Innovation Quarterly

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Print to Fit
Accelerating the additive manufacturing revolution

Robot Ready
Advancing automation

Partnership in the U.K.
Leading technology for economic growth

A publication of The Boeing Company

Innovation
Quarterly

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ON THE COVER
On the cover: Fatmata Barrie is a Boeing engineering researcher working in partnership with the U.S. Department of Energy's Oak Ridge National Laboratory in Tennessee.

PHOTOGRAPHY BY ELIZABETH MORRELL

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Specializing in metals and ceramics, Fatmata Barrie's ongoing work to produce more stable 3D printed parts is a personal, as well as professional challenge.

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Innovation in aircraft manufacturing and application and use of novel fabrication and assembly technologies and systems in aircraft factories is of crucial importance for Boeing. Maintaining high level of manufacturing equipment efficiency, and developing new production systems to improve quality and reduce cost, ensures competitive advantage and establishes Boeing as the technology leader in the aircraft industry.

36 | A Century of Boeing Innovation in Nondestructive Evaluation (NDE)

Boeing has been a world leader in nondestructive evaluation innovation, developing technology and methods for ensuring the structures with which it builds its many aerospace products are safe and are performing as designed. This paper introduces the subject and purpose of NDE, and addresses important past, present and future elements of NDE development at Boeing.

Producing an industrial leader

We're proud and honored to be the world's leader in aerospace innovation. To strengthen this distinction—and continue delivering for our customers and changing the world—we work hard every day on what we create and how we create it.

That's why I'm pleased that this edition of IQ is exploring our advanced manufacturing activities, which I think is one of the more underappreciated aspects of Boeing. At our sites across the globe, Boeing colleagues work diligently to not only design, build and support the world's most capable aerospace products and services, but also to find ways to improve how we perform these tasks.

That's why we invest in advanced manufacturing equipment that enhances the quality of our products, the safety of our workplaces, and the efficiency of our processes. As one example of our many achievements in this area, last year we helped create the world's largest solid 3D printed item, a wing trim and drill tool, measuring 17.5 feet long, 5.5 feet wide and 1.5 feet tall, for use in building our forthcoming 777X airplane. We have 20 years of experience in 3D printing because we saw early on how this technique saves energy, time and costs. In fact, thanks to 3D printing, the time needed to create that record-setting 777X tool was sliced from several months to about 30 hours.

Our products and services inspire awe because they change the world. But also remember that there's an inspirational tale behind the way our talented people bring these products and services to life. IQ

GREG HYSLOP
Boeing Chief Technology Officer
Senior Vice President, Engineering, Test & Technology

Recognizing Advanced Developments and Research

Technology RADAR

People working in Boeing's Technology Intelligence and Trends community of practice are human sensors in the world of science and technology. We make it our business to watch for innovations in practice, new business models and new ways of thinking. Here's a peek at a few signals on the screen.

Electrotunable Nanoplasmonic Liquid Mirror

LOCATION
London, England

PROJECT URL
imperial.ac.uk

MESSAGE
Researchers at Imperial College, London, have developed a tunable nanoparticle filter that can switch between a mirror and a window.

Thermal Testing for Composites

LOCATION
Reid, Austria

PROJECT URL
facc.com

MESSAGE
New active thermography inspection of fiber-composite material aircraft components may be faster and more accurate than traditional ultrasonic approach. Developed by FACC, in partnership with Upper Austria University of Applied Sciences and the Higher Technical School, Andorf, the method detects component defects by measuring thermal waves.

Quantum Computing for Artificial Intelligence

LOCATION
Toronto, Canada

PROJECT URL
utoronto.ca

MESSAGE
The Creative Destruction Lab, a seed-stage accelerator at the University of Toronto, has launched a program to harness the nascent power of quantum computing for artificial intelligence applications.

Multilingual Intelligent Embodied Agent

LOCATION
Barcelona, Spain

PROJECT URL
kristina-project.eu

MESSAGE
The KRISTINA Project is developing a translation application with human-like multimodal communications capabilities including culture-specific facial expression and gesture generation and analysis. A prototype is currently being evaluated.

Agriculture City in Egypt

LOCATION
Qattara Depression, Egypt

PROJECT URL
eng.korea-arab.org

MESSAGE
An agricultural "city" comprising 50,000 smart greenhouses, seawater desalination and solar power plants, and other agriculturally focused technical projects is being built in Egypt as part of a $10 billion cooperative protocol of the country and the Korea-Arab Society.

Extra-Galactic Starstuff

LOCATION
Malargüe, Argentina

PROJECT URL
auger.org

MESSAGE
Researchers studying cosmic rays as part of the Pierre Auger Collaboration have determined that these rare, high-energy particles originate outside the Milky Way galaxy.

Drone Emergency Medical Aid Delivery

LOCATION
Dodoma, Tanzania

PROJECT URL
flyzipline.com

MESSAGE
The government of Tanzania will begin using drones for just-in-time delivery of emergency and life-saving medical supplies to public health facilities across the country. The company Zipline, which owns and operates the drones, has been providing emergency blood deliveries to transfusion clinics in Rwanda since October 2016.

Innovation and the **disruption**

Through research and perseverance, a researcher pursues a technology that will revolutionize industries the world over.

BY DAN RALEY, BOEING WRITER | PHOTOGRAPHY BY ELIZABETH MORRELL

Fatmata Barrie is a firm believer there's always a solution if you've got a plan.

Like the time she went tandem skydiving in Alabama and the parachute malfunctioned. The backup chute worked just fine.

Or in Indonesia where she stared at multiple lanes of fast-moving traffic and wondered how she could possibly cross to a waiting taxi. The driver stepped into the street, put up a hand, and everyone stopped.

At Oak Ridge National Laboratory outside of Knoxville, Tennessee, Barrie, a Boeing metals expert, has a much different challenge: She seeks ways to use additive manufacturing, or 3D printing, to produce structurally critical parts for commercial jetliners. It's a high-priority quest if not an ongoing trial for the aerospace industry.

Specifically, engineers such as Barrie are pursuing innovative processes in this production area that are repeatable and robust, that provide the same airplane part on the same machine over and over. This kind of commonality is necessary to gain Federal Aviation Administration certification to use the part.

"Honestly, my goal is to be an expert in this field," Barrie said. "Being surrounded by people very knowledgeable in this field is ideal. I'm still learning."

To many large companies, including Boeing, the recent innovation surge in additive manufacturing brings both enthusiasm and trepidation. The technology is widely recognized as a major worldwide industrial disruptor.

On one hand, it has the power to dramatically decrease cost, enable greater design freedom and speed time to production—a great advantage for established businesses. On the other hand, the barrier to enter the industrial manufacturing market could practically disappear for newcomers.

Oak Ridge is home to complex supercomputers and powerful nuclear reactors and supported by the U.S. Department of Energy. It is a sprawling science and technology campus—the largest of its kind in the United States. Barrie works in the Manufacturing Demonstration Facility, a fairly new complex where she says "industry meets research." Scientists, engineers, university professors and doctoral students surround her, sharing the latest knowledge and discoveries. Cutting-edge machines fill the building's high bay.

In less than a decade, the United States has lost more than a third of its tool and die makers, and so the country imports 70 to 80 percent of the tools it uses. It is hoped that additive manufacturing can reverse or slow this development, said Bill Peter, Manufacturing Demonstration Facility director at Oak Ridge.

"Additive manufacturing is critical because we really need to spur on innovation for us to stay competitive as a country when we look at the future in manufacturing," he said.

Conventional manufacturing might be viewed as uninteresting and a dirty process to the next engineers, but high school and college undergraduate and grad students have been drawn to additive manufacturing

"Honestly, my goal is to be an expert in this field, Being surrounded by people very knowledgeable in this field is ideal. I'm still learning."

FATMATA BARRIE

FROM POWDER TO PART
Boeing materials scientist Fatmata Barrie shows the progress in metallic 3D printing, where powdered metal is fused to create structural objects.

COLLABORATIVE EFFECT
Barrie works with multiple experts at the Oak Ridge National Lab in Tennessee. Pictured here with Barrie, from left Vincent Paquit, Barrie, Peng Liu and Brittany Cramer.

because of the automation and innovation, Peter added.

"It allows people to come up with great ideas," he said. "They can go over and print and try things out. It's made the younger generation get very excited about additive manufacturing."

While additive manufacturing is not new to aerospace, producing larger and more structurally demanding commercial airplane parts through 3D printing would be a significant next step, said Peter Bocchini, a Boeing materials and process engineer in Huntsville, Alabama. A recognized expert in the field, he trades daily messages each day with Barrie on several projects.

"There's definitely a lot of hurdles to overcome to make it mainstream," Bocchini said. "I think Fatmata is going to play a big part in making that happen."

Barrie hails from Alexandria, Virginia. That's where she first pursued engineering while attending T.C. Williams High School, which was depicted in the popular 2000 film "Remember the Titans."

Barrie received undergraduate and master's degrees in mechanical engineering from Carnegie Mellon University and Texas A&M University, respectively, and completed a doctorate in materials science and engineering at the University of Florida.

She studied shape memory alloys, which involves a deformed material reverting to its original form; and composite fracture toughness, examining the amount of energy that materials can absorb before breaking, such as an airplane wing. As a student, she received an internship in the auto industry at Ford and helped create a software tool that showed the efficiency of different operators in the factories.

Barrie also took breaks from the classroom and traveled extensively. In 2006, she visited Sierra Leone, the birthplace of her parents, to learn more about her cultural heritage. She presented her composites work in England and toured China through a university program.

Before joining Boeing, Barrie chose to go through Indonesia first. Receiving a Fulbright U.S. Student Program grant, she spent 13 months in the Southeast Asian nation learning the language and researching a commodity people there could use that was sustainable and cost effective—she studied bamboo and its ability to reinforce concrete.

Through the end of 2014, while doing her research at the Bandung Institute of Technology on the island of Java, Barrie determined that bamboo had more of a toughness to withstand cracks when cut into strips rather than used in its full form because of its geometry. She was pleasantly surprised by the outcome. She found that bamboo naturally replenished itself whereas other studies had shown that building materials, such as rebar, corroded and chipped away at the concrete over time in the form. Also, bamboo, as a construction resource, was plentiful to the region. Studies continue on whether to use bamboo in this manner, with a Brazilian group conducting further testing.

"I wanted something different than what I was used to."

FATMATA BARRIE

HANDS ON
Barrie, who has a doctorate in materials science and engineering, works on-site at Oak Ridge perfecting the craft of titanium additive parts.

When she wasn't conducting research, Barrie traveled throughout the South Pacific islands on planes, trains and buses to whet her appetite for new places and adventure. She went to see the Komodo dragon, the world's largest lizard and native only to Indonesia, relying on stick-wielding guides to keep her safe.

"I wanted to do something non-Western to get a different perspective," she said. "I wanted something different than what I was used to."

Additive manufacturing became a by-product of Barrie's adventures and engineering experiences.

In 2015, she joined Boeing and entered the metals and ceramics program in Huntsville. She worked on several projects, among them ICME, or Integrated Computational Materials Engineering. This involved using computers and modeling efforts to engineer materials.

Barrie studied the replacement of aluminum alloys with lighter compositions of the same material, specifically in airplane stringers, or strips that hold fuselage skin, for possible use in future airplanes.

She analyzed processing methods, researching the science behind them to see if changes could be made to make them more cost effective. She impressed Boeing colleagues with her educational credentials and her natural curiosity.

"She is like everyone else, in the sense that we're all driven, but sometimes she comes up with questions that not everyone would think to ask," said Karen Thacker, a metal, ceramics and metal parts engineer in Huntsville who has worked on various projects with and mentored Barrie. "That, I think, will serve her well."

Barrie joined in an MAI project, or Metals Affordability Initiative. Working on modeling of forged titanium, she was asked to analyze wire feed samples, where wire was melted and deposited continuously, layer-by-layer, to build up a titanium part. She tested the titanium for its hardness and evaluated the microstructure of the material. After work from other Boeing engineers, the FAA later approved its use to build an airplane.

This led Barrie from Huntsville to Knoxville, cities that

"Additive manufacturing is critical because we really need to spur on innovation for us to stay competitive as a country when we look at the future in manufacturing."

BILL PETER, MANUFACTURING DEMONSTRATION FACILITY DIRECTOR AT OAK RIDGE NATIONAL LAB

are three hours apart by car, and to Oak Ridge and the evolving world of additive manufacturing.

"It's like a playground for a metallurgist," Bocchini said.

At the national lab, Barrie works on different projects across the Boeing enterprise. She interacts with the scientists on site. She confers with aerospace suppliers. She can usually find an answer to any technology question somewhere on campus.

"I'm making inroads," Barrie said. "From the metal side of things, with my background, it would be really great to get to a point to make structurally critical parts with additive manufacturing. That would be ideal. It will take some time."

Barrie focuses a lot of her attention on a powder bed additive manufacturing machine. The bed melts metal material with an electron beam and deposits and rakes powder into the resulting composition, which forms a part. She studies how the components react to each other, always seeking clues.

It's an evolving process that requires close collaboration between Boeing and the Oak Ridge National Lab to make progress, and Barrie has been a smart fit, said Ryan Dehoff, Oak Ridge deposition science and technology group leader, who works closely with her.

"She has an incredible understanding of the technology, the current challenges the industry is facing in regard to additive implementation, and has guided the collaboration between the ORNL and Boeing to bridge the fundamental to applied sciences," Dehoff said. "It is a great partnership." IQ

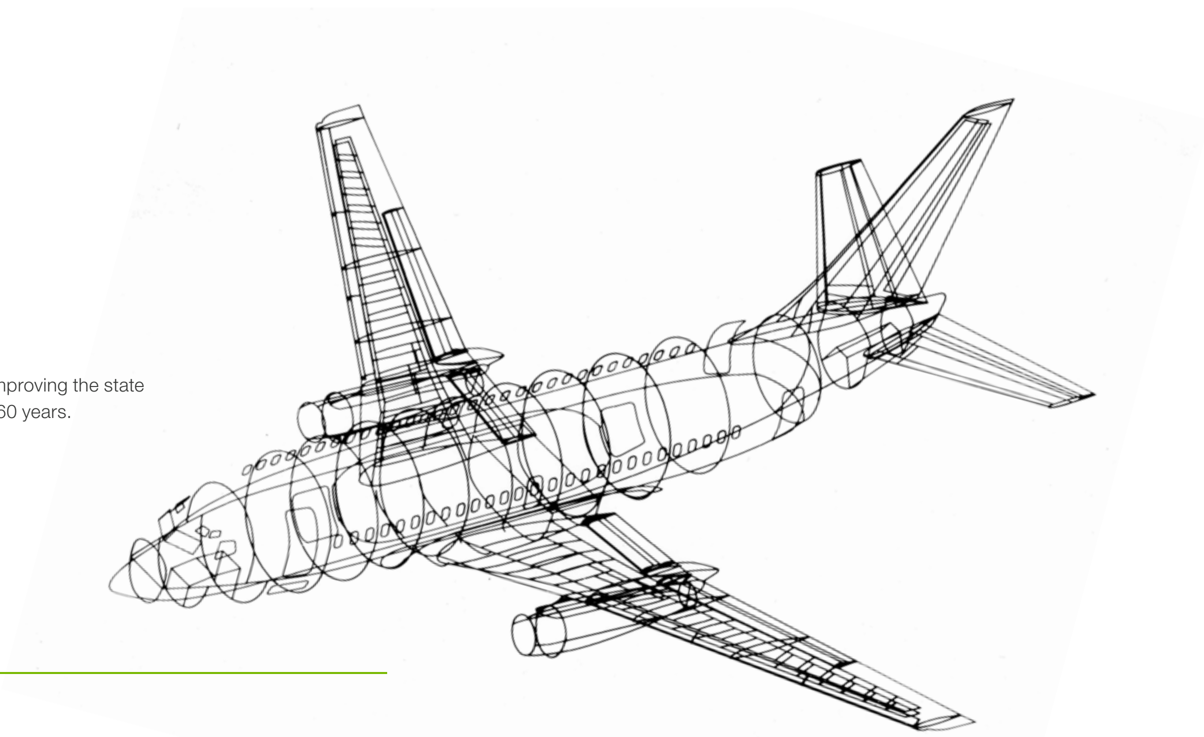
Something worth seeing

Boeing has a long history in computer graphics technology development.

BY TOM KOEHLER, BOEING WRITER

MODEL SIMULATION
3D graphic of a 787 Dreamliner created with a Boeing-developed visualization system.

ILLUSTRATION: BOEING



FROM PENCIL TO PIXEL
Boeing designers have been improving the state of computer art for more than 60 years.

ILLUSTRATION: BOEING

Six decades ago, before most people even knew what a computer was—let alone what it did—a Boeing illustrator and manager started calling the technical drawings they were creating electronically "computer graphics."

The term stuck, and those employees—Verne Hudson and William Fetter—further popularized it throughout the early 1960s while describing how computer-based drawing could reduce cost while improving the design exploration taking place at Boeing's plant in Wichita, Kansas.

That's how and when computer graphics started to make computers easier for people to use. And ever-improving images are helping people better understand and interpret data produced from all of today's computing applications including science, education, engineering, multimedia, finance and medicine.

From the beginnings of the computer age, Boeing has been active in creating, monitoring and intelligently applying the world's most advanced computer graphics and visualization technology to the company's engineering and operations functions.

Modern aircraft and aerospace systems are complex and have unique technical challenges and scale issues to overcome. So, when no one else could provide computing solutions, Boeing has found ways to move forward itself, said Anne Kao, a Boeing Senior Technical Fellow and expert in data and visual analytics.

"Over the years, our Boeing computing research and development team has been a competitive differentiator, helping the company to maintain its position," Kao said.

"Having indigenous technical depth at Boeing has been essential in developing new capabilities in-house, as well as helping to evaluate technology from vendors and competitors," added Jim Troy, a Boeing Associate Technical Fellow and expert in 3D visualization tools, haptics, human modeling, virtual reality, augmented reality, as well as custom robotics and measurement applications.

While much of the early development of computing technology was done at universities and government laboratories, Boeing became an early adopter of computers as standard tools for the core business of designing, developing and supporting commercial and military aerospace products.

"Boeing has invested heavily in computing technology," said Dave Kasik, a Boeing Senior Technical Fellow emeritus and 3D graphics expert who developed the Boeing concepts for the first user interface management system, massive model visualization, visual analytics and others. "As a result, we have advanced the state-of-the-art in computing and enabled beyond state-of-the-art aerospace products."

Boeing's record of accomplishment in computer graphics technology development includes these milestones:

- Development in the 1960s of the first digital model of a human body for ergonomic design purposes.
- Pioneering research in the late 1970s for rendering B-spline surface geometry—B-spline surfaces digitally define the vast majority of Boeing products.
- Creation in the early 1980s of the first user interface management system to simplify programming for applications employing visualization.
- Early exploration in the late 1980s of ways to augment live direct or indirect views of physical, real-world environments with computer-generated input such as video and graphics data for potential use in manufacturing applications. This field is now known as "augmented reality".
- Ground-breaking work in the early 1990s on design and development of large-scale 3D visualization tools that enabled users to virtually fly through aircraft. This led to the 777 being the first jetliner completely digitally designed in three-dimensions. The 777 was the first to be preassembled on computers, eliminating the need to build costly, full-scale physical mock-ups. It provided the basis for more-robust 3D visualization tools developed at Boeing that were essential to the creation and assembly of the 787 Dreamliner, KC-46A Pegasus Tanker, P-8A Poseidon and other aircraft.
- Formation of efficient 3D collision detection and response software (Voxmap PointShell) in the late 1990s to detect, in real-time during the design process, collisions between parts in large and complex environments, which also enabled real-time physics-based simulation for haptic force-feedback applications.
- Creation of "massive model visualization" (MMV) tools in the early 2000s that gave Boeing-developed 3D visualization applications the capacity to interactively view an entire airplane in a single session. MMV gives users access to significantly more data now available for efficient design, assembly and support.
- Recent advances in visual analytics that enable the rapid exploration of large, complex datasets to gain new business insight and take advantage of data as a strategic asset.

Looking to the future, Boeing will continue to introduce new computer graphics technology into aerospace.

For example, Boeing has been pushing the transition of augmented reality technology into the production environment as a more-effective way to provide location documentation and maintenance, and assembly instructions for mechanics. This year, through the Boeing HorizonX innovation cell that is focused on accelerating potentially transformative aerospace technologies and manufacturing innovations, the company announced its involvement in Upskill, a company that provides software for augmented reality wearables that enhance productivity, quality and safety in manufacturing.

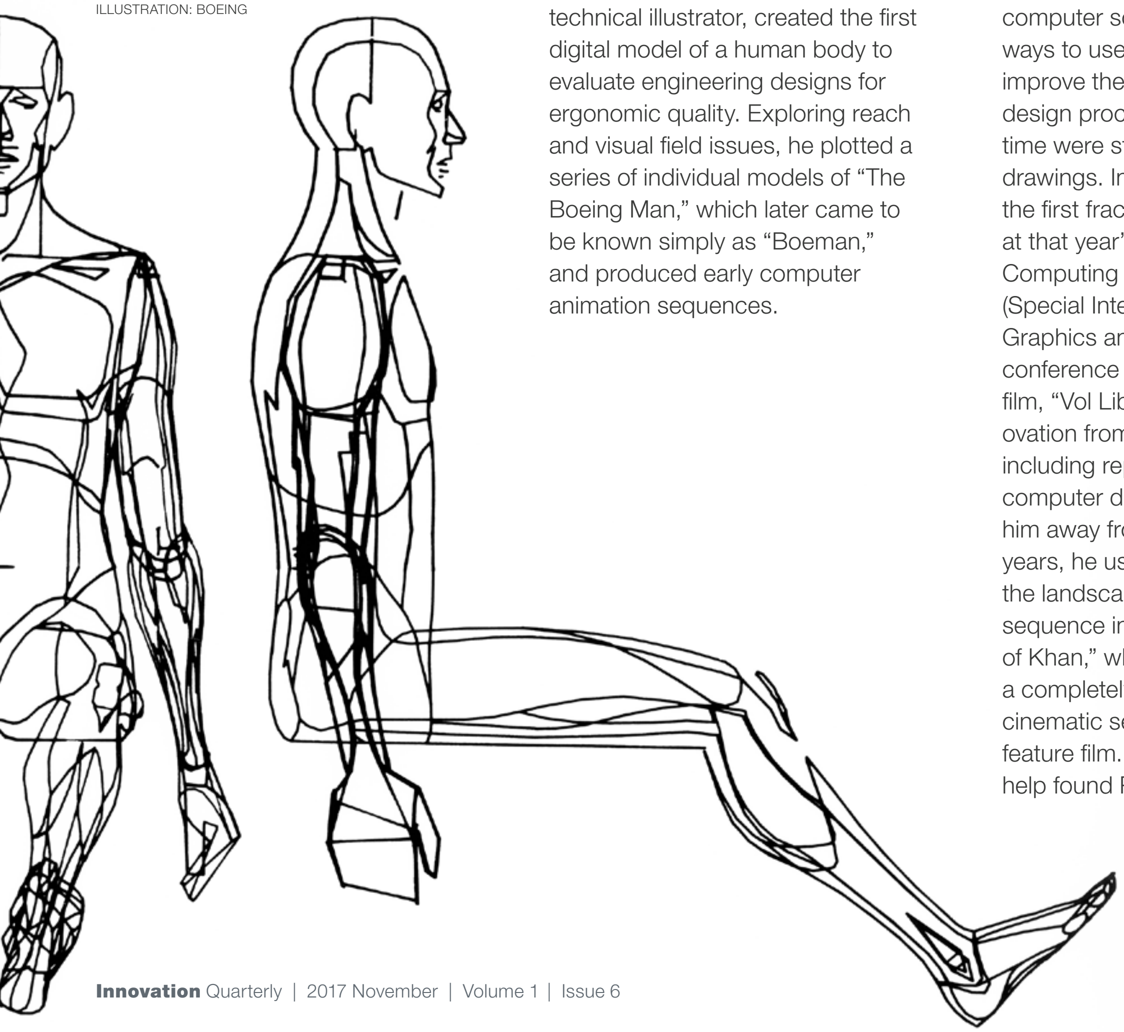
> "Over the years, our Boeing computing research and development team has been a competitive differentiator, helping the company to maintain its position."

ANNE KAO, BOEING SENIOR TECHNICAL FELLOW FOR DATA AND VISUAL ANALYTICS

Boeing has had a hand in multiple computer graphics "firsts"

Over the years Boeing has been associated with more than a few computer graphics firsts, including:

ILLUSTRATION: BOEING



Human models

In 1964, William Fetter, a Boeing technical illustrator, created the first digital model of a human body to evaluate engineering designs for ergonomic quality. Exploring reach and visual field issues, he plotted a series of individual models of "The Boeing Man," which later came to be known simply as "Boeman," and produced early computer animation sequences.

SOURCE: "VOL LIBRE" BY LOREN CARPENTER

Fractals

In 1980, Loren Carpenter, a Boeing computer scientist, was working on ways to use computer technology to improve the company's mechanical design processes, which at that time were still based on engineering drawings. In his off hours, he created the first fractal film, which he showed at that year's Association for Computing Machinery's SIGGRAPH (Special Interest Group on Computer Graphics and Interactive Techniques) conference in Seattle. The two-minute film, "Vol Libre," received a standing ovation from those in attendance, including representatives of Lucasfilm's computer division, who quickly hired him away from Boeing. Within two years, he used fractals to generate the landscape for the "Genesis effect" sequence in "Star Trek II: The Wrath of Khan," which was the first time a completely computer-generated cinematic sequence appeared in a feature film. Carpenter went on to help found Pixar Animation Studios.

PHOTO: BOEING

Augmented Reality

Because of the intricacies involved in aircraft manufacturing, Boeing in the late 1980s, through company researchers Tom Caudell and David Mizell, began investigating ways to augment live direct or indirect views of physical, real-world environments with computer-generated input such as video and graphics data. As the field grew, Caudell coined the term "augmented reality." Technology development was slowed early on by cumbersome video capture equipment and display head gear, but it has gained speed in recent years and is reaching production. Boeing owns several patents in augmented reality, including display devices.

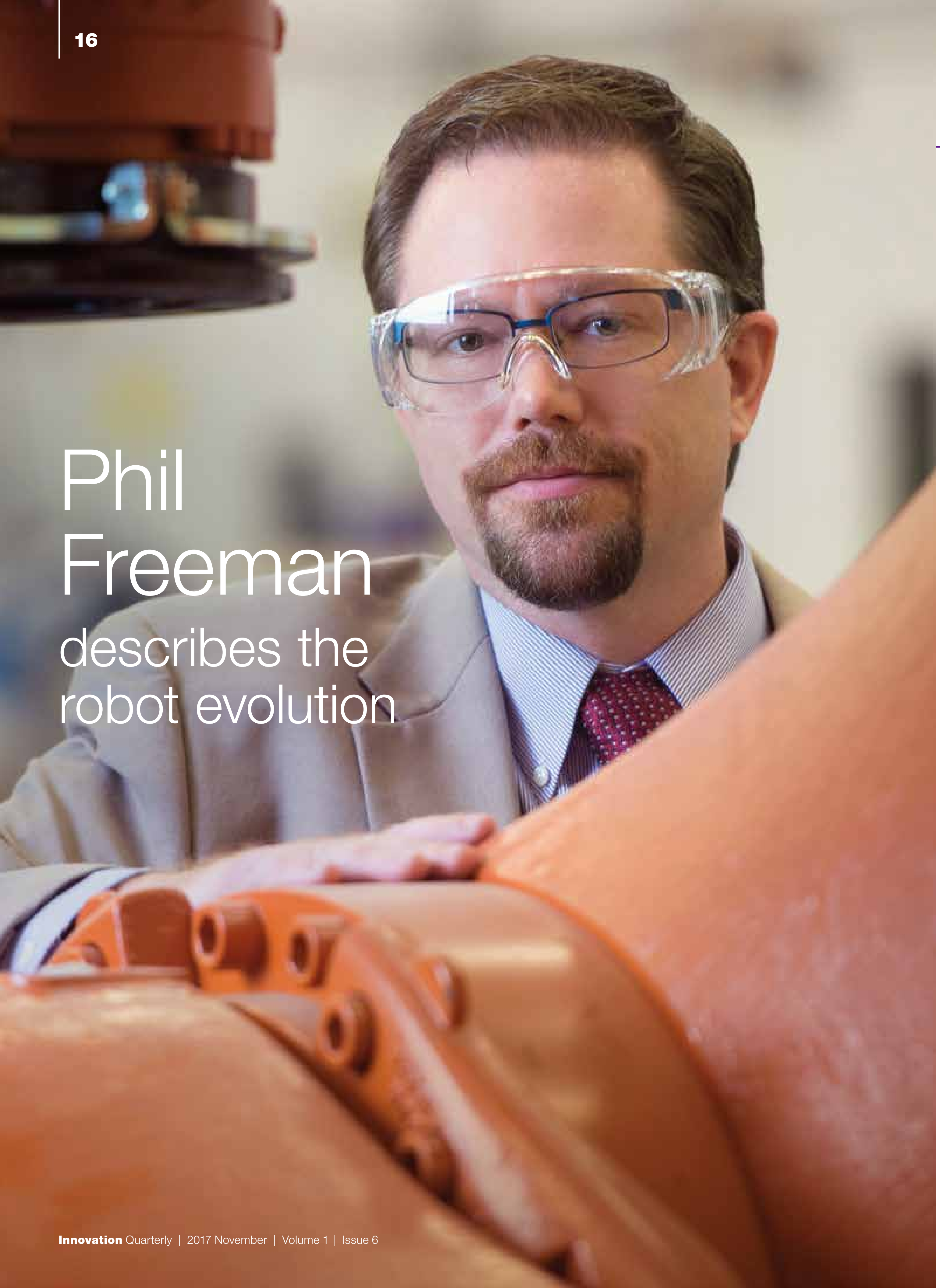
Boeing's digitization vision

Substantial shifts are taking place in design and manufacturing across many industries using proven and emerging 21st century technologies to improve cost, quality and productivity.

Part of Boeing's strategy for the future is to better capture the value of digitization. The company is working to integrate its digital tools across the product life cycle–from requirements and design through manufacturing and in-service support.

According to Boeing Senior Technical Fellow Anne Kao, increased digitization can reduce costs in design and manufacturing, improve first-pass quality and provide service-life value to customers. A stronger digital thread can impact the supply chain as well, she said.

"We imagine a day where you can make a digital twin, which documents an engineer's design decision and how it translates from engineering into manufacturing instructions, automation programs, and necessary support information available through Boeing and our supplier networks," Kao said. "The digital thread then enables information collected during manufacturing to travel with the airplane through its entire life cycle, providing valuable insight to maintenance and operations decision-making." IQ



Phil Freeman describes the robot evolution

Robots have operated in Boeing factories for years. But the merger of autonomy and automation may lead to a cleaner, safer factory of the future for people.

BY VIENNA CATALANI | PHOTOGRAPHY BY ALAN MARTS

Q&A with Boeing's Senior Technical Fellow for automation research and application on what lies beyond a quickly approaching production horizon

HUMAN PERSPECTIVE
Senior Technical Fellow Phil Freeman, who is based in Charleston, South Carolina.

Q **What is changing how industrial robots operate?**

A There is a lot of innovation and technology development in robotics that is on our roadmap. My big interest is in making robots and automation easier to integrate, deploy and use in complex manufacturing environments.

Today's industrial robots are more or less programmed the same way they were in the '80s and '90s. The robot is taught how to do the automated operation either by directly moving the robot through the work, or by moving a virtual robot in a virtual factory. Either way, the resulting program is a list of steps and motions that the robot repeats in strict sequence. This works great if what you have is a simple set of actions that need to be repeated over-and-over in an environment that never changes. However, if you ever have to change the plan, motions, actions, or anything else, it requires robot programmers to create and test new instructions.

Contrast that with technology like autonomous flight or self-driving cars. The vehicle knows about the general operating environment, and how the system performs. From this, it decides how best to go about accomplishing the goals it has been given, and then adjusts to the changing environment it encounters. For example, you might tell your self-driving car to take you to the movies. It then determines the best route to take, does all of the navigation, traffic management, reacting to lights and signs, and re-routing as needed on its own. And it does this planning continuously in the background, adjusting the plan to the conditions encountered.

We are working on bringing similar technology to industrial robotics. While the long-term vision may still be a few years away, we are working to continuously deploy the technology into the factory as it becomes mature.

Q How do you envision an aerospace factory of the future? Will work or tasks be eliminated?

A I see automation changing the way work is done, rather than eliminating work or tasks.

In automation, we often talk about the “3 Ds”: dangerous, dull, and dirty. Those are the jobs where automation typically excels. Automating dangerous jobs helps us create factories that are safer for everyone and moves us closer to our goal of an incident and injury free workplace.

Automating the “dull” parts frees up people’s minds to focus on finding, fixing, and preventing problems. Work that doesn’t take advantage of the creativity and problem solving of the human brain is a waste of our teammates’ talents.

We want everyone to be fully engaged in the work they do solving problems as they arise. Looking at what jobs are “dirty” helps us think about places where automation will improve the overall work environment, changing the work to something people want to do rather than struggle through.

I like to add a fourth “D”—low dexterity. There is a lot of work in Boeing factories that requires a person to manipulate complex, flexible objects in ways that robots simply cannot mimic. For example, it’s really difficult for a robot to tie a knot, or thread a needle. That level of fine, dexterous manipulation is still best suited for people, not robots.

Q Is it safe for humans to work alongside robots? What safety measures have been implemented?

A An automated aerospace factory wouldn’t be empty of people, rather it would be full of people that are doing what people are good at—solving problems, improving the process, and focusing their talent on safe, clean, and engaging work. People will use and interact with robots in ways that are natural and human-centered, rather than machine- or function-centered.

Industrial robots have historically been large powerful machines with limited situational awareness of the work space around them. Newer robots, however, have become more sophisticated enabling industry standards that allow collaborative operation. These systems monitor the safe-guarded space and use robots with advanced safety controls and sometimes power and force limited designs that are inherently safe to be around.

PHOTO: BOEING

“I see automation changing the way work is done, rather than eliminating work or tasks.”

PHIL FREEMAN

With that said, for any robotic system to operate safely, a risk assessment performed by an expert is required.

Q What advancements have been made, and where are they being used?

A We have an awesome team of automation experts around the world. We’ve successfully developed and deployed automation in the U.S., Canada, Australia and Europe.

Boeing recently deployed a robot in Australia that automatically plans its motion to do composite layup tool cleaning. Our team in Charleston has been working with the 777 fuselage automated upright build production engineering team to automatically generate programs for drilling the 777X fuselage directly from the MBE (model-based engineering). We have demonstrated reliable automated planning from MBE for nut running in limited access areas such as frames on the 787. IQ

Advanced manufacturing partnership in Atlanta

Transitional applied research at Georgia Tech

BY JANELLE BERNALES | WILL WILSON, BOEING WRITERS

Chris Marince knows that being able to transition an idea from the lab to a commercial prototype is a crucial skill for engineers.

“We have experience integrating research into production settings and we’re excited to be able to help the next generation of engineers learn how,” said Marince, a Boeing assembly and automation engineer.

Marince and fellow Boeing engineer Joshua Johnson work side-by-side with Georgia Tech students and faculty at the new Boeing Manufacturing Development Center (BMDC).

Located within the Delta Advanced Manufacturing Pilot Facility on the Georgia Tech campus, the BMDC is an experimental research partnership between Boeing and the university. It explores and develops the nontraditional use of automation in industrial applications, as well as determines the viability of practical applications that could lead to production system and manufacturing processes at later technology readiness levels (TRL).

Collaboration between industrial technology companies and research institutions in the early-stage development of potentially disruptive technologies could lay the crucial foundation for advancement.

The first technological area that researchers are working on at the center relates to utilizing industrial robotics for new automated precision machining and fabrication applications.

For example, articulated robotic arms are often used in the automotive manufacturing world with pick-and-place, as well as joining applications. However, as Johnson explains, aerospace manufacturing hasn’t been able to take advantage of these technologies, both because the scale is larger and because the robots are not accurate enough for aerospace tolerance requirements, which are typically higher for cars.

“To give you context, most of our parts have tolerances of five-thousandths of an inch,” he explained. “And a human hair is about three thousandths of an inch.”

This collaboration at the center also provides the students a meaningful applied research opportunity that helps them obtain valuable experience and might even become the topic of a thesis or dissertation.

Georgia Tech has been collaborating with Boeing on research for a decade, with ongoing research topics that include manufacturing flow, robotic assembly, model-based manufacturing and sustainable manufacturing. Research partnerships like this also diversify the company’s research portfolio and increase its robust talent pipeline.

“Working together with Boeing engineers, this research allows our students and faculty to mature low TRL research to higher TRL and actually transition them into technologies that could be applied on the factory floor by Boeing,” said Shreyes Melkote, professor of mechanical engineering at Georgia Tech. “Very few schools can claim to have that capability.” IQ

PHOTO: GEORGIA TECH

STRENGTHENING RESEARCH TIES

Stephen Cross, adjunct professor and Georgia Tech executive vice president for research, speaks at the opening of the Boeing Manufacturing Development Center on June 22.

RICHARD ASTON, SENIOR TECHNICAL FELLOW

3D printing done right

Applying additive manufacturing in integrated mechanical designs

Satellite design is characterized by extreme mass criticality, multifunctional structures, low production volumes, low duty cycles, high reliability and speed to market. Because of that, spacecraft and satellite platforms have presented an ideal opportunity for the design and analysis of flight vehicle products using additive manufacturing.

> Additive manufacturing—also known as 3D printing—enables an efficient design process that can achieve design solutions that we could not have imagined in the past.

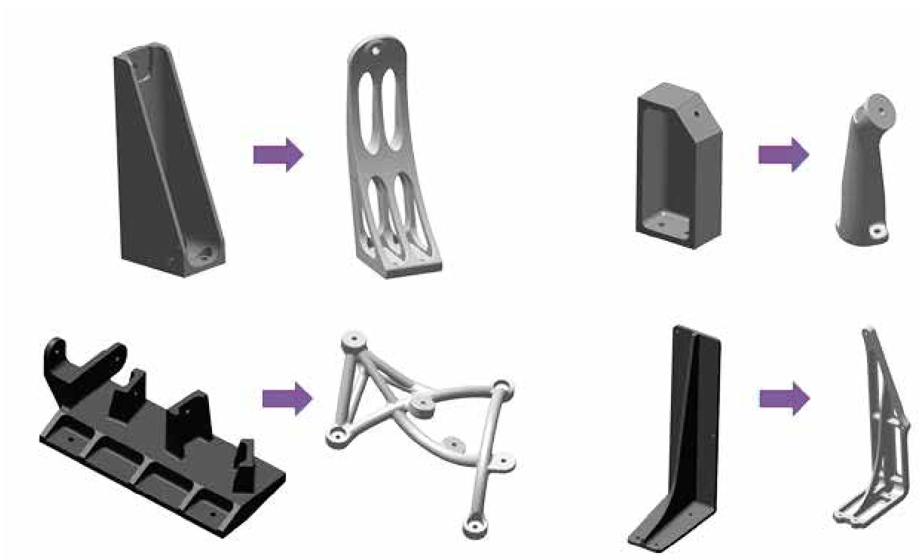
With the 702SP satellite development program, Boeing changed the engineering model. We established an integrated design approach with all mechanical elements consolidated under a single technical lead. This lead engineer was responsible for platform mechanical architecture, load paths, subsystem integration, development of new materials, and the synergistic execution of loads development, design, stress and manufacturing. The lead engineer also held all the budgets for the various disciplines and was accountable not only for the design, but also for the manufacturability and test of the platform mechanical subsystem.

A major part of the approach was to proactively use additive manufacturing, which enabled "free form" design. Design configurations that had once been un-producible were now possible. This new capability enabled engineers to "think additively" and be creative in the development of structural solutions.

Our success was a function of several factors, including a multi-skilled team with individuals capable of design, stress, materials and manufacturing engineering, and full product ownership from concept to launch.

A systems approach to additive manufacturing

The first significant application of additive manufacturing in this area of Boeing was to the SES-15 spacecraft. The team identified several areas of opportunity, including a new design for a nadir surface mounted optical bench. This architecture required a systems approach, which not only addressed additive manufacturing but also the way that the additively manufactured components would function in an integrated assembly.



DESIGN FREEDOM
The ability to print parts opens the possibility to create more efficient mechanical designs.

ILLUSTRATION: BOEING

GAME CHANGER
Boeing applied additive manufacturing technology to the CST-100 program to reduce mass, cost and cycle time. The team was awarded a NASA Spaceflight Awareness Award. Some of the members of the team are pictured here with astronaut Ricky Arnold, from left, Erick Li, Nicole Hastings, Matt Herrmann, Sean Dungan, Nick Meyer, Anna Tomzynska, Andrew Scott, Emily Woods and Richard Aston.

PHOTO: BOEING

Additive manufacturing alone did not offer significant technical advantages. But additive manufacturing when applied in concert with new composite and adhesive materials yielded a lightweight, low cost and thermally stable design solution.

The SES-15 project was used to establish the acceptance test regime that is now applied to all flight hardware that is 3D printed within the Boeing Space and Missile Systems organization.

As additive production has been deployed, cost and cycle time data have been collected and reflected back into future part selection decisions. With three different material systems at TRL 9 and an expanding supply base, additive manufacturing is now being actively traded and applied to flight systems.

Going mainstream

At Boeing, we have moved beyond satellites and human-rated spacecraft and applied the technology to missiles, helicopters and airplanes. In space systems alone, a small, multi-skilled team is delivering nearly 1,000 additively manufactured parts to flight programs.

> As additive manufacturing becomes a mainstream fabrication method, significant manufacturability improvement and cost reduction can be achieved by approaching design as an integrated mechanical system. Optimizing additive components will not be possible without sufficient understanding and redesign of the entire system design as a whole.

The most efficient future state for rapid development programs will be an additive ecosystem grounded in mechanical systems engineering and integrated design. This would be complemented by multi-skilled engineers who have depth of knowledge in design, stress analysis, materials, manufacturing and loads to develop innovative and cost-effective solutions for the life cycle of the product.

Additive manufacturing machine technology is evolving quickly. Reduction of piece parts and part weight can be achieved through appropriate implementation of additive manufacturing, while simultaneously improving system performance. IQ

Richard Aston is a Senior Technical Fellow for satellite systems and an expert in composite technology and additive manufacturing. He has more than 30 patents and patents pending, and is the co-inventor of the Boeing 702HP and 702SP space platforms.

TECHNICAL EXCELLENCE. **ENGINEERING ACHIEVEMENT.**

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William Peterson
David Phillips
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Chad Winkler

Manufacturing the **revolution**

Boeing and the University of Sheffield reawaken an industrial champion.

BY CANDACE BARRON, BOEING WRITER

GOING DIGITAL
AMRC Fellow Ruby Hughes demonstrates the simulation potential at Factory 2050.

PHOTO: UNIVERSITY OF SHEFFIELD, AMRC

The Cutlers' Hall in Sheffield, England, is ornamented from floor-to-ceiling with a millennium-old legacy of advancing the art and craft of metal work. Blades of all sizes and functions. Spoons. Forks. Tools and implements for a variety of tasks dating from the Middle Ages.

Not only has metal production here been perfected and practiced officially on behalf of the British Crown, the work done in Sheffield over the centuries has directly influenced industry around the world.

And it was at the Cutlers' Hall in September that representatives from Boeing said they would humbly accept inclusion in this legacy when the company's first European factory opens in 2018.

The facility—Boeing Sheffield—will manufacture high-tech actuation components and systems used in Boeing's Next-Generation 737, 737 MAX and 777 aircraft.

"It has always been our aspiration that one day Boeing would open a manufacturing facility in Sheffield," said Keith Ridgway, professor of engineering at the nearby University of Sheffield. "This is the culmination of a successful relationship that we have nurtured for more than a decade."

The Boeing Sheffield story began 16 years ago with the creation of the University of Sheffield's Advanced Manufacturing Research Centre with Boeing (AMRC). The center is a £150 million research cluster employing more than 600 staff, pairing academia with industry partners to accelerate the adoption of advanced, and increasingly digitalized, manufacturing techniques into major production systems.

Ridgway, who is also executive dean of the AMRC, has worked tirelessly to transform a region that once teetered on the verge of permanent decline. Today the AMRC has investment from over 100 partners from sectors such as aerospace, medical, automotive and construction. The AMRC has become a global model for industrial research, and its partners are now also the centerpiece for the Sheffield City Region's Advanced Manufacturing Innovation District.

From blight to brilliant

Standing on a hillside between the cities of Sheffield and Rotherham, the landscape around the AMRC looks like any other burgeoning economy. Buildings within the AMRC campus itself are bright and new. Housing developments are under construction. The place exudes renewal and enthusiasm.

Difficult as it is to imagine, this innovation district was once the site of a decaying coking plant and an infamously brutal confrontation between striking coal mine workers and police. The Battle of Orgreave in 1984 was one of the most violent labor clashes in modern British history, and continues to this day to be a public controversy.

"You look around this place, and you can't understand what it was like," said Adrian Allen, executive director and co-founder of the AMRC, standing inside the complex's Factory 2050, a glass-walled jewel on the hill at Catcliffe, South Yorkshire. "It was here at Orgreave only 30 years ago, where you had neighbor fighting neighbor. The unemployment. The depression that followed."

This, too, is part of Sheffield's legacy.

Gen. Ulysses Grant, just having left his second term as the 18th President of the United States, stood for supper at the Cutlers' Hall and appealed to the industrialists of South Yorkshire to work together with the United States for mutually beneficial economic prosperity.

"Business with us at this time is a little depressed," Grant said, according to The American News Company's account of his visit in September 1877. "But the day is not far distant … when trade and commerce will revive."

When Grant visited Sheffield, the West was experiencing the advent of the Second Industrial Revolution, a dramatic transformation of manufacturing by the introduction of inexpensively forged steel and increasingly advanced machinery in factories.

The innovation of the Bessemer process, named for its inventor Sir Henry Bessemer, established Sheffield's capability and reputation for steel in the 1850s. Thanks to metallurgist Harry Brearley in the early 1900s, Sheffield also introduced the world to stainless steel.

The mass of coal available in South Yorkshire fed the needs

"So far there have been nearly 1,000 AMRC apprentices trained, and every one of them has a different and better future because of what we are doing here today."

SIR KEITH BURNETT, PRESIDENT AND VICE CHANCELLOR OF THE UNIVERSITY OF SHEFFIELD

PHOTO: UNIVERSITY OF SHEFFIELD, AMRC

The university-industry collaboration has been so successful, Boeing has replicated the AMRC model with more than a half dozen universities in locations around the globe.

FACTORY OF THE FUTURE
The carbon-neutral production facility sponsored by Rolls-Royce rests on the former Orgreave Colliery site, the scene of an infamous confrontation between striking coal miners and police.

PHOTO: JOHN HARRIS, REPORTDIGITAL.CO.UK

BATTLE OF ORGREAVE
A military-style confrontation between police and coal mine workers in 1984 was a critical point in the history of British labor politics and was even memorialized in a song by British rock band Dire Straits.

of the region for decades, especially the energy-hungry steel works dotting the landscape. The coal and steel economy created post-war prosperity in the North of England.

But like many steel- and coal-heavy regions of the world, by the time the Second Industrial Revolution waned, giving way to the speed of computers and the information age, the region's prosperity declined. Coal mines were closed, steel works shuttered. Thousands of people were put out of work.

"It was a hard time, still is for a lot of people," said Ken Worsdale, owner of Foxwood Diesel, an engine rebuild shop in the town of Chesterfield, just south of Sheffield.

Worsdale remembers moving to the area in 1988 when he and a friend started a business refurbishing and selling engine parts. They drove all over Yorkshire for business—past rusted, ghostly factories and neglected fenced up coal pits. "You could smell the coal. It was everywhere," he said.

Today, he marvels at some of the same landscape as he drives by.

"Some neighborhoods, they're still not great," he explained. "But you drive by (the Orgreave site) and it's amazing really. Every couple of months, it seems like something else is going in."

The Sheffield model

The plan for the AMRC with Boeing was initially hatched during a chance hallway conversation at Boeing's St. Louis site in 1999 between Pete Hoffman and Adrian Allen.

Hoffman, who at the time was developing technology relationships to support Boeing's international sales efforts, was introduced to Allen, and they discussed advanced metal machining techniques that could help Boeing improve its current production.

Allen had a state-of-the-art titanium cutting tool that his company had developed with the help of Ridgway and his students. Allen tried to sell the tool to Boeing.

"It was quite an innovation, this cutter," Allen said. He was unsuccessful selling the tool. But through further conversation with Hoffman, it struck both Allen and Ridgway that the research-and-development process they used to develop that cutter might be even more valuable.

For Hoffman's part, he saw the active collaboration between academic researchers and an industry partner as a potential solution to traversing what is commonly referred to in industry as the "valley of death."

The valley is the perilous investment gap between bold, new technology borne of university-level research and the readiness of that technology to become a commercial product. The valley is unavoidable for many promising technologies because of the costly risk needed by private companies to develop those technologies into application.

But if they built a consortium, and many private companies pitched in on the R&D, then the individual investment risk would be reduced. The valley of death could be crossed.

Hoffman brought Boeing leaders into the conversation, and they all decided to give the consortium a go.

"We started with a modest investment of money, but we also brought our own research and know-how to the table. The real key was figuring out how to structure research agreements that ensured we protected everyone's intellectual property, while pursuing mutually beneficial innovation," explained Hoffman, who is now Boeing vice president for Intellectual Property Management.

With the Sheffield model, the supply chain also comes to the table and has "skin in the game," Hoffman added. As lower tier members of the research consortium, they received access to advanced techniques with less investment, "So innovations get absorbed into the supply chain faster and cheaper."

The university-industry collaboration has been so successful, Boeing has replicated the AMRC model with more than a half dozen universities in locations around the globe.

Planning for the future

The first AMRC with Boeing building opened in 2001, and with added investment from the U.K. government and the European Union, the campus grew quickly thereafter. Big name industrials such as BAE Systems, DMG Mori Seiki, and even Airbus, joined the consortium. Jet engine maker Rolls-Royce sponsored an AMRC building called the Factory of the Future in 2008.

In 2013, another dream was achieved when they opened the AMRC Training Centre, where young people gain the knowledge and learn the skills needed to drive a revitalized manufacturing economy through industry-sponsored apprenticeships.

When their dream first emerged, Allen and Ridgway had already been partners through Technicut—Allen's company—a local

PHOTO: BOEING

REAL VISION
Adrian Allen (left), executive director and co-founder of the AMRC, with Keith Ridgway (right), executive dean of the AMRC and professor of engineering at the University of Sheffield

employer with a need for development work, and Ridgway having given that work to his engineering students.

"Keith and I set out to create a radical, unique collaborative research environment, one that would quickly grow and attract a pool of skilled talent, technology and inward investment," Allen said. "This would be the critical success factor in achieving the vision."

A long-established apprentice system in the U.K. pairs students just out of secondary school with simultaneous on-the-job training and formal education. Apprentices may take longer to earn a college degree, but they are employed throughout the process. Local companies typically partner with a college or university to provide apprenticeships.

"So far there have been nearly 1,000 AMRC apprentices trained, and every one of them has a different and better future because of what we are doing here today," said Sir Keith Burnett, president and vice chancellor of the University of Sheffield. "We are changing the very ground we stand on, repositioning Sheffield as a high-value manufacturing city. We are bringing in new ways of thinking and new ambitions. We are opening up opportunities for young people in the Sheffield City Region and around the world."

Because they work while they learn and are less likely to amass student loan debt, "the apprentice plan is appealing to a lot of young people" said Leigh Worsdale, Ken Worsdale's daughter and Foxwood Diesel apprentice, who was named the AMRC Apprentice of the Year in 2017.

As part of the U.K. business plan, Boeing has hired 19 apprentices who are being trained at the AMRC in advance of the Boeing Sheffield factory opening in late 2018.

"We're all very excited to have the opportunity," said Thomas Pledger, a Boeing apprentice, whose family is several generations South Yorkshire. His parents worked in coal, as did his grandparents. "Most of our (Boeing apprentices) families worked in the pits," he said.

Pledger said he had been taking regular college classes for the last two years, but "absolutely hated it." The academic work wasn't the put-off; the facilities and training equipment were inadequate. He felt hindered. When the chance to apply to the AMRC program presented itself, he jumped at it. And he said he was even more excited when he was asked to interview for Boeing.

"The AMRC Training Centre has all the best equipment and tools to learn on," he said, cracking a smile while talking about the time he'll get to work in a real Boeing factory.

The Boeing effect

Boeing Sheffield is expected to continue hiring new employees throughout 2018—capitalizing on the skilled workforce in Sheffield, as well as the AMRC's existing capabilities.

Ridgway, Allen and many of their community and government partners knew that being connected to a company with a global reputation like Boeing's would attract other industrial champions.

They call it "the Boeing effect." That is to say, because Boeing employs a world-wide supply chain, wherever the company goes, a support economy grows up around it. That support economy then attracts other companies.

Earlier this year, McLaren Automotive announced plans to site a new production facility near the AMRC in the innovation district.

"These announcements send out a powerful signal that our region is a leading location for high-value advanced manufacturing," Ridgway said.

Areas such as Sheffield could play a crucial role in a new industrial revolution for the United Kingdom, one centered on science and innovation working hand-in-hand with industry, Burnett added. For example, the AMRC is working with China's Shanghai Academy of Spaceflight Technology to create light-weight, high-performance metals for their rockets and space station.

"I was told early in our relationship, 'Boeing don't do small,'" Allen said. The AMRC started with a few dedicated colleagues. It now employs nearly 500 highly qualified researchers and engineers.

And the relationship has been a catalyst for an industrial resurgence, one that may transcend the current information age into the next industrial revolution bringing on artificial intelligence, additive manufacturing, autonomy and quantum computing.

The newest addition to the Sheffield legacy is Factory 2050, which opened earlier in 2017. A reconfigurable, digital production facility, it will develop techniques for digitally assisted assembly, component manufacturing and machining technologies. The factory is capable of rapidly switching production between different high-value components and one-off parts.

"When we first started, it was about getting people back into work," Allen said. "Today, we're talking about ushering in the Fourth Industrial Revolution. That's a long way to come in just two decades." IQ

"The apprentice plan is appealing to a lot of young people."

LEIGH WORSDALE, AMRC APPRENTICE OF THE YEAR 2017

EARN WHILE YOU LEARN
Apprentice Leigh Worsdale and her father, Ken, use her practical learning experience back at the family's shop.

PHOTO: BOEING

Fabrication from England to Oregon

A collaboration launched in early 2017 intends to advance the competitiveness of metals manufacturing in the United States.

A FAB OPPORTUNITY
Boeing and AMRC partners break ground on Boeing's first European factory in South Yorkshire, U.K. Left to right: Don Hendrickson (Boeing); Keith Ridgway (AMRC); Kim Smith (Boeing); James Needham (Boeing); Sir Michael Arthur (Boeing); Mike Starr (Boeing); Adrian Allen (AMRC)

PHOTO: BOEING

Replicating the success of the University of Sheffield Advanced Manufacturing Research Centre with Boeing, the Oregon Manufacturing Innovation Center (OMIC), located about 20 miles northwest of Portland, has the backing of local academia and at least a half dozen other large local manufacturing employers, in addition to Boeing.

"We're excited to build this R&D capability on the West Coast of the U.S.," said William Gerry, Portland-based program manager in Boeing's Global Technology group. Boeing's Portland facility is one of the world's largest titanium machine shops, but has faced increased pressure from competition in recent years.

Creating a regionally based advanced manufacturing research and development capability linked to Boeing Portland, while working in a global partnership with the AMRC in the U.K., as they support the new Boeing Sheffield factory, will allow innovative manufacturing technologies to be quickly and seamlessly transitioned between the partners creating opportunities for both U.S. and U.K. manufacturers, he explained.

University partners in OMIC include Portland State University, Oregon State University, and the Oregon Institute of Technology. Additionally, Portland Community College has pledged to build a training center also modeled after the AMRC. The training facility is expected to establish an apprenticeship program that offers on-the-job experience alongside academic study.

So far, the OMIC effort has been surrounded by local enthusiasm, Gerry said.

During the 2016 session, the Oregon legislature appropriated $7.5 million to get it started. The state's Higher Education Coordinating Commission was provided with $5 million XI-G bond proceeds so that Portland Community College could finance the creation of the training center. And lottery revenue bonds were approved to provide $2.5 million to the Oregon Business Development Department to support OMIC research and development infrastructure. This $2.5 million in funding along with $3.25 million from Oregon Institute of Technology allowed OMIC to secure a 33,000 square foot facility in Scappoose, Oregon.

Following on the 2017 legislative session, Oregon State lawmakers allocated an additional $13.85 million in state funding to support OMIC operational, infrastructure and R&D needs. Initial projects will focus on precision manufacturing processes, and rapid- and lower-cost tooling technologies.

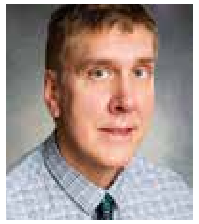
The combination of industry-driven research and development and workforce training provided through OMIC ensures that local industry has a competitive edge, Gerry said. IQ

Selections from the Boeing Technical Journal

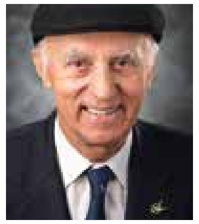
The Boeing Technical Journal is a peer-reviewed periodical for Boeing subject matter experts to capture and leverage knowledge. Research coverage includes all manner of commercial and defense product development, and products and services spanning land and sea, to air and space, and cyberspace.

Contributing Authors

ELECTROMAGNETS FOR AIRCRAFT ASSEMBLY

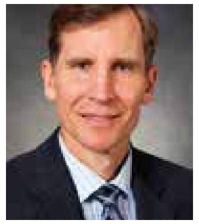


Samuel Dobbs is a mechanical engineer and senior equipment engineer currently working on 737 production engineering.



Branko Sarh is a recently retired Senior Technical Fellow for automated assembly systems with experience developing technologies used in both commercial and defense production.

A CENTURY OF BOEING INNOVATION IN NONDESTRUCTIVE EVALUATION (NDE)



Gary Georgeson is Boeing Senior Technical Fellow for nondestructive evaluation, whose expertise has supported commercial, defense and advanced research programs.

The Journal is a proprietary publication, but the articles on the following pages are summaries of technical papers approved for public release and available online at Boeing.com.

Electromagnets for Aircraft Assembly

Summary

BY SAMUEL DOBBS | BRANKO SARH

Developing and integrating electromagnets into aircraft assembly systems was a major innovative step in improving assembly processes for manual and semi-automated operations. Within this paper, the design and equipment characteristics are described in some detail, and opportunities for advancing the part clamping methodology with emerging electropermanent magnets is described.

Today's aircraft assembly involves several methodologies and systems, ranging from conventional manual assembly to mechanized, semi-automated and fully automated systems. What assembly technology is being used depends on type of components, structural configuration, available equipment, investment and the level of innovation created during the development of advanced assembly techniques and systems.

Conventional assembly processes use manual tasks to join parts to small sub-assemblies, and then integrate stepwise multiple sub-assemblies and panels to major components like fuselage and wing structures. Basic processes involved in manual assembly include:

a. Positioning detail parts relative to each other in assembly fixtures, or using determinate (pre-drilled holes generated during the part fabrication process) and tacking parts with Clecos (a temporary fastener).

b. Drilling/countersinking holes using hand tools (drill guns).

c. Disassembling parts, deburring hole exit areas and cleaning parts (removing chips and lubricants).

d. Applying sealant to faying surfaces.

e. Re-assembling parts and installing rivets or fasteners.

The manual process is very time consuming. Figure 1 "Cleco Clamping" illustrates the behavior of parts during the manual assembly. As can be seen, the drilling is performed in-between two Clecos, and as soon as the first part is drilled, parts spring back—the drill bit continuously applying drilling force to the second part—resulting in a gap between parts. Chips enter the gap, necessitating part disassembly and cleaning, which leads to a two-step assembly process.

Decades ago, aircraft manufacturers motivated suppliers to develop a machine, which could accomplish "one-up-assembly" by clamping pre-assembled parts at the drilling location to avoid gaps between parts, and to eliminate part disassembly and the cleaning process. A variety of C-frame and D-frame machines and systems are available today to perform "one-up-assembly" for rivets or fastener installation, significantly improving process efficiency and reducing time and cost of structural assembly.

Machine part clamping requires two bushings (one on each side of the sub-assembly), and active and re-active clamping forces are carried around the part by the C-frame machine structure (see Figure 1 "C-Frame Clamping"). Because of the force flow around the sub-assembly, only certain types and sizes of structures can be assembled with these machines—for example, single, super and mega fuselage and wing panels, allowing access to both sides of the structure (open structure).

Figures 2 and 3 show fuselage and wing type of structures and assembly levels required to build step-by-step a complete fuselage and wing. The fuselage is built in five assembly steps (single, super/mega panels, half shells, barrels and complete fuselage) and wing is built in four major assembly steps (single panels, spars and ribs, spar/rib grid, and upper and lower panels assembly—creating the box), and integrating wing center box with the left and right wing box. However, if assembly of "closed structures" like fuselage barrels and wing boxes is required, these C-frame machines cannot be used. All assembly operations had to be performed manually.

Innovation and development of new assembly methodologies were required to eliminate manual assembly of "closed structures." Leading the aircraft industry, we at Boeing invented, developed and implemented semi-automated systems using electromagnets for "closed structures" such as fuselage barrel sections and wing box assemblies. Several patents have been issued, as well.

Instead of C frames to clamp sub-assemblies, we developed electromagnets, generating magnetic flux, penetrating the aluminum or composite structure, pulling a steel block (positioned inside structure) towards the electromagnet, and clamping parts in-between, as depicted in Figure 1 "Electromagnetic Clamping."

Clamping force at the drilling location can be adjusted to satisfy process requirements by manipulating the voltage of the electromagnet and size of the steel block/plate inside the structure. Principles of clamping force generation with electromagnets and potential applications of this assembly methodology for fuselage and wing box structures are depicted in Figure 4.

For a given structural stack-up (gap), specific electromagnet process parameters must be used (electric current, steel volume) to clamp parts sufficiently, eliminating gaps during the drilling/countersinking and interference fastener insertion. For thin structural stack-ups, low clamping forces will suffice, generated by applying low current to the electromagnet. However, for thick stack-ups, sometimes a magnitude higher clamping forces are required and are generated by applying higher current to the electromagnet.

One potential concept using electromagnets is with flexible assembly systems, whereby the electromagnet is integrated with a Multi-Function-End-Effector (MFEE) moving on the rails positioned on the outside of the fuselage. A mechanic on the inside of the fuselage is handling a gun with a steel block, positioning it opposite of the MFEE to support the generation of clamping force. After a

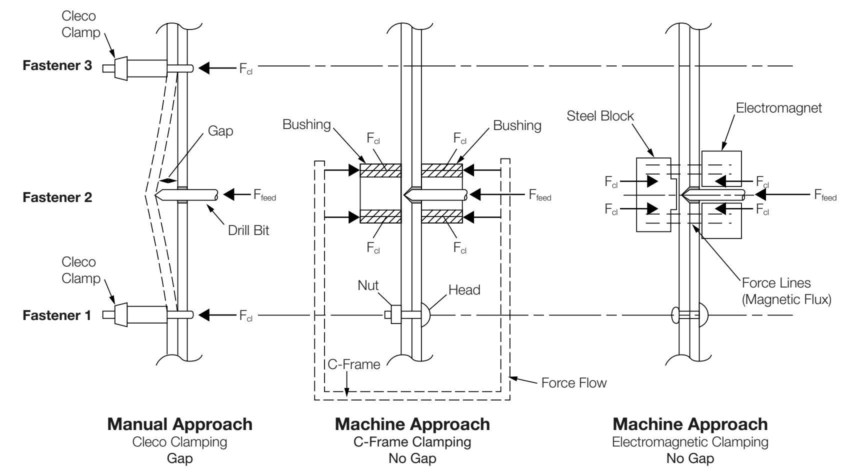


FIGURE 1.
Manual versus machine process principles during drilling and interference fastener insertion.

SOURCE: BOEING

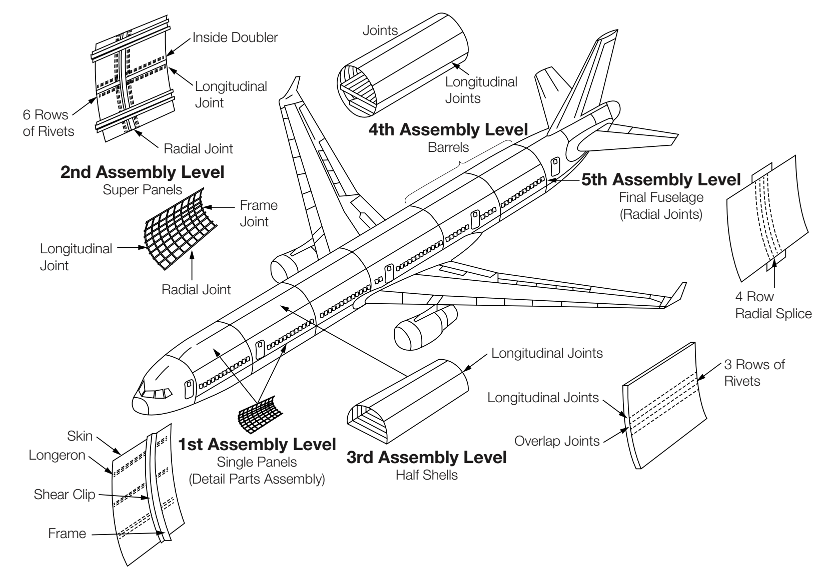


FIGURE 2.
Fuselage assembly levels and joint types.

SOURCE: BOEING

Developing and integrating electromagnets into aircraft assembly systems was a major innovative step in improving assembly processes for manual and semi-automated operations.

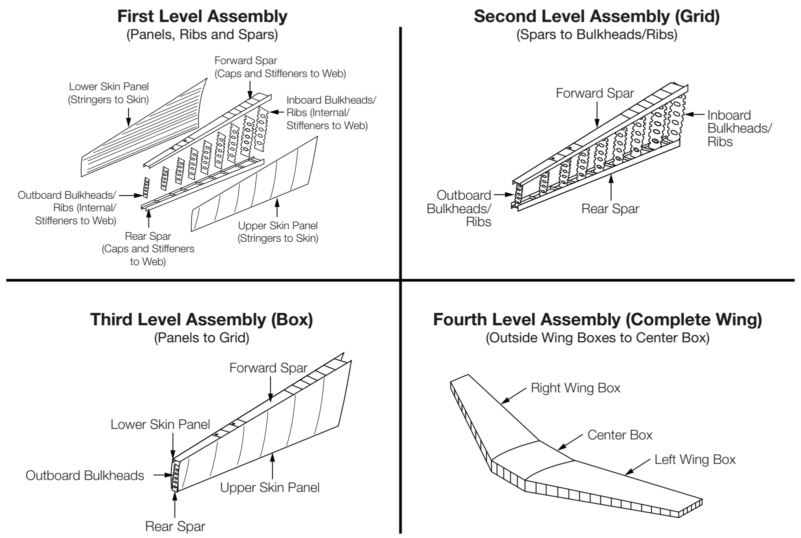


FIGURE 3.
Assembly levels for wing primary structures.

SOURCE: BOEING

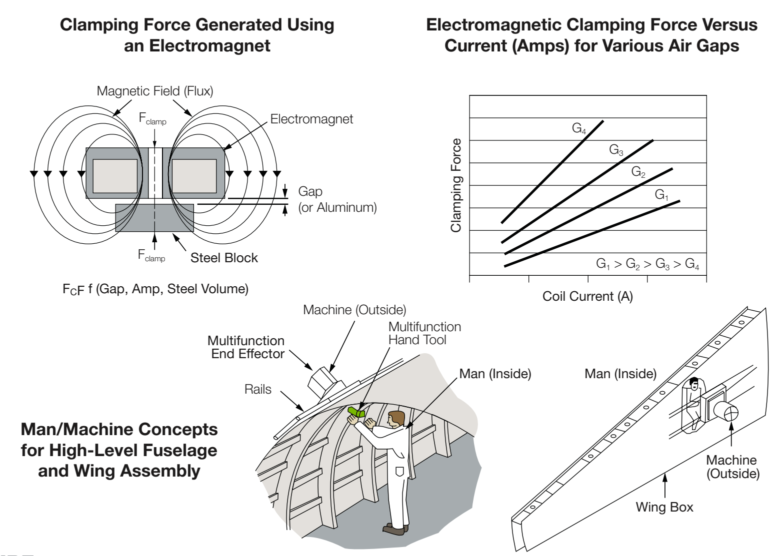


FIGURE 4.
Clamping force concepts and aircraft applications.

SOURCE: BOEING

fastener is inserted by the MFEE, the mechanic will install a collar or nut onto the fastener with a hand tool. Similar methodology using flexible assembly systems can be applied to wing box structures.

With emergence of composite materials and innovative aircraft configurations, the assembly technologies have to be adapted to satisfy new process requirements. The 787 wing was the first composite commercial aviation primary structure embracing the advantages of these new materials.

Furthermore, the traditional wing box major assembly methodology at that time was changing from a vertical to horizontal approach for the 787, thereby eliminating large expensive assembly jigs, and replacing them with Determinant Assembly (DA) philosophy. Pre-drilled DA holes during the part fabrication enable pre-assembling and tacking components to create the wing box with minimized tooling. The horizontal assembly technique was also well suited to facilitate one-up assembly processes providing new opportunities for automation.

Today's competitive aerospace business demands that new automation increase rate, improve quality, reduce cost and improve safety. The Automated Wing Fastener Insertion System fulfills the first two initiatives but comes at a high cost and with safety concessions. If electromagnetic clamping is going to prosper in the future, significant strides will need to be made to overcome these detractors.

For example, an electric coil inside the steel shell of the electromagnet generates heat, necessitating cooling to avoid damage to coil windings and wire installation. For low clamping forces, achieved by applying low current to the coil, heat energy generated can be removed by blowing pressurized air through channels in-between coil windings. However, for maximum clamping force, water cooling is needed to sufficiently extract heat generated by higher electric current.

Elimination of expansive recirculating water chiller systems will require new magnet technologies. The amount of energy required to generate 1,000 pounds of clamping force for some 737 wing box lower panel assembly generates a lot of heat. An elaborated fluid cooling system was built and implemented to keep horizontal build line electromagnets below 50 degrees Fahrenheit at all times, driving higher capital investments for production implementation.

To address this challenge, Boeing is supporting research at the Massachusetts Institute of Technology with a focus on new innovative concepts to reduce or eliminate the need for electromagnet cooling.

Potential solutions investigated and tested at MIT involve the combination of permanent and electromagnets called electropermanent magnet assembly. An aluminum-nickel-cobalt permanent magnet is surrounded by a copper coil, and those are placed inside a steel shell. On the opposite side of the simulated aluminum stack-up is a steel plate which is pulled towards the electropermanent magnet after magnet activation.

The function of the copper coil is to magnetize and/or de-magnetize the Al Ni Co permanent magnet. Magnetic flux density and corresponding clamping force between electropermanent magnet and steel plate is controlled by the magnitude, direction and sequence of current pulses through the magnetizing coil. To nullify the established magnetic field of the permanent magnet and correspondingly minimizing or eliminating clamping force, an electric pulse is applied through the coil in a reverse direction from the one used for magnetizing.

With the modulation of the input, current magnitude and direction, and to the sequence of momentary pulses (on the order of milliseconds), the Al Ni Co core material is partially magnetized or de-magnetized.

Once the target clamping force is achieved, no input energy is required to indefinitely maintain the clamping force. Because of very short energy pulses needed to magnetize or de-magnetize the system, no heat is generated eliminating the need for any magnet cooling system.

Also worth mentioning is the possibility of utilizing alternative magnetic clamping devices, such as trapped-flux superconductors which have already been successfully incorporated into flexible "pogo" tooling fixtures used to hold mandrels while laying-up, curing and trimming composite panels. In the future, this or other alternative methods of generating magnetic fields could be adapted to automated fastening systems to alleviate the need for cooling.

Another future trend will surely be the development of confined-space automation for handling steel backing plates to eliminate the ergonomic and safety issues associated with the current process, as well as non-value-added extra work.

To handle steel backing plates when fastening upper panels (prior to loading lower panel), robots could easily be used. Robots will overcome the gravity challenge (holding the steel plate up during fastening), however clever steel backing plate designs will need to be developed to limit the number of steel plate geometries required. Nevertheless, the automation will require a multitude of plates with quick-disconnect adapters and stored in a tool changer.

A prototype deployable arm robot that could enter the wing box to position steel backing plates for AWFIS was tested, but did not prove robust enough for production. However, technological advances in the future should open doors for this type of automation. IQ

To read and download the complete Boeing Technical Journal paper titled:

"Electromagnets for Aircraft Assembly"

Please visit **boeing.com/IQ.**

A Century of Boeing Innovation in Nondestructive Evaluation (NDE)

Summary

GARY GEORGESON

Nondestructive Evaluation (NDE) is a critical technology area for Boeing that has grown and developed along with the company throughout its 100 years. The future will continue to rely on innovation in the non-destructive inspection of our aircraft. This is a brief overview of NDE development at Boeing.

Nondestructive Evaluation has paralleled and sometimes enabled many other technologies. At times this core competency is referred to NDI (Nondestructive Inspection) or NDT (Nondestructive Testing), depending upon its particular application or industry of use.

NDE can generally be defined as the evaluation of a structure without harming or affecting its purpose. This definition sets NDE apart from destructive or mechanical testing of subscale or full-scale structures, which allows the determination of properties or flaws, but which makes the part unusable afterwards. NDE for aerospace covers two distinct but related application areas: NDE during production and NDE during in-service usage.

The specific goals of NDE (and NDI or NDT) were expressed very well by Robert McMaster in the 1959 version of the American Society of Nondestructive Testing Handbook:

- Ensuring reliability of the product
- Preventing accidents and saving lives
- Making a profit for the user
- Ensuring customer satisfaction
- Aiding in better product design—weight and cost savings
- Controlling manufacturing processes
- Maintaining uniform quality level
- Providing early warning of impending maintenance issues
- New products and business opportunities

Ensuring reliability of the product and preventing accidents and saving lives are important and obvious goals for NDE. The goal of “making a profit for the user” is often underappreciated, yet is essential to the effective use of NDE for a manufacturer like Boeing. As aerospace manufacturing platforms have grown more competitive in the recent decades, NDE development as a cost and flow-time-reducer has become more critical.

The early history of NDE emergence into aerospace is a fascinating one. The first commercial Boeing airplane structures were visually inspected during manufacturing to verify proper wood frame assembly, fabric attachment and adhesive application during fabrication. No instruments beyond the human eye were used, except possibly lighting aids or magnification to improve defect detectability.

Visual inspection was exclusively used in the early years of aircraft up to the early 1930s, when the first all metal airplane, the Boeing Model 247, was introduced. Industrial radiographic inspection processes for metals and the first magnetic induction/magnetic particle inspection approach were introduced in the 1920s. These were applied on a limited basis for inspection of Model 247 components, as well as the more mass-produced Douglas DC-3 that came along in 1936.

World War II saw the development of the first eddy current instruments, as well as the first ultrasonic testing method. These became the crux of aerospace NDE as Boeing entered the jet age in the mid-1950s. As the space program came along in the 1960s, McDonnell had a hand in the development of the first Sondicator to support inspection of heat shield bonds on the Gemini spacecraft, probably the most critical element of the vehicle. The early Sondicator led to development of more advanced low-frequency bond testing methods still used today for inspection of adhesive bonds.

While visual inspection continued to be the primary NDE method, visual inspection could no longer address the defect and damage detection needs, especially in-service. Metal fatigue caused by the cyclic stresses of aircraft flight produces small cracks that must be identified before they grow to the point of structural failure.

These fatigue cracks, and cracks generated by excessive loads or corrosion could be identified using an NDE method called dye penetrant, which relies on a dye wicking into surface cracks. Structural parts made with most steels could be inspected with magnetic particle inspection. Both these methods essentially enhanced visual inspection. Visual inspections require human reckoning that require high skill interpretation and judgment. As the need for inspection increased, new instrumented methods had to be developed to allow discovery with less judgment.

Several major air catastrophes drove the need for better NDE. The F-111 crashes of the late 1960s and early 1970s led to the introduction of the fail-safe/damage-tolerant design philosophy. The first aircraft designed in the damage tolerance era was the Boeing (McDonnell Douglas) F-15. Boeing, along with Pratt & Whitney from the engine side, took the lead in addressing inspection reliability in conjunction with all NDE processes used to support manufacturing.

Boeing also was first to use structural analysis and NDE reliability assessments to define in-service inspection intervals. The 1988 Aloha Airlines fuselage peeling led to an “aging aircraft” monitoring approach. This explosive decompression incident was caused by widespread fatigue damage. The incident, along with the United Airlines DC-10 crash in 1989 (engine) and corrosion failures associated with the KC-135 in the early 1990s, led the FAA to join with the Department of Defense and NASA to cooperatively address aging issues. This resulted in significant funding going to aging aircraft research, including NDE.

As the complexity and design criticality have increased, composites, as a percentage of an airplane structure, have increased as well. Ultrasonic inspection of composites has benefited from improvements over the years with electronics, automation and computing power, so that 2D and 3D imaging and analysis of UT data is now commonplace.

Boeing has been a world leader in the development of automated ultrasonic scanning systems, for production and in-service inspection of composite structure. Two examples of Boeing Automated Ultrasonic Scanning System (AUSS) options are shown in Figures 5a and 5b.

To date, over 70 AUSS gantry systems (such as shown in Figure 5a) are used across the aerospace industry, and more than 130 mobile systems (Figure 5b) have been sold in support of manufacturing, maintenance and research and development. In total, the influence of Boeing’s advances in automated systems have resulted in over $100 million dollars in equipment sales and billions of dollars in cost savings, through reduced inspection time and improvements in quality.

Boeing has taken the initiative to develop various automated tools for NDE that can extend or supplement the important AUSS product line, particularly for in-service inspections, and provide for greater personnel safety by eliminating the requirement to be on or adjacent to the aircraft under

PHOTO: BOEING

FIGURE 5A.
Boeing AUSS Tower, used for NDE of large composite structure during manufacturing.

PHOTO: BOEING

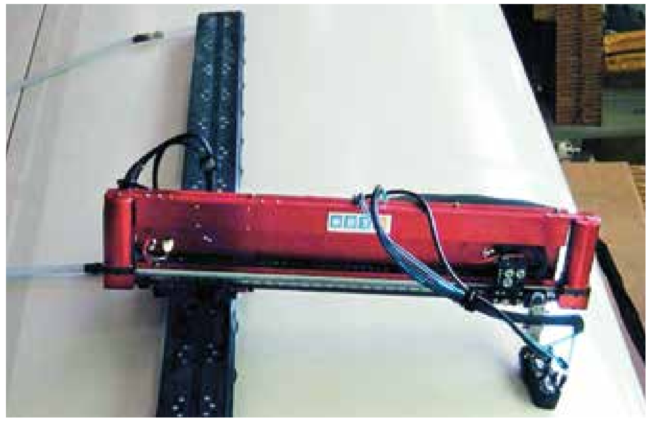


FIGURE 5B.
Boeing AUSS Mobile, used for on-aircraft in-service NDE applications.

Major types of nondestructive evaluation techniques

EDDY CURRENT (EC) TESTING

An electric current-based method developed first in the industries making and inspecting pipes and tubes. It was the first significantly used instrumented method of NDE in aerospace. With this method, a changing electromagnetic field is generated by a coil containing alternating or pulsed electric current. The field produces corresponding electric (eddy) currents in the metal, whose paths are modified by cracks. The same coil or a separate receive coil senses the field change that the eddy currents produce, thereby allowing detection of cracks using electronic circuitry and (first) analog then (later) digital display.

MAGNETO-OPTICAL IMAGING (MOI)

Developed in the 1980s to enable 2D EC-based imaging of cracks around fasteners in fuselage lap joints and other structures. Linear EC arrays have more recently been developed that can be swept along a lap joint for in-service inspection for cracks around fasteners.

FILM X-RAY

The first radiographic NDE method used for aerospace structure to find cracks, voids and foreign material. It was also very effective with moisture detection in metal honeycomb used for flight control surfaces, like flaps and trim tabs. Boeing was involved in the development and implementation of advanced radiographic inspection processes in the 1990s, including DR and CT.

DIGITAL RADIOGRAPHY (DR)

Digital radiography and other digital forms of x-ray have replaced film x-ray for many aerospace applications in recent decades, due also to the development and advancement of x-ray detector panels. The film-to-digital transition was driven by the advantages of digital data sets, as well as the cost reductions and environmental benefits of eliminating film, processing chemicals and disposal.

X-RAY COMPUTED TOMOGRAPHY (CT)

Standards were established in the early to mid-1990s for aerospace components and the resulting reports are still referenced today. CT provides 2D and 3D imaging of material density, voids, porosity and geometry with very high resolution capability for smaller parts. Today, CT is a key technology in supporting qualification and certification of metallic parts fabricated using additive manufacturing processes.

ULTRASONIC TESTING (UT)

Another important NDE method for aerospace structure. UT uses high frequency stress waves generated at the surface of a structure to interrogate a structure for defects that reflect or attenuate the signal. UT can be performed from one side of a part with a single transducer that sends and receives an ultrasonic signal, or in a through-transmission mode, with a sensing transducer listening for losses in transmission that is caused by flaws. UT has the benefit of being able to see deeper flaws than EC, and will work in non-electrically conductive media.

PHASED ARRAY ULTRASOUND (PAUT)

Originally developed in the medical field for looking into the human body. With this technology, a linear set of transducers can be activated in various time-phased or simultaneous options that dramatically increase ultrasounds' speed and capabilities over traditional single transducer inspections. Boeing researchers have developed and implemented many end effector innovations using ultrasonic PAUT technology.

inspection. Two recent innovations are the ROVER (Remotely Operated Vacuum Enabled Robot) for aircraft exterior structural inspection, and the Boeing "Blade Crawler" for rotorcraft rotorblade NDE.

More about the ROVER and Blade Crawler is described in the full journal paper online.

Other Boeing developed NDE technology innovations are changing the way the industry assesses aerospace structures. One example is the Boeing-developed X-ray Backscatter system that creates an image of the interior of a structure by scanning an x-ray pencil beam across it and collecting the x-rays that scatter back.

X-ray Backscatter was originally proposed by Boeing as an NDE method in the 1970s, but then set aside due to the cost and speed limitations of legacy technology. Because of terrorism and border security concerns of the 1990s, the security industry rapidly evolved the technology to decrease the cost and size and increase its capability, therefore, making it more attractive to develop as an NDE tool.

X-ray Backscatter does not require access to both sides of a structure in order to do an inspection, which is an advantage for NDE of both large and in-service structures. It also selectively scatters from and discriminates between materials. The method is particularly sensitive to adhesives, moisture ingress, density changes, voids, and foreign object debris. It has recently been shown to be able to characterize composite heat damage and detect wrinkles in composites. More research is needed to quantify these new capabilities.

It is worth noting that the NDE technologies developed and matured by the Boeing team have found valuable applications beyond characterizing defects during

Factory flow will be optimized for speed and cost with automated crawling NDE platforms. NDE sensors will see significant technology innovation.

inspection. Imaging technology and methodologies like photogrammetry and profilometry that were originally developed to characterize defects in the shape or finish of a surface are now being used for reverse engineering applications to support 3D modeling of legacy aircraft during modification and upgrade efforts.

Past NDE-related radio frequency research has now been spun to create RFID technology used to track products and inventories in our factories.

So, what are key NDE development areas that we can expect to see within Boeing as we look into the future?

NDE in the future will include automated data analysis that increases throughput by reducing time-consuming human-based data analysis. Lower cost pedestal and modular NDE robots will replace the current higher cost, large footprint, stationary scanning systems.

Factory flow will be optimized for speed and cost with automated crawling NDE platforms. NDE sensors will see significant technology innovation. Waterless stand-off NDE sensors, such as Laser Ultrasound Arrays, will inspect complex shapes and edges faster, without having to touch the part or deal with water collection and recirculation issues. Thinner laminates, like the 787 barrel skin, could soon be inspected with faster, large area NDE methods, such as Infrared Thermography (IRT), with UT used only for characterization of flaws.

The value of utilizing NDE and other measurement data as a process control tool is only now being fully appreciated. The goal is to move inspection (such as UT, IRT, CT, etc.) back up the manufacturing chain so it becomes transparent to the fabrication process. This approach will drive quality improvements through trend analysis, and reductions in process variations. In-process sensor feedback during manufacturing will be expanded to newer manufacturing methods, like additive manufacturing.

Ultimately, this approach will tie the NDE and measurement data into a "digital thread" that supports cost-effective implementation and maintenance during the entire life cycle of the aircraft. Better NDE planning during the design process reduces the uncertainty of new manufacturing capability and allows design teams to have confidence to optimize the design and not add costly overdesign to account for uncertainty. Better NDE during development helps optimize the production process, which results in fewer requirements for NDE in perpetuity.

For in-service NDE, some new capabilities that are likely to be implemented to reduce NDE costs include nanotechnology-based self-sensing structures/surfaces, robotic surgical NDE, and fully networked remote expert (tele-operational) NDE that extends the reach of the expert to virtually any place in the world. Advances in radiographic methods, including Computed Tomography, X-ray Backscatter, and Neutron Radiography are also part of Boeing's long-term research and development plan to provide the best possible NDE tools when new critical, difficult or time-sensitive challenges arise.

Of course, the future is impossible to fully predict. Many factors will determine the direction of technology development in any field. However, we can point to the fact that Boeing has been a leader in NDE innovation this past century. IQ

To read and download the complete Boeing Technical Journal paper titled:

"A Century of Boeing Innovation in Nondestructive Evaluation (NDE)"

Please visit **boeing.com/IQ.**

Co-bots in the Land Down Under

Where humans and automation work together.

BY DOMINIC WIERZBICKI,
ROBOTICS, MECHATRONICS AND SOFTWARE ENGINEER
BOEING RESEARCH & TECHNOLOGY

PHOTO: BOEING

ROBOT HELPER
A co-bot at work on an airplane component at a Boeing production facility in Melbourne, Australia.

Collaborative robots, or "co-bots" as they are affectionately known, represent an evolution in robot technology.

Co-bots are a new class of lightweight robotic arms that differ from traditional industrial robots in that a co-bot is force-limited and designed to work alongside people.

Collaborative robots therefore challenge the restrictions typically imposed on robots on the factory floor, such as spatial boundaries between human operators and robots. Because collaborative robots can share an overlapping workspace with an operator, they may take up less space than traditional robots and can more easily be incorporated into an existing assembly process.

Since the 2008 establishment of Boeing's advanced research and development unit in Australia, Boeing researchers have pushed the limits of what collaborative robots might achieve in various facets of industry, including assembly, fabrication and repair.

A recent area of improvement is on the 737 component production system. Integrating new technology like co-bots on an existing system can be a challenge because factory layouts are already configured, operators are experienced and skilled in existing processes, and there is often limited capital available for a system change. Implementing a new robot cell needs to be low cost, cause minimal disruption, and deliver rapid payback of value to an already streamlined production system.

Many 737 components have hundreds of rivets that, upon installation, need machining to a nominal height. It is time-consuming work that could lead to repetitive strain on human operators. Additionally, there is the risk of damage to the components, as manually-operated shavers can slip, leading to costly rework.

A Universal Robot UR10 was integrated with a small linear track and controlled by customized modular, Boeing-written software. The existing hand shaver tool was attached to the end and the manual process became automated.

The team spent considerable effort designing a system that is lightweight, unobtrusive and contains redundant safety measures, both with respect to the co-bot and the shaver tool that it applies. Furthermore, the team analyzed the robot system for all robot-human contact scenarios. The team simulated contact with the robot and human using pressure sensing technology confirming adherence to the latest ISO 15066 Collaborative Robot standard.

Since the introduction of this low-cost, low-disturbance system last year, this co-bot has saved hundreds of hours of ergonomically difficult labor, demonstrating that robots can be a mechanism to reduce human risk even as they work side-by-side with people. Furthermore, as an unanticipated tangible benefit, machining cutter consumption dropped through efficient manipulation only possible by an automated solution.

This implementation by Boeing in Melbourne represents human-robot collaboration and a vision of the future for factories. IQ

Global Scale

Unmanned ocean monitoring for high seas and high latitudes

Texas A&M University researchers have deployed a Wave Glider in the Gulf of Mexico to monitor post-Hurricane Harvey water quality data for possible effects to coral reefs and ecosystems. Wave Glider is an unmanned surface vehicle from Boeing subsidiary Liquid Robotics, which recently released an upgraded Wave Glider that can be used in high sea states and also offers advanced navigation in polar latitudes. The advancements also support for heavier payloads and greater power collection and storage.

Heavy maintenance and modifications in China

China-based Xiamen Airlines completed the first 787-8 base maintenance check—an extensive check of airplane systems and components—to be performed by Boeing Shanghai Aviation Services. A joint venture between Boeing, Shanghai Airport Authorities and China Eastern Airlines, Boeing Shanghai provides engineering, maintenance, and modifications for multiple plane models, including major and minor checks, composite repair, structural modifications including winglet and pylon, cabin upgrades, engine and landing gear replacement, and a full paint hangar. China is estimated to need more than 7,200 new airplanes in service over the next 20 years.

Testing LIDAR on the ecoDemonstrator

As part of an ongoing research collaboration with the Japan Aerospace Exploration Agency, Boeing's ecoDemonstrator research program will be testing long-range light detection and ranging (LIDAR) technology starting in 2018. LIDAR's laser pulses could measure winds as much as 17.5 kilometers (10.9 miles) in front of planes, giving pilots about a one-minute warning, which may help them navigate around wind shear and clear air turbulence. LIDAR will be one of more than 30 technologies to be flight-tested in 2018 on a FedEx-owned 777 Freighter, as part of a Boeing-FedEx research partnership to advance technology that improves performance and reduces environmental impact.

PHOTO: BOEING

PHOTO: 1776

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From the top, left to right:

BOEING INNOVATION AWARDS

Associate Technical Fellow Tanni Sisco (middle), one of 49 teammates honored with Boeing's highest award for technical achievement, stands with John Hamilton (left), vice president of commercial airplanes engineering, and Steve Chisholm, director of commercial structures engineering (right). Sisco and other honoress were celebrated at a gala ceremony on Oct. 19, at Seattle's Museum of Flight. Her winning invention helps prevent structural damage to an aircraft from potential lightning strikes while enabling critical production efficiencies for the 787 Dreamliner. Boeing sponsors the Innovation Awards annually.

PITCHING INNOVATION IN DUBAI

Ishita Sood, of WakeCap Technologies, delivers the winning pitch at Challenge Cup Dubai, Sept. 21. Sponsored by Boeing and technology incubator and seed funder 1776, the Dubai event was part of a global competition among startups. WakeCap's wearable tech improves the safety and productivity of construction workers by monitoring heat stress levels.

GEEKING OUT IN SEATTLE

Boeing is 100-years-young as Seattle's original tech startup, and the company is pursuing a bold, new agenda for the next century, said Greg Hyslop (right), Boeing chief technology officer, addressing the GeekWire Summit 2017 in Seattle on Oct. 11. Pictured on stage with co-founders Todd Bishop, (left) and John Cook (middle) of GeekWire, a digital technology news site.

#WOMENMAKEUSBETTER

Ted Colbert, Boeing chief information officer, takes a selfie with Boeing teammates at the Women of Color in STEM conference on Oct. 6, in Detroit, where 45 Boeing women were recognized for their technical accomplishments.


CALLING ALL
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