2013-01-2338

Mobile Automated Robotic Drilling, Inspection, and Fastening

Troy Gray, Daniel Orf, Greg Adams
Electroimpact Inc.

ABSTRACT

The versatility of the accurate robot has been increased by coupling it with a mobile platform with vertical axis. The automation can be presented to fixed aircraft components such as wings, fuselage sections, flaps, or other aircraft assemblies requiring accurate drilling, inspection, and fastening.

The platform accommodates a tool changer, ride along coupon stand, fastener feed system, and other systems critical for quality automated aircraft assembly. The accurate robot's flexibility is increased by a floor resynchronization system. The indexing system is replaced by an automated two-camera onboard vision system and miniature targets embedded in the factory floor, with accuracy comparable to cup and cone alternatives. The accurate robot can be deployed by casters, curvilinear rail, or air bearings.

INTRODUCTION

The rapidly increasing demand for flexible automation in aerospace assembly is realized with the introduction of the mobile accurate robot. The mobile robot is a highly accurate robotic system used for automated drilling, inspection, and fastening of aircraft equipment.

The mobile robot consists of a stiff platform contacting the foundation at 3 points, a Y-Sled for vertical positioning, and for the mobile robot described an accurate KUKA KR500-L340 robot with secondary feedback. These systems work in conjunction to accurately present the end effector to a host of aircraft assemblies. A typical end effector consists of, but is not limited to a drill spindle, secondary drill spindle, hole probe, fastener inserter, resynchronization camera, and an auto normalizing nose piece. The platform of the mobile robot also carries a coupon stand, an automatic tool changer, a fastener feed system, and overview cameras. The mobile robot assembly can be moved utilizing casters or air bearings; a curvilinear rail can be utilized for guidance.

The mobile robot has an unlimited number of positions from which its expanded volume can operate. The setup time of the Electroimpact mobile robot has been maximized for speed. The mobile robot can be equipped with traditional indexing methods such as cup and cone or a floor resynchronization indexing design that does not require anchor floor embedment.

MOBILE ROBOT SUMMARY

Overall dimensions can change by configuration. However, the mobile robot described has rough over all dimensions of 4260mm wide by 3485mm deep by 2955mm tall. The mass of the entire system is 11,800 kg.

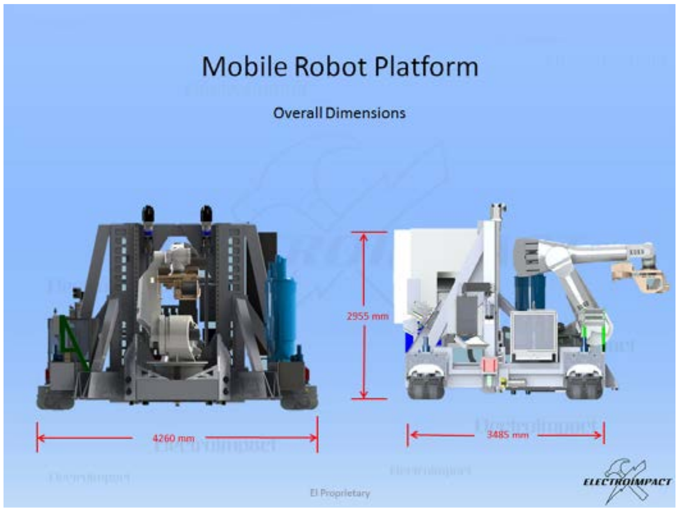

Figure 1 - Overall Dimensions Mobile Robot

OFF-PART accuracy tests of the robot end effector combination have produced 3-sigma accuracy of +/-0.12mm over a 3.5 cubic meter working volume when measured at the TCP [1] using an enhanced kinematic model. ON-PART accuracy using the same enhanced kinematic model and other calibration methods achieve accuracies of +/-0.25mm or better [2].

For drill only, the mobile robot can drill diameter 3.97mm holes at 11 holes per minute in a 3.4mm coupon stack. The robot is able to drill holes to meet fastener insertion quality specifications with the following criteria: hole diameter tolerance of +/- 25 microns, countersink depth +/- 80 microns with an inspection method of Cpk 1.33 or better.

The following is a table of the major auxiliary systems of the mobile robot.

Table 1. Mobile Robot Auxiliary Systems

• Platform • Y-Sled • Accurate Robot with Secondary Feedback • End Effector • Floor Indexing Method with Camera Resync • Coupon Stand • Automatic Tool Changer • Fastener Feed Systems • Movement Methods

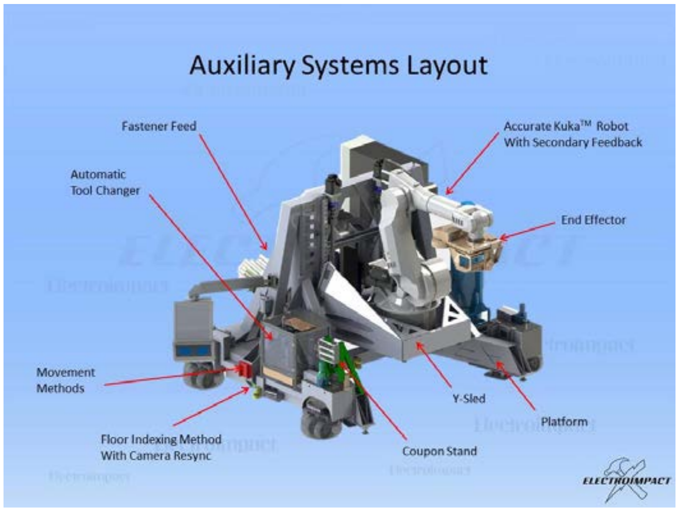

Figure 2 - Mobile Robot Auxiliary Systems

Platform

The platform was designed with minimum deflection as the overriding criteria. There are three main components to the platform frame; the back frame and the two front legs. Having removable front legs serves two purposes. Removable legs allow for easy container transport. More importantly, it is possible to machine the Y-sled rail mounting surfaces with greater accuracy with the CNC machining head able to ride as close as possible to the rail mounting surface.

For stability the platform has a low CG and 3 point contact with the foundation. Each steel indexing foot has a knurled contact surface and is 102mm in diameter resulting in a 4Mpa floor loading at each foot. During maximum robot extension and accelerations the overall CG is well within the foundation contact foot print and never closer than .8m to a tipping line.

Figure 3 - Platform Back Frame

Y-Sled

The Y-Sled increases the overall reach of the mobile robot adding 1750mm of vertical travel. The configuration of the sled was chosen to be stiff and to maximize robot access to aircraft geometry close to the ground. Dual ball screws, each with redundant braking on the motor and ball screw, increase the safety of the 4,900 kg payload. Each ball screw is individually capable of statically supporting the entire load with a factor of safety of 2.5. Motors and gear boxes were chosen to allow speeds up to 150 mm/s.

The design of the Y-Sled was an iterative process that made extensive use of Finite Element Analysis. It was designed to be light weight, stiff, and have minimal deflections under normal use and clamp.

Accurate Robot with Secondary Feedback

The mobile robot center piece is a KUKA KR500-L340 robot equipped with a secondary feedback system that greatly enhances its positional accuracy. The feedback provides very good repeatability, which in turn enables the system to be calibrated to high accuracy. The system as a whole is patent pending. The accurate robot is controlled by a Siemens 840Dsl CNC which handles all process functions, robot motion, and executes software technologies developed for superior positional accuracy including enhanced kinematic, automated normality correction, and anti-skid correction.

A typical, non-enhanced, 3 meter reach robot using a nominal kinematic model exhibits an accuracy of about +/- 2 to 4mm within its working volume. However, developing a unique kinematic model for each robot can increase its positional accuracy to +/-0.5mm. Furthermore, secondary positional feedback encoders mounted at the output axes rather than the input axes provide another magnitude of accuracy to the robot. With real-time compensation the system can maintain ON-

PART accuracy of +/-0.25mm or better [2]. Figure 4 - Robot Accuracy and Figure 5 - Secondary Feedback show robot accuracy and secondary encoder.

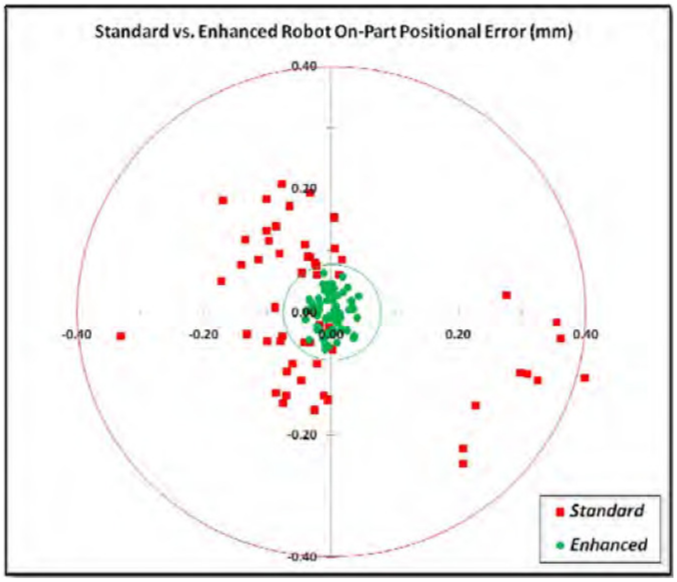

Figure 4 - Robot Accuracy

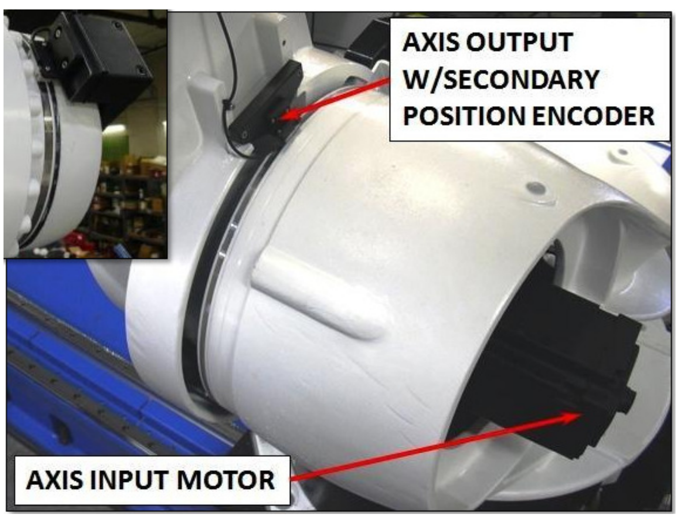

Figure 5 - Secondary Feedback

End Effector

The end effector has an aluminum mounting base for weight consideration. It comes equipped with a separate clamp axis for precision clamping on part. The shuttle table has special design considerations to minimize the effects of thermal expansion differences between process tools and their mounting surface. The shuttle table delivers each tool to its process position, generally centered behind the nose piece. Typical process tools include a drill spindle, hole probe, resync camera, and fastener inserter.

The drill spindle is liquid cooled, rated for 20,000 RPM, axially servo controlled, and has an accuracy of face runout of .001mm MAX T.I.R.. The hole probe is able to measure countersink depth, hole diameter, hole profile, and stack thickness. For different hole diameters, the bore gage probe tip of the hole probe can be automatically changed. The hole probe can achieve accuracies of +/-.005mm measuring hole diameters and +/-.05mm when measuring countersink depth. The hole probe runs its auto calibration cycle before every measurement to compensate for environmental factors such as thermal expansion. The auto calibration cycle is done during hole drilling to save process time. The resync camera is used for local position correction. It is capable of visually inspecting and identifying various targets and features such as holes, fasteners, and other fiducials and datum. The set of targets and shapes are teachable and trainable. The resync camera can also be used for different types of analysis such as reading QR codes.

The fastener inserter can install a wide range of fasteners into the work piece. For example, the robot described is capable of installing protruding head and flush HST fasteners with diameters ranging from -5 to -10 and grip lengths from -2 through -7. During drill operation the fastener is sent at high speed through plastic tube from the fastener feed rack to the injector located on the end effector. The injector features a damping mechanism permitting extremely fast bolt feeding without marking the fastener. Additionally the injector indexes between 4 different feed tubes eliminating the need for manual intervention during diameter tool changes.

The auto-normalizing nose piece can be configured to address individual customer part requirements including configurations with minimal access. Figure 6 is a picture of an end effector from the described mobile robot.

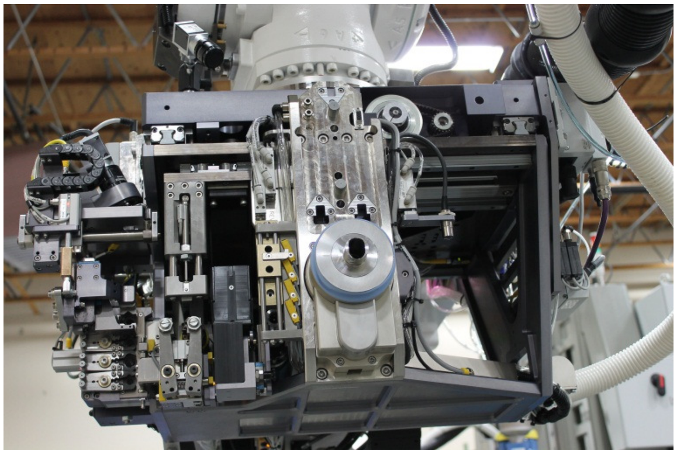

Figure 6 End Effector from Described Mobile Robot

Floor Indexing Method with Camera Resync

The mobile robot has expanded flexibility with the introduction of the Floor Resynchronization System. The Floor Resynchronization System allows for the mobile robot to be easily moved and placed in various working positions on the factory floor without a need for beds, rails or locking cup-and-cone interface. This system relies on miniature embedded targets and a high resolution, two-camera, vision system to accurately orient and locate the mobile robot on the factory floor.

The stainless steel targets are embedded flush in the factory foundation at nominal locations below the cameras of each mobile robot at each operating position. Actual target locations are valued in the FRS by laser tracker and the offsets from nominal are noted for use in rigid body transforms later. The targets are low cost, flexibly deployed, and simple to expand down the road.

Figure 7 – Floor Resynchronization Target

Figure 8 – Floor Resynchronization Camera

The two vision system cameras, rigidly mounted to the mobile robot frame, are calibrated to Robot Coordinate System (RCS) with the help of a calibration plate and laser tracker. The calibration plate features five fiducials which are designed to be valued by the vision system and laser tracker. The laser tracker values these fiducials in the RCS while the cameras initially record values in individual camera image space with Cognex VisionPro software. Using both sets of values (5 fiducial locations per camera, 10 total), VisionPro calculates the 6 degree of freedom (6DOF) transformation on each camera completing camera calibrations. All readings performed by the vision system after calibration are in the RCS.

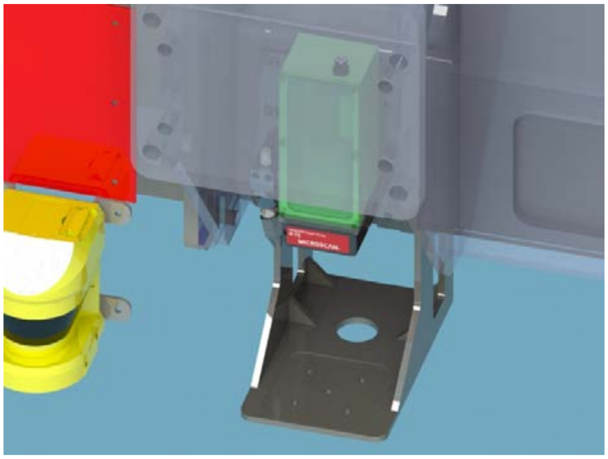

Figure 9 – Floor Resynchronization Calibration

When the mobile robot is moved and placed, it must be set down with both targets within camera fields of view (+/- 25mm). Placement is guided by downward-pointing lasers adjacent to each camera. Once placed, the vision system locates both targets in RCS. Since the targets are also at known locations in the FRS, it is now possible to calculate the mobile robot location in the FRS with a 3DOF transformation. The jig and aircraft parts are also at known locations within the FRS – using the new transformation, the robot can now rapidly approach the aircraft part with its end effector. Each time the mobile robot moves to a new location, the mobile robot 3DOF transformation is calculated upon placement.

For robotic aerospace automation systems in which flexible placement is paramount, the Floor Resynchronization System enables rapid and flexible placement where machine rail beds and cup-and-cone location are not feasible.

Automatic Tool Changer

The Automatic tool changer in the configuration shown has 24 modular pockets that can hold HSK 32 tool holders, HSK 40 tool holders, and probe tips. The tool changer has an RFID read write head for reading tool holder information. A sensor measures pocket occupancy.

The tool changer has a singular axis design which is more compact and precise than standard conveyor tool changer designs. The enclosed design prevents accumulation of chips, dust, and coolant. Figure 10 is a picture of the ATC from the described mobile robot.

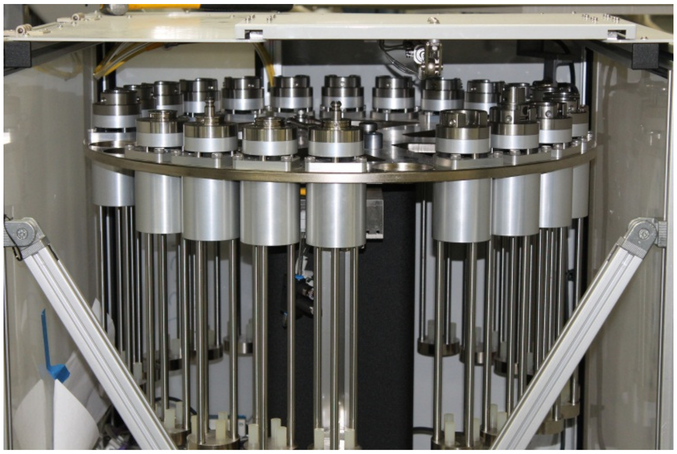

Figure 10 Automatic Tool Changer

Fastener Feed Systems

The mobile robot can be equipped with an Electroimpact fastener feed system, or an original equipment manufacturer fastener feed system. Pictured below in Figure 11 the Electroimpact fastener feed system has 18 hoppers and 24 hangers.

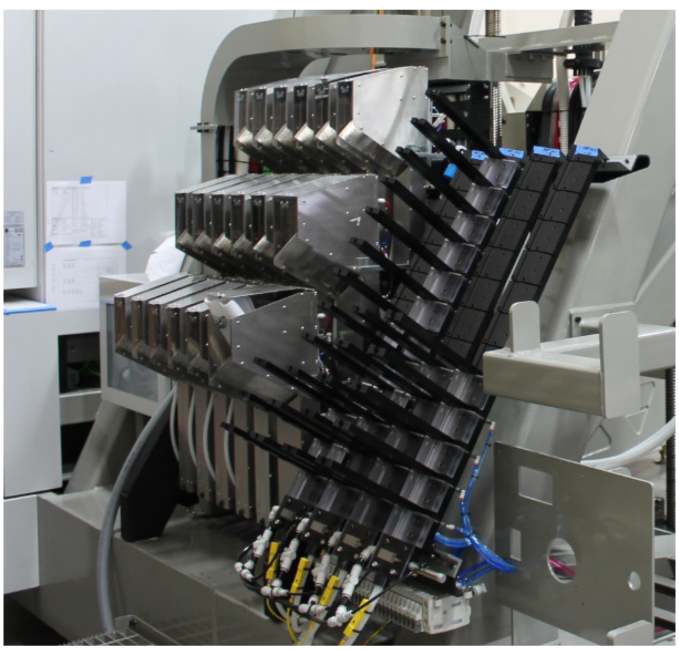

Figure 11 Electroimpact Fastener Feed System

The configuration shown above can accommodate 42 different grip lengths for fasteners sized 5/32, 3/16, 1/4, and 5/16 for HST10 and HST11 fasteners. Other sizes can also be accommodated. Drop tubes allow for single fastener insertion for testing and for low quantity production runs.

Movement Methods

The mobile robot can be moved on full swiveling wheel casters or air casters. The movement is handled with battery powered electric tugs, or in some cases, pushed by hand. For the mobile robot described the electric tugs used are manufactured by MasterMover™.

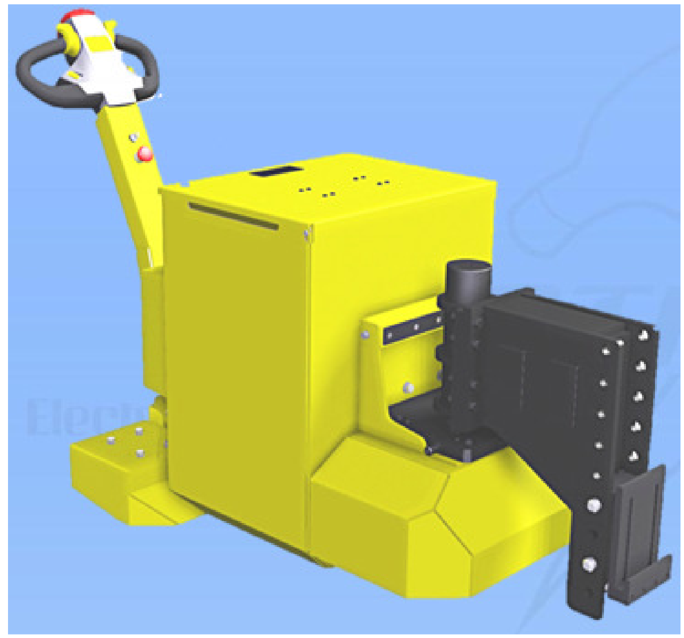

Figure 12 MasterMover

Transport moves are generally handled with the wheel casters, and two operators using a pair of electric tugs on a single mobile robot; the electrica tugs are positioned opposite each other on the sides of the mobile robot frame and allow maximum freedom of movement.

In jig and precision moves are facilitated with the help of a guide rail that is mounted in the floor. The rail used is Strothmann™ flush floor round track. Electroimpact has adapted the rail product to include curved sections, which increases the scope of guided moves that can be accomplished in sensitive and limited access areas. The Strothmann rail guidance yields single axis precision of +/- 1mm throughout the guided movement.

The mobile robot guided movements can be accomplished with the mobile robot frame supported by either the wheel casters or the air casters.

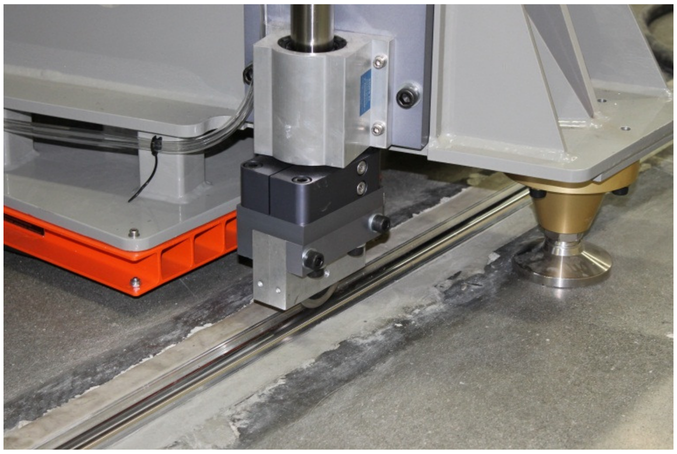

Figure 13 Air Caster and Strothmann Rail

The wheel caster system uses one wheel caster at each corner of the mobile robot. The wheel casters incorporate a powered vertical axis that lifts the mobile robot frame off the floor for movement on the wheel casters. This arrangement gives the frame the most rigid contact with the floor during use of the robot. Electroimpact has used two methods for actuating the vertical axis on the wheel casters; one method employs screws, motors, and caster frames with suspension, the other method employs airbags as both the lifting and suspension mechanism, with air circuitry that permits the load to be kept level during lifting.

The air caster system uses an air caster near each corner of the mobile robot, and two air actuated brakes. The air caster system is arranged to facilitate short in-jig movements with the mobile robot being pushed between positions by the operator, without the need to use additional equipment such as an electric tug. The air actuated brakes are deployed by default, and must be released by the operator; this prevents drifting of the mobile robot platform when the air casters are energized, and reduces workload on the operator as the mobile robot is pushed into its next position.

The mobile robot can be positioned very accurately without mechanical guidance in areas where clearance is not a concern using a pair of “acute angle chevrons” marked on the floor and a pair of lasers mounted on the mobile robot frame and powered by an on-board battery. The operator keeps the laser dot on the floor between the two converging lines of the chevron, and is easily able to steer the dot to the point where the two lines converge. First time operators with no training have routinely been able to complete a rough 10 meter course and position both alignment laser dots in a pair of 25mm diameter circles at the point of the chevrons in times of under 5 minutes total without the aid of chevrons.

With additional features, the mobile robot can also be positioned in close proximity to difficult to access work pieces by positioning the vertical axis of the mobile robot for work piece clearance and moving the frame into position, such that the vertical axis movement is limited, but access of the robot is enhanced.

SUMMARY/CONCLUSIONS

The mobile robot is an all-in-one solution for automated drilling, countersinking, and fastener insertion of aircraft equipment. Mobility, flexibility, speed, and accuracy were the overriding design goals. The robot can be moved using casters, air caster, or rail. The flexibility of a 6 axis KUKA robot has been greatly increased coupling it with a 7th axis Y-Sled on a mobile platform giving it an infinite number of locations it can operate from. The end effector can host a variety of process tools that build upon more than 25 years of experience in the automated aircraft assembly industry. Finally, borrowing from Electroimpact’s line of accurate robots the solution is able to offer exceptional positional OFF-PART and ON-PART accuracies to best meet the stringent criteria of leading aircraft manufacturers.

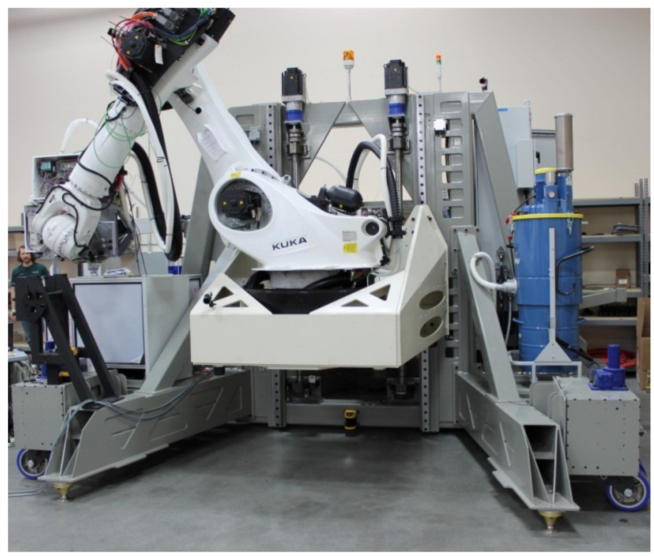

Figure 14 – Electroimpact Mobile Robot

Table 2. Electroimpact Mobile Robot Specifications

Width	4260mm
Depth	3485
Height	2955mm
Weight	11,800kg
Vertical Travel	1750mm
Tool Changer Positions	24
Robot Type	KUKA KR500-L340
Controls System	Siemens 840Dsl CNC

REFERENCES

1. Russell DeVlieg, "Applied Accurate Robotic Drilling for Aircraft Fuselage," SAE Technical Paper 2010-01-1836, 2010.
2. Russell DeVlieg, "High-Accuracy Robotic Drilling/Milling of 737 Inboard Flaps," SAE Technical Paper 2011-01-2733, 2011, doi:10.4271/2011-01-2733.

CONTACT INFORMATION

Troy Gray, Electroimpact, Mukilteo, WA 425-348-8090

Daniel Orf, Electroimpact, Mukilteo, WA 425-348-8090

Greg Adams, Electroimpact, Mukilteo, WA 425-348-8090

ACKNOWLEDGMENTS

Russell DeVlieg, Lead Robotic Engineer, Electroimpact

Siemens, www.sea.siemens.com

KUKA Robotics, www.kukarobotics.com

DEFINITIONS/ABBREVIATIONS

ATC	Automatic Tool Changer
DOF	Degree of Freedom
FRS	Foundation Reference System
QR Code	Quick Response Code
RCS	Robot Coordinate System
RFID	Radio Frequency Identification
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
TCP	Tool Center Point
T.I.R.	Total Indicated Runout