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In-Process Hole and Fastener Inspection Using a High-Accuracy Laser Sensor

Zachary Luker and Erin Stansbury Electroimpact Inc.

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Abstract

Electroimpact has produced a new in-process inspection system for use on drilling and fastening systems. The system uses a high-accuracy, non-contact, laser system to measure the flushness of installed fasteners. The system is also capable of measuring part normality and providing feedback to the machine for correction. One drawback to many automatic inspection systems is measurement error. Many sources of measurement error exist in a production environment, including drilling chips, lubrication, and fastener head markings. Electroimpact's latest system can create a visualization of the measured fastener for the operator to interpret. This allows the operator to determine the cause of a failed measurement, thus reducing machine downtime due to false negatives.

Electroimpact created a custom C# WPF application that queries the point-cloud data and analyzes the raw data. A custom "circle Hough transform" scoring algorithm is used to find the center of the nosepiece (pressure foot). A best fit plane is calculated from the point cloud data to find the panel surface. This plane is then used to output panel normality in the A and B axes. Flushness is determined by computing the distance of each point in the fastener point-cloud to the best fit plane previously calculated. Finally, the point cloud is made into a surface and displayed on the screen using HelixToolkit open source 3D libraries. This allows the user to rotate, zoom, and center the 3D image on the PC.

Introduction

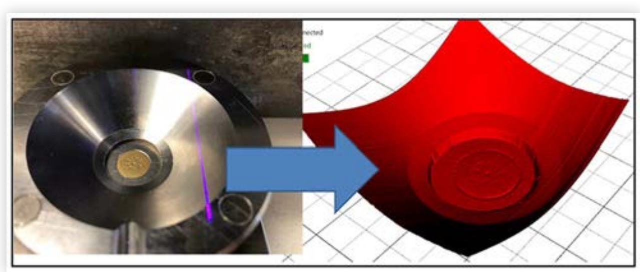
In automated aerospace fastening there is a constant push for faster, more accurate, in-process, non-contact inspection techniques.

The goal is to get to a "lights out" point where the operator doesn't need to inspect or touch the aircraft part. While that goal is still in the near future, Electroimpact has developed a high-accuracy in-process 3D scan of the panel and fastener head that can calculate process critical items such as panel normality, fastener head flushness, nosepiece diameter, and location. It also provides a large, clear, interactive, high definition 3D image to the operator.

One of the most difficult items to inspect and automate is countersink depth (and the resulting fastener head flushness). The difficulty lies in the tight tolerance required, the limits of the vision/laser systems available, and the unfavorable conditions in an industrial drilling environment. Electroimpact has developed many technologies for contact [1] and non-contact [2] ways of measuring countersink and fastener head flushness. While these have had success in production, continued development has led to this new application.

Using a KEYENCE LJ-V7080 2D laser mounted to a SMC CE1 encoded cylinder it's possible to quickly sweep the working area to get a high resolution contour of the surface. Using the raw data of the contour it is possible to analyze many different aspects of the surface and the fastener.

FIGURE 1 Image of an actual fastener and nosepiece compared to the composite 3D image after scanning.



Difficulties

Packaging

One of the biggest difficulties with incorporating multi-dimensional inspection equipment into auto fastening equipment is simple packaging. Of the sensors currently on the market it appears that increasing dimensional ability causes an exponential increase in the sensor size.

On a simple conveyer belt system there is a large amount of space available for inspection. On a machine tool such as

TABLE 1 Size comparison between various sensors of different capability.

Sensor Model	Type	Length (mm)	Width (mm)	Height (mm)	Volume (mm^3)
Baumer OADM12	1D	35	37	12	15,540
Keyence LJ-V7080	2D	71	96	42	286,272
Keyence XR-HT40	3D	120	250	54	1,620,000
Keyence WI-001	3D	157	237	76	2,827,884

an automatic riveter, the toolpoint is taken up by drill spindles, fastener injectors, bucking anvils, sealant applicators, diameter probes, etc. Space is at a premium. One of the often used and preferred sensors at Electroimpact is the Baumer OADM12 which is a high accuracy 1-dimensional distance measurement sensor in a small 35x37x12 mm package. This is the optimal size for packaging. Unfortunately when looking at high accuracy 2D and 3D sensors, the packaging increases substantially. Table 1 below shows the dimensions of some various sensors.

Resolution

The next difficulty is sensor accuracy and resolution. Flushness tolerances for aircraft parts are typically in the range of +/-0.003" (+/-0.076mm). In order to have a measurement device that can be relied upon, the true accuracy of the system needs to be an order of magnitude or more better than manufacturing tolerance that it is measuring. The specification for many industrial applications require flushness measurement accuracy of +/- 0.0005" (+/- 0.0127 mm) or better. While many devices exist with this level of accuracy, achieving this accuracy in a production environment with an automated measurement system is far from simple.

The sensor used for this application, the Keyence LJ-V7080, has an advertised height repeatability of 0.0005 mm. This number is likely in a clean room with ideal lighting and ideal target geometry. In our experience, in a real-world production environment it is difficult to obtain consistent, accurate results less than 0.0005".

Environment

As stated before, industrial machines often operate in extreme environments. In the drilling/fastening sector there is lubricant, CFRP dust, aluminum chips, aircraft sealant, and machine packaging constraints. All of these variables combine to make achieving an accurate measurement exceedingly difficult when using an automated device.

The automated measurement system is being compared to a typical hand measurement using an indicator. While hand measurement has the benefits of cleaning before the measurement process, any in-process non-contact inspection does not have the ability to clean, rotate, and repeat the measurement. Therefore an automated system has a significant disadvantage with regards to measurement accuracy. In order to have an accurate automated measurement in a production environment, there must be a way to account or compensate for contamination and environmental factors.

Solution

Hardware Selection

A Keyence LJ-V7080 laser routed into a Keyence LJ-V7001 was used because of previous experience with the LJ-V series and their high resolution. The LJ-V7080 was mounted onto a SMC CE1 distance coded pneumatic cylinder. The riveting machine controller is a FANUC 30iB CNC.

The final piece of hardware is a B&R APC910 Windows based PC. The PC runs the custom EI application and communicates with the 30iB CNC and the LJ-V7001 controller through Fanuc and Keyence supplied .NET libraries.

Packaging

Packaging is a major constraint when trying to use such a high-resolution measurement device on a machine tool. As previously discussed, the newest crop of high-accuracy laser sensors are quite large relative to many components on a machine process head. Additionally, the sensor must be very close to the workpiece - approximately 3in (75mm) in this case. 3D sensors also exist, but they tend to be even larger and do not have as high of resolution as the best 2D sensors available.

On top of the difficulty of packaging a relatively large sensor, the overall system must also be fast enough for a production application. Ideally major machine axes do not have to move to take a measurement.

To address all of these packaging constraints, the sensor was attached to a distance measuring air cylinder. This allows the sensor to be deployed immediately after drilling and inserting a fastener, without moving the process head. The measurement is taken though the upper nosepiece. The air cylinder position is fed to the Keyence controller, allowing a 3D image to be assembled.

Why Custom Application?

The Keyence LJ-V7001 controller has a software suite, LJ Navigator, which can be used to configure the advanced calculations on the laser profile, provide basic visualization, and output digital and analog values directly to the Fanuc CNC.

Keyence also offers a more advanced controller in the XG-X series with 3D capabilities which could have solved

FIGURE 2 Simplified connection diagram of hardware used.

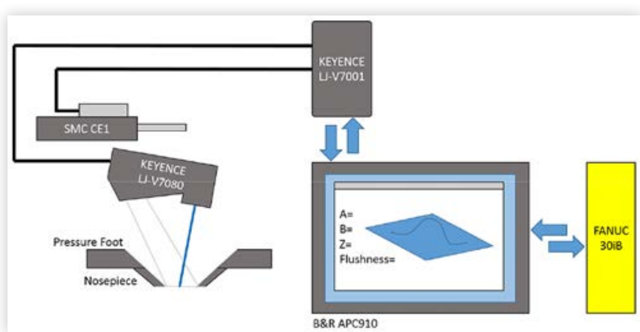
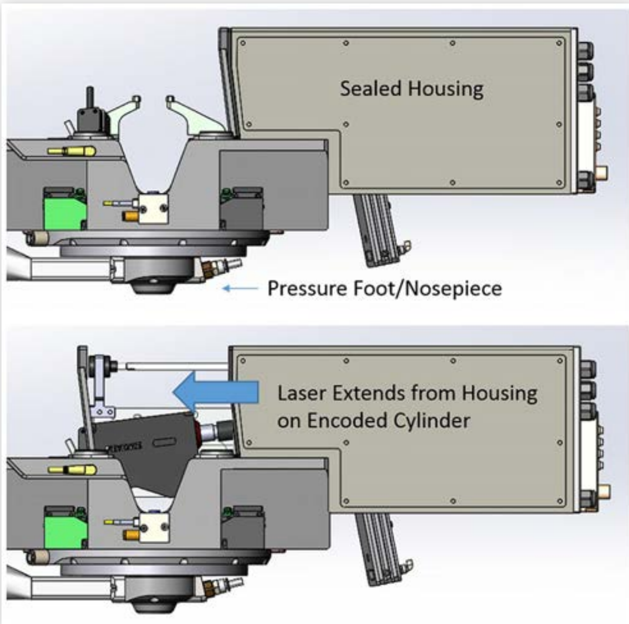


FIGURE 3 Image of the location of the laser with the pneumatic cylinder retracted and extended.



some of the problems identified. However, because of hardware and software costs, user interface limitation, and lack of total control over the raw data, this solution was ruled out.

Electroimpact has used the built-in Keyence functions on many applications in the past, but it was determined that the limitations on feature detection, output timing, and 3D visualization necessitated a fully custom approach.

Utilizing the raw XYZ point cloud data requires a larger up-front investment in development but it opens the door to limitless mathematical analytics and visualizations.

The LJ-V7001 controller has a setting called "high-speed mode" which skips any internal processing and provides only the raw point cloud data to an external .NET application. This is the selected operating mode for the controller.

For the custom application, Windows Presentation Format (WPF) was chosen for its superior 3D visualization capabilities. The code is a mix of XAML and C#, with C# doing most of the heavy lifting through custom algorithms and 3rd party supplied .NET libraries.

FIGURE 4 Simplified comparison of Keyence "High Speed Mode" vs. "Advanced Mode".

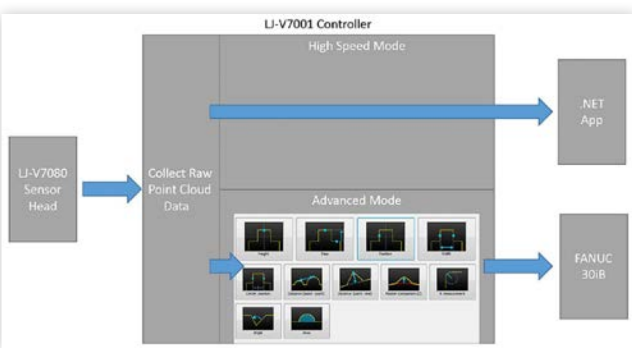
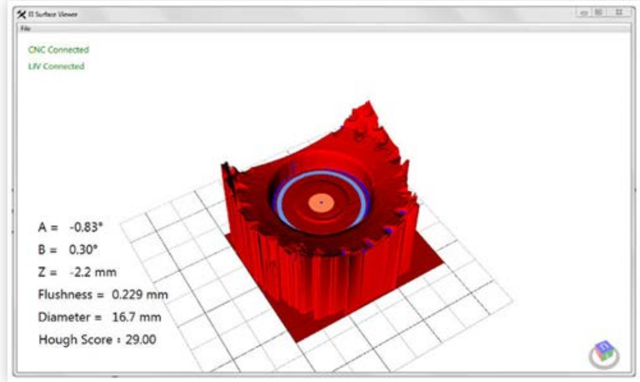


FIGURE 5 Image of the user interface.



The user interface is designed to be as clean and simple as possible for easy viewing and navigating. The format is a large white window with the 3D surface displayed in the center, the calculated outputs displayed on the side, and the connection status of the 30iB and LJ-V7001 in the corner.

Using open source HelixToolkit libraries allows the 3D surface to be rotated, re-centered, and zoomed with a standard mouse.

How It Works

The entire auto fastening machine is controlled by the FANUC 30iB CNC. The CNC acts as the master in the system. The laser inspection routine is begun by running a simple M-code. Then the CNC extends the distance coded pneumatic cylinder, handshakes the PC app to begin data acquisition, retracts the pneumatic cylinder, and then handshakes the PC app again to stop the profile collection and begin the analyze/render methods.

PC Application

The PC application queries the LJ-V unit for batch profile data which is saved in local arrays. Then the XYZ data points are averaged to find the rough center for plotting.

FIGURE 6 Image of the point cloud without the composite rendered surface.

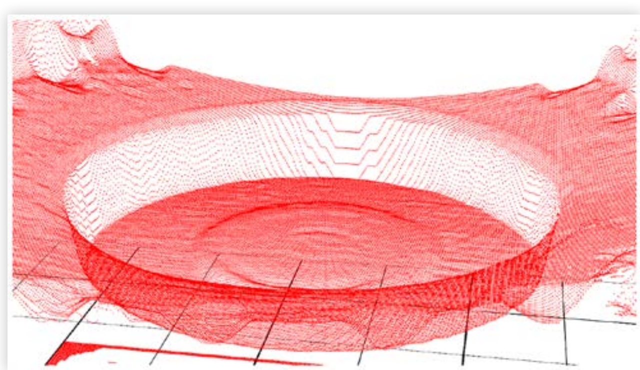
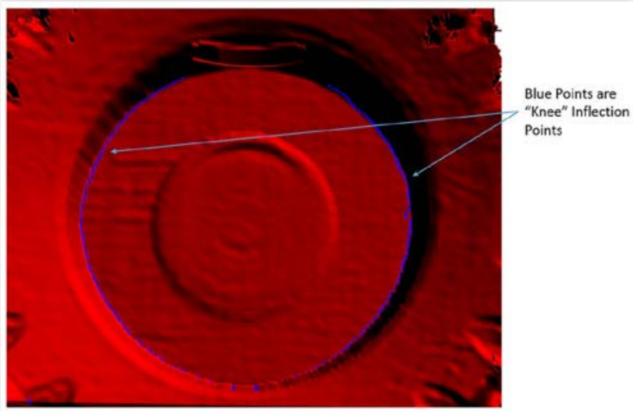


FIGURE 7 Example of the “knee” inflection points located at the inner diameter of the nosepiece.



Custom method “FindKnees” is run to determine inflection points of a specific angle and intensity that could be the edge of the nosepiece. The filtering criteria has been adjusted to specifically find edges similar to the nosepiece geometry.

These points are then run through another custom method called “FindCircleWithHough” to determine a best fit circle from random data points. This is based on the Circle Hough Transform (CHT) which is commonly used in image processing to find circles of known radius. Because the radius is not known, the CHT is run with all radii between 5-25mm in increments of 0.1 mm. A scoring method is used to rank the best fit circle of the group. The resulting score is output on the main screen next to the label “Hough Score”. When programming a CHT algorithm, there is a tradeoff between search criteria granularity and processing time where increasing the search resolution can have an exponential effect on processing. The search resolution has been tuned for the best results with the lowest time.

The final result of the multiple CHT loops is the XY position of the center of the nosepiece and the diameter of the nosepiece.

Using the XY center position it is possible to create two groups of points: points within the panel region, and points

FIGURE 8 Image of the “panel” and “fastener” groups used to determine the normality and flushness.

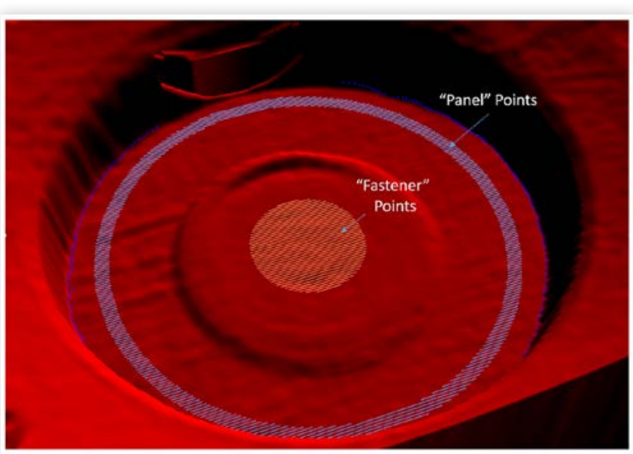
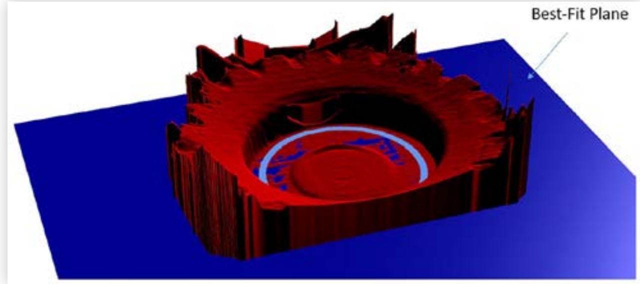


FIGURE 9 The resulting plane from a best-fit of the “panel” point cloud.



within the center of the fastener head. The points within the panel region are all points that are mathematically between two radii from the center of the nosepiece. The radii is defined by the diameter of the nosepiece. This results in a 1mm “ring” of points that all lie on the surface of the panel. See Figure 8 for more info. Similarly, the points located at the center of the fastener are defined as all points mathematically located within a much smaller radii from the center of the nosepiece. It is assumed that the fastener is located at the center of the nosepiece. This dimension is controlled by the alignment of the drill spindle to the pressure foot and is a reasonable assumption.

A custom method “MakeTriangles” is used to loop through all points in the cloud and tessellate the surface into large matrix of triangles. These triangles are required for the 3D rendering.

A simple method “RemoveOutliers” runs through the special “panel” and “fastener” points to remove possible anomalies. There is much more room for future improvement in this area.

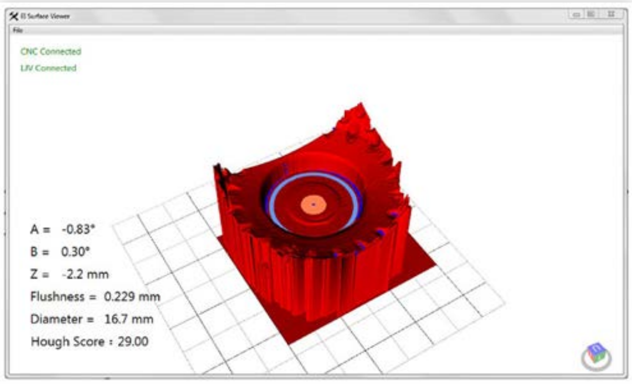
Then, using only the “panel” points, a best-fit plane is found in a method called “LeastSquares”. This involves creating two large matrices and using MathNet.Numerics libraries and the Cholesky Decomposition to solve for the coefficients [abc] of the best fit plane. These coefficients are then used to calculate the angle about X and the angle about Y, referred to here as A and B respectively. Then, using a simple averaging of all Z positions within the “panel” group, the average height, or Z position, is found.

Now that the best-fit plane of the panel has been found, a method “CalculateFlushness” is run in which the distance from each point within the “fastener” group to the plane is calculated. The resulting flushness can be configured to be the maximum distance from a single point to the plane, or the average distance of all points to the plane. The result is a highly accurate representation of the same flushness measurement done by hand.

Outputs

After the application has finished, the following outputs have been calculated and displayed: diameter, A angle, B angle, Z height, flushness, and Hough Score.

FIGURE 10 Image of the calculated and visual output in the user interface.



The diameter of the nosepiece is used to cross check that the correct tooling has been installed. The A, B, and Z are used to determine and correct the machine orientation in relation to the panel. The flushness is relayed to the operator and checked to ensure it is within tolerance. And finally the Hough Score is not entirely necessary for the operator, but it gives an example of the circle strength and possible need to clean the nosepiece or the laser.

Other than calculated outputs, one of the most important outputs is the large clear visual display of the fastener head. The operator can quickly identify the scan as good or bad. Any anomalies such as debris or reflection can be spotted and disregarded. The operator can also zoom and rotate the 3D image easily with a standard mouse. The image rotates in space similar to most CAD programs. This is detailed and valuable feedback for the operator.

Accuracy Data

Test Description

To test the accuracy of the system the machine drilled and installed 25 YP8 bolts into a test "coupon" of uncoated 7075 aluminum. The countersink was intentionally modified throughout the test so as to get a good range of data. The laser system was then used to measure each fastener to determine flushness.

FIGURE 11 Test "coupon" used for accuracy test with 25 YP8 bolts installed.

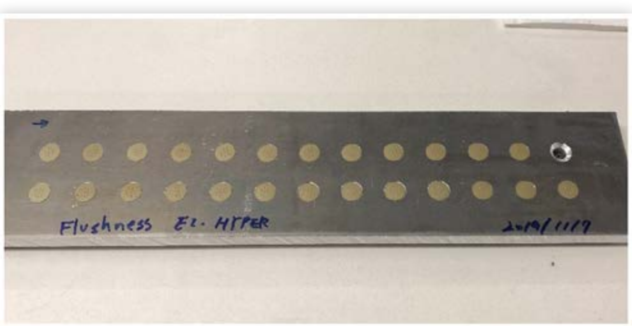
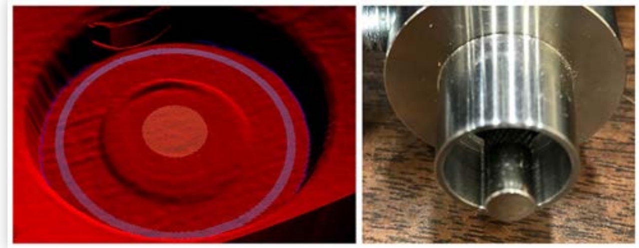


FIGURE 12 Comparison of software to the custom hand measurement tool.



Each fastener was also measured by hand using a digital Mitutoyo drop indicator and a custom surface contact ring that is designed to mimic the same measurement points as the software.

By comparing the hand measurements to the laser measurements, it is possible to calculate the error.

Results

Results for the 25 samples are below.

TABLE 2 Accuracy results of flushness for 25 samples of YP8 bolts.

Hand Measurement (mm)	Laser Measurement (mm)	Error (mm)	Error (in)
0.187	0.177	0.010	0.0004
0.201	0.196	0.005	0.0002
0.229	0.221	0.008	0.0003
0.212	0.216	-0.004	-0.0001
0.192	0.189	0.003	0.0001
0.203	0.209	-0.006	-0.0002
0.211	0.229	-0.018	-0.0007
0.170	0.173	-0.003	-0.0001
0.182	0.184	-0.002	-0.0001
0.214	0.220	-0.006	-0.0002
0.207	0.208	-0.001	-0.0001
0.202	0.203	-0.001	0.0000
0.164	0.166	-0.002	-0.0001
0.159	0.165	-0.006	-0.0002
0.151	0.154	-0.003	-0.0001
0.147	0.155	-0.008	-0.0003
0.175	0.168	0.007	0.0003
0.145	0.134	0.011	0.0004
0.050	0.047	0.003	0.0001
0.094	0.089	0.005	0.0002
0.036	0.032	0.004	0.0001
0.041	0.040	0.001	0.0001
0.284	0.283	0.001	0.0000
0.192	0.195	-0.003	-0.0001
0.271	0.278	-0.007	-0.0003

TABLE 3 Statistical summary of the accuracy results.

	Millimeters	Inches
Max Error	0.011	0.0004
Min Error	-0.018	-0.0007
Ave Error	0.000	0.0000
Std Dev	0.006	0.0003

From the 25 samples tested, the error was +11/-18 μm with a standard deviation of 6 μm.

These results were obtained on a clean sample without countersink sealant. The accuracy is expected to be worse in a production environment with different fasteners, lighting conditions, surface conditions, and debris conditions.

Conclusion

There is increasing demand for high accuracy in-process inspection techniques in the aerospace industry. There are many difficulties in reaching the desired specifications including: sensor technology, packaging, obstructions, visibility, and speed.

Advantages of the System

Electroimpact's latest in-process inspection system for automatic fastening equipment solves many of these problems with the combination of Keyence LJV series components and a custom PC application. The sensor deploys directly over the fastening point for speed. The application accurately calculates panel normality, fastener head flushness, nosepiece diameter and location. It also provides a large, clear, interactive, high definition 3D image to the operator.

This system quickly gives the operator a detailed view of the fastener while providing accurate measurement data.

Disadvantages of the System

One disadvantage to the system is that it takes too much time to run every cycle. In the automated fastening industry cycle time is critical and milliseconds add up. This inspection technique is on the order of seconds rather than milliseconds. This means that it is best suited for periodic interval inspection rather than running on every fastener cycle.

Another disadvantage is that it's not currently designed to make automatic adjustments to process critical settings, such as countersink depth, while running on production parts. Automatic adjustment is enabled on test coupons, but risk of incorrect adjustment is still beyond the confidence of the inspection technique.

Continued Development

There is much more potential for developing this technology. Ideas for continued development include: refining the image clarity, include more automated feature recognition, intelligently handle outlier data and reflections, increasing processing time through multithreading and optimization, and measuring other stages of build-up such as direct countersink measurement.

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Contact Information

Zachary Luker
Controls Engineer
Electroimpact Inc.
zackl@electroimpact.com

Erin Stansbury
Mechanical Engineer, PM
Electroimpact Inc.
erins@electroimpact.com

Definitions/Abbreviations

WPF - Windows Presentation Format

CHT - Circle Hough Transform

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