High-Capacity Mobile Robotic Drilling and Fastening System

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Special acknowledgement:
The Boeing Company
High-Capacity Mobile Robotic Drilling and Fastening System
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What to expect in the next 25 minutes:

- Application
- Brief System Familiarization
- Quick Comparison
- System Design Requirements/Constraints
- Interaction with Jigs
- Automation System Basics
  - Mobile Platform
  - Robot
  - End Effector
- Drilling Process
  - Skins
  - Fittings
- Short Videos
- Questions
Application: Aircraft Wing Section

- **Automation Goals**
  - Maximize quality
  - Reduce manual labor
    - Reduce dependence on drill plates
    - Reduce dependence on power feed drills
Application: Aircraft Wing Section

- **Skins to Structure**
  - Drill, CSK, Measure, Temp Fasten
  - Drill sizes 3/16 - 3/8” (4.8 - 9.5mm)
  - Aluminum only

- **Fittings, Skins, Structure**
  - Spot/Endmill, Drill, Ream, Measure
  - Drill sizes 1/4 - 9/16” (6.4 – 14.3mm)
  - High-strength materials and various aluminum alloys
• **Skins to Structure**
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System Familiarization

- Multi-function end effector
- Siemens 840D control system
- Accurate Robot
- Tool Change Station
- Air-powered drive wheel (x2)
- Fastener Delivery
- Air Bearings (x4)
- Indexing System
- Air-powered drive wheel (x2)
- Mobility System Battery Cell
Compare to Typical Robotic Drilling System

**Robot**
- Reach: 10% increase (4.3m vs. 3.9m)
- Payload Capacity: 2.2x (750kg vs. 340kg)
- Stiffness Increase: ~2.5x

**Stiffness and stability – no bushing guiding drill**
Compare to Typical Robotic Drilling System

- **Robot**
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- **Process Head**
  - Clamp load: 2.2x (1200 lbf vs. 550 lbf)
  - Spindle: HSK63 vs. HSK40
    - Power Increase: 2.8x (25kW vs. 9kW)
    - Torque Increase: 2.7x (40Nm vs. 15Nm)
    - Hole size in Ti: 2x (~25mm vs. 13mm)

- **Extras**
  - On board tool swap
  - Integral mobility system (pendent and/or camera controlled)
Application-Specific Requirements/Constraints
Requirements/Constraints: Existing Tools

- System must reach all areas of product without collision with tool
- Tools are mobile. System must lock in.
Requirements/Constraints: Reach All Corners
Requirements/Constraints: Reach Top of Part
Requirements/Constraints: Existing Factory

- Introducing automation to line already at full rate production
- System must fit within existing layout and navigate around
Requirements/Constraints: Existing Factory

Close clearances dictate system packaging
Requirements/Constraints: Potential Side-by-Side Operation
Requirements/Constraints: +/-0.010” Positional Accuracy
Requirements/Constraints: Integral Lift

- Manually float in place
- Engage indexes on jig
- Robot mates with lift structure
Interaction Between Machine and Jig(s)
Two Index Points between Robot and Platform

Two Index Points between Jig and Lift Platform

Primary Indexes

Two Index Points between Robot and Platform
Indexes

Hook Index (machine)

Guide and Index Receiver (lift)
• Automated indexes provide solid union between machine and jig
Indexes

- Automated indexes provide solid union between machine and jig
**Integral Lift Platform**

- 60 inches of lift with lowered height of 10.5 inches
- 2,000lbs lifting capacity.
- Reclinable handrail along one side of platform with swing gate on each end.
Automation System Basics
KR1000L750 enhanced with EI Accurate robot technology

Siemens 840Dsl CNC

EI Multi-function end effector

Air Bearings (x4)

Air-powered drive wheel (x2)

Indexing System
System Overview

Operator Interface

Centrix Fastener Feed System
System Overview

- Vacuum and Flood System
- Safety Scanners
- Rotary Tool Changer and Coupon Stand
Platform

Machine CG. Triangle shows foot locations
Mobility Drive System

Drive and Steering

Air Bearings

Feet
Mobility Drive System

- Wireless Handheld Remote
- Integrated Battery/Charger for Controls
- Propulsion
  - Drive & Steering
  - Air Bearings (lift)
Drive Modes
Motion Simulation
Accurate Robot

Enhanced KR1000L750
Position Feedback on All Joints
• Standard industrial grade optical encoders
• Drive-Cliq compatible
• 50nm resolution ... Millions of counts per rev
Offset from Nominal Measurements

How the Robot Deforms with Force (due to link and payload mass, as well as external)

F
Process Head:
• Servo clamp axis w/load cell feedback
• Servo tool shuttle axis w/encoder
• Servo spindle feed axis
• 12,000 rpm cartridge spindle
  • HSK63 ATC
  • High-torque
  • Thru-tool coolant
• Servo hole probe
  • In-process feedback of hole and countersink diameter
• Automated vision system
  • On-axis camera
• Servo Centrix fastener installation module
• 3-Position tool swapping system
• Balluff RFID for cutting tools
End Effector

- CLAMP
- SHUTTLE
- FASTENER INSERTION
- VISION SYSTEM
- HOLE PROBE
- SPINDLE
Tool Changer
Tool Changer

Automation Access
Tool Changer
Thru-bit Cutters

Drills
- Holes direct coolant towards work piece.

Reamers
- Coolant holes are located ahead of cutting edges
- Direct coolant back at cutting edges and is extracted by the vacuum through the hole
Flood Pump and Vacuum

- Pump motor speed controlled with variable frequency drive
- Coolant flow rate is programmable
Fastener Feed
Automated Centrix Installation
-6, -8 Full Size
Length and diameter inspection
Precise control/feedback of angle/torque
~10% of locations receive fastener
Provides support for high-speed drilling

Hanger Storage System
Siemens CNC Controller
• 840Dsl
• Siemens servo and spindle drives
• Remote I/O via Profibus communication
• High speed I/O for load cell feedback, and hole diameter profiling
• Controls entire drilling system (robot, tool changer, and process head)
Operator Interface/Controls
- Boom mounted HMI
- Pendent with live-man switch enables reduced feed rate remote control of jogging, setup, and tape tryout.
Safety

Small zone with aid of robot hard stops

Scanners keep people clear of the machine and lift.
When the robot is rotated far enough, a safety switch on Axis 1 causes the rear scanner to enable.
A vertical plane laser scanner keeps the robot from extending beyond the side of the platform and reduces the size of the restricted space.
Production Process: Skin to Substructure
Process: Skin Drilling

• **Skins to Structure**
  • Drill, CSK, Measure, Temp Fasten
  • Drill sizes 3/16 - 3/8” (4.8 - 9.5mm)
  • Aluminum only

**Steps:**

• “Scan” part using vision system
• Clamp, normalize
• Drill, CSK
• Measure drill/CSK/grip
• Install fastener
Process: Skin Drilling – Scan Part

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Automated Vision System

- Integrated on-axis lighting
- Mounted to shuttle table to enable alignment with TCP (camera view is thru spindle axis)

Similar production end effector shown
Steps

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- Clamp, normalize
- Drill, CSK
- Measure drill/CSK/grip
- Install fastener
Steps
- “Scan” part using vision system
- **Clamp, normalize**
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**Nose Piece**
- Quick-connect w/damage-preventing breakaway feature
- Integrated Boelube delivery
- Angle feedback for auto-normalization
- Chip blast and vacuum extraction

Process: Skin Drilling – Clamp/Normalize
Nose Piece Features:
- Angle-sensing swivel tip
- Chip blast, Boelube delivery, vacuum

Steps
- “Scan” part using vision system
- **Clamp, normalize**
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- Install fastener

Process: Skin Drilling – Clamp/Normalize
Steps
- “Scan” part using vision system
- **Clamp, normalize**
- Drill, CSK
- Measure drill/CSK/grip
- Install fastener

**Skin Cell Nose Piece Features:**
- Large inner diameter to accommodate Tribos ‘R’ tool holders as well as Centrix inserter nose
Process: Skin Drilling – Clamp/Normalize

Steps
- “Scan” part using vision system
- **Clamp, normalize**
- Drill, CSK
- Measure drill/CSK/grip
- Install fastener

Skin Cell Nose Piece Features:
- ±4° Spherical Compliance with angle feedback
Quick change contact tips:
• 3 contact tips for use in skin cell
• Boelube delivery on all contact tips

Steps
• “Scan” part using vision system
• **Clamp, normalize**
• Drill, CSK
• Measure drill/CSK/grip
• Install fastener

Process: Skin Drilling – Clamp/Normalize
Process: Skin Drilling – Clamp/Normalize

Steps
- “Scan” part using vision system
- **Clamp, normalize**
- Drill, CSK
- Measure drill/CSK/grip
- Install fastener

**Clamp Drive**
- Servo-controlled with load cell feedback
- All process tools mount to clamp axis
Steps

- “Scan” part using vision system
- Clamp, normalize
- **Drill, CSK**
- Measure drill/CSK/grip
- Install fastener
Process: Skin Drilling – Drill/CSK

Steps
- “Scan” part using vision system
- Clamp, normalize
- **Drill, CSK**
- Measure drill/CSK/grip
- Install fastener

**Spindle**
- Fischer 12,000 rpm, 40Nm (350 in-lbs.) continuous torque
- Hydraulic-release drawbar, HSK63A taper
- Liquid-cooled
- Servo/ball screw feed with linear encoder secondary feedback
Process: Skin Drilling – Drill/CSK

Steps
- “Scan” part using vision system
- Clamp, normalize
- **Drill, CSK**
- Measure drill/CSK/grip
- Install fastener
Process: Skin Drilling – Drill/CSK

Steps
- “Scan” part using vision system
- Clamp, normalize
- **Drill, CSK**
- Measure drill/CSK/grip
- Install fastener

Drill Thrust Feedback
- Process debug
- Cutter life tracking
- Broken bit detection

Drill Wear vs Maximum Measured Thrust

Spindle Thrust Load Cell
Steps

- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- **Measure drill/CSK/grip**
- Install fastener
Process: Skin Drilling – Measure

Steps
- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- **Measure drill/CSK/grip**
- Install fastener
Process: Skin Drilling – Measure

Steps
- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- **Measure drill/CSK/grip**
- Install fastener

• 1/1 ratio of encoder movement to bore gage diameter change
Process: Skin Drilling – Measure

Steps
- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- **Measure drill/CSK/grip**
- Install fastener
Steps
- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- **Measure drill/CSK/grip**
- Install fastener
Steps

- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- **Measure drill/CSK/grip**
- Install fastener
Process: Skin Drilling – Install Fastener

Steps
- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- Measure drill/CSK/grip
- Install fastener
Process: Skin Drilling – Install Fastener

Steps
- “Scan” part using vision system
- Clamp, normalize
- Drill, CSK
- Measure drill/CSK/grip
- **Install fastener**
Fastener is drawn in and clamped by rotating inner drive to programmed torque
Process: Skin Drilling – Install Fastener
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Process: Skin Drilling – Install Fastener
Production Process: Fittings to Substructure
Process: Drilling/Reaming Fittings

- **Fittings, Skins, Structure**
  - Spot/Endmill, Drill, Ream, Measure
  - Drill sizes 1/4 - 9/16” (6.4 – 14.3mm)
  - High-strength materials and various aluminum alloys
Process: Drilling/Reaming Fittings

- **Fittings, Skins, Structure**
  - Spot/Endmill, Drill, Ream, Measure
  - Drill sizes -8 to -18
  - High-strength materials and aluminum

**Steps**
- “Scan” (if needed) using vision system
- Clamp
- Spot/EM, Drill, Ream
- Measure
Process: Drilling/Reaming Fittings - Clamp

Steps
- “Scan” part using vision system
- **Clamp**
- Spot/EM, Drill, Ream
- Measure

Narrow Nosepiece
- Retains functionality of standard nosepiece less auto-normality
- Narrow profile give clearance for drilling next to fitting geometry
Steps

- “Scan” part using vision system
- **Clamp**
- Spot/EM, Drill, Ream
- Measure

**Process: Drilling/Reaming Fittings - Clamp**

- Chip Blast Air
- External lubricant
- Vacuum
Process: Drilling/Reaming Fittings - Clamp

Steps
- “Scan” part using vision system
- **Clamp**
- Spot/EM, Drill, Ream
- Measure

Spherically compliant tip allows for up to 8° off-normal drilling

Clearance for largest reamers/drills
Process: Drilling/Reaming Fittings - Clamp

Steps
- “Scan” part using vision system
- **Clamp**
- Spot/EM, Drill, Ream
- Measure

**Intermediate Narrow Nosepiece**
- Retains functionality of standard nosepiece less auto-normality
- Allows tool holder to extend further into nosepiece than with narrow nosepiece
Process: Drilling/Reaming Fittings - Clamp

Steps
- “Scan” part using vision system
- **Clamp**
- Spot/EM, Drill, Ream
- Measure

Spherically compliant tip allows for up to 8° off-normal drilling

Clearance for tool holder and extension
Process: Drilling/Reaming Fittings – Tool Swap

Steps
- “Scan” part using vision system
- Clamp
- **Spot/EM, Drill, Ream**
- Measure

![Diagram of drilling/reaming setup with labels for reamer or spot face tool and empty slot for picking up current tool.](image-url)
Steps
- “Scan” part using vision system
- Clamp
- **Spot/EM, Drill, Ream**
- Measure

**Tool Selection:** 3-position cylinder

**Gripper actuator (3x)**

- Can hold any HSK63A tool
- All pneumatic
- Minimized overall width (7”)

**Process:** Drilling/Reaming Fittings – Tool Swap
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Steps
- “Scan” part using vision system
- Clamp
- **Spot/EM, Drill, Ream**
- Measure

Process: Drilling/Reaming Fittings – Cutters

Drill/Ream thru narrow nose (2.5” plunge shown)
Process: Drilling/Reaming Fittings – Cutters

Steps
- “Scan” part using vision system
- Clamp
- **Spot/EM, Drill, Ream**
- Measure

Drill/Ream thru narrow nose with floating reamer
Process: Drilling/Reaming Fittings – Cutters