Fully Automated Robotic Tool Change

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Abstract

An improved aircraft assembly line incorporates fully automated robotic tool change. Ten machine tools, each with two onboard 6-axis robots, drill and fasten airplane structural components. The robots change 100% of the process tooling (drill bits, bolt anvils, hole probes, and nosepieces) to allow seamless transition across the entire range of hole and fastener sizes (3/16″-7/16″). To support required rate, total tool change time (including automatic calibration) is less than 80 seconds. This paper describes the robots and their end effector hardware, reliability testing, and simulations for both mechanical clearance and cycle time estimation.

Introduction

Electroimpact won a contract to design, build and install an improved aircraft assembly line. Key requirements included improved ergonomics and cycle time of the tool change process, as previous manual tool change procedures involved lifting heavy tools and take approximately ten minutes to complete. Additionally, neighboring machines in the cell had to simultaneously work on one aircraft part which reduced access to offline tool racks. The new automated process completely eliminated human-performed actions in favor of an onboard fully Automated Tool Change (ATC) process requiring less than 80 seconds to complete.

Electroimpact drew on previous experience for various portions of the new ATC process, for example changing drill bits and bolting anvils on the E7000 squeeze machine [1]. However, this latest ATC process contained unique challenges in terms of the variety of onboard pickup and drop off locations, tool shapes, and tool payloads.

After considering the limited machine envelope (driven by factory space) as well as the variety and location of tool payloads, Electroimpact implemented two onboard 6-axis robots to perform the ATC process due to their size and flexibility.

The ATC Process

The FANUC M10iA/12 and M20iA/35M robots ride on the machine gantry. They remain in a safe parked position during normal machine drill/fasten cycles. Figure 1 shows locations of the ATC system components.

All drill bits, hole probes and bolting anvils not in use on the current machine cycle are stored in a rack located above the M10 robot. Similarly, all nosepieces not in current use are stored on the side of the machine tool tower. All ATC components fly with the machine so that tool change can be performed at any location in the cell. This saves time as it eliminates the need for the machine to drive to a specific location.

A CNC is connected to a robot controller and starts the tool change via an NC code. The (smaller) M10 robot exchanges drill bit, hole probe, and bolting anvil tools between the machine tool's process shuttle table and onboard storage rack.

Simultaneously, the (larger) M20 robot swaps out the heavier machine nosepieces which include a collar swage or nutrunner nosepiece on the far side of the machine, and a combined clamping and vacuum nosepiece on the near side. The robot also swaps the vacuum hose between clamping nosepieces.

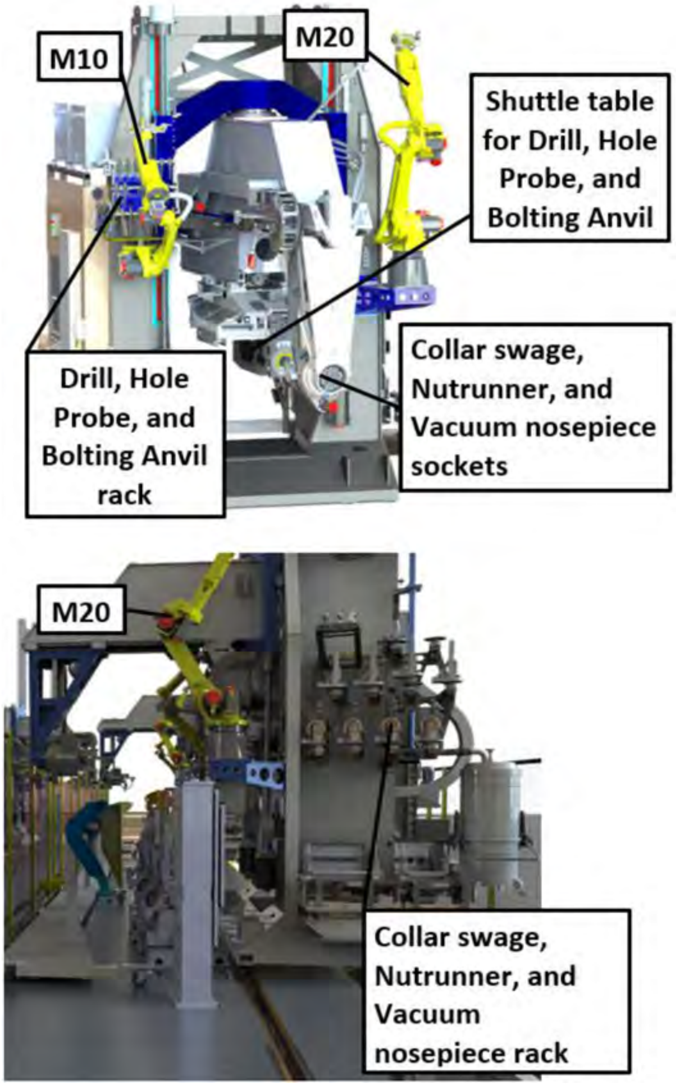

Figure 1. Machine front/side views showing locations of ATC components. These include M10/M20 robots, tool storage racks, and the machine sockets/ shuttle table housing in-use tools.

Payload and Shape Variety of Interchangeable Tools

Each interchangeable tool performs a unique function (drilling, measuring, bolting, collar swaging and nut running) and hence has a different shape and weight. Further, a given category of tool has variants to work on different diameters - for example, there are ten different drill bits to produce the airplane part. However, a single End Of Arm Tooling (EOAT) configuration on each robot has the lowest cost, complexity, and eliminates the need to change out EOAT.

Electroimpact consolidated the number of shapes to be gripped to facilitate a single EOAT per robot. Specifically, the M20 EOAT grips all collar/nutrunner nosepieces utilizing a common bolt-on interface block which in turn is designed to mimic the shape of the vacuum nosepiece, whose shape was determined by other factors.

A similar approach was taken on the M10 EOAT, where ATC features of every hole probe and bolting anvil match the stock HSK standard toolholder for the drill bit, as shown in Figure 2.

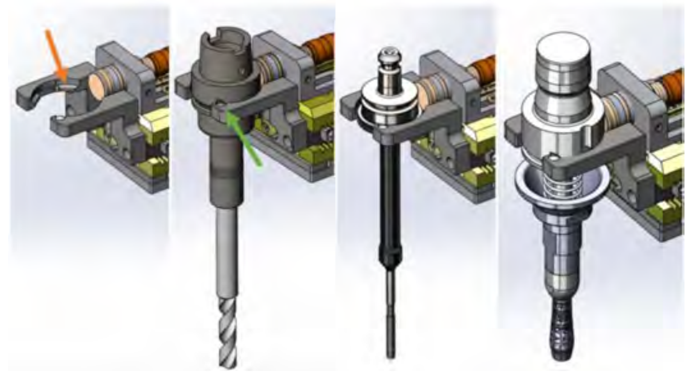

Figure 2. M10 EOAT in various states. Left to right: empty, gripping drill bit, gripping hole probe, gripping bolting anvil. Note all tools mate with the same gripper locating taper (orange arrow) and clocking dowel (green arrow).

The M20 EOAT carries payloads as small as a 3/16″ vacuum nosepiece (0.7 kg and fist-sized, shown in Figure 3), and as large as a 3/8″ nutrunner nosepiece (20 kg and larger than a basketball, shown in Figure 4). For the heavier nosepieces, toolchange performance was aided by keeping center of mass close to the robot wrist.

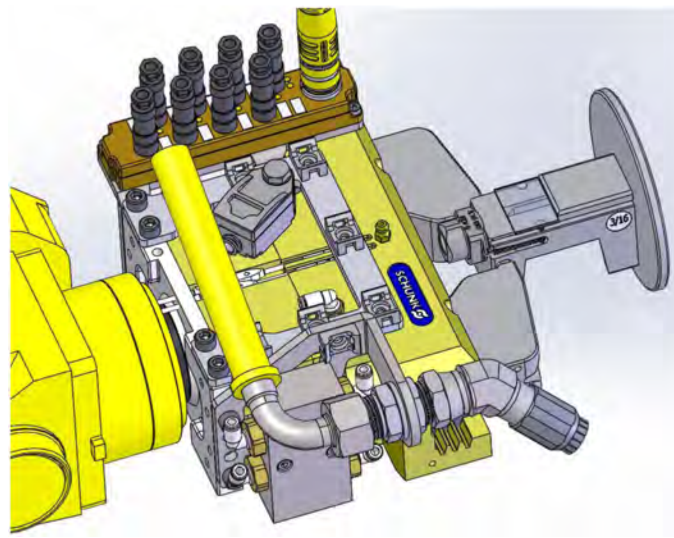

Figure 3. 3/16″ vacuum nosepiece in M20 EOAT

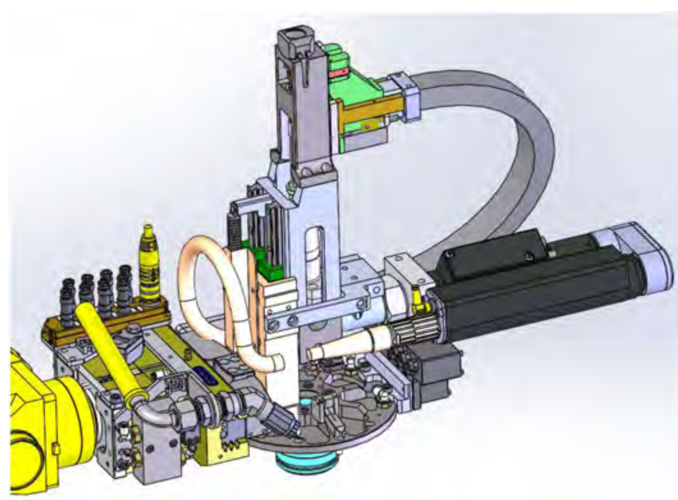

Figure 4. 3/8″ nutrunner nosepiece in M20 EOAT

The range of payloads carried by the M20 presented a challenge. Preliminary testing showed +/−2 mm vertical accuracy across the payload range. This required multiple taught positions dependent on the current payload and move (either pickup or drop off). Upon the application of gravity compensation the vertical accuracy range was reduced to +/−0.1 mm. The narrower range enabled a single taught position to be used across all payloads and move types - reducing both programming and setup time. Ease of maintenance was also a primary concern during design of both M10 and M20 EOAT and tool racks, discussed next.

The M10 Robot

Electroimpact chose a FANUC M10iA/12 6-axis robot to change drill bits, hole probes and bolting anvils (Figure 5 and Figure 6). The axis count allows the robot to obtain the required pick-drop positions despite a tight robot envelope created between machine tool components, aircraft parts, and tooling fixtures. A hollow-wrist robot configuration enables easier cable routing to the EOAT.

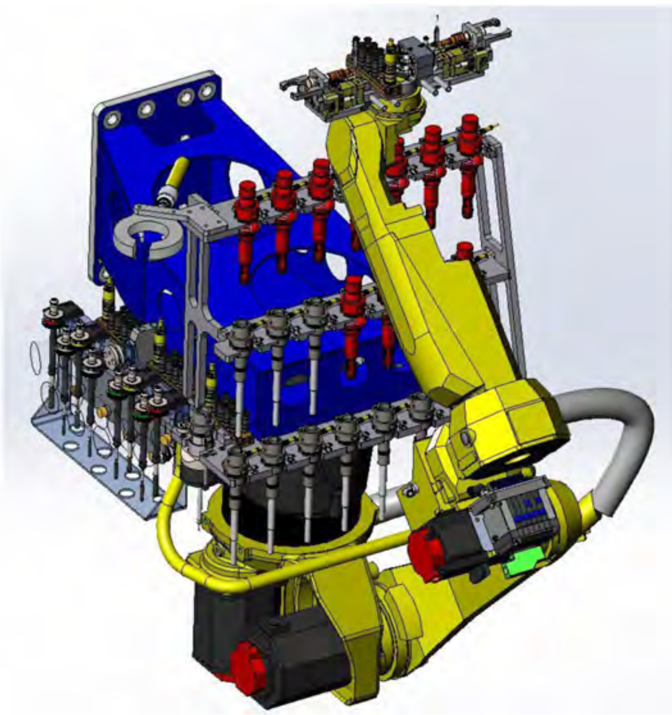

Figure 5. M10 robot with tool rack containing drill bits, hole probes and bolting anvils.

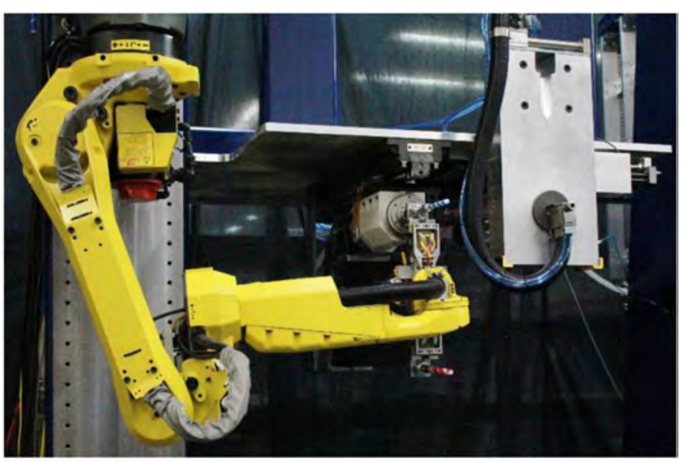

Figure 6. M10 robot at drill spindle during drill bit pickup.

M10 EOAT

The M10 EOAT (Figure 7) has two symmetric grippers and transits twice between storage rack and shuttle table during a full ATC cycle. The dual-gripper configuration allows optimal workload balance.

Equipping the both M10 and M20 EOAT with multiple layers of protection against dropping tools was carefully considered. These are detailed later.

A Balluff Radio Frequency Identification (RFID) reader mounted on each gripper allows on-the-fly read/write of process data to/from chips mounted in each drill bit holder. This requires no extra ATC cycle time since data transmission occurs while the robot transits between machine sockets and tool storage rack.

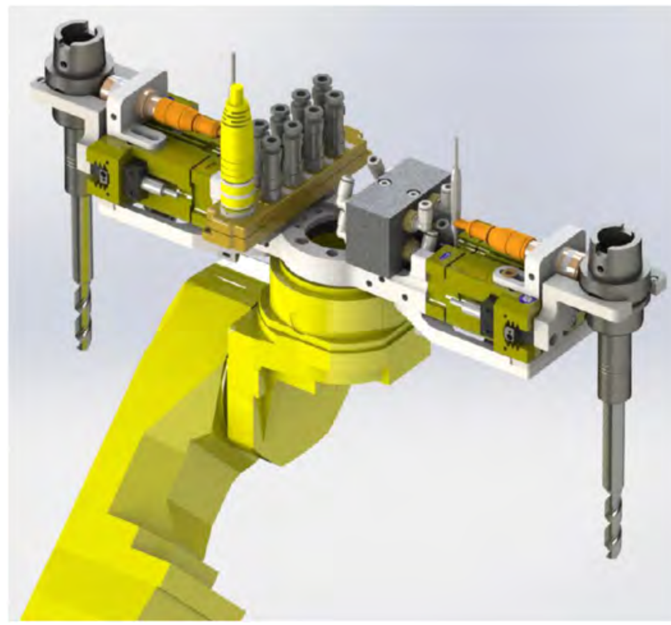

Figure 7. M10 robot EOAT

M10 Tool Storage

A rack located above the M10's base contains pockets for up to 22 drill bits and bolting anvils, 8 hole diameter measurement probes, and a touch probe. Tools are densely arranged in a linear “stadium seating” configuration. Every tool pocket has an inductive proximity sensor to indicate each tool is fully seated in its pocket. The machine tracks location of all interchangeable tools, but in addition color-coded labels allow quick visual confirmation that each tool is in the proper pocket.

Hole probes sit in their own detachable rack to allow easy removal for ultrasonic cleaning of aircraft sealant.

Drilling debris buildup is a reality of airframe work despite onboard machine tool vacuums. An air knife mounted to the tool rack automates cleaning of each picked tool's shank prior to insertion in the machine socket, thus replacing the older “operator with a rag” cleaning method. This ensures a reliable tool drop-off every cycle.

The M20 Robot

Electroimpact chose a FANUC M20iA/35M 6-axis robot to change collar swage, nutrunner, and vacuum nosepieces (Figure 8 and Figure 9). This is the high payload variant of the standard M20 and was chosen to accommodate the heaviest nutrunner nosepiece along with the M20 EOAT mass itself, which have a total payload of 26 kg and center of gravity (CG) 250mm off the face of the M20 wrist.

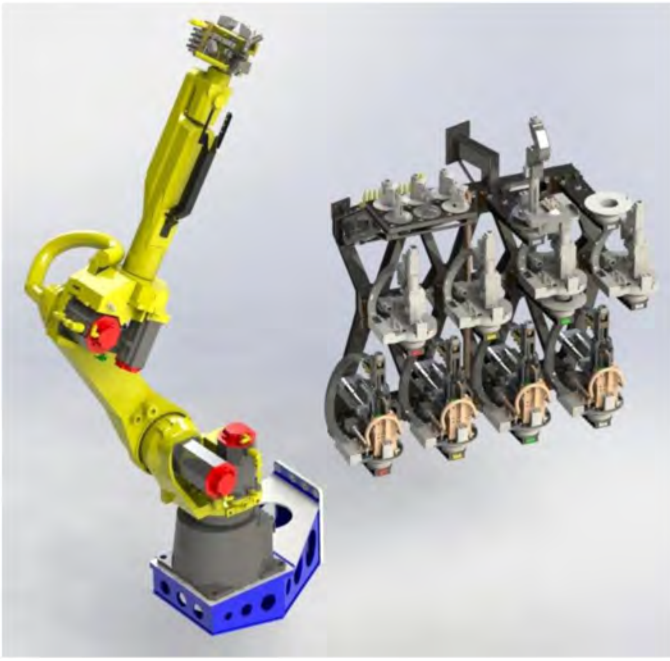

Figure 8. M20 robot with nosepiece rack.

Figure 9. M20 robot at machine socket during a nosepiece tool pickup.

M20 EOAT

The M20 EOAT is a single gripper configuration (Figure 10). A Schunk PGN+ pneumatic parallel gripper was chosen for its robust multiple-tooth guidance design which spreads loads across many shoulders. This gives the gripper a high moment capacity while minimizing wear and play over the service life, thus minimizing maintenance down time.

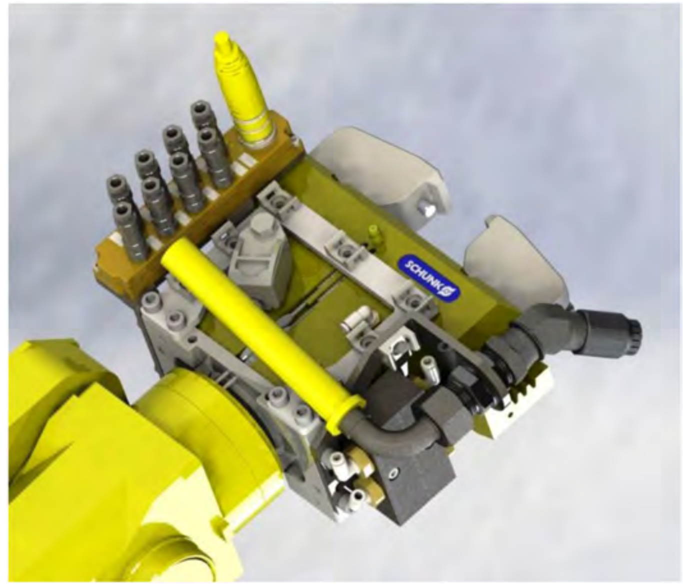

Figure 10. M20 robot EOAT

The M20 EOAT gripper fingers clamp tools using a wedge design (yellow arrows in Figure 11). This allows the gripper to "lead-in" from an approximate location, when gripper is unclamped, to a final precise location, when gripper is fully clamped on the workpiece. This helps compensate for the inaccuracy inherent to serial manipulators.

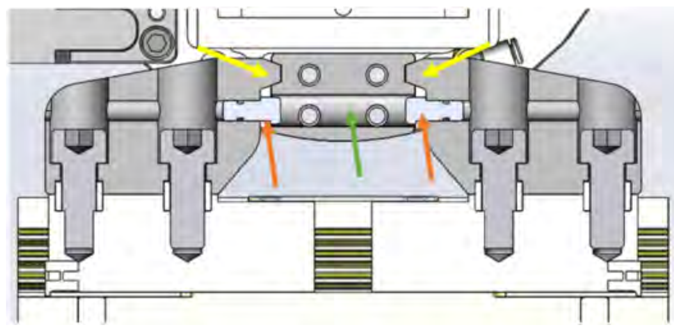

Figure 11. M20 EOAT gripper finger wedge and backup pin cross-section.

An air nozzle on the M20 EOAT cleans drilling debris off the vacuum nosepiece receiver socket prior to nosepiece install (Figure 12).

Figure 12. The M20 EOAT cleans a machine tool socket immediately prior to installing the vacuum nosepiece.

EOAT Safety Features

Since the nutrunner and collar swage nosepieces must be transported over an aircraft part during toolchange, and carbide drill bits and precision hole probes can be damaged by dropping, multiple safety mechanisms were implemented to minimize chance of tool drops on both robots. These include:

1. On the M20 EOAT, a low angle wedge grips the nosepiece (yellow arrow in Figure 11) and backup pins catch a clearance bore in the event the wedge fails (orange and green arrows in Figure 11). The M20 gripper clamps with 497 lbf of force; combined with the wedge design this results in very high resistance to cam-out.
2. All M10 and M20 grippers are spring-closed by default.
3. A combination of sensors confirms all M10 and M20 gripper fingers are clamped to a proper width and differentiate between "clamped with tool", "clamped without tool" and "unclamped".
4. Pressure maintenance valves "lock" the current pneumatic state of every gripper in case of sudden air loss. This prevents both uncontrolled opening and closing (a pinch hazard).
5. Every M10 and M20 gripper uses a dual-solenoid "bistable" pneumatic valve that requires two opposite control inputs (ON+OFF or OFF+ON) to open or close the gripper. The redundancy protects against unintended gripper motion during controller power cycles or resets.

These multiple levels of protection result in remarkably reliable tool pickups and drop-offs.

M20 Tool Storage

After careful consideration of the allowable machine envelope and robot reach simulations in both Solidworks and FANUC ROBOGUIDE, the nosepiece storage rack was located on the side of the machine tower (Figure 13). The initial design of a structural wall integral to the tower limited M20 access to the tool rack. Simulations and physical mockups (Figure 14) guided a revision to the structural wall and confirmed the rack layout. This solution was implemented prior to the manufacturing phase of the project.

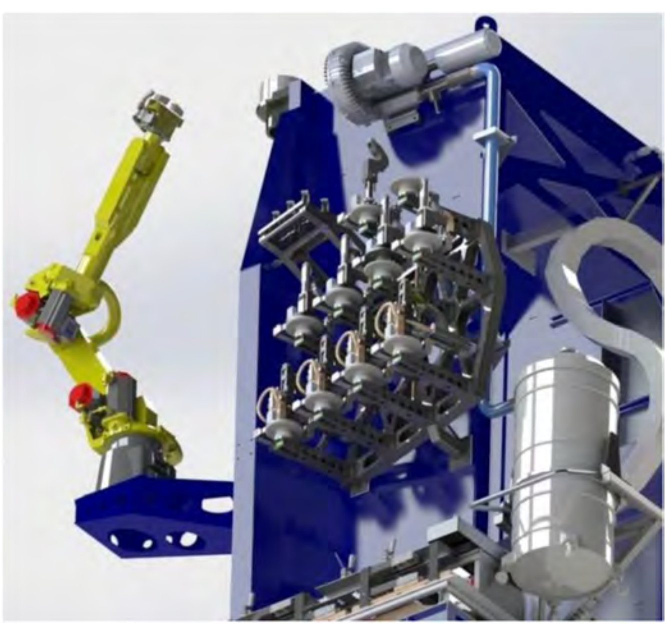

Figure 13. Nosepiece rack on side of machine tower. Note the structural wall between robot and rack.

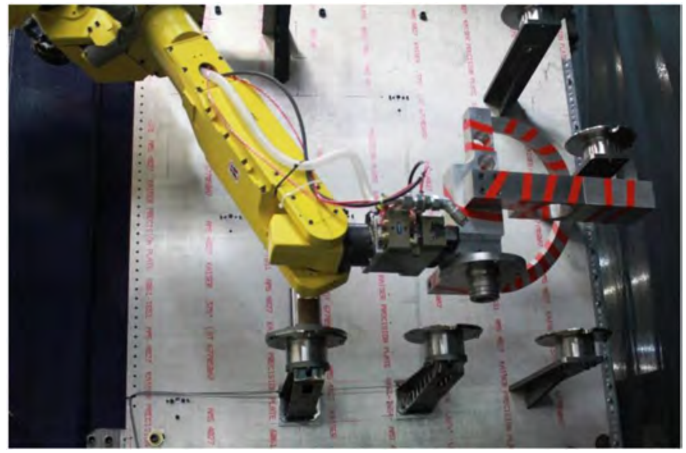

Figure 14. M20 robot reaching to the collar swage / nutrunner / vacuum nosepiece tool rack during high payload testing.

The machine has storage for ten large nosepieces, including four nutrunners, four collar swaging tools, one specialty drill only nosepiece, and a spare socket. Additionally, there is space for six small vacuum nosepieces. Every nosepiece pocket has a proximity sensor to confirm the nosepiece is fully seated before the gripper lets go.

A stiff storage rack facilitates reliable tool pickup regardless of mass. Finite Element Analysis (FEA) helped create a nosepiece tool storage rack that deflects a maximum of 0.003″ at each tool cradle (Figure 15). Known pocket locations allows the pickup and drop off locations to be programmatically entered rather than taught individually, reducing programming time. Positions are stored independently, however, as this allows for a single position to be quickly re-taught in the event an anomaly alters one position on the tool rack but not the others. This in turn reduces downtime and increases ease of maintenance.

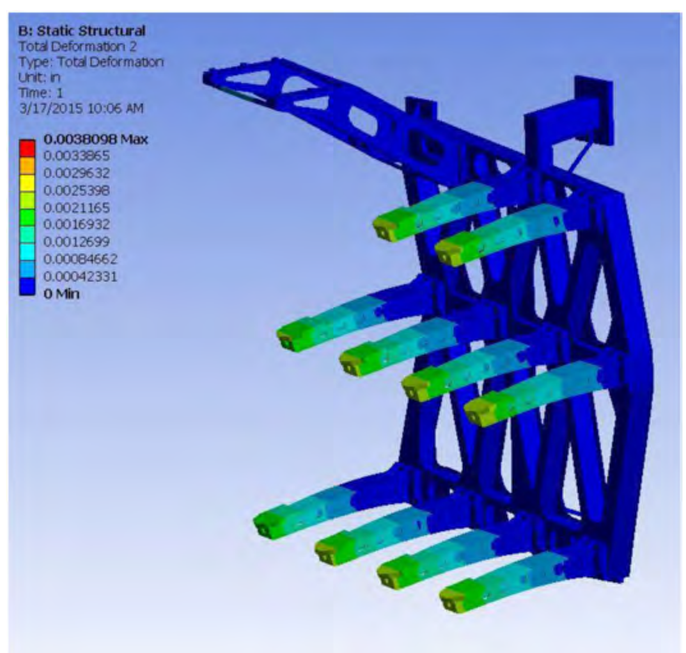

Figure 15. FEA of M20 tool rack indicates 0.003″ deflection at tool cradle (yellow to blue differential).

FEA also helped minimize machine weight (important in the event of machine transport using a factory overhead crane). The resulting tool rack frame is very structurally efficient, weighing only 117 kg yet carrying an additional 125 kg of tools.

Tool Identification

In addition to structural stiffness, a robust ATC process requires the machine to know the position of every interchangeable tool at all times, and to be able to recover if a human bypasses a robot and installs a tool by hand.

Tool identification is performed through a combination of methods. For vacuum nosepieces, a unique pattern of counterbores in each nosepiece mates with a unique pattern of protruding pins in each socket on the rack. Each nosepiece will fully seat in only one correct pocket on the rack and trigger the "fully seated" proximity sensor (Figure 16).

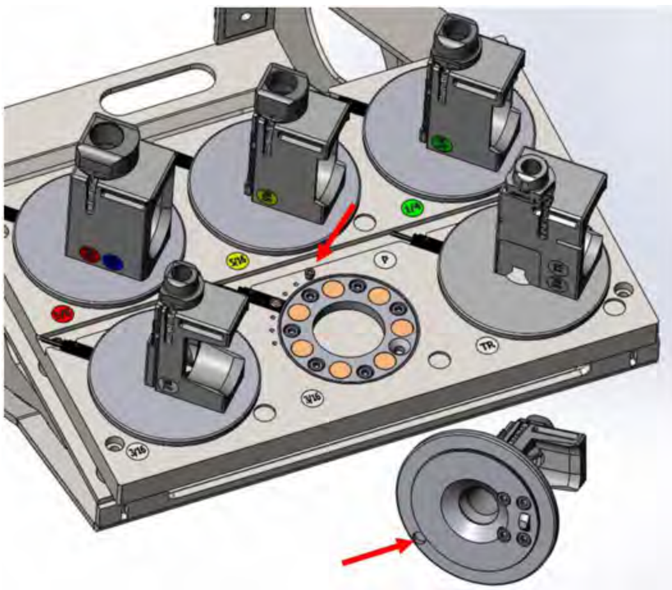

Figure 16. Vacuum nosepiece tool identification. Each nosepiece has a unique counterbore pattern which mates with a unique pin pattern on the rack (red arrows).

Large nosepieces utilize Dual In-line Package (DIP) switches for unique identification.

Drill bits and bolting anvils are identified via an RFID chip previously discussed in the M10 EOAT section.

Hole probe tips are designed with unique lengths to allow a linear transducer to identify the currently installed tip.

These methods combined create a state machine that increases the reliability of the ATC process.

Reliability of the ATC Process and the ATC Testbench

The overall machine tool is designed for 15 years' life of major components. This served as a benchmark during high cycle ATC testing. Every toolchange process had to be run for an equivalent 15 years' worth of cycles to refine wear-prone areas of the design.

The machine cell schedule did not permit time for debugging the ATC process on the actual machine tools; a separate testbench was needed. Over a period of 9 months, a testbench with all ATC components was designed, built and used for extensive cycle testing.

The required high cycle count meant that continuous human monitoring was not feasible. To ensure all errors were logged for analysis, a combination of cameras, cycle counters, and FANUC error logs were used to track each cycle test. Periodic inspections by engineers allowed for any early signs of wear or faults to be caught and addressed.

The ATC testbench was built while the machine design continued. As such, a number of geometric inconsistencies developed between the two over time. This difficulty was overcome by a modular testbench design that allowed the ATC components to be re-positioned in space relative to each other to mimic the latest machine design.

Close-clearance situations found in ROBOGUIDE were physically checked on the testbench to confirm access (Figure 17).

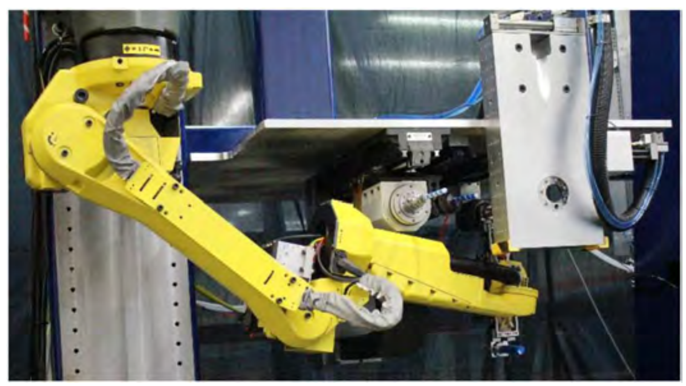

Figure 17. M10 robot in position for a close clearance pick on ATC testbench.

Another result of testbench testing was a better tailoring of alloys for mating parts. As an example, the M10 EOAT gripper fingers were initially made from 17-4 stainless steel at an H1150 temper, resulting in alloy hardness of 28-37 HRC. Although this allowed the grippers to be cost effective parts due to material availability and machinability, gripper wear after several hundred thousand cycles (Figure 18) led to the grip being "sticky".

As a result, the gripper material was changed to A2 tool steel, hardened to 56-60 HRC, and critical surfaces polished. This design has eliminated any significant wear and "sticky" grips. Although the parts are slightly more expensive, their initial cost will be recovered many times over in saved maintenance labor.

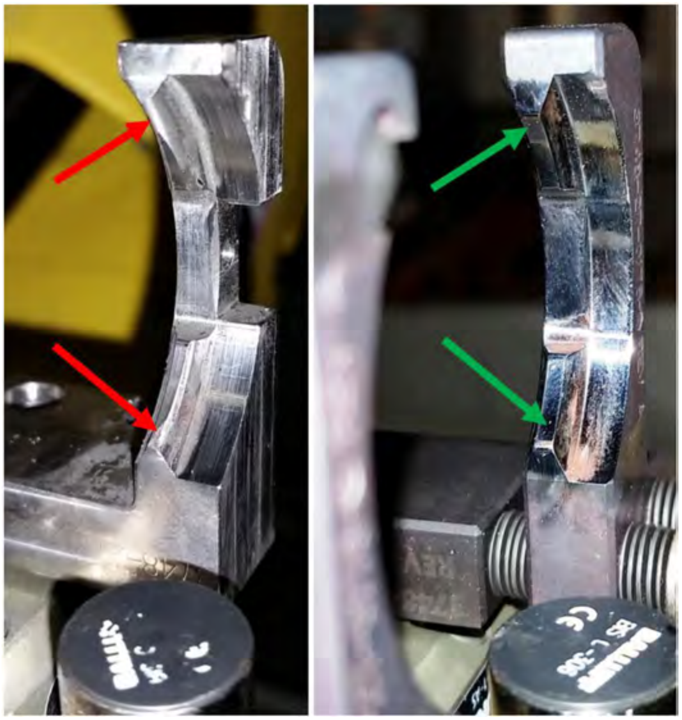

Figure 18. Wear on M10 EOAT gripper fingers after several hundred thousand cycles (at left). Compare this to a brand new set of fingers (right).

The nine-month long testbench proving period was successfully completed prior to the first machine build, thus compressing overall schedule while resulting in a high degree of confidence that all components are designed robustly to minimize maintenance over the entire life of the improved assembly line.

Alignment

A challenge faced by the robots is ensuring the alignment of the tool in the EOAT is within tolerance relative to its destination, be it a socket on a machine process tool or a pocket on a tool rack. Several alignment calibration methods were tested, and the resulting precision allowed tens of thousands of tool change cycles to be performed without error.

Two alternative alignment methods were tested and accepted as useable:

1. Robotic Vision, a software tool that allows physical targets placed on the machine to aide in the quick setting of a few key points. From these points an alignment can be established. This is convenient for initial set up, but the requirement of attaching a camera to the robot makes it cumbersome to perform on-the-fly (Figure 19).
2. A combination of operator vision and dial indicators. An operator with an EOAT-held dial indicator (Figure 20) and a ruler can correct the alignment of an individual tool or rack location.

Other methods were investigated to aide in alignment, including laser tracking and soft-floating the robot to allow for greater misalignment. However, these were ultimately rejected after consideration.

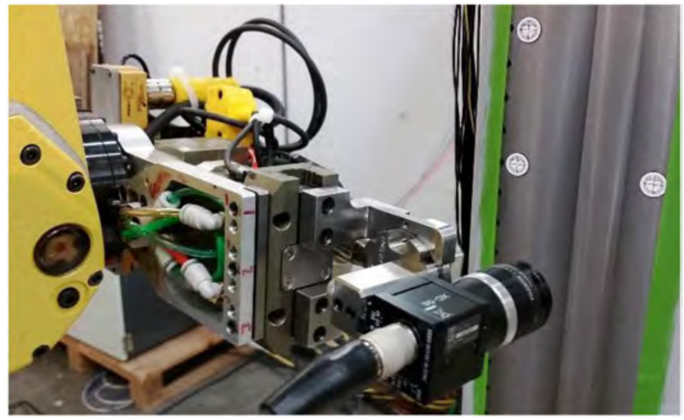

Figure 19. Robotic Vision testing using a camera held in the M10 EOAT sighting three targets.

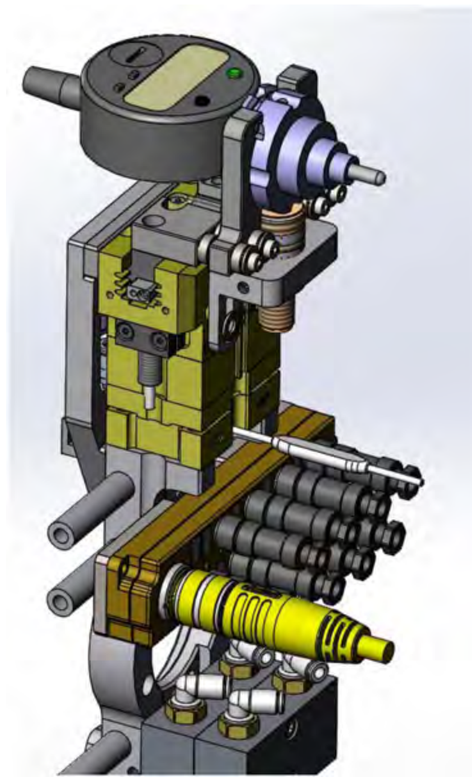

Figure 20. Plunger gage alignment tool in M10 EOAT.

Simulation

Electroimpact positioned the robots on the machine tool using simulation software. Simulation also allowed the generation of robot programs before the manufacturing of hardware components. Clearance and access checks were conducted in the virtual environment using near final programs. The early development of programs shortened the startup time required for the actual cell.

In addition, simulations provided accurate cycle times estimates during the design phase. The estimates allowed for the ATC process to be confirmed and revisions made before manufacturing - reducing both cost and startup time.

Summary/Conclusions

Manual tool change requires several undesirable human/machine interactions: operators must lift heavy and sharp tools, consistency of tool installation is operator dependent, and change time can take up to ten minutes. Automatic tool change address all concerns: no operator interaction is required, a robot repeats tool installation identically every cycle, and change time is under 80 seconds. Robotic tool change provides an efficient solution where machine envelope, tool diversity, and cycle time are concerns.

References

1. Stansbury, E., Bigoney, B., and Allen, R., "E7000 High-Speed CNC Fuselage Riveting Cell," *SAE Int. J. Mater. Manf.* 7(1):37-44, 2014, doi:10.4271/2013-01-2150.

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Definitions/Abbreviations

ATC - Automated Tool Change.

Bolting anvil - Interchangeable tool that pushes a bolt into a drilled hole (and also provides reaction force if swaging a collar) during fastening of aircraft parts.

CG - Center of Gravity.

CNC - Computer Numerical Control.

Collar swage nosepiece - Interchangeable tool that clamps on aircraft parts to prevent their movement while feeding and swaging a collar onto a bolt tail, thus fastening the aircraft parts together.

DIP switch - Dual In-line Package switch. A manual electrical switch.

EOAT - End Of Arm Tooling.

FANUC ROBOGUIDE - Offline robot simulation software from FANUC Corporation. Used for simulating robotic work cells and processes in 3D space.

FEA - Finite Element Analysis.

Hole probe - Interchangeable tool that precisely measures the diameter of a drilled hole, which allows a machine tool to ensure the hole is within quality specifications.

HRC - Hardness on the Rockwell "C" scale, used for relatively hard steels.

Linear motor - Electric induction motor that produces straight-line motion.

M10 - FANUC M10iA/12 robot.

M20 - FANUC M20iA/35M robot.

Nosepiece - Interchangeable tool that clamps aircraft parts together to prevent their movement while the aircraft parts are drilled and fastened together.

Nutrunner nosepiece - Interchangeable tool that clamps on aircraft parts to prevent their movement while feeding and tightening a nut onto a bolt tail, thus fastening the aircraft parts together.

RFID - Radio Frequency Identification.

Shuttle table - A linear-motor driven axis that moves process tools into required position to perform work on the aircraft.

State machine - A device that stores the status of something at a given time and can operate on input to change the status and/or cause an action or output to take place for any given change.

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