Innovation Quarterly

2019 Q4
Volume 3, Issue 13

Prolific inventors
Patents from perseverance

Learning from spiders
Technology insights from nature

3D-printed tooling
The maturation of additive manufacturing

A publication of The Boeing Company

Innovation
Quarterly

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COMMENTS
Comments and letters are welcome and may be published in subsequent editions. To submit a letter to the editor, email **junu.kim@boeing.com**

WEBSITE
boeing.com/IQ

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Jeff Hunt is a Boeing Senior Technical Fellow based in El Segundo, California.

PHOTOGRAPHY BY PAUL PINNER

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In a model-based engineering (MBE) framework, engineering artifacts are readily captured in a "digital thread" for reference throughout the product life cycle. Trade studies are among these artifacts and are used to develop requirements, to choose between potential solutions that meet those requirements, and to help make decisions related to those solutions throughout a program's life cycle. Model-Based Trades Implementation Framework (MBTIF) represents a significant advancement in the conduct of trade studies in an integrated MBE environment.

Inventions that **change the world**, over and over again

What's the difference between technology and innovation? Technology may be impressive, but innovation creates value by solving a problem. This distinction has motivated generations of innovators at Boeing to put their sweat equity into innovations that improve people's lives.

The closing passage of the Engineering Code reads: "I am a steward of Boeing's technical heritage and lineage, and I apply, share, protect, and build upon this foundation by embracing change and competition, learning from failure, and striving to continuously innovate and improve. I am proud to know that my work changes the world."

Those words aptly describe the innovators featured in this edition of Innovation Quarterly — people whose creativity and commitment to excellence are changing the world. They make the world a better place for our customers, our teammates and the billions of people who place their trust in Boeing each day.

Prolific inventors like Gary Georgeson, Marc Matsen and Jeff Hunt (profiled on page 6) are amazing not for the raw number of patents, but instead because of the value they have created for teammates and customers.

Every innovator in these pages shares that passion to innovate. Thanks to their entrepreneurial mindset, collaborative spirit and commitment to technical excellence, these innovators bring to life our Boeing mission to connect, protect, explore and inspire the world through aerospace innovation. They generate value for our customers by both achieving technical breakthroughs and replicating them. They make us more competitive and help us win in the marketplace.

The future we see improves lives in ways we are only just now beginning to imagine. Our teammates featured in this edition, and those who will follow them, will make this future a reality, building on our legacy of safety, quality and integrity. IQ

GREG HYSLOP
Chief Engineer

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.

How to measure innovation

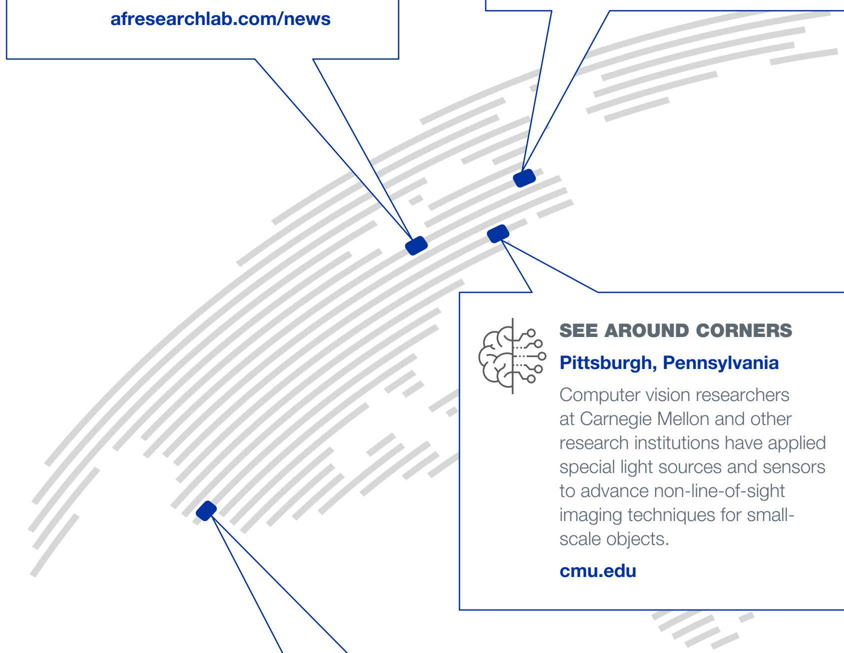
New research has shown that organizational structures and company workforce composition can be tailored to pursue specific innovation objectives.

For example, large groups have been shown to excel at building on recent developments in a field, whereas small groups tend to disrupt with new ideas.

Other research looked at creative capacity based on workforce tenure. Shorter tenure resulted in conceptual innovations that challenge conventional wisdom. Longer tenure led to creativity of an experimental nature that involved novel ways of synthesizing accumulated knowledge to form new understanding.

Likewise, corporate innovative efficiency has been tied to pro-diversity workforce policies.

In short, team composition factors may be as important to achieving desired innovation outcomes as product development or market opportunity. IQ



TRANSPARENT ALUMINUM

Dayton, Ohio

The Air Force Research Laboratory has developed a transparent aluminum-based ceramic to create lighter armor with ballistic protection, superior to traditional glass laminates.

afresearchlab.com/news

PROFESSORS, TAKE NOTE

Hanover, New Hampshire

New research from Dartmouth College has provided evidence that people learn better when they see an object before hearing its description.

dartmouth.edu

SEE AROUND CORNERS

Pittsburgh, Pennsylvania

Computer vision researchers at Carnegie Mellon and other research institutions have applied special light sources and sensors to advance non-line-of-sight imaging techniques for small-scale objects.

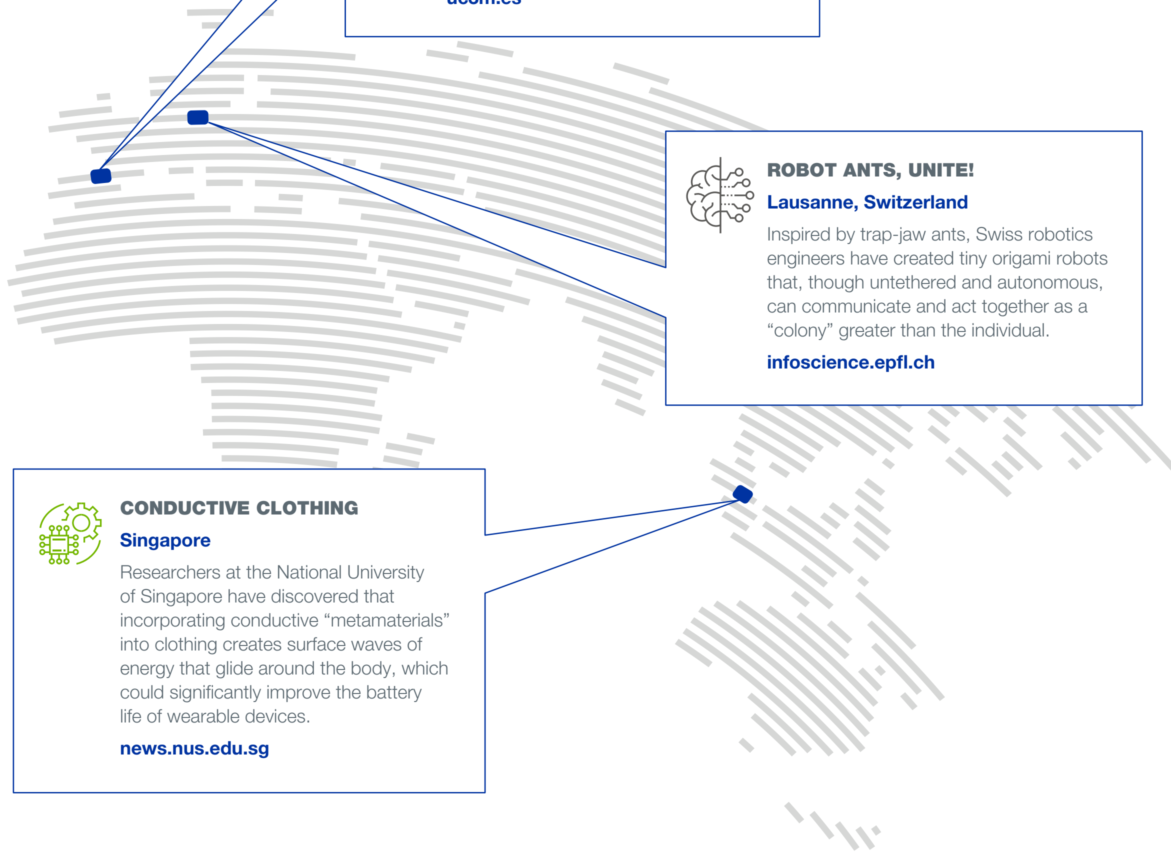
cmu.edu

CHIP-SIZED SATELLITES IN ORBIT

Mountain View, California

NASA's KickSat-2 satellite deployed more than 100 chip-sized "Sprite" satellites earlier this year, demonstrating the low-cost potential of these tiny spacecraft for collecting data from space, as well as Earth's mesosphere.

nasa.gov/ames/kicksat



ROBOTS USING SIGN LANGUAGE

Madrid, Spain

A humanoid robot developed by scientists from Universidad Carlos III de Madrid has communicated with deaf people using sign language.

uc3m.es

ROBOT ANTS, UNITE!

Lausanne, Switzerland

Inspired by trap-jaw ants, Swiss robotics engineers have created tiny origami robots that, though untethered and autonomous, can communicate and act together as a "colony" greater than the individual.

infoscience.epfl.ch

CONDUCTIVE CLOTHING

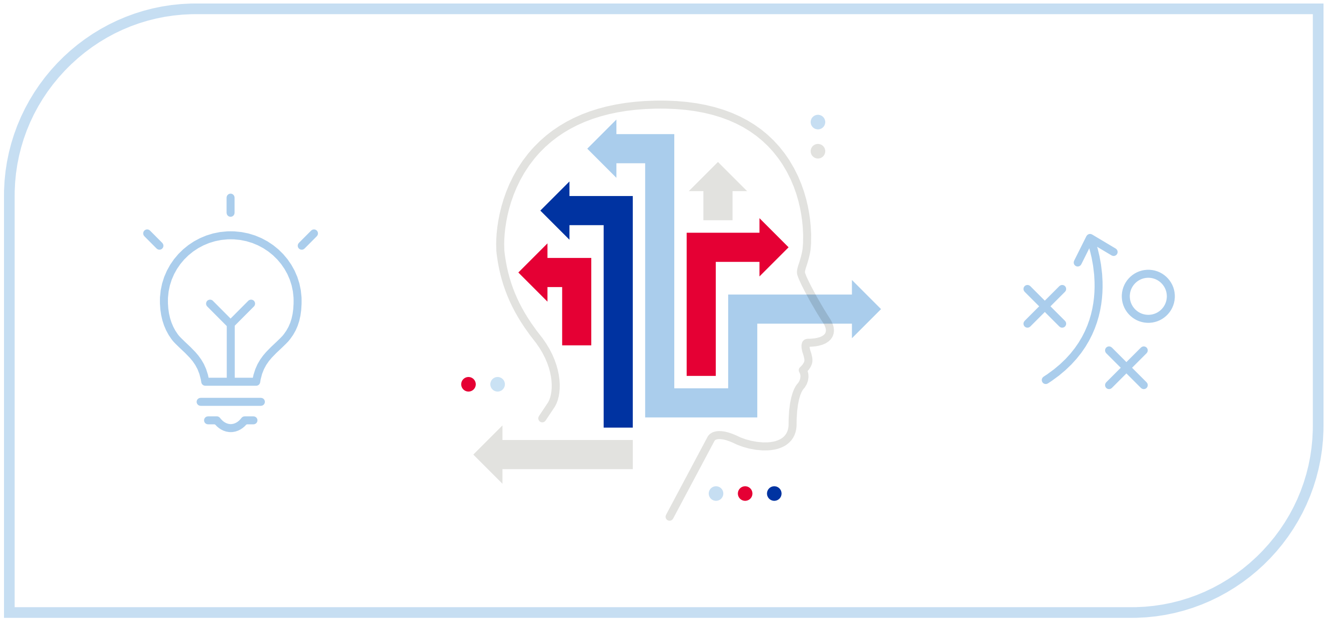
Singapore

Researchers at the National University of Singapore have discovered that incorporating conductive "metamaterials" into clothing creates surface waves of energy that glide around the body, which could significantly improve the battery life of wearable devices.

news.nus.edu.sg

TECHNOLOGY CATEGORIES

- Cyber & Artificial Intelligence
- Integrated Platform Performance
- Materials & Manufacturing
- Platform Systems & Subsystems



A patented **approach**

Boeing's top inventors are spurred on by their novel ideas — and the drive to overcome setbacks.

BY DAN CAHILL, BOEING WRITER

With a fresh copy of his doctoral degree in hand, Gary Georgeson ambitiously embarked on his career at Boeing in 1988 with a team of seasoned engineers developing nondestructive evaluation (NDE) and methods.

The ever-inventive University of California at Santa Barbara graduate didn't waste any time before trying to add value to the company.

"We submitted several invention disclosures," he said. "They all got turned down."

Feeling "it's not even worth the effort," the NDE composite specialist didn't submit any patents for more than a decade.

But two decades later, Georgeson is Boeing's most prolific inventor, with 238 patents as of Aug. 20, 2019.

One would never know it from their body of work, but patents didn't come easy for Boeing's top three inventors — Georgeson, Marc Matsen and Jeff Hunt. Long before the group cumulatively registered more than 460 inventions, "no" was a refrain they often heard. But those rejections couldn't suppress the creative passion that defines all three.

Inventions and patents are more than just a scorecard for innovation. As the world's leading exporter, Boeing relies on patents to protect its intellectual property in an ever-increasing global market.

As Georgeson struggled to get going, another early-career engineer, Matsen, was beginning to experience some success with composite inventions.

"Just because an idea isn't patented doesn't mean it's not a good idea," said Matsen, who has 122 patents on his ideas. "Many times it's that Boeing chooses not to patent it for affordability, or it's not strategic enough. I didn't take it that it wasn't a good idea."

For Matsen, negativity was the mother of invention, always spurring him on to another idea.

Georgeson, who knew of Matsen, followed his lead and credits Matsen for changing his own attitude.

"I'm glad he did, because he ended up coming up with a lot of great ideas," Matsen said.

Hunt couldn't wait to share his Massachusetts Institute of Technology and University of California at Berkeley educational experience when he began his condensed-matter and optical properties physicist career at Rockwell Corp. in 1988. But it wasn't until Rockwell became part of Boeing in 1996 that Hunt applied for his first patent. He recites the issue date: "April 22, 1997, four days after my 40th birthday."

It's hard to draw a causal relationship from the setbacks, but the motivation to invent seems rooted in each engineer's early disappointment.

For Hunt, that breakthrough patent had him running back to an old notebook to find 30 he had never pursued. He couldn't file them fast enough. Soon after, he scored 15 patents in one year.

As Hunt chronicles the progressing litany of his inventions, the cadence of his made-for-radio voice quickens: "From 2011 to 2012, I hit 50. I had a head of steam built up. Hit 100 last October. I have 107 now with two more that have been allowed."

> "If Boeing competes on innovation, we win. That's how we survive as a company."
>
> **JEFF HUNT**

Though the others concede that Georgeson is too far out in front (and too nice a person) to ever surpass, a friendly rivalry does creep into the mix as they jockey back and forth on the leaderboard.

The master innovators offered sage advice for budding inventors at Boeing.

"I tell my proteges, this is how Boeing works," Hunt said. "If Boeing competes on price, we lose. If Boeing competes on innovation, we win. That's how we survive as a company."

Hunt added that would-be inventors shouldn't be scared off by the disclosure form. What at first took him two hours to fill out, he now "bangs out" in 20 minutes.

Perhaps the most interesting advice on inventing comes from the leader himself, Georgeson, who constantly deflects attention from himself and stresses that he's always been a collaborative innovator.

In presentations around the globe, Georgeson begins by telling young innovators that they need to be working with a diverse team.

"People coming from diverse points of view create much better innovation," Georgeson said. "And this is going to sound strange, but the real key to innovation is love. I tell these early-career engineers that if you love what you do and love the people that you're doing it for and doing it with, you will find that people will trust you, and they'll want to work with you, and they'll share ideas with you.

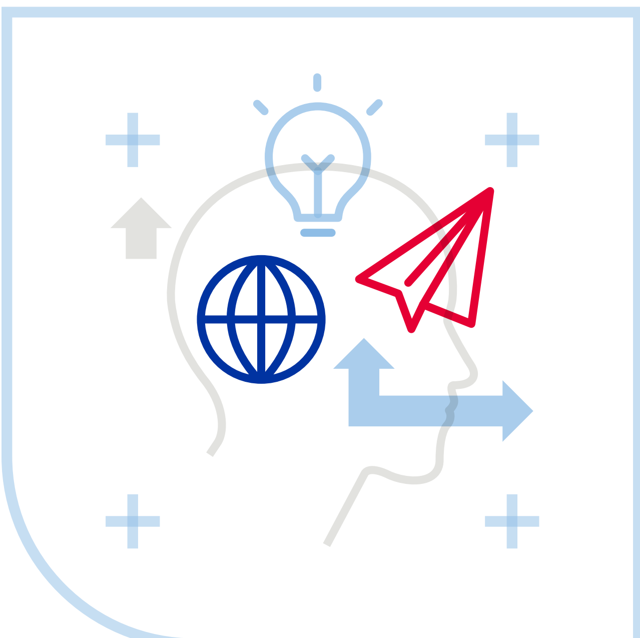
"Part of that love is appreciating that people are different and they come from different points of view. Some of the best work comes out of a team that is unselfish and trusts each other. And boom! Good stuff happens." IQ

Turn to the next page to read about Georgeson, Hunt and Matsen discussing their coolest ideas.

The inventive side

Prolific patenters point to coolest work

With hundreds of inventions, it's hard to choose one favorite. But Boeing's top inventors definitely have thoughts about their coolest ideas.



"[The best ideas come] before all the thoughts about your day fill your head."

GARY GEORGESON

PHOTO: MARIAN LOCKHART

Gary Georgeson

When it comes to ideas with a high cool factor, Georgeson cites a Boeing rover system that crawls around on the outer skin of an airplane to detect imperfections. Georgeson said what made it so cool was the exceptional team he worked with and that it was his 100th patent.

"We had a luncheon and our team was recognized," said Georgeson, always giving credit to the team first. "That made it extra special for me."

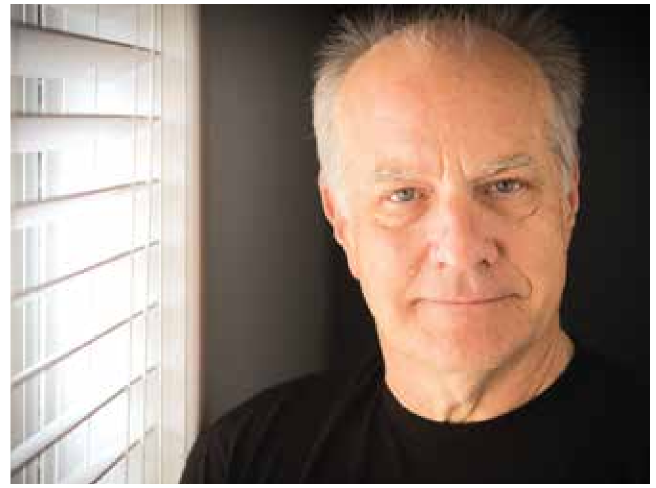
The crawling rover robot uses a floating vacuum base that hangs onto the airplane. It's driven by holonomic wheels so it can maneuver in any direction and doesn't have to be steered. A lightweight sensor array goes on the rover and collects data as it runs over the surface. The team also invented a local positioning system that tracks and guides it.

"It's a Roomba on an airplane," Georgeson said. "The difference is it's very easy to drive around a crawler on a flat horizontal surface but very difficult on a curved, nonhorizontal surface such as an airplane fuselage."

Georgeson said the best ideas usually come to him during quiet moments — walking in the morning or even showering. "When you're just at that moment before all the thoughts about your day fill your head," he said.

From there, it's the "spitball and popcorning" at small team meetings where ideas are born and refined. IQ

PHOTO: MARIAN LOCKHART



Jeff Hunt

The coolest innovation for Hunt was a remote sensing system to quickly measure and characterize the shape of the 787 fuselage pieces as they were coming to the factory.

The only problem was the patent wasn't picked up. The system was demonstrated in Washington, D.C., years ago. "It was spectacular," he said.

Hunt had another patent — a concept for an integrated optical circuit made from silicon — that wasn't picked up because it was difficult to manufacture.

"There had to be a way to come up with making a laser with silicon," Hunt said. "I showed a way that if you use nanoparticles with silicon, it changed the electric band structure. Once I had that, I had everything you need to make an integrated optical circuit out of silicon and patented that concept. And that's when they went forward."

More recently, Hunt has moved into the quantum world, focusing on key distribution and encryption.

Hunt chuckles about when he came up with an anti-hacking patent through quantum key distribution. A website posted a headline saying something like "Boeing solves problem of internet security."

"The patent was valid, but it was a stretch to say that," he said. IQ

PHOTO: MARIAN LOCKHART

Marc Matsen

Matsen points out that many of his patents are based on one invention of his: "The idea of ferromagnetic materials and electromagnetic energy and how when ferromagnetic materials change from magnetic to nonmagnetic, and all the ramifications of that and how we take those results and use them to our advantage to process anything from thermoset materials to superalloys."

Still with us?

"Take those results and use them to our advantage."

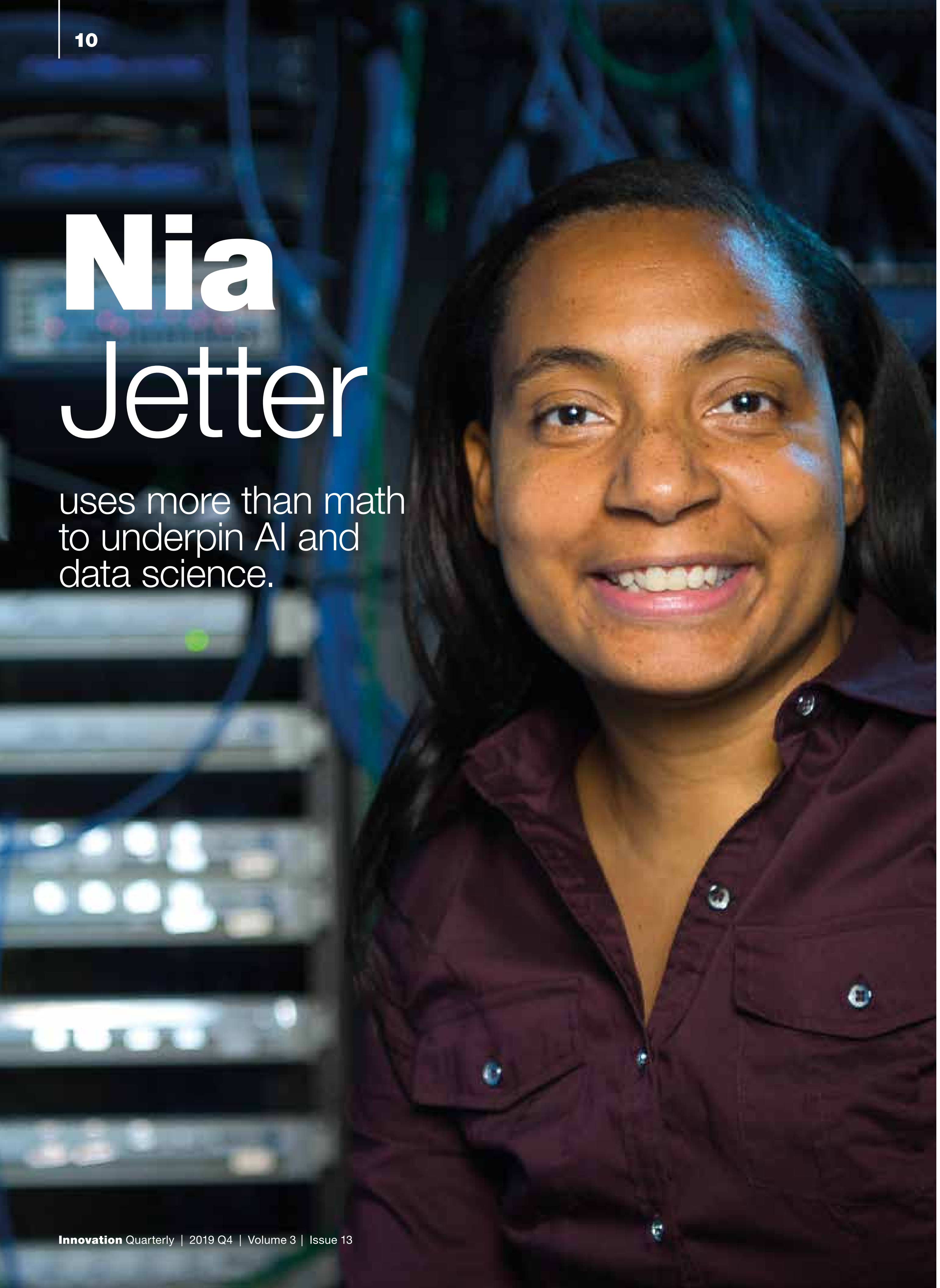
MARC MATSEN

Matsen took that concept and applied it to a debulking system in Salt Lake City for the large horizontal stabilizer skin on the 787.

"For each one of these skins, there's what is called a 'hot debulk cycle' that is required," Matsen said. "The layup of the skin is done, but then you transfer the tool over to this debulk cell and this inductively heated blanket that has smart susceptors (ferromagnetic material) in it."

When the electromagnetic energy from the induction coil interacts with the smart susceptor, it produces uniform temperatures over large areas, which is key to preparing composite airplane materials.

"It's all intrinsically controlled by the change in properties from the magnetic to nonmagnetic," he said. IQ



Nia Jetter

uses more than math to underpin AI and data science.

Artificial intelligence is increasingly integrated into our daily lives at home and at work. How is AI going to change how we live? And how can we shape our AI world?

BY WILL WILSON, BOEING WRITER | PHOTOGRAPHY BY PAUL PINNER

Q&A with Nia Jetter, Boeing's Domain Lead for artificial intelligence, cybersecurity and data science, about the importance of artificial intelligence to life as we know it, why diversity matters, and the courage it takes to change the world.

Q What do you do at Boeing?

A One of the things we're looking at within Boeing is where and how AI should be implemented into our product life cycle. I drive enterprise collaboration and develop the strategy for the company in these technology areas, including strategic assessments to determine, for example, where partnering with others in industry or leveraging existing solutions makes sense as opposed to developing new capabilities within Boeing.

My work focuses on the AI applications for Boeing processes and products, but it's bigger than that. From dynamic, analytics-driven air traffic management for piloted and unpiloted vehicles to smart factories of the future, AI will change our world.

Part of my job is to help ensure the safe and successful development and implementation of AI with that bigger picture in mind. Even as we deliver products and services for our customers with current and emerging technologies, it is also important that we stay at the forefront of this technological innovation so that we can help the world adopt and adapt. This is where the world is going, and we have an incredible opportunity here to help positively shape the future.

Q You mean acculturating new technology in daily life?

A There's a people-focused aspect of my work as well. A big part of our technology planning also focuses on how people will use and understand AI-enabled products.

People have genuine concerns about what a future more fully enabled by AI would look like. Addressing those concerns is as much a part of our technical strategy as the technology itself. It is critical that we as a society develop human-AI interface in a way that achieves trust. It is crucial that people are comfortable with the evolution of our culture and technology as AI is integrated more and more in daily activities.

That's especially true when it comes to educating people so that they understand where the human-AI overlap requires their assistance. For example, with some of the autonomous car capabilities already on the road, we're seeing how people learn this new way of engaging as a driver.

Q What do you see as the big picture effects of increasingly AI-enabled technology for how people live and work?

A Many tasks that are time-consuming, monotonous, physically challenging or dangerous for people could instead be performed by machines. That's the first thing I think about.

I also see how there will be some parallels to what happened during the Industrial Revolution. The insertion of AI will lead to a significant change in our culture and our work, including some of the roles that people play. Change is the one constant that you can rely on!

I think that this change will be good in general — when we have machines doing more of the dirty and dangerous work — but there will also be challenges. Some jobs that people perform will be replaced. But new jobs — particularly ones that require coding skills — will be created. Many companies, including Boeing, are figuring out ways to help employees develop those new skills so that they can grow in their careers and make the transition as the development of AI changes how we all work.

Q What drives you?

A Where I work in El Segundo, California, there is a wall with the names and photos of all of the Boeing Technical Fellows who work on-site. When I started working here, there were no African American women on that wall. I saw that often. There aren't a lot of people who look like me working in AI and technology. I want to change that.

In El Segundo, I did change that. My picture went up on the wall in 2013 when I made Associate Technical Fellow — the first of hopefully many African American women who will appear on that wall. I will never forget the moment I first saw my face on the wall and how it stood out to me.

In 2017, I became one of the first two African American women engineers at The Boeing Company to reach the level of Boeing Technical Fellow. [A third African American woman, a medical doctor, is also a Technical Fellow at Boeing; for more about the Technical Fellowship, see below.]

About the Boeing Technical Fellowship

The Boeing Technical Fellowship, founded in 1989, allows select engineers and scientists to continue their professional growth on a technical career path, as an alternative to a management career track.

Fellowship members are called on across the company to help anticipate, avoid, identify and mitigate technical risks, and to help develop and guide future leaders. Employees seeking to earn selection into the Fellowship must demonstrate their achievements in five areas: knowledge, innovation, leadership, mentorship and vision.

The Fellowship has five levels, with increasing degrees of influence: Associate Technical Fellow, Technical Fellow, Senior Technical Fellow, Principal Senior Technical Fellow and Distinguished Senior Technical Fellow. The top three levels combined include only about 0.1% of Boeing's entire technical population.

PHOTO: PAUL PINNER

> "From dynamic, analytics-driven air traffic management for piloted and unpiloted vehicles to smart factories of the future, AI will change our world."
>
> **NIA JETTER**

Exposure to diversity matters. I understand that more than ever since my picture went up on that wall. I've had more than one person say to me, "I didn't know we have African American women who are Technical Fellows." Now people see me and reach out to me for mentoring, career or technical growth discussions, and even just to say, "You go, girl!"

Math offers proof that diversity makes a difference. Mathematics shows us that diversity can help to enable quick convergence onto an optimal solution. In a genetic algorithm, you introduce mutation into the reproduction algorithm because it is how you can make sure that you do not get stuck on a local minimum or maximum. Adding the right amount of diversity to the data will pull you off of a suboptimal solution and onto an optimal one.

Q What do you enjoy most about your work?

A I get to be the change I want to see in the world.

I participate in groups focused on advancing our society through science and technology in addition to actively supporting groups focused on increasing diversity in technology and STEM fields, especially concrete actions to increase the inclusion of women, African Americans, other people of color and underrepresented groups.

The other day I was in a town hall and people were asking me about biases in data. We had a conversation about how algorithms don't have biases, but the people who write the algorithms might. We need to acknowledge this and identify biases when we see them, and listen to each other in order to expand our worldview.

We are at an exciting point in time with a life-changing technology, and we're shaping the future. Every day I'm at the heart of something that matters. IQ

Make it much **better**

Boeing is using flexible hybrid and additive electronics to develop new ways to produce intricate components that provide big advantages in many areas.

BY JOHN D. WILLIAMS, ASSOCIATE TECHNICAL FELLOW, AND ROBERT SMITH, TECHNICAL FELLOW, BOEING RESEARCH & TECHNOLOGY

Over the past two decades, electronics systems have become ubiquitous in people's lives thanks to the increasing availability — and the continual reduction in size and cost — of open source electronic components.

The iPhone combined internal acoustic, vibration, temperature and GPS sensing into a single commercial product for open source programing in 2007. However, these sensors were dedicated to the prescribed functionality of the phone.

Then a relatively quiet shift came in the everyday use of low-cost, microcontroller-driven transducers, initiated by the release of the Arduino in 2008. Makerbot followed in 2011, promising the ability to 3D print — in your garage — any plastic structure desired.

Next came Raspberry Pi in 2012, which gave teenagers a $50 computer to program and code. By 2015 nearly every engineer — and most American high school students — interested in sensing applications, robotics or technology development had daily access to every one of these products.

Despite this advance, these devices are still clumsy. Adapting them to a specific and reliable sensing application is not trivial and requires multiple connectors between rigid circuit boards through wires, cables and wireless networks.

Today, the maturation and combination of silver ink processes, with laser machining, and 3D printing is poised to provide the next revolution in ubiquitous low-cost sensing platforms. Boeing is using flexible hybrid and additive electronics to develop new ways to produce antennas, sensors and multilayer circuit boards that maintain performance while providing advantages in component cost and weight with dramatic savings potential for integration and test.

By 2022, many maker-space products will use tools that combine additive manufacturing with computer numerical control milling, laser drilling and printed electronics to enable electronics and sensing architectures on or in flexible and 3D-printed structures.

STARRY SKIES
The Starry Skies concept, an advanced lighting and projection system, enhances the flying experience.

IMAGE: BOEING

Both flexible hybrid and additive electronics require precision patterning of multiple electronic materials with critical dimensions of 1 mil or less on both planar and curved surfaces. The limiting factor for realizing this vision is sufficient process control when printing multilayer electronics and the die attachment of integrated circuits to eliminate conventional connectors, cabling and bulky sensor packages required today.

Many of these applications benefit from small low-cost sensor arrays and wireless networks that are becoming a tool for monitoring, manufacturing and operation of mechanical and aerospace systems. These systems become new data collection devices to enable big data analytical capabilities.

This technology has been under development at Boeing for more than five years. Important examples include the printed Starry Skies concept for cabin lighting in airplanes and conformal patch antennas for Boeing Defense, Space & Security.

In 2016, Boeing joined the NextFlex Consortium, a manufacturing innovation institute established by the U.S. Department of Defense, to support industrywide improvements in the manufacturing readiness level (MRL) of these technologies. Through NextFlex, Boeing has provided industrial leadership in materials testing, multilayer fabrication, radio frequency applications and industrial health monitoring device architectures.

The results to date provide a general-purpose MRL 5 or higher for flexible hybrid electronics technologies. Within the next two years, our team will widen these efforts to include unmanned autonomous vehicle flight, composite health monitoring, multilayer flexible PCBs and dozens of sensing applications across the company.

This will be achieved through extensive use of thinned microcontroller integrated circuits mounted directly to the flex board. Coupling these achievements with materials characterization, in situ process monitoring and large-area digital printing will provide Boeing with an MRL 7 small-scale production capability for the next generation of electronic sensing. By 2022, Boeing will have the manufacturing readiness required to implement flexible hybrid electronic devices in both stand-alone and 3D-printed industrial products. IQ

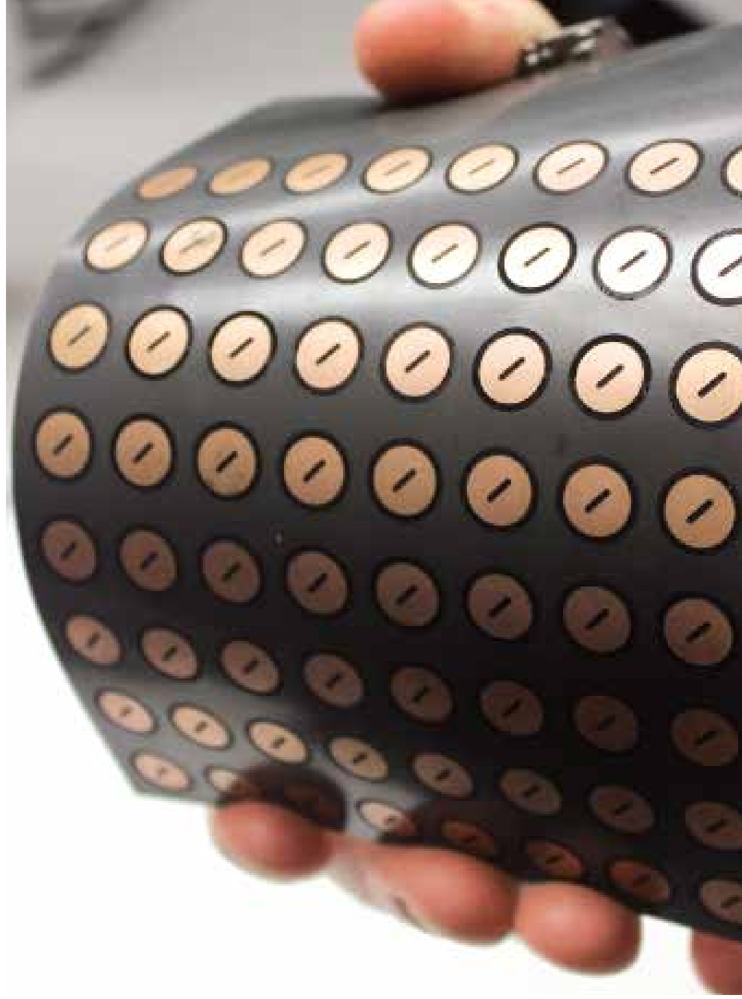


FIGURE 2.
Boeing has developed unique patented flexible antenna arrays. The antenna design shown here has been manufactured for a wide range of applications between 900 MHz and 85 GHz. The design provides a 10% bandwidth at the center frequency and are roughly one-tenth the thickness expected from a conformal patch array. The team has also shown how the performance of these antennas varies as a function of the shape they are mounted on. This flexible antenna array technology is now being tested for communication links throughout Boeing, including electromagnetic monitoring of the 787 factory floor in North Charleston, South Carolina.
PHOTO: BOEING

PHOTO: BOEING

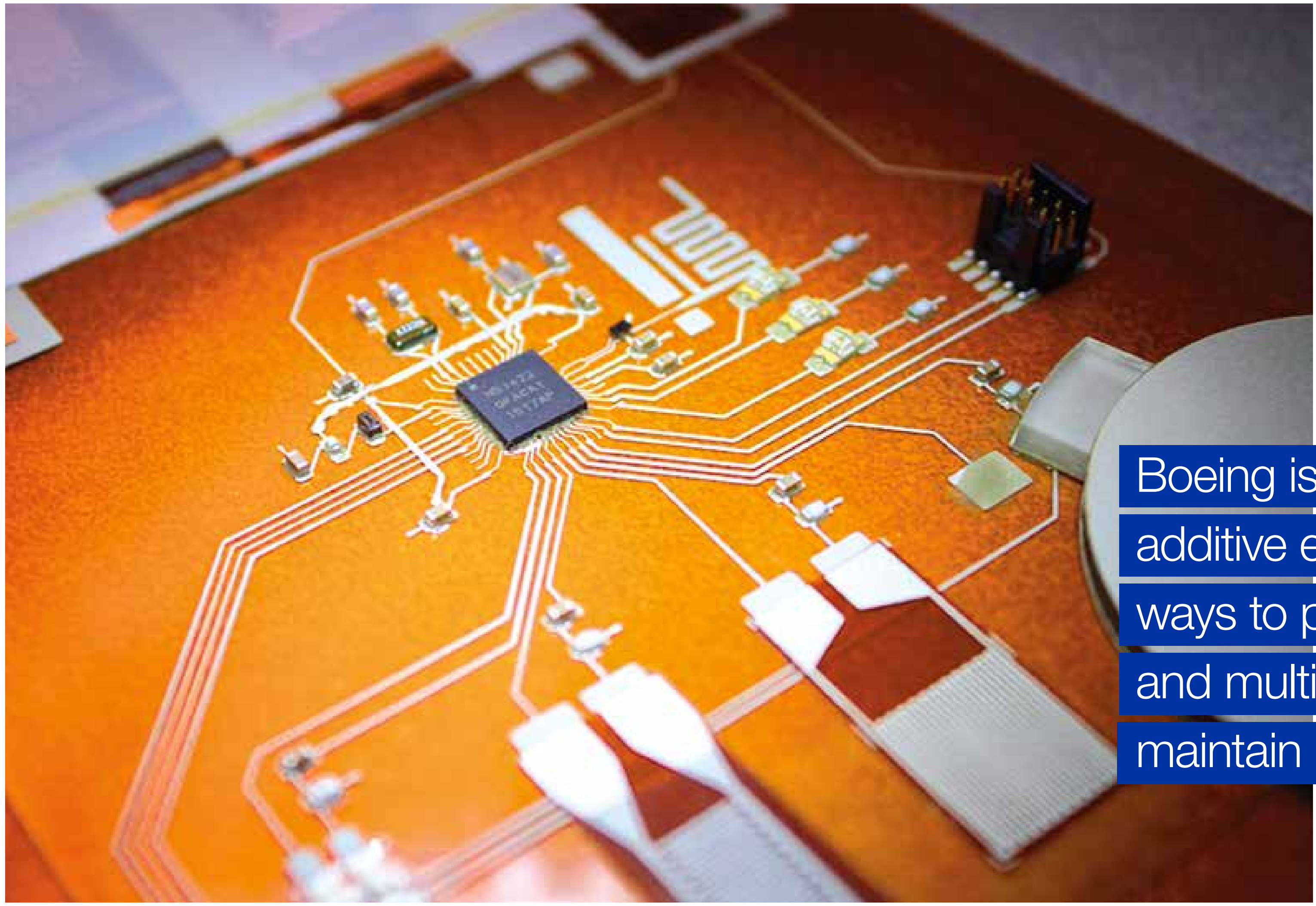


FIGURE 1.
The first printed sensor system with on-board power and wireless interface is now in development. The condition monitoring sensor array prototype, shown here, combines a microcontroller, battery, Bluetooth data link and four sensors onto a single flex circuit. The Boeing team is working to combine these technologies into a 2x3-inch footprint and test them in a factory environment. This development effort has led to a number of small sensor maturation efforts for Boeing Commercial Airplanes, in which the team has programmed and tested sensors for UV monitoring and wing gap detection on the 777X product line.

Boeing is using flexible hybrid and additive electronics to develop new ways to produce antennas, sensors and multilayer circuit boards that maintain performance

What orb spiders can teach us **about 3D printing**

Researchers examine the Australian orb spider to toughen composite laminates using additive manufacturing.

BY CHRISTOPHER HOWE, ASSOCIATE TECHNICAL FELLOW, BOEING RESEARCH & TECHNOLOGY, AND
JUSTIN HICKS, PHD RESEARCHER, RMIT UNIVERSITY

Spider silk is known to be one of the toughest materials in nature because of the molecular arrangement of proteins. Spiders are able to readily fabricate lightweight webs that are durable, resilient and easily repaired.

Interestingly, these requirements are also common to aircraft materials and structures.

Developing advanced composite materials that enable higher-performance and lighter-weight aircraft structures is an enduring challenge for materials engineers. Current interlayer technology, used in resin-infused composite structures, is described as a continuous filament mat in random orientation, like fairy floss, with limitations on the minimum thread diameter and areal weight.

A spider does not fabricate a random pattern for its web, but rather a controlled structure at many scales, from the molecules to web architecture. The key features from spider web structural hierarchy can be translated into improved toughening interlayers for composite laminates.

We can now replicate the efficient controlled structure of webs made by Australian orb spiders and rapidly deposit web-like interlayers onto carbon fabrics. To enable this level of control for applying toughening interlayers in composites, Boeing and Australia's RMIT University researchers looked to additive manufacturing of thermoplastics to fabricate spider weblike interlayers. This level of control was based on different scales, including controlling the level of crystallinity, filament diameter and web patterns of 3D-printed polyamides.

The process flow for controlled fabrication of weblike interlayers on carbon reinforcement using 3D printing of polyamide includes design, coding and deposition. A reduced content of thermoplastic can be achieved when depositing the weblike interlayers, compared to current random mat interlayers. Each strand of the web interlayer, located between carbon fabric plies, contributes to stopping or catching cracks caused from impact damage to composite laminates.

Learnings from nature indicate that highly ordered thermoplastic interlaminar architectures provide greater toughening efficiency than less-ordered architectures. Results of this work showed weblike interlayers could be manufactured using fused filament fabrication of thermoplastics with excellent control of the areal weight, surface morphology, thread diameters, thread properties, mesh width and nodal intersections. These types of patterns are captured by a Boeing U.S. patent.

A further pending Boeing patent is based on the method of creating the fine silklike threads from the 3D-printing nozzle, based on a drop, draw and extrude method. This method enables controlled fabrication of continuous fine filament threads, akin to the spider.

The effective toughening of the web-inspired interlayers achieved a 40% reduction in damage area, for web areal weights less than 1.5 grams per square meter (gsm). Current random mat interlayers are 6 gsm, to achieve the same effective toughening. The crack path and direction were also controlled based on the location and geometry of the web filaments.

This bio-inspired study showed that new materials can be designed that are more effective at toughening composite laminates by controlling the content and arrangement of thermoplastic through use of 3D-printing technology.

We can think and act like spiders to engineer controlled structures for aircraft materials.

Spider silk is known to be one of the toughest materials in nature because of the molecular arrangement of proteins.

STRONG WEB
(Opposite and right) Golden orb spider, Nephila edulis, found in New South Wales, Australia

PHOTO: BOEING

Global Scale

Air traffic management modernization in India

Boeing and the Airports Authority of India recently agreed to create a 10-year road map to modernize air traffic management in the country. For the project, Boeing will analyze current technologies and processes to identify efficiency improvements via capacity-enhancing communications, navigation and surveillance capabilities that can be implemented while maintaining a practical and safe airspace system. The objective of the agreement is to support India's exponential civil aviation growth with safe and efficient aircraft operations, along with airport infrastructure improvements.

Flying on sustainable fuel from Seattle to Cairo

For the delivery of its fifth 787-9 Dreamliner, EGYPTAIR took advantage of a new Boeing program that offers the use of sustainable aviation biofuel for delivery flights. The 5,925 nautical mile (10,973 kilometer) trip flight from Seattle to Cairo represented the longest 787 delivery flight using sustainable fuel. Sustainable aviation fuels have been shown to reduce carbon dioxide emissions by up to 80%.

Additive in Australia

Boeing Aerostructures Australia has opened an Additive Manufacturing Innovation Cell in Melbourne. With access to 3D-drawing tuition and low-cost, do-it-yourself 3D-printing equipment for prototypes, the cell offers space and opportunity for employees to collaborate on how to apply additive manufacturing techniques to traditional manufacturing processes.

Out in the wild

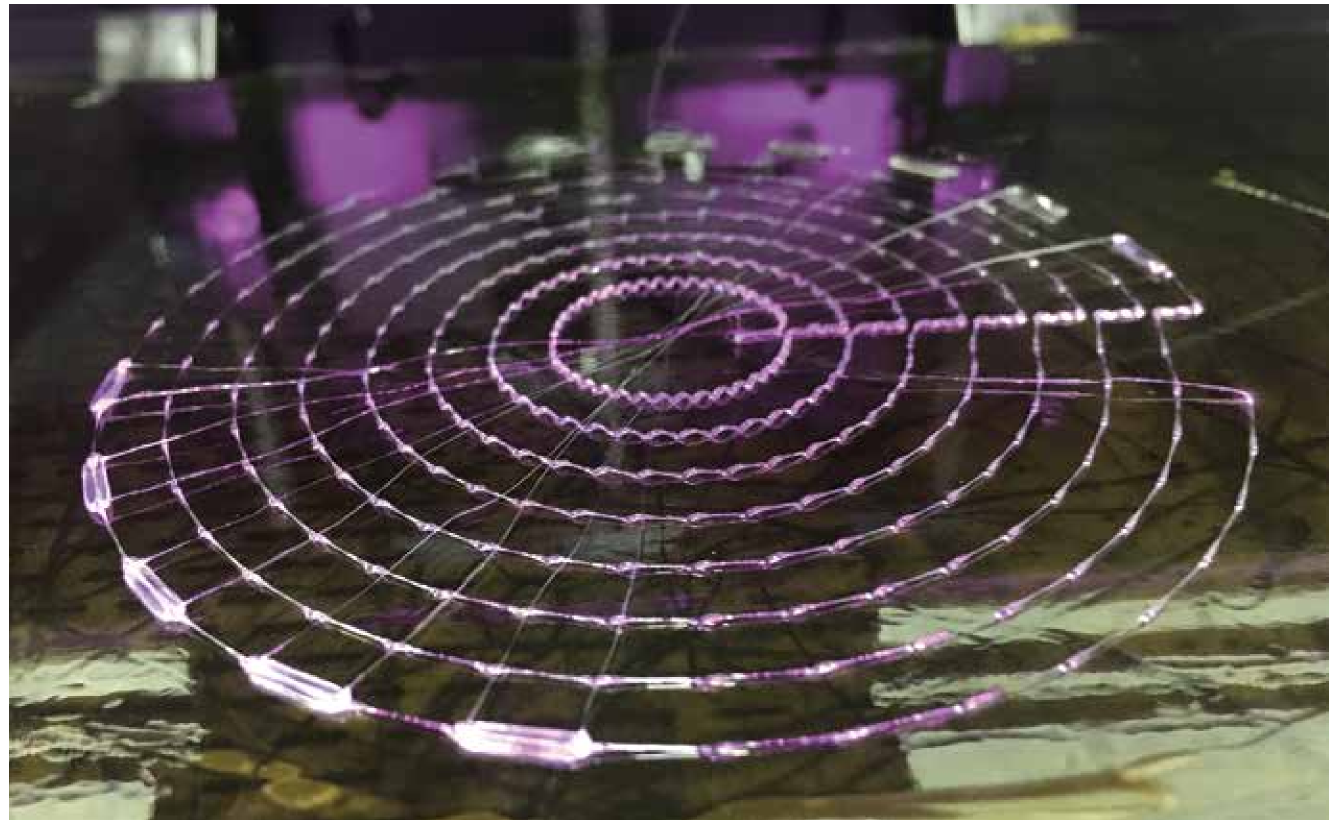
To understand why spider webs are effective structures, researchers from Boeing and RMIT University, along with Mary Whitehouse from Australia's Commonwealth Scientific and Industrial Research Organisation, visited the outback of New South Wales to study two spider species: Eriophora transmarina, commonly known as the garden orb spider, and Nephila edulis, the golden orb spider.

The nocturnal garden orb spider rapidly creates a new lightweight web every night to catch airborne insects. The silk is extremely fine and easily repaired when damaged. When dawn arrives, the spider digests the web and finds a secure hiding spot. This web is designed around speed with minimum effort required to catch prey.

The larger golden orb spider, however, spends more time creating a more robust web that lasts many days. The web contains stiff dragline threads that can span many meters, with finer silk acting as the radial threads for catching prey. The golden orb also creates a space-framelike shield, around the main web to protect against enemies.

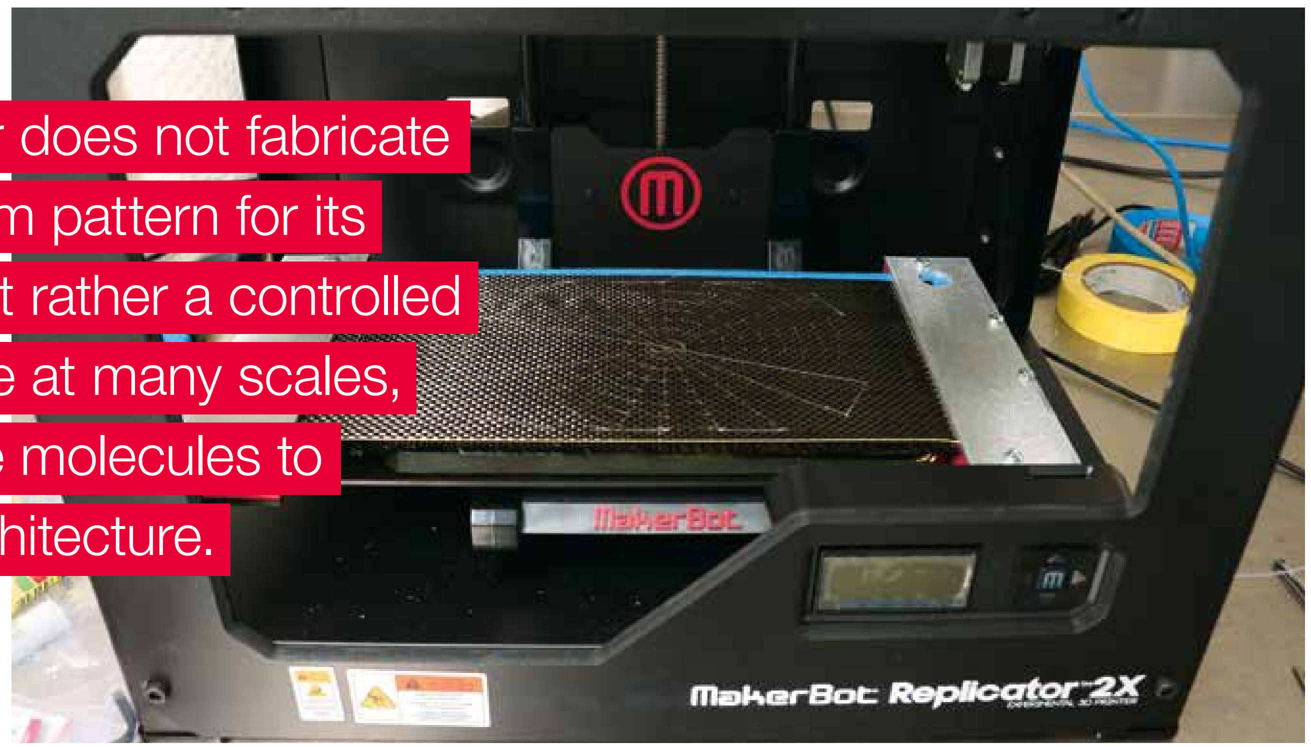
The orb spider can tailor the silk to be either flexible in order to serve as the catching net for prey or stiff for use as the supporting draglines. IQ

PHOTO: BOEING



DESIGN AT DIFFERENT SCALES
Shown here are spider-inspired nanostructures (lower right) and controlled fabrication of spider weblike interlayers on carbon reinforcement (below, on the bed of the machine, and above) using 3D printing on polyamide.

A spider does not fabricate a random pattern for its web, but rather a controlled structure at many scales, from the molecules to web architecture.



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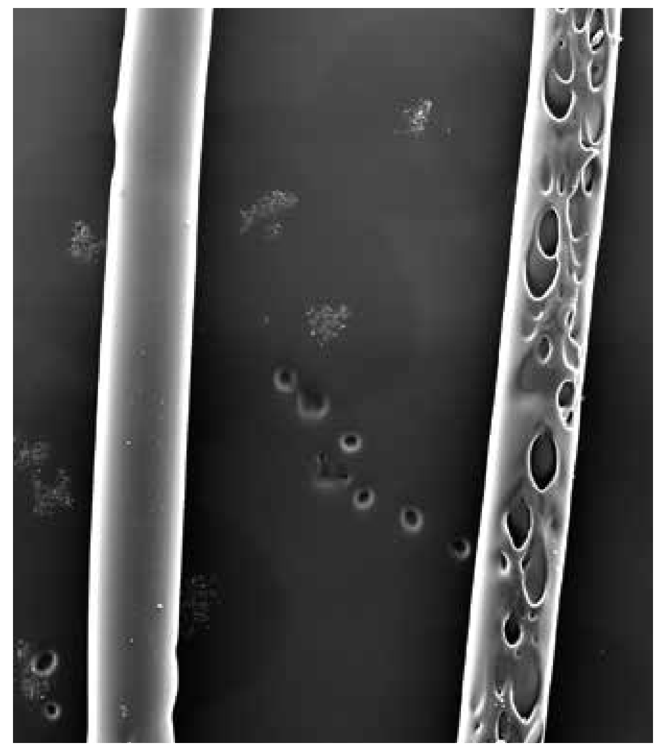


PHOTO: BOEING

BRIAN KLEIN
DIRECTOR,
IP PORTFOLIO
STRATEGY AND
DEVELOPMENT

Our inventions, **our future**

Protecting ideas is a critical complement to developing innovations.

Two short years after The Boeing Company was founded in 1916, employee James Foley patented a “Controlling Device for Aeroplanes” that allowed pilots to control the engine throttle with their foot while still controlling the rudder. While this technology seems rudimentary by today’s standards, the passion to innovate and make airplanes safe and high performing still resonates. Today, Boeing teammates invent breakthroughs daily that would amaze and delight Foley (after some explanation).

> Some 101 years after Foley’s patent, Boeing continues to expend time and money on protecting our intellectual property.

But why? To have more patents than our global competition? Because we like presenting invention plaques to our talented inventors? Because we have a long tradition of protecting our IP?

One important reason we protect our IP is to ensure that Boeing has the freedom to operate within the global aerospace industry. By publicly disclosing our technological innovations, we ensure that others cannot patent our technology first. If that were to happen, it would limit our ability to incorporate our own ingenuity into our products and services.

Beyond our ability to market our products and services, another goal of patenting Boeing technology is to ensure that others cannot copy our hard-earned technology and use it without our permission. While we appreciate the good work of others in our field, the incentive to innovate — to invest in research and development and improvements that benefit customers — depends on an investment return. And with the ease in sharing digital information, the loss of IP to others around the world is a common problem.

We all need to respect the intellectual property of others, in order to have ours respected in return. With this as a basis of the bargain, we patent our technology to ensure that our innovations find their way onto our products and services, rather than others.

Another key purpose of the Boeing invention process has nothing to do with patents. Rather, we hold the majority of our inventions and know-how as trade secrets. Retaining technology within Boeing — where it embodies the essence of how we design and produce our products — is vital. Our legacy of creating awe-inspiring products is supported by decades of techniques and knowledge passed between generations of Boeing engineers and scientists. Our team studies, challenges, tears down and rebuilds these techniques and knowledge as technology and thinking progresses. These critical, evolving trade secrets and their progeny define how we think and define our secret sauce.

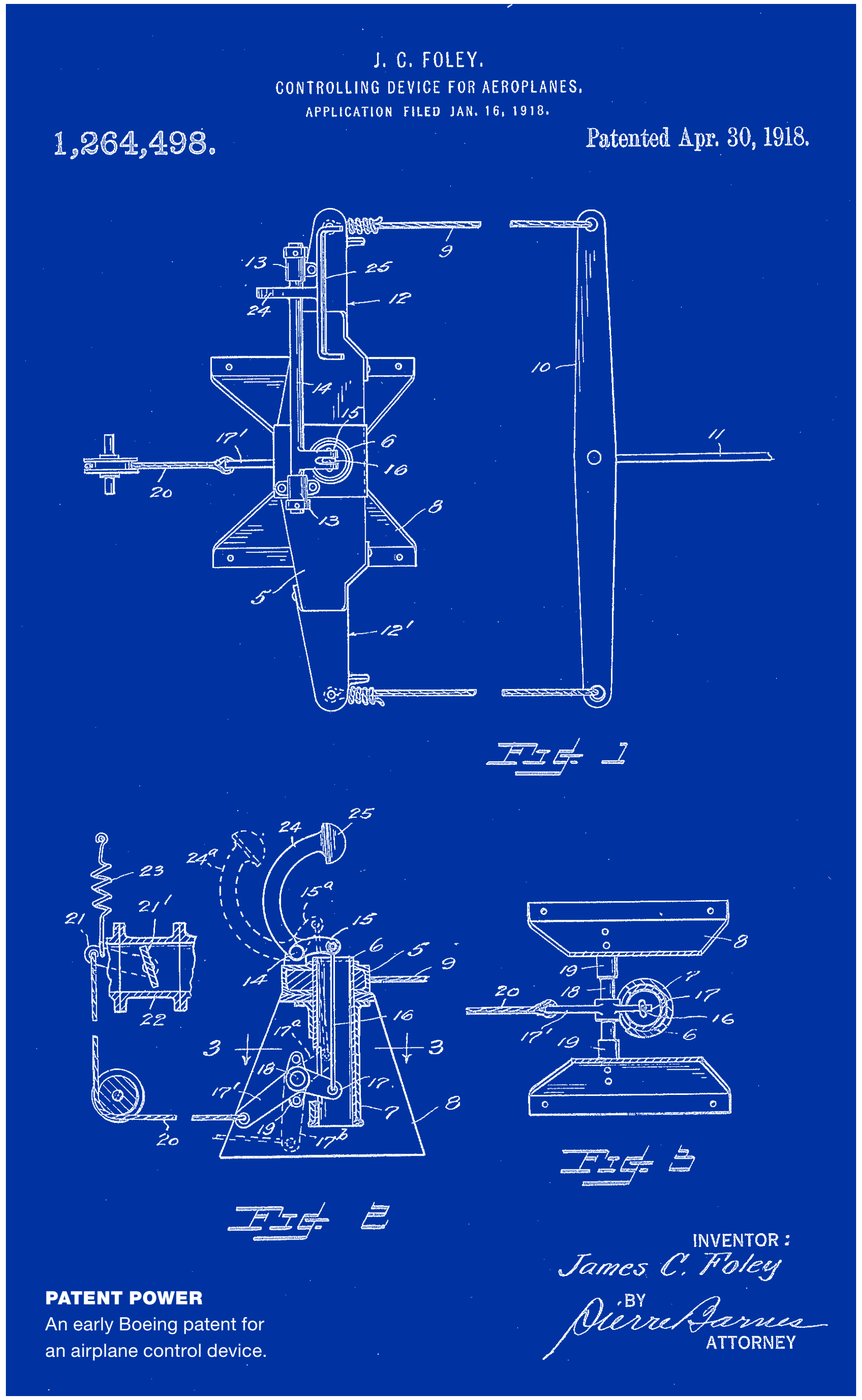
But patents and IP protection are not solely competitive in nature. Strong industrywide mutual benefits also result from the pursuit and protection of IP. Indeed, ensuring that ideas are widely shared, reviewed and improved upon by other sharp minds around the world supports a robust and advancing aerospace industry. Through this global competition for innovative, world-changing ideas, we all win — Boeing, our competitors and all of our customers — with more advanced and efficient products and services.

Most importantly, our innovations encourage and inspire the next generation of inventors, ensuring that we in aerospace can recruit and fill the talent pipeline with ingenious and interested people. When they see us doing innovative, amazing things — and respecting, valuing and protecting the ideas that drive them— those entrepreneurs and innovators will want to work here at Boeing and elsewhere in the aerospace industry.

Finally, sometimes protected technology is worth sharing. Maybe our team invents something that turns out to be of little use to Boeing but of great use to others, like suppliers. In other cases, allowing others to use our technology as part of a collaboration may advance the technology more quickly than we could alone. In those cases, a technology license provides a ready means to provide technology to another for use while Boeing benefits from a royalty, a license back of other technology or the speedy development of knowledge.

> Whatever the rationale, smart IP protection is developed on a case-by-case basis, tailoring the protection to the technology and the situation.

That, at any rate, has been the enduring legacy of Boeing’s technological innovation and IP protection — all while presenting stacks of patent plaques to Boeing innovators. IQ



PATENT POWER
An early Boeing patent for an airplane control device.

> “Most importantly, our innovations encourage and inspire the next generation of inventors.”
>
> **BRIAN KLEIN**

Additive manufacturing insight

3D printing matures for tooling.

BY ADAM BRODA,
SENIOR PRODUCTION ENGINEERING MANAGER,
BOEING ADDITIVE MANUFACTURING

PHOTO: MARIAN LOCKHART

Today more than 70,000 3D-printed production parts fly on Boeing's commercial and defense programs.

GROWING TECHNOLOGY
Adam Broda is based at Boeing's Auburn, Washington, production facility, a key company site for additive manufacturing.

While additive manufacturing (AM) may still feel like an experimental technology, it has matured far beyond the adolescent state of desktop 3D printers and plastic filament. In fact, today more than 70,000 3D-printed production parts fly through Boeing commercial and defense programs. The technology is evolving from research and development projects and low-cost tooling to printing high volumes of high-value metallic components and large families of tools that require stress analysis.

What will it take for AM to further mature and become more viable in production systems and product life cycles? For this discussion, let's consider tooling and focus on scale, training and supply as key factors in the continuing maturation of AM.

Tooling at scale

Aerospace tooling can be as complicated and unique as "fly-away" parts, but the requirements to produce load-bearing tools can be far less rigorous. Parts that will fly on a plane may take several years of testing and certification to ensure safety and quality — and for that same reason, may have more rigidly defined processes for production.

With tooling, there is more freedom to create processes for design and fabrication. More latitude is provided to determine how long it should take to design and test new technologies, define tooling specifications and ultimately advance industry standards. For the last decade, several dedicated tooling teams throughout Boeing have worked to analyze and characterize cutting-edge materials, optimize new printing processes and explore new opportunity spaces for tooling design applications.

In what was once a very nonstandard field, the Boeing AM tooling community has created a methodology for developing tooling standards for a wide variety of materials and printing methods, such as high-temperature polymer materials and large-area printer qualification specifications. This methodology unifies and standardizes the ways different programs and business units apply AM and makes the process of leveraging the technology more accessible and efficient for everyone.

For example, an AM production center at the Boeing Interiors Responsibility Center (IRC) in Everett, Washington, was set up several years ago to explore large-area polymer printing systems and tooling applications. By 2020, there will be not only large-polymer production tooling in use at the IRC but also material standards for the types of plastic that they print with, as well as a qualification specification for the printer that defines and controls the quality of the products being produced. Because of this, standards structure teams throughout Boeing will leverage the experience and expertise of the additive tooling groups in the IRC and share their knowledge with other tool engineers throughout the company.

Such a model facilitates rapidly scaling the development and application of AM in the company, which is proven to be successful. In 2018, Boeing fabricated over 7,500 additive tools. That figure has already exceeded 14,000 this year.

Training

Boeing is training users to enable them with the tools they need to do more with 3D-printing technologies, but training is more than teaching people how to apply and design with AM. Additive, like all technologies, is ultimately about value creation: understanding when to use AM to help lower costs, shorten delivery times, reduce weight and assembly, and increase quality and part durability.

To fully capitalize on AM's potential opportunity, Boeing has created training courses and design guides to help designers, engineers and other users make these types of assessments. For example, in 2018 Boeing and the Massachusetts Institute of Technology launched an online certification course, led jointly by Boeing additive experts and MIT professors, to teach engineers how to take advantage of the potential benefits of AM. To date, more than 1,000 Boeing engineers have taken the course, as well as many more thousands of people outside Boeing.

Boeing also partnered with Washington State University on a pilot project earlier this year to provide an online AM course and hands-on learning opportunities to Boeing engineers. Shorter internal training modules have also been developed to provide targeted overviews about designing for AM, such as explaining when AM can best be leveraged to reduce cost and weight.

AM has evolved from a new technology used primarily for prototyping to a full-scale manufacturing tool in the design-for-life-cycle toolbox.

Supply

Another key to maturation will be turning cost and flow from a constraint to an advantage. As Boeing and other companies expand the capacity to produce additive production tools and parts for aerospace and other industrial applications, a corresponding supply-chain-at-scale is necessary.

With respect to both raw material purchasing and parts providers, a growing and competitive supply base of AM vendors can ultimately reduce the cost of AM fabrication while maintaining or improving quality and consistency of

IT ALL ADDS UP
Boeing additive manufacturing teammates (left to right) Leon C. Cheung, Adam Broda, Mike A. Johnson and Jasmine Trass.

PHOTO: MARIAN LOCKHART

> Additive is a highly dynamic industry with new startups and technologies making entrances frequently.

the production system — which will benefit the maturation of AM within industry as a whole.

Looking at additive from end to end, printing itself generally accounts for the lesser share of the total fabrication cost. As the implementation of AM has increased, Boeing has integrated raw material purchasing within its broader enterprise supply chain strategy. Consequently, cost reduction in materials such as titanium powder has been substantial.

Likewise, a growing number of qualified suppliers are beginning to create a viable AM supply base. It's one thing for a supplier to own a 3D printer capable of printing a tool; it's another to demonstrate that they can deliver at scale, meet rigorous aerospace specifications and tolerances, and execute with fixed and repeatable processes. Increasing industry standardization in the additive area is enabling a robust global supply chain to support the need for capable, qualified AM aerospace products.

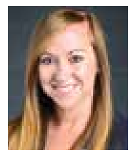
These are, of course, not the only areas that will mature as AM grows in practice and sophistication. Additive is a highly dynamic industry with new startups and technologies making entrances frequently. There also key challenges that still need to be solved in order for higher levels of advancement to occur. The speed of laser powder-bed metal printers, for example, continues to be a constraint, and the industry is focused on increasing the number of lasers, or layer thickness, within a machine to shorten printing time. Challenges and constraints aside, AM continues to grow rapidly, and Boeing's continued investment in the field is driving value-focused technology development and adoption. Value in the form of cost savings, time savings, design capabilities, quality and sustainability is enabling the transformation of production systems and changing the way we design and manufacture parts and tools. IQ

Selections from the **Boeing Technical Journal**

The Boeing Technical Journal is a peer-reviewed periodical for Boeing subject matter experts to capture and share 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

Using Statistical Process Control to Protect Allowables: A Standard Process for Qualifying Materials Suppliers



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Model-Based Trades Implementation Framework

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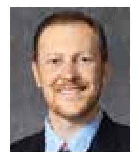

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Using Statistical Process Control to Protect Allowables: A Standard Process for Qualifying Materials Suppliers

Summary

BY KELSEA COX, LINDSAY JONES, R. MICHAEL LAWTON, FRODE STAVEHAUG

Qualification is required before Boeing accepts materials from a supplier. This qualification ensures that the material meets Boeing requirements in the form of criteria for statistical distributions of material properties. Often, these criteria include requirements for both central tendency and spread of the distribution. However, it is also common for these requirements to take the form of more complex distribution attributes. Specifically, A- and B-basis requirements, as defined in the MMPDS Handbook [1], are often used to ensure that no more than a specified percentage of the distribution will fall below a defined value. The A-basis requirement states that 99% of the distribution falls above a defined value with 95% confidence, and the B-basis requirements states that 90% of the distribution falls above a defined value with 95% confidence. These types of requirements are known as allowables because they allow only a pre-specified percentage of samples to fall below a given value.

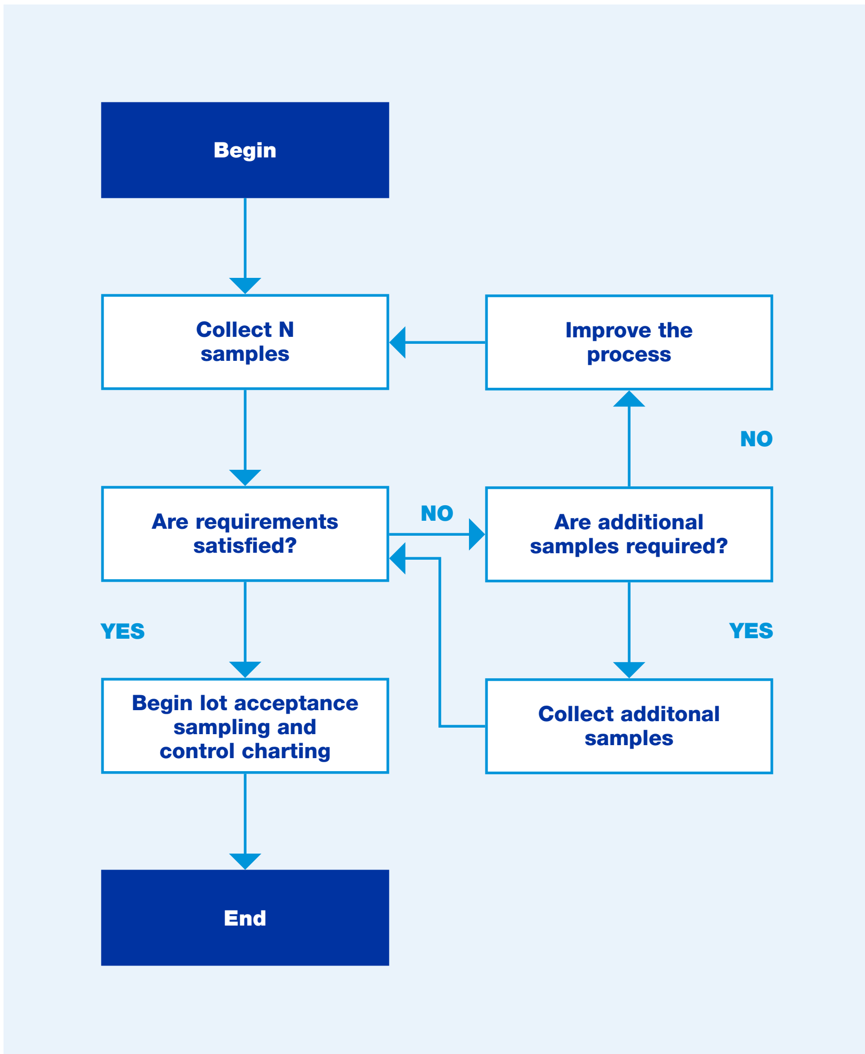

FIGURE 1.
Flow chart for SPC

To provide context for this effort, when a second source is introduced to produce an existing material, the new material must meet requirements defined by the primary source. Verification that the supplier meets these allowables requirements can be difficult and expensive, as narrow confidence intervals about quantiles require many samples. MMPDS provides guidance on how to qualify a second source; however, limitations of current methodology are well-known in the community.

Once the supplier is qualified, lot release testing is required for acceptance of the supplier materials. This process is very similar to statistical process control (SPC) found in industrial statistics and six sigma practices.

SPC traditionally begins with a requirement on the process capability index (Cpk) which provides a measure of the location and spread of the distribution with respect to specification limits. A high Cpk indicates low fallout rates. Figure 1 provides a detailed flow diagram of the SPC process.

This paper provides an explanation of how merging allowables methodologies with traditional SPC approaches can benefit the qualification process by enabling acceptable sources to qualify without sacrificing the integrity of published allowables. By framing the problem of supplier qualification in the language of SPC, we not only benefit from the sound theory of standard industrial statistics but also bring to bear the accompanying suite of monitoring methodologies. This paper describes the calculation of Cpk to qualify a second source material. Once a second source is qualified, traditional SPC principles can easily be implemented per standard textbook practices.

In order to assess performance of each of two legacy methods and the proposed SPC approach across a broad range of possible baseline and alternate material distributions, we carry out the previously described simulation process for every combination of the test conditions given in Table 1. In total, we evaluate test performance for over 150,000 test cases. In each test case, we simulate 10,000 samples from the alternate supplier and apply each of the three statistical methods, computing error rates for each method. From this collection of observed Type I error rates, we determine the maximum Type I error rate for each method and examine the distribution of Type I error rates across all test cases for each method. The true expected outcome for allowables verification Type I error should be less than 5% because allowables are defined as a 95% mathematical confidence bound about a quantile.

Across all test cases, the maximum Type I error rate for SPC method and the Legacy Approach 2 was never significantly greater than 5%, thus the Type I error rate is controlled in these tests and our published allowable is protected when we accept new suppliers. Legacy Approach 1, on the other hand, has a maximum Type I error rate close to 75%. This method fails to protect the allowable, and suppliers we accept using this method may not truly meet the requirement, which may lead to inappropriate design use and potential escapes. The SPC method and Legacy Approach 2 perform as expected for a statistical test claiming a 95% level of confidence. Legacy Approach 1, in contrast, exhibits many values above the expected Type I error rate, indicating that it violates the purported level of confidence. The fact that the SPC method performs as expected results from its foundation in sound statistical theory. In fact, the Legacy Approach 2 method simplifies to the

OVERALL PERFORMANCE

Variable	Low	High	Increment
Equivalence margin	0	2	1
Baseline Mean	70	80	2
Baseline SD	0.5	3	0.5
Baseline Sample Size	300	300	NA
Second Source Mean	66	80	0.5
Second Source SD	0.5	3	0.1
Second Source Sample Size	40	80	40

TABLE 1.
Simulation parameters vary for each simulated test case. This table describes the upper and lower bounds of the simulation input parameters as well as the increment used to describe all test cases evaluated.

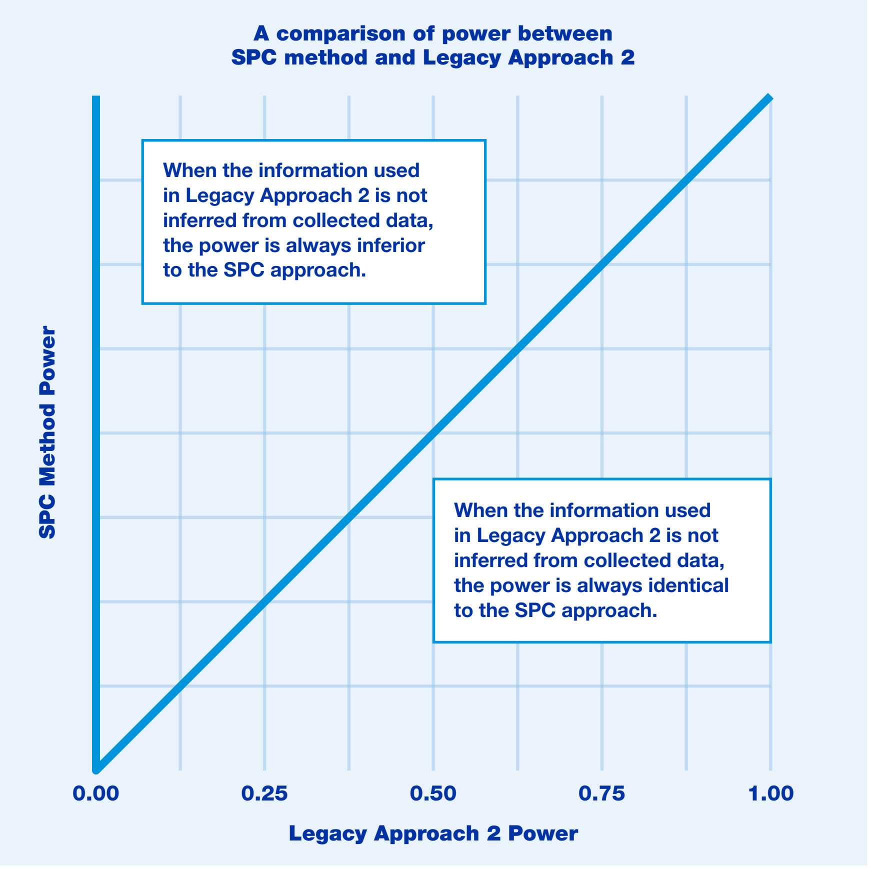

FIGURE 2.
A comparison of power for verification of B-basis for the Legacy Approach 2 method (on the x-axis) and the SPC method (on the y-axis). When Legacy Approach 2 uses statistics inferred from data, the power of the tests is the same, as shown by the wide range of values on the y = x line. However, when the Legacy Approach 2 method uses information not inferred from data, the power is zero when the SPC approach would provide additional probability of accepting an alternate material.

SPC approach when the information utilized in the approach is inferred from data collected. However, the power of Legacy Approach 2 decreases to zero when information is not inferred from the data. That is, due to the use of lookup tables in the implementation of Legacy Approach 2, under certain conditions, the test will not allow for acceptance of a second source supplier even if the performance of the second source is demonstrated to be far superior to that of the baseline supplier. This can be seen in Figure 2. Note that Type II error can only be fairly evaluated for methods with controlled Type I error. Because the Type I error rate was not controlled for Legacy Method 1, this method's Type II error rate was not assessed.

Type II Error Example

We provide an example in order to illustrate the mechanisms behind the performance comparison in terms of Type II error. In this example, an alternate second source material is simulated through draws from a normal distribution characterized by a known mean and standard deviation.

In this example, we examine the behavior of each method in a case for which we expect to accept the alternate material. We stipulate an alternate material following a normal distribution with a mean of 72.5 ksi and standard deviation of 0.5 ksi. The 10th percentile of this distribution is 71.9 ksi, and we specify a requirement of 72 ksi with a 1 ksi equivalence margin, meaning that the B-basis must be within 1 ksi of the requirement. Therefore, the alternate supplier meets the requirement, and we expect to accept the supplier given sufficient sample size. For this example, we consider sample sizes of 40 and 80, for which we expect B-basis values of approximately 72 ksi.

Acceptance rates from simulation for the three methods are shown in Table 2. Due to the use of lookup tables, Legacy Approach 2 never accepts the material for either of the examined sample sizes. Legacy Approach 1 only accepts the material 3.3% of the time for a sample size of 40 and 5.0% of the time for a sample size of 80. The SPC approach, on the other hand, accepts the material 100% of the time for sample sizes of both 40 and 80. While Type II error is not as severe as a Type I error in terms of risk avoidance, a high Type II error rate is indicative of increased cost. Although we did not consider overall Type II error rates for Legacy Method 1 in the previous section due to the method's uncontrolled Type I error rate, this example demonstrates that the method will perform poorly in terms of Type II error in specific test cases as well. Conclusions drawn from this example indicate that both Legacy Method 1 and Legacy Method 2 can inflate Type II error (increasing cost due to unnecessary material rejection).

Now that we understand the behaviors of each statistical method, we can assess the practical use for each approach. While Legacy Approach 2 is statistically sound for our use case (in the sense that it has a controlled Type I error rate), it imposes a more rigorous sampling plan and thus unnecessarily increases cost. The SPC approach, however, maintains an accepted Type I error rate while providing the lowest Type II error theory allows. For these reasons, the SPC approach is the most appropriate method for qualifying second source materials.

Conclusions

In this paper we have introduced and described a method for second-source supplier qualification using theoretically sound tools from SPC that are standard to industrial statistics. We conclude that this approach is superior to previously proposed methods for second-source qualification through simulation and analysis. Furthermore, this approach opens the door to the reconciliation of common practices such as lot acceptance sampling and the development of SPC control charts, an avenue to advancing and standardizing supplier quality control. By allowing application of these SPC methods to quality control of raw materials, we can enable process monitoring and early fault detection capabilities already appreciated by other high-throughput industrial applications.

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N	Legacy Approach 1	Legacy Approach 2	SPC Approach
40	3.3%	0.0%	100%
80	5.0%	0.0%	100%

TABLE 2.
Acceptance rates for Example 2 for sample sizes of 40 and 80 (based on 10,000 Monte Carlo simulations) indicate that the SPC approach accepts adequate material when the other methods reject the same material.

Qualification is required before Boeing accepts materials from a supplier. This qualification ensures that the material meets Boeing requirements in the form of criteria for statistical distributions of material properties.

To read and download the complete Boeing Technical Journal paper:

"Using Statistical Process Control to Protect Allowables: A Standard Process for Qualifying Materials Suppliers"

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

Model-Based Trades Implementation Framework

Summary

BY CLARK KINGSFORD, ASSOCIATE TECHNICAL FELLOW; JAMES M. MILSTEAD, ASSOCIATE TECHNICAL FELLOW; THERON E. RUFF, ASSOCIATE TECHNICAL FELLOW; ELISE R. HALEY; AND MAXWELL T. YAVARASKI

With the expansion of model-based engineering (MBE) capabilities in system development and design, a developmental program can establish a system architecture model (SAM) to readily manage system requirements, engineering information and design products. In an MBE framework, engineering artifacts are readily captured in a "digital thread" for more effective communication within the engineering team and among stakeholders during product development and for reference throughout the product life cycle. Trade studies are among these artifacts and are used to develop requirements, to choose between potential solutions that meet those requirements, and to help make decisions related to those solutions throughout a program's life cycle. Model-Based Trades Implementation Framework (MBTIF) represents a significant advancement in the conduct of trade studies in an integrated MBE environment.

Utilizing MBTIF, design engineers can easily conduct trades studies from within a SAM that captures other system design artifacts. In particular, MBTIF:

- Implements a uniform process for conducting trades.
- Streamlines trade study review and approval.
- Provides easy selection of requirements to be traded.
- Provides a standard set of evaluation criteria to select from.
- Facilitates use of a single source of truth in the trade studies and integrates trades and trade artifacts with other design artifacts.
- Applies a standard set of trade computations to all trades.
- Provides a persistent environment where trades are easily revisited.
- Captures trades data and results for the life of the program and beyond.

The main innovation of MBTIF is the highly integrated linkage of the trade input data in an MBE environment to the trade math engine through ModelCenter, as shown in Figure 1. This linkage of the data to the math engine is accomplished through a custom-developed analysis execution plug-in. There are existing solutions on the market that can integrate model-based systems engineering tools (such as Cameo) with analytical tools (such as Excel, Matlab, or ModelCenter) — Phoenix Integration's MBSEPak1 is an example. However, none of these solutions support the features necessary to address the multiplicity of trade study input or the ability to ingest diagrams and visualization (such as criteria-weighting sensitivity plots) necessary to help the trade study user fully capture and effectively convey the results in an MBE environment.

We implemented the Boeing nine-step trade study process in MBTIF, shown in Table 1.

A uniform process and a standard tool set for conducting design trade studies based on Analytical Hierarchy Process (AHP) 2 is implemented in MBTIF.

The user (typically a design engineer or design team conducting a trade study) is guided by MBTIF-embedded instructions to conduct the trade in an easy-to-use standards-based systems modeling language (SysML) layout diagram in Cameo, referred to as the MBTIF Dashboard. Figure 2 shows the Cameo Dashboard that serves as the interface for loading and viewing trade study data.

Each dashboard element links to a separate Cameo diagram used to enter trade data, execute computations or display trade data. Substeps are included in some cases in order to execute automated MBTIF functions.

After the user defines the trade study objectives, selects evaluation criteria and completes pairwise criteria comparison using MBTIF, the user invokes the math engine to calculate the criteria weighting based on the pairwise comparison inputs from within MBTIF.

In addition to the actual criteria weighting, the math engine returns a consistency ratio. The consistency ratio logic applies the transitive law (if A is greater than B and if B is greater than C, then A must be greater than C) to assess how consistent the design team has been in pairwise comparison of the criteria.

Number	Step in MBTIF
1	Define trade study objectives
2	Select applicable evaluation criteria
3	Assign weights to evaluation criteria
4	Define viable candidate solution alternatives
5	Present trade study plan to design decision authority
6	Score each candidate alternative
7	Perform sensitivity analysis of criteria weighting
8	Present trade study results to design decision authority
9	Prepare and issue trade study report

TABLE 1.
Trade study process steps

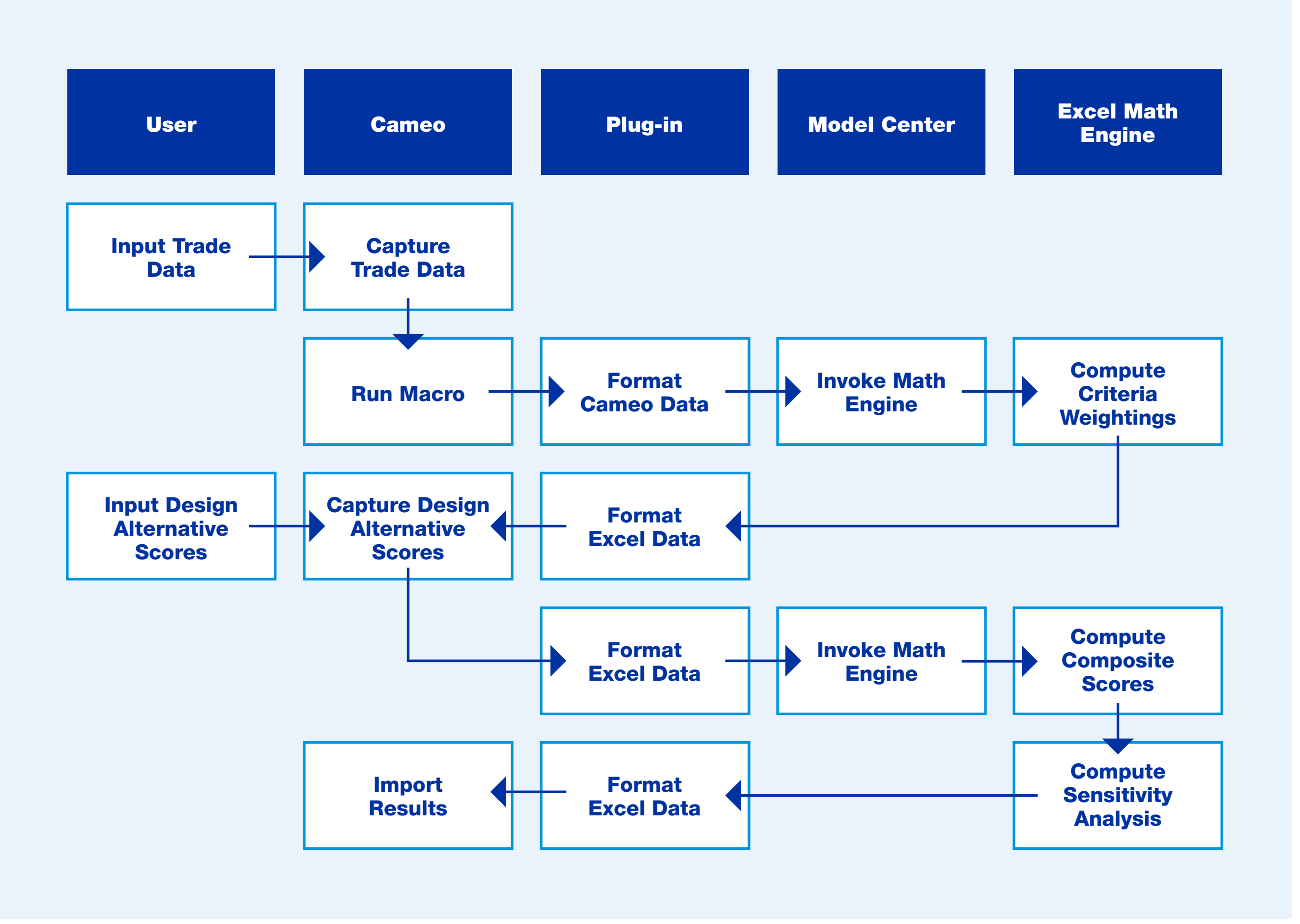


FIGURE 1.
MBTIF structure

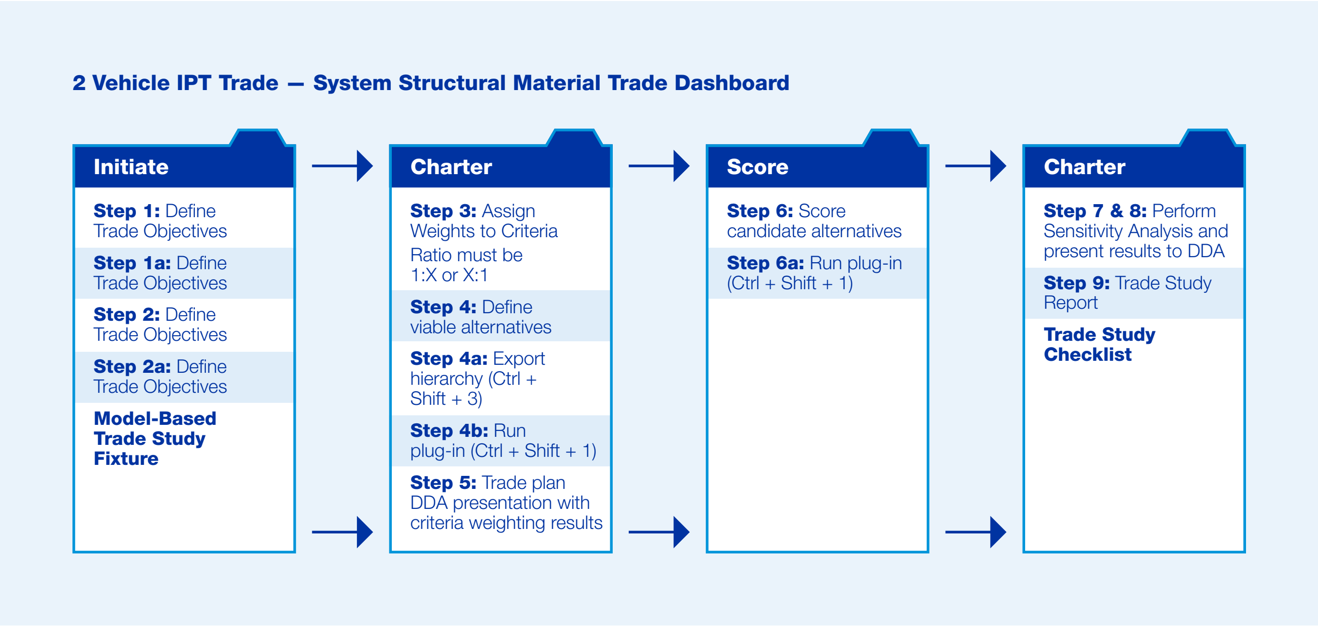


FIGURE 2.
Cameo MBTIF Dashboard

When scoring the trade alternatives, MBTIF supports three scoring methods:

1. Subjective scoring

2. Objective scoring

3. Combined scoring

The subjective scoring method, also referred to as the qualitative scoring method, is based on the subjective judgment of the trade study team.

An entire trade can be completed in MBTIF using only the subjective scoring method. This method can be particularly useful early in a developmental program, when design details have not be defined.

The objective scoring method can be used if all the evaluation criteria can be populated with raw data. In some cases, raw data is not available for one or more of the criteria for a given trade. In this case, MBTIF supports combined scoring logic. MBTIF automatically determines which scoring logic to apply based on the data entered into the scoring diagram, and the math engine then combines the raw data scores and the subjective scores to calculate the composite

SENSITIVITY ANALYSIS/TRADE STUDY RESULTS

Standard Scoring	Criteria					
	1	2	3	4	5	
	Schedule	Cost	Product Fielding Cost	Safety	Mass Properties	
Weight	4.11%	18.20%	13.16%	38.40%	26.13%	100.00%
Alternatives						**Final Scores**
Aluminum	0.60	0.44	0.45	0.20	0.20	**0.29**
Composite	0.20	0.20	0.37	0.20	0.47	**0.29**
Metallic Skin	0.20	0.36	0.18	0.60	0.33	**0.41**
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

FIGURE 3.
Design Alternative Scoring Results

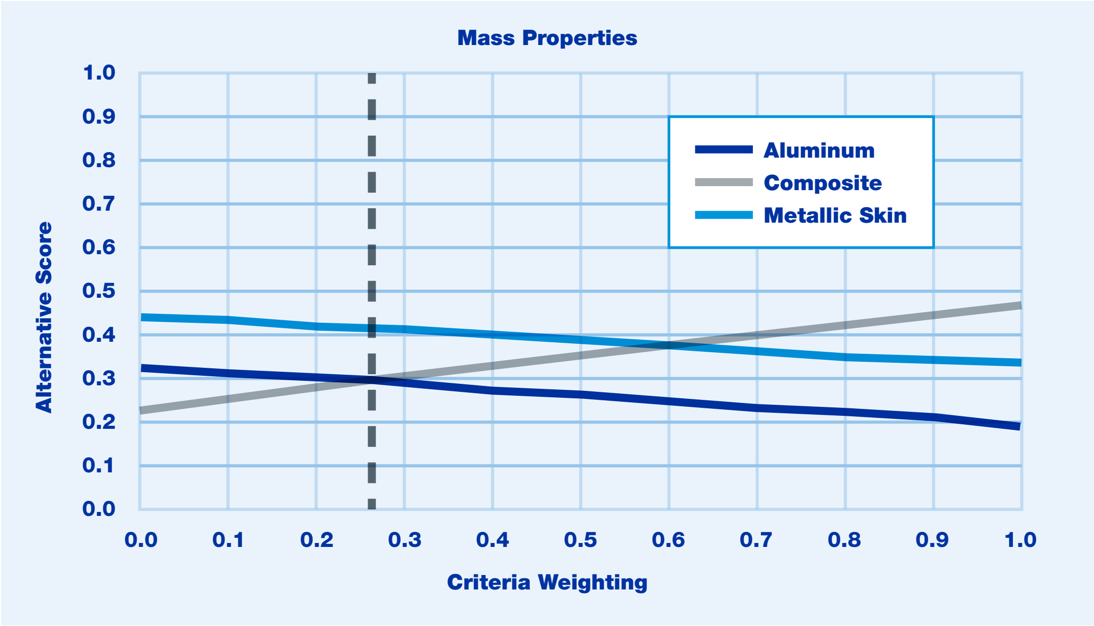


FIGURE 4.
Criteria-weighting sensitivity analysis curve example

The implementation of a common trade study tool within a SAM promotes consistency in the way trade studies are conducted and use of the most current system data in trade studies. A single source of truth for requirements, evaluation criteria definition, and supporting design data are powerful features of MBTIF. In addition, the linkage to analysis data and resulting baseline design models serve to improve the design data integrity and preserve trade study results for the life of the program.

scores for each design alternative. While combined data scoring retains some subjectivity, it is still a preferred method to the subjective scoring method when raw data for one or more criteria is available.

After the alternative scores are entered by the user, the math engine calculates the trade study composite scores for each alternative by criterion. Figure 3 shows the trade study results. The highest total (final) score indicates the "best" design alternative.

For cases where design alternative scoring results are close, it is important to examine the sensitivity analysis of the trade results. The analysis shows the impact of the criteria weightings on the outcome of the trade. The basic sensitivity analysis logic varies the weighting of the subject criterion across the range from 0.0 to 1.0 while the other criteria weighting is held constant. In this way, the trade team can see how much of a change in a given criterion weight would change the outcome of a trade. An example of a sensitivity analysis curve from the example trade is shown in Figure 4.

References

1. MBSEPak. https://www.phoenix-int.com/product/mbsepak/

2. Robert A. Smith, PhD, Boeing Technical Fellow. "Use of the Analytical Hierarchy Process (AHP) for Concept Definition and Trade Analysis." March 8, 2017.

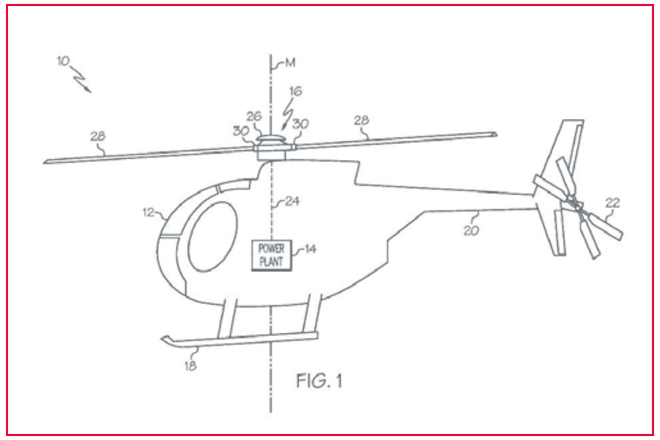
To read and download the complete Boeing Technical Journal paper:

"Model-Based Trades Implementation Framework (MBTIF)"

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

Patent **spotlight**

Check out a few of Boeing's latest ideas and technical breakthroughs recently granted or published by the U.S. Patent and Trademark Office.



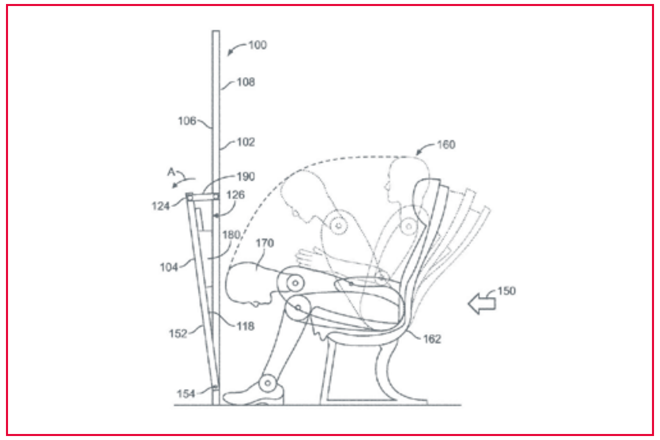
Rotorcraft and associated rotor blade position monitoring system and method

U.S. PATENT: 10,287,007
INVENTORS: JEFFREY M. THOMAS, DAVID ALDERETE, RICHARD COSTELLO

Rotorcraft, such as helicopters, use rotor blades to generate lift. To enhance control and stability, rotorcraft are often provided with articulatable rotor blades. Two common modes of articulation are "flapping" and "feathering." Flapping involves pivoting a rotor blade relative to the rotor hub about a horizontal flap axis. Feathering involves pitching a rotor blade relative to the rotor hub about a longitudinal feather axis.

When flight testing a rotorcraft, knowing the position of the flap angle and the feather angle of each rotor blade is important. Therefore, sensors were installed on the exterior surface of the rotor hub to collect rotor blade position data. However, installing such sensors requires unrepairable modifications (such as drilling and taping holes) to the rotor hub. Placing sensors on the exterior of the rotor hub also exposes the sensors to the elements, which requires frequent repairs and influences the quality of the positioning data. These effects can consume time and be expensive.

This recently issued Boeing patent describes a new design and system for monitoring the position of the rotor blades without requiring modification to the main rotor hub for installation. A sensor assembly is configured to sense angular displacement of a pitch housing (and associated rotor blade) relative to a rotor hub about a flap axis and/or angular displacement of the pitch house (and associated rotor blade) relative to the rotor hub about a feather axis. Its small size allows it to fit inside the rotor hub, thus protecting it from the elements and improving the quality of the data for these data points.



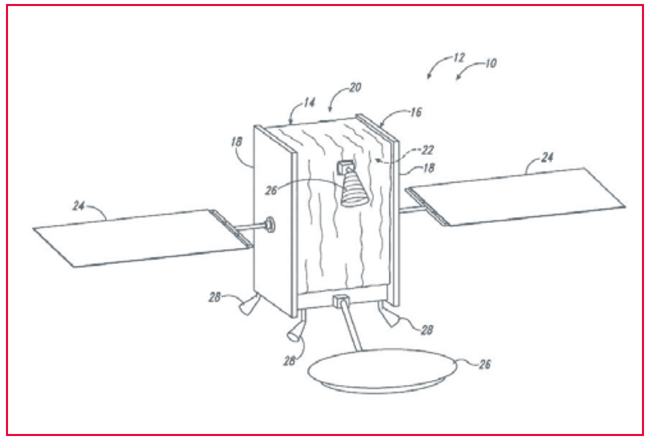
Deployable clearance panel system, method and assembly for a monument within an internal cabin of an aircraft

U.S. PATENT: 10,336,455
INVENTORS: DARREN CARL MCINTOSH, JEFF S. SIEGMETH

The interior cabin of an aircraft often includes certain monuments or walls of some sort positioned in front of a row of seats. The FAA requires a wall to be set apart a distance from a seat, defining a head-strike zone in certain circumstances. Cabin space is limited, and it is desirable to safely position one or more seats closer to a monument without compromising passenger safety or requiring extra safety devices.

This newly issued Boeing patent describes a potential solution: a system and method for a deployable clearance panel as part of a monument. The clearance panel is configured to move from a nondeployed state into a deployed state when a force that meets or exceeds a predetermined threshold is exerted into the monument. In other words, the clearance panel itself moves out of the way when subjected to certain loads in order to avoid a potential head strike. The clearance panel may also include one or more bracing members that prevent it from moving from the deployed state back to its nondeployed state.

This invention may provide improved safety aboard the aircraft; better space utilization within its internal cabin; and a lightweight, simple, cost-effective, aesthetically unobtrusive system and assembly.

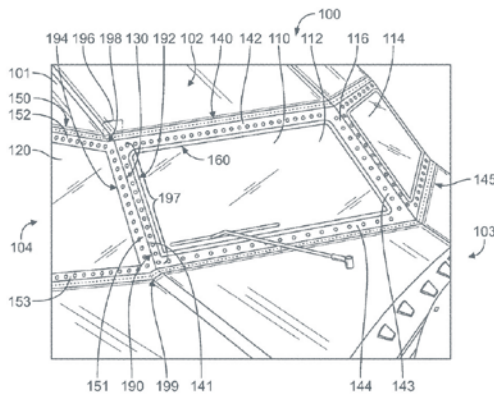


Spacecraft and spacecraft protective blankets

U.S. PATENT: 10,265,930
INVENTORS: RICHARD W. ASTON, ANNA MARIA TOMZYNSKA, ERIC S. MINDOCK

The significant expense of launching and maintaining a spacecraft directly correlates to the mass of the spacecraft. Once in orbit, a spacecraft is vulnerable to collisions with space debris, as well as to electromagnetic interference (EMI) to its payloads, which include electronic equipment. As such, a need exists to reduce the mass of spacecraft, while at the same time ensuring the spacecraft has adequate protection against damage by space debris and harm to its electronic equipment by EMI.

This recent Boeing patent describes a flexible, protective blanket to be attached to the body of a spacecraft. The blanket includes a number of sheets of material, at least one of which is composed of carbon nanotube material. The carbon nanotube sheets display ballistic protection and electromagnetic interference attenuation, two things that are critical functions of spacecraft shielding.



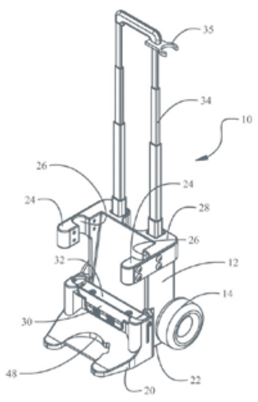
Apparatuses and methods for aerodynamic window assemblies

U.S. PATENT: 10,293,915
INVENTORS: RANDAL H. SMITH, PHILIPPE R. SPALART, STEPHEN T. LEDOUX, HUGH POLING, JERALD C. BAILLE

Window assemblies are used to surround or enclose the cockpit of an aircraft. Such structures, however, depending on their exact shape, can have issues related to flow separation. Flow separation creates turbulence and may increase noise, which can disturb the comfort and concentration of the pilot and flight crew. Moreover, flow separation may also increase drag, which may reduce aircraft performance.

This recent Boeing patent describes apparatuses and methods that both reduce flow separation and improve airflow around the window assemblies. The window assembly includes a windshield, a side window, a post between the windows and an airflow surface. The airflow surface is on the exterior of the windows and post and has a first radius of curvature proximate the leading edge and a second radius of curvature proximate the trailing edge, wherein the first radius of curvature is less than the second radius of curvature. The contour of the airflow surface reduces the peak Mach number and the shock-wave strength, thus significantly reducing flow separation.

Reducing flow separation reduces flight deck noise by weakening the pressure fluctuations on the side window, which improves pilot and crew comfort while potentially benefitting aircraft performance.



Ergonomic safety solution for orbital drills

U.S. PATENT: 10,308,266
INVENTOR: REBECCA COOK

Orbital drills for modern machining are massive and so heavy that their weight may exceed allowable standard ergonomic lifting weight requirements. Nonetheless, orbital drills must be moved regularly within a factory for use or maintenance requirements.

This newly issued Boeing patent describes a tool handcart for moving an orbital drill safely and efficiently. The cart is similar to a collapsible hand truck, in that it has a body with a pair of rotatable wheels on the lower rear edge of the body and a collapsible handle that retractably extends upward from the body. A pair of arms with vertically oriented channels extends from the front of the body and is configured with vertically oriented channels that correspond to receive the side members of a drill. The cart rests with stability on a base extending from a bottom surface of the cart.

When the handle is retracted into the body of the cart to a first position, it can receive the frame of an orbital drill vertically into its arm slots. When the handle is extended to second position, the body is configured to tilt from an upright standing position to a canted position, supporting the body by the pair of wheels and able to be rolled by pulling the handle.

Not only does this cart allow for the safe transport of orbital drills, but it can also be built to allow the drill to function while inside the cart. Ergonomic tools for movement of machining equipment such as this improve safety and help employees stay in compliance with companywide, as well as industrywide, ergonomic lifting limits.

A celebration of innovation

To be recognized for achievement in innovation at a forward-focused company like Boeing is quite an accomplishment. That's what makes the company's annual Boeing Innovation Awards so remarkable.

Boeing recognized its newest group of Innovation Awards honorees on Oct. 24 during a ceremony at the Museum of Flight in Seattle.

The Boeing Innovation Awards, the company's highest awards for technical achievement, feature two separate, complementary categories: the Special Invention Award, which recognizes technical innovations that create business value for Boeing and its customers; and the Technical Replication Award, which honors teams that have applied existing capability in new ways throughout Boeing, enabling business process or technology improvements.

PHOTO: MARIAN LOCKHART

VALUE OF INNOVATION
Boeing systems engineer Taiboo Song accepts a Special Invention Award on behalf of his team for their work enabling additional options or how airline customers can configure seating arrangements.

PHOTO: MARIAN LOCKHART

THE INVENTORS
2019 Boeing Innovation Award winners

PHOTO: MARIAN LOCKHART

COMMEMORATING GREAT IDEAS
The Museum of Flight in Seattle proved to be a perfect setting to celebrate Boeing's top innovators.

—CONGRATULATIONS TO THE—

2019 INNOVATION AWARD WINNERS

Special Invention Awards

- **Logistics Simulation Analysis Suite**
  Adrienne Miller, Steven Saylor
- **Methods and Apparatus to Perform Observer-Based Control of a Vehicle**
  Eugene Lavretsky, Kevin Wise
- **Additively Manufactured Heat Transfer Device**
  Richard Aston, Nicole Hastings, Matthew Herrmann, Michael Langmack, Sumit Purohit
- **Structural Pre-Cured Repair Patch for Repair to Highly Loaded Primary and Secondary Structural Components**
  Aydin Akdeniz, David Anderson, Blake Bertrand, Steven Blanchard, John Dardis II, Jeffrey L. Duce, Michael Evens, Joseph Hafenrichter, Arne Lewis, John Spalding
- **Seating Systems, Seating-System Kits and Methods of Configurating Seating Systems**
  Jun Chen, Sami Movsesian
- **System Architecture to Provide Folding Wingtip Functionality on Commercial Aircraft**
  Chad Douglas, Mark Gardner, Mark Good, Brian Hill, Jared Houten, Charles E. Jokisch, Kelly Jones, Terence Kenning, Mark W. Lesyna, George Moy, Michael Renzelmann, Paul Walker
- **Customer Aircraft Customization System**
  Lorene S. Paulette, Taiboo Song

Technical Replication Awards

- **BDS Aircraft Security Door Handling System**
  Nick Brimlow, Eddie Duarte, Kevin Irving, James T. Johnstone, Carrie Lin, Kirk March, Ryan O'Connor, Matthew L. Prendergast, Greg Swanson, Arthur E. Whitson Jr.
- **Production System Model-Based Systems Engineering**
  Joe Cabotaje, Navin Johnson, Hung Le Nguyen, John R. Palmer
- **Failure Reporting Analysis and Corrective Action System — Component Assessment Reliability Tracking System**
  Neil Berkowitz, Augustine Bravo, Molly Cuka, Julian Doan, Terry Greene, Charles Lofton, Vraj Patel, Arthur Pinto
- **ARINC 781 SwiftBroadband SATCOM Implementation**
  James Scott Coleman, Shahram Hariri, Ryan Mustoe, Greg Nelson, Huong Ngo, Vu Thanh Nguyen, Jon Rider, Reynaldo Ruiz, Glenn Torgerson, Dan Touchette
- **Unstructured Grid Generation**
  Andrew Cary, Mark S. Fisher, Joshua Krakos, Matthew Lakebrink, Brian Lambert, Pei Li, Todd Michal, Nic Moffitt

PHOTO: JOHN HARRINGTON

Spreading the word to change the world

PHOTO: BOEING

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From the top, left to right:

"ALL-IN" FOR DIVERSITY AND INCLUSION
Boeing team members celebrate and stand in support of the LGBTQ+ community at the Out & Equal Summit in Washington, D.C., in October.

THE FUTURE OF STEM
Boeing CEO Dennis Muilenburg and Boeing team members met students, early-career technologists and industry leaders at the Society of Asian Scientists and Engineers annual conference held in Pittsburgh in October.

PARTNERING FOR THE FUTURE
Naveed Hussain, vice president and general manager, Boeing Research & Technology, shakes hands with Dr. Yaping Zhang, vice president, Chinese Academy of Sciences (CAS), at a Memorandum of Understanding signing in Beijing. Boeing engineers and CAS scholars are partnering to research across a wide range of technologies over the coming years.

BRINGING FLIGHT CLOSER TO HOME
The experimental prototype Passenger Air Vehicle (PAV) was on display at the Paris Air Show in July. PAV will bring flight closer to home with fully autonomous flight from takeoff to landing, including dynamic route planning and the ability to detect and avoid unexpected obstacles in order to safely transform urban air mobility.

Carrier-based aerial refuelers, then and now

Refuelers on the flight deck

Shortly after World War II, Boeing heritage company North American Aviation began designing a carrier-based bomber to fulfill a request made by the U.S. Navy. The result was the AJ Savage.

The Savage entered service in 1949 and began operating on aircraft carriers the following year. A number of Savages were later converted into aerial tankers, serving with various U.S. Navy heavy-attack squadrons and even refueling John Glenn's Vought F8U-1P Crusader during his record-setting Project Bullet flight in 1956.

The future of naval refueling is unmanned — and Boeing and the U.S. Navy took a big step in September with the first test flight of the MQ-25. A carrier-based unmanned aerial refueler, the MQ-25 will allow for better use of the Navy's combat strike fighters by extending the range of deployed aircraft. MQ-25 will also seamlessly integrate with a carrier's catapult launch and recovery systems. The autonomous two-hour first flight was completed under the direction of Boeing test pilots operating from a ground control station at MidAmerica St. Louis Airport in Mascoutah, Illinois, where the Boeing T1 test asset is based.

The MQ-25 will carry on Boeing and its heritage companies' legacy of aerial refuelers and will become the Navy's first operational unmanned carrier aircraft. IQ

PHOTO: BOEING

AJ-2 Savage refueling an FJ-3 Fury, with an FJ-4 Fury in the foreground.

PHOTO: BOEING

MQ-25 lifts off on its first test flight.