Robotic Drilling and Countersinking on Highly Curved Surfaces

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Abstract

Electroimpact has developed a novel method for accurately drilling and countersinking holes on highly convex parts using an articulated arm robotic drilling system. Highly curved parts, such as the leading edge of an aircraft wing, present numerous challenges when attempting to drill normal to the part surface and produce tight tolerance countersinks. Electroipmact's Accurate Robot technology allows extremely accurate positioning of the tool point and the spindle vector orientation. However, due to the high local curvature of the part, even a small positional deviation of the tool point can result in a significantly different normal vector than expected from an NC program. An off-normal hole will result in an out of tolerance countersink and a non-flush fastener. A compliant contact pad with normality feedback is commonly used to locally normalize to a work part but in the case of highly curved parts, a flat contact pad has too small of a contact area with the panel to allow accurate local normalization. Electroimpact has developed a pneumatically actuated four-point lander on a compliant contact pad with normality feedback. This development, along with Electroimpact's Accurate Robot technology allows for automated drilling and countersinking on parts that have previously been unachievable with robotic drilling systems.

Introduction

Advances in the accuracy of articulated arm robots has led to their increasing use in aerospace manufacturing. Articulated arm robots are frequently used as the positioner of an automated drilling system. Robotic drilling systems offer the advantage of flexibility and reduced cost over traditional machine tools.

Electroimpact's Accurate Robot consists of an off-the-shelf 6-axis robot provided by KUKA Robotics and fitted with secondary position encoders on each robot joint. The robot's multifunction end effector (MFEE) consists of a clamp axis and a shuttle table with process tools including a drill spindle, resynch camera, hole probe and optionally a bolt inserter. The robot arm, MFEE and any external axes are controlled by a single Siemens 840dsl CNC. The addition of secondary feedback on the robot axis allow the system to be calibrated to achieve positional accuracies of the toolpoint of +/− .25mm over a large working volume. This allows the robotic drilling system to achieve the accuracies required of aerospace manufacturing while relying only on offline generated NC program as opposed to earlier systems that may require in-cell teaching and/or real-time metrology guidance.

Figure 1. An articulated arm robot with secondary feedback on all axes and a multi-function end effector.

As the use of robotic drilling systems in aerospace manufacturing has increased, so too has the scope of their work in the factory. While early robotic drilling systems traditionally worked largely on the mostly flat surfaces of wings or flaps, there is increased demand for robotic drilling systems that can work on leading edges and other surfaces with high curvature. Automating the drilling and countersinking of leading edge panels eliminates the need for drill jigs and associated tooling, which results in a more lean and flexible manufacturing process. This paper will cover recently developed hardware and processes that were needed to enable a robotic drilling system to drill and countersink high quality holes on highly curved surfaces.

Panel Normalization

In aerospace manufacturing the orientation of the drill spindle vector relative to the part while drilling is critical to creating quality holes. This is especially true when drilling and countersinking. A countersunk hole that is drilled off-normal will result in a countersink that is not of equal depth on all sides. With such a hole, an installed fastener will not be flush to the part surface an all sides. The Accurate Robot exhibits excellent orientational accuracy, but orientational accuracy and an NC program alone are often not sufficient to achieve the best possible hole normality.

Due to manufacturing variations, the orientation of a part may differ from the nominal position in the NC program. To account for these variations in part orientation the MFEE utilizes a spherically compliant clamp pad with normality feedback. As the MFEE clamps up to the part prior to drilling, the compliance of the clamp pad allows it to normalize to the part regardless of the orientation of the MFEE. Three built-in displacement sensors are used to measure the movement of the clamp pad relative to the MFEE and the robot arm rotates the MFEE about the tool point until the spindle vector is normal to the part surface within 0.15 degrees.

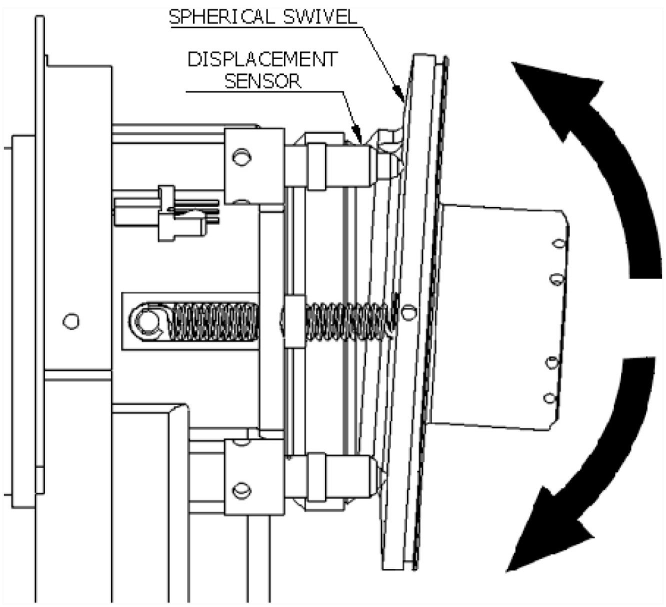

Figure 2. A spherically compliant contact pad with displacement sensors for normality feedback.

This method of local normalization is very effective for flat and moderately curved surfaces but no longer works once the bend radius of a part surface is smaller than 670mm. With a highly curved surface there is not enough contact area between the contact pad and the part, and a compliant contact pad will wobble or cock to one side as shown in figure 3.

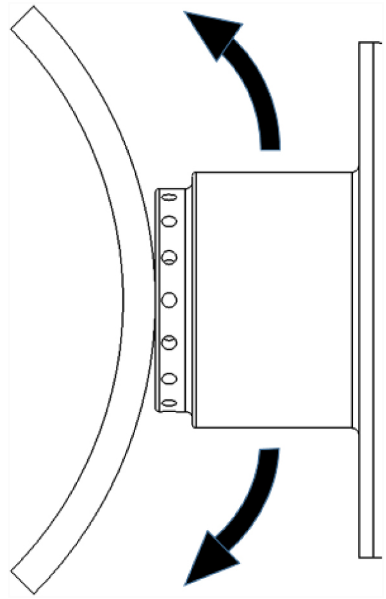

Figure 3. A compliant contact pad with a flat contact surface will wobble or cock to one side when clamped against a highly curved surface.

Potential Error without Local Normality

Highly curved surfaces are difficult to normalize on with a compliant clamp pad but curved surfaces are where local normalization is most critical. On a highly curved surface, a small positional deviation of the tool point can result in a large change in the part normal vector. When manufacturing variations and positional error of the robotic drilling system are combined, the actual part normal vector can differ by 0.8 degrees from the nominal orientation in the NC program.

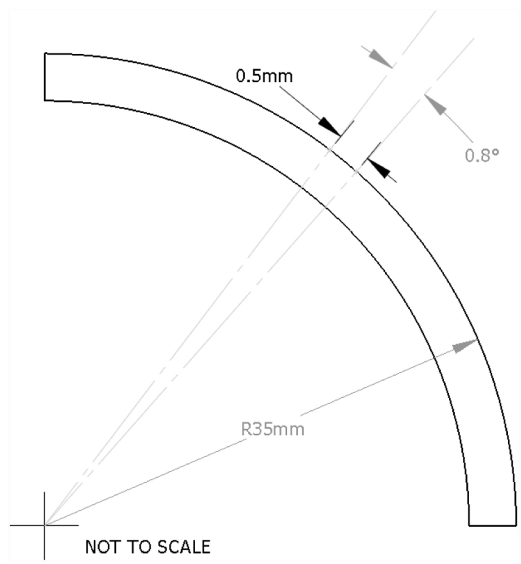

Figure 4. On a highly curved surface, a positional change of 0.5mm can change the angle of the normal vector by 0.8 degrees.

As an example, a countersunk hole for a 3/16″ flathead fastener that is drilled 0.8 degrees off-normal on a curved surface can result in a fastener head sitting 0.1mm proud of the part surface as shown in Figure 5. Drilling and countersinking on highly curved surfaces without on-part normalization will not consistently produce holes that results in adequate fastener flushness.

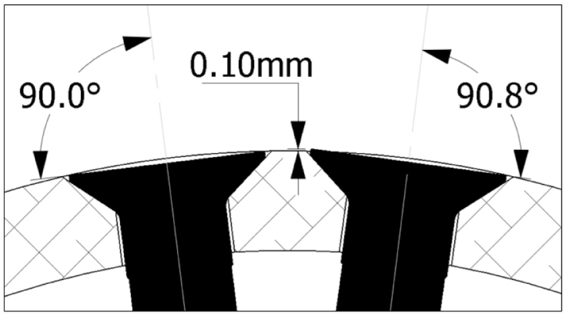

Figure 5. Fastener head protrusion caused by off-normal drilling and countersinking. Shown are 3/16″ flat head fasteners on a curved panel with 45mm bend radius.

Four Point Lander

A compliant contact pad with a widely-spaced four point lander as opposed to a flat contact surface allows for a wide base of contact with a highly curved part. The four point lander, as shown in Figure 6, prevents wobbling or cocking of the compliant lander and allows normalization even on curved surfaces. While the four point lander solves one issue it also creates a significant problem. When the four point lander is clamped up to surfaces of various different radii of curvature, the contact pad does not have a consistent gage length relative to the part surface. In this case a lengthy panel touch-off procedure is required to establish panel position, which must be known in order to drill countersinks to an accurate depth.

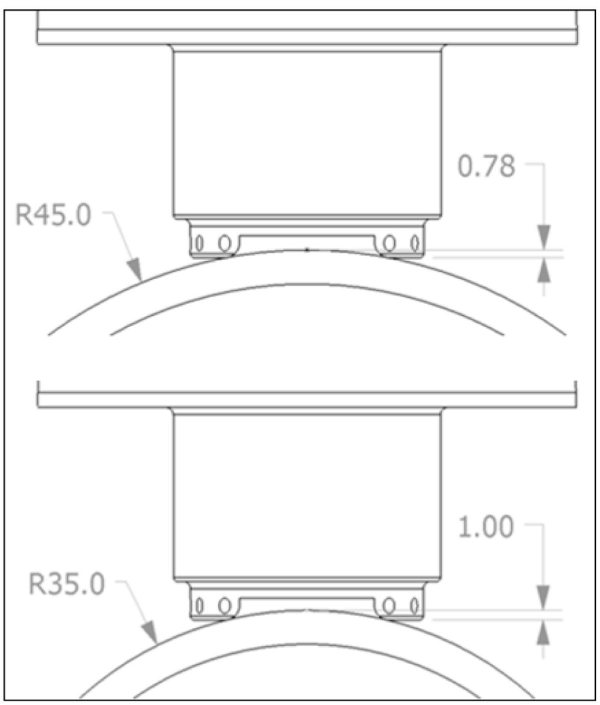

Figure 6. A four point lander prevents wobbling of compliant lander but induces uncertainty in panel position. Dimensions in mm.

Actuated Four Point Lander

To solve the problem of unknown panel position presented by a four point lander, an actuated four point lander was developed. The actuated lander has four spherical pads and enshrouds a rigid base contact surface. Compressed air is used to extend the actuated lander so the spherical pads are proud of the base contact surface.

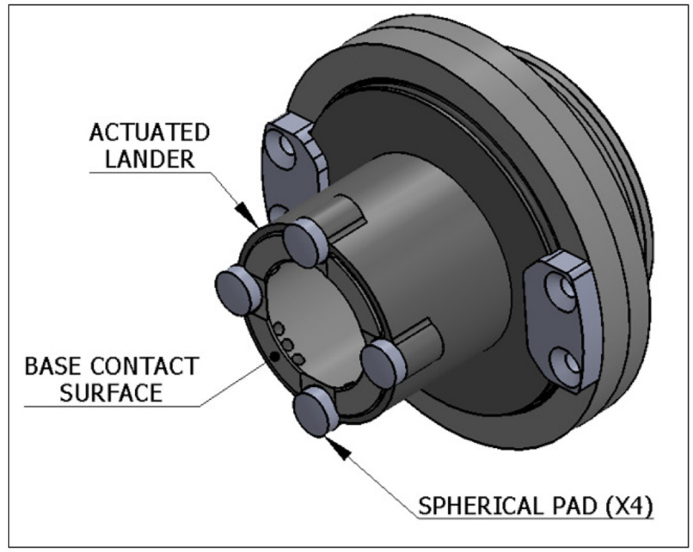

Figure 7. Actuated four point lander.

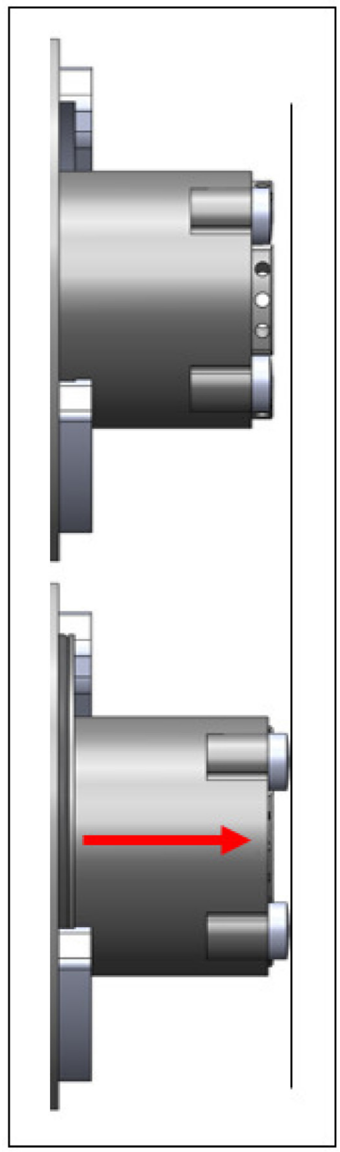

Figure 7. Compressed air is used to extend the spherical pads forward of the base contact surface. The actuated lander is shown in the retracted position, upper, and extended position, lower.

High Curvature Clamping Routine

One of the key benefits of Electroimpact's solution to the high curve clamping problem is that cycle time is not impacted by the new hardware. The routine for high curve clamping is nearly identical to low curve clamping. The only difference is that the spherical pads are actuated forward at the beginning of the routine, then disabled at the end of clamping. The full routine is detailed below, to better explain how the tip works.

1. The robot head is oriented so that the 4 points on the lander will straddle the axis of curvature. Offline programmers have 4 possible head orientations to choose from
2. Clamping routine begins. The high curve lander is actuated forward and the clamp axis servo begins driving the head towards the panel
3. The four spherical pads of the lander make contact with the panel
4. Once 20 kg force is seen by the load cell on the MFEE, the robot begins responding to normality sensor feedback. 20 kg is the minimum force required to swivel the robots nosepiece and indicates that the normality sensor readings are accurate to the real world
5. Normality correction is injected as the robot continues to clamp. The force of the actuated lander (~25 kg) is soon overcome by the clamp force, and the 4 points of contact are pushed backwards
6. The base of the contact pad makes contact with the panel. This forms two line contacts bringing the total number of contact points up to six.
7. Final normality corrections are made as the clamp load approaches the target
8. Target clamp load is reached, normality corrections are complete. Pressure to the pneumatic lander is disabled and the clamp routine finishes.

Since the base contact surface still makes contact with the part, panel position is known implicitly. This is because the base contact surface is part of the rigid structure of the head. The four point lander actuates forward to assist in normality, but does not interfere with the rigid base's final line contact with the panel. Where other systems require a panel touchoff before drilling and countersinking, this solution does not. The robot is able to continue onto drilling and countersinking immediately after clamping, meaning that cycle time is not impacted by the use of the high curve lander.

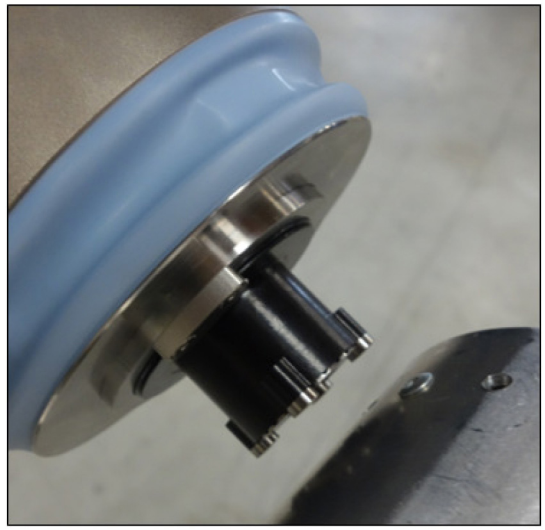

Figure 8. Photograph of the production version of a compliant contact pad and actuated lander.

Conclusion/Summary

Drilling and countersinking on highly curved surfaces has remained largely a manually performed task even as automated drilling system have become commonplace in aerospace manufacturing. The actuated four point lander was designed to overcome the technical challenges preventing robotic drilling systems from working on highly curved surfaces. This technology is production ready and has proven effective for drilling and countersinking quality holes on highly curved surfaces without any negative impact to cycle time. The expansion of drilling capabilities to include both flat and curved surfaces greatly increase the value of *Accurate* Robots for use in aerospace manufacturing.

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Definitions/Abbreviations

NC - Numeric Control

MFEE - Multi-Function End Effector

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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