also will contain error if the part does not lie perfectly horizontally. The hold angle Φ is calculated for each rotational angle θ by

$$\emptyset(\theta) = \tan^{-1}\left(\frac{C_{x1}(\theta) - C_{xN}(\theta)}{(x_1 - x_N) \times LSC}\right)$$

in which $C_{x1}(\theta)$ and $C_{x2}(\theta)$ are calculated values of center position at each rotational angle, at linear positions x_1 and x_N, respectively. The positions x_1 and x_N represent the location of the first and last scans for a segment. Once the hold angle for a full rotation is known, the corrected diameter, D_c, is calculated, where

$$D_c(\theta) = D(\theta)\cos(\emptyset(\theta))$$

The values of D_c over each full rotation are averaged to yield the diameter value. Additionally the roundness for that segment is found by

$$R = 0.5(D_{c,max} - D_{c,min})$$

Finally, the concentricity between segments is found by extending center lines of each segment to a midpoint, x_{mid}, and calculating the length between the crossings of the center lines and the midpoint line. This is performed for each rotational angle. x_{mid} is found by

$$x_{mid} = 0.5(x_{A,N} + x_{B,1})$$

where subscripts A and B denote different segments, and N and 1 represent the Nth and 1st rotations on those segments, respectively. The

position that the center line of the first segment intersects the midpoint line is

$$C_{A,mid}(\theta) = (x_{mid} - x_{A,1})\left(\frac{C_{A,N}(\theta) - C_{A,1}(\theta)}{x_{A,N} - x_{A,1}}\right) + C_{A,1}(\theta)$$

Similarly, the intersection of the second segment center line and the midpoint line is

$$C_{B,mid}(\theta) = C_{B,N}(\theta) - (x_{B,N} - x_{mid})\left(\frac{C_{B,N}(\theta) - C_{B,1}(\theta)}{x_{B,N} - x_{B,1}}\right)$$

With these values known for each rotational position, the concentricity is found as the max value of all

$$Conc = |C_{B,mid}(\theta) - C_{A,mid}(\theta)|\cos(\emptyset(\theta))$$

After the rotational sequence is performed, the linear stage returns to the start position. Displays on the detailed data screen are updated with all calculated values. Calculated values are compared against specs found in a linked spec file, and the pass/fail determination is calculated for each. If all values pass, the operator is notified by an "overall pass" LED on the rivet testing tab. In addition, a csv file is written with all the pertinent test information. The file contains a header section with test information including test timestamp, unit ID, operator ID, rivet model, lot number, part number, and inspection type. Following this is the data section, which contains measured dimensions, specifications, and pass/fail evaluations. Also included is a calibration section, which includes all current calibration setting information.
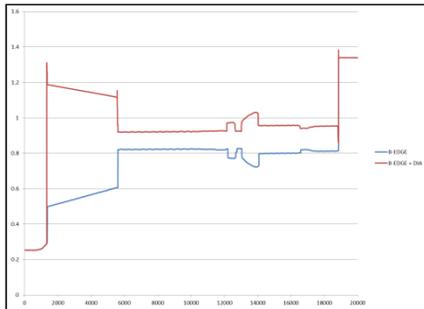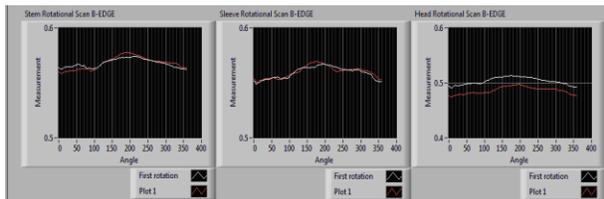
TESTING

Linear Scan:
First test results:

Improvements:

1) Added second stage block for balance and stabilization of the linear stage.

2) Replaced bearings with self-aligning linear bearings at all four contact points for smoother

3) Adjusted the position of the anti-backlash nut to improve the alignment of the lead screw
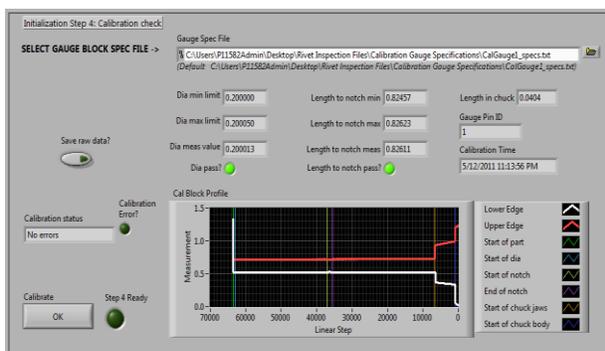
Second test results:

Rotational Scan:

Once the rotational setup was constructed and working mechanically, there were no adjustments made to change how the data was acquired. Measurements were taken was part of the complete system LabVIEW scan.

Calibration Routine:

A LabVIEW run sequence was written in order to check the calibration of the machine. Using a precision gauge pin, known data was entered with desired tolerances. As long as the measures fell within the tolerance lengths and diameters, the system was in proper calibration. It will be recommended to Cherry Aerospace to run

this calibration sequence every time the machine is turned on in order to make sure system stays within calibration requirements.

Complete System Scan:
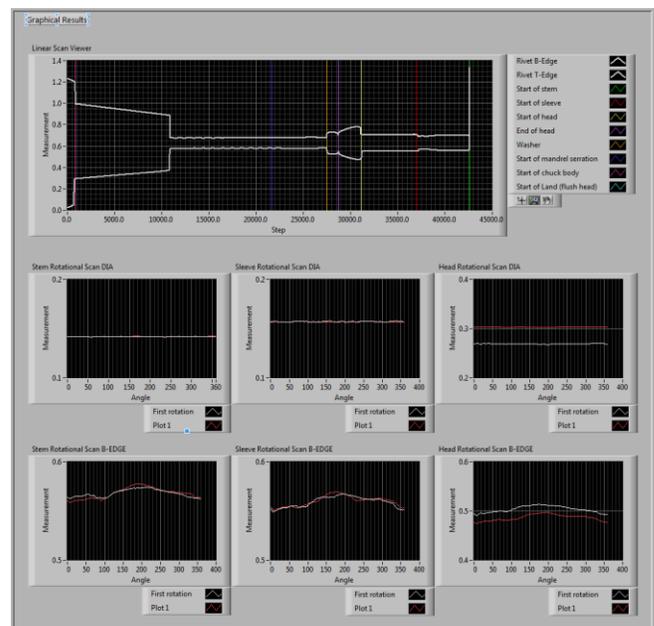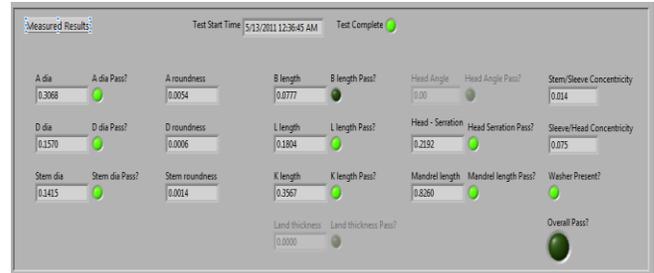
Final test of the system was a complete rivet scan using the LabVIEW sequence written. Data was recorded, linear data was scanned the image was plotted as well as the rotational data.

RESULTS AND DISCUSSION

Based on the individual test results the project has met the deliverables. The test demonstrated that the system adequately measures and analyzes the rivet dimensions as outlined in the engineering specifications.

The overall time to scan a rivet and interpret the data is approximately two minutes. This time is slightly over our original predicted marginal value for cycle time. However, the customer had stressed the importance of being able to obtain

the desired measurements over the importance of the cycle time. The cycle time of the device can be easily improved through slight changes to the system.

CONCLUSIONS AND RECOMMENDATIONS

Our findings are that the automated inspection system meets the customer needs. The system is able to correctly analyze a rivet and the program provides a "go/no go" interface to be used by an operator.

For the system as a whole, the overall cycle time to scan and measure the rivet can be improved. The size of the stepper motors that were purchased limited the speed of the movement of the device. A larger motor could move the stages at a faster speed and decrease a significant portion of the time to scan the rivet.

The linear and rotational stages of the device could be altered for better precision and movement. The majority of the parts for the machine were hand machined in the RIT's machine shop. By using a CNC machine the precision could be improved significantly with less room for variability. Alternatively, purchasing pre-fabricated stages would allow the company to avoid any misalignment between the motors and the lead screw. They would also reduce the noise component that is currently introduced during the running of the device.

The programming portion of the device would be enhanced through the integration of statistical process control (SPC) tracking. SPC would allow the company to track changes that occur in a lot and catch any slight variations that occur during processing.

ACKNOWLEDGMENTS