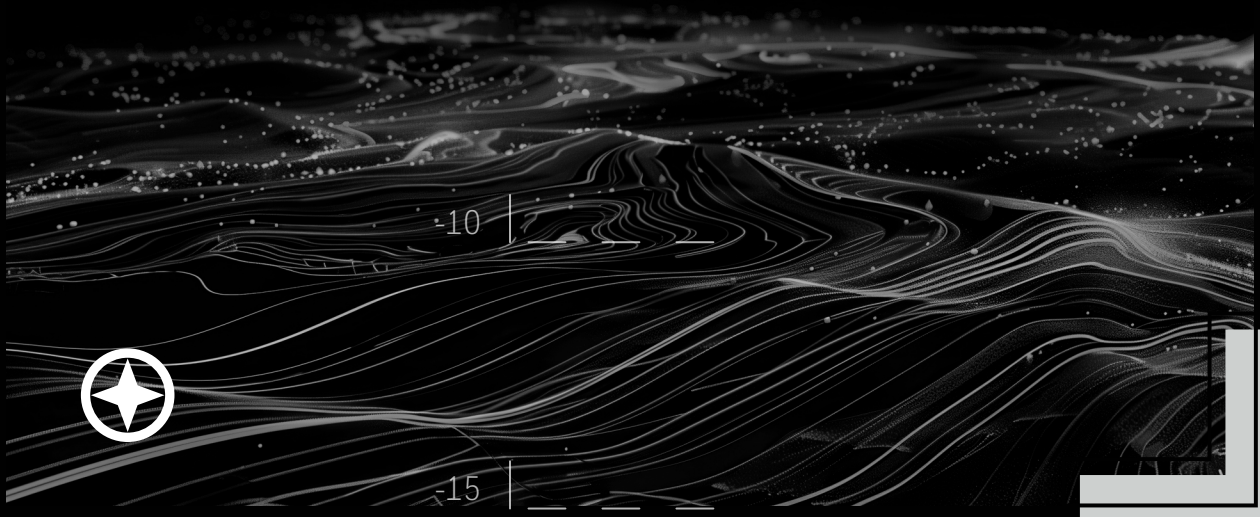


FUTURE OF AVIATION
NAVIGATION RESILIENCE



Modern navigation systems need to perform flawlessly even when global navigation satellite system signals are denied, deceived or degraded. Resilient navigation architectures fuse inertial, satellite and alternative inputs to let flight crews know where they are, where they're going and how they'll get there.

Honeywell
AEROSPACE


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TRUST FOR THE FUTURE: SHAPING THE NEW AGE OF NAVIGATION RESILIENCE

"Resilient navigation is knowing where you are and where you're going with a high degree of confidence, even when traditional navigation sources are disrupted. What we're finding is that there is no single 'silver bullet.' Resilient navigation systems are layered and multimodal, meaning they rely on complementary navigation sources working together rather than on any single technology acting alone."

Matt Picchetti Vice President, General Manager, Honeywell Aerospace Navigation & Sensors Enterprise

In the early days of aviation, pilots followed rivers, roadways, railroad tracks and other landmarks below to guide them from Point A to Point B. This approach had its drawbacks. In 1938, Douglas Corrigan filed a flight plan from New York to California, but landed in Ireland instead, earning the nickname "Wrong Way" Corrigan.[1]

Pilotage and dead reckoning soon gave way to radio beacons, which enabled pilots to fly beyond visual landmarks and in more challenging conditions, and to spinning-iron gyrocompasses, pioneered by one of Honeywell Aerospace's founding fathers, Elmer Sperry.[2]

Navigation has evolved from intuition to instrumentation to intelligent fusion over 12 decades. This progression has been marked by advancements such as solid-state inertial navigation systems (INS) in the 1950s and '60s, global navigation satellite systems (GNSS) in the '90s, and the latest innovations in multimodal navigation, which fuse INS with GNSS or alternative navigation technologies.




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MAKING THE CASE FOR MULTIMODAL NAVIGATION

"INS provides the independent, physics-based source of truth needed in navigation," said Simon Innocent, Senior Director of Offering Management for the Honeywell Aerospace navigation business. "It provides continuous, self-contained position, velocity and attitude information independent of external signals like GNSS."

But inertial systems drift over time, which is why INS needs a secondary source of absolute reference to bound errors and maintain accuracy over time and distance. GNSS usually provides that secondary source of data. By blending satellite updates with inertial measurements, the system can continuously bound accumulated errors and deliver stable, trusted position, navigation and timing (PNT).

However, GNSS signals are vulnerable to intentional disruption through "jamming," which blocks legitimate signals, and "spoofing," which introduces counterfeit data to the navigation system.



SEEKING SOLUTIONS FOR JAMMING AND SPOOFING

"Modern military conflicts demonstrate how contested the electromagnetic and navigation environment is today," said Mike Vallillo, Vice President of International Defense for Honeywell Aerospace.

"The war between Russia and Ukraine has shown just how vulnerable navigation has become," Vallillo said. "As drones and unmanned systems are used more and more, adversaries are finding ways to jam or spoof their navigation systems. That's why having backup systems and alternative navigation methods is becoming absolutely critical."

Crewed and uncrewed military flights are the usual targets of jamming and spoofing attempts, especially in contested regions. But GNSS interference can degrade navigation systems for any aircraft within range.

Case in point: In August 2025, an aircraft carrying European Commission President Ursula von der Leyen experienced satellite signal disruption during approach to Plovdiv, Bulgaria, forcing the crew to revert to paper charts and ground-based navigation aids to land safely.[3]

Jamming and spoofing incidents occur more than 1,500 times a day worldwide,[4] directly affecting the safety, mission effectiveness and operational efficiency of military and civil operations.

EXPANDING BEYOND SINGLE-SOURCE RELIANCE

Despite these challenges, the aviation community isn't abandoning satellite-based navigation. But the industry is expanding beyond GNSS by increasing reliance on alternative navigation modalities such as vision-aided navigation, magnetic anomaly–aided navigation and low Earth orbit (LEO) satellite aiding, along with breakthroughs like quantum navigation.

"The core questions of 'Where am I?' 'Where am I going?' and 'How do I get there safely?' don't change," said Julie Heck, General Manager for Navigation and Sensors at Honeywell Aerospace. "But technologies and system architectures will evolve significantly over the next 5-10 years as navigation systems become more modular, open and adaptable.

"The importance of resilient navigation will only continue to grow as threats become more severe and advances in artificial intelligence, autonomy and sensor fusion accelerate," Heck added.

IN THIS WHITEPAPER

Honeywell Aerospace examines the shift toward resilient, multi-layered navigation architectures. We cover the evolving threat landscape, the technologies behind layered sensing and intelligent fusion, and the groundbreaking work our navigation and sensing teams are doing to shape the future of resilient navigation.



INERTIAL SYSTEMS: SETTING RESILIENT NAVIGATION'S CORNERSTONE

Modern inertial navigation systems trace their roots to early gyroscopic navigation innovations pioneered by Honeywell Aerospace legacy company Sperry Gyroscope more than 115 years ago.[5] Technology has evolved considerably since then, but the fundamental physics behind inertial navigation still apply.

An INS determines position, velocity and attitude using gyroscopes to measure rotation and accelerometers to measure motion. Starting from a known location, the self-contained INS continuously integrates these measurements to calculate where the aircraft or other vehicle is, in which direction it's moving and how fast it's going. All this is achieved without the need for external data.

The bulky mechanical gyros of an earlier age have given way to modern solid-state ring-laser, fiber-optic and microelectromechanical system (MEMS) gyroscopes. These sensors are smaller, lighter, more efficient and scalable, enabling precise positioning and motion sensing for aircraft, missiles, spacecraft, naval vessels, autonomous vehicles and uncrewed aerial systems of every size and shape

Over time, an INS will experience small errors that accumulate and cause "drift." This is why an INS must be paired with an external aid such as GNSS or an alternative sensor to correct errors and maintain long-term accuracy. Intelligent sensor fusion blends multiple inputs in real time to deliver trusted results even in degraded or contested environments where GNSS is unavailable or unreliable.

"No single sensor can be trusted alone in all conditions," said Andrea Pizzarulli, CEO of the Honeywell Aerospace Civitanavi Systems business. "Robustness comes from tightly integrating inertial sensors with diverse sensing technologies so that each sensor supports the others to create complementary failure modes. This makes navigation systems more reliable and adaptable across environments where individual sensors may intermittently fail or degrade."

"Inertial systems are inherently more resilient because they are based on physics rather than external signals, which means they can't be 'tricked' in the way that GNSS or other radio-frequency technologies can. This built-in resilience comes with a known limitation. INS drifts over time, so it must be intelligently aided by alternative sensors to achieve navigation resilience."

Ann Witt
Senior Director
Business Development
Honeywell Aerospace
Advanced Programs




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INTELLIGENT SENSOR FUSION: DELIVERING TRUSTWORTHY PNT



Intelligent sensor fusion is the fulcrum of resilient navigation because it seamlessly blends and cross-validates multiple sources of position, navigation and timing (PNT). The INS uses sophisticated algorithms to assess and sort GNSS signals and other available inputs in real time to produce a single trusted PNT estimate. The result is a navigation architecture that is more reliable, accurate and resilient.

Ann Witt describes intelligent sensor fusion as "the ability to combine multiple navigation and timing sources into a single, coherent solution and use sophisticated algorithms to determine which can be trusted at a given moment. The INS lets us cross-check all aiding sources and dynamically assess and switch between them, so users have full confidence in their PNT at all times."

GLOBAL NAVIGATION SATELLITE SYSTEMS

GNSS is a key building block of resilient navigation, with systems like the United States' Global Positioning System (GPS) and the European Union's Galileo system providing highly accurate position and timing information – as long as satellite signals are available, authentic and free from interference.

Over the last three decades, GNSS has become the world's predominant navigation resource, guiding everything from modern jetliners and military platforms to the family car and scout troops on a hike. In fact, an estimated 10.2 billion GNSS-enabled devices are in use worldwide, with that number expected to grow to about 17 billion over the next five years.[6]

GNSS uses satellite signals to calculate precise position and timing by measuring how long it takes signals from multiple satellites to reach a receiver, then using that data to pinpoint an exact location on Earth.

"Satellite navigation is foundational to modern aviation because it delivers highly reliable, absolute position information anywhere on Earth," said Matt Picchetti. "This ability to provide a consistent, absolute position update regardless of environment makes GNSS extraordinarily valuable.

"Vulnerabilities such as jamming and spoofing reinforce the need for resilient, layered navigation architectures, but GNSS continues to set the benchmark for accuracy and global availability against which all other navigation modalities are measured," he concluded.

"Resilient navigation is really about layering aiding sources to create a solution that doesn't rely on any single sensor. We start with inertial navigation as the foundation, use GNSS when it's available and then layer in additional aiding sources to create resilience even when one input is degraded or unavailable."

Julie Heck
General Manager
Navigation and Sensors
Honeywell Aerospace

ALTERNATIVE NAVIGATION ARCHITECTURES

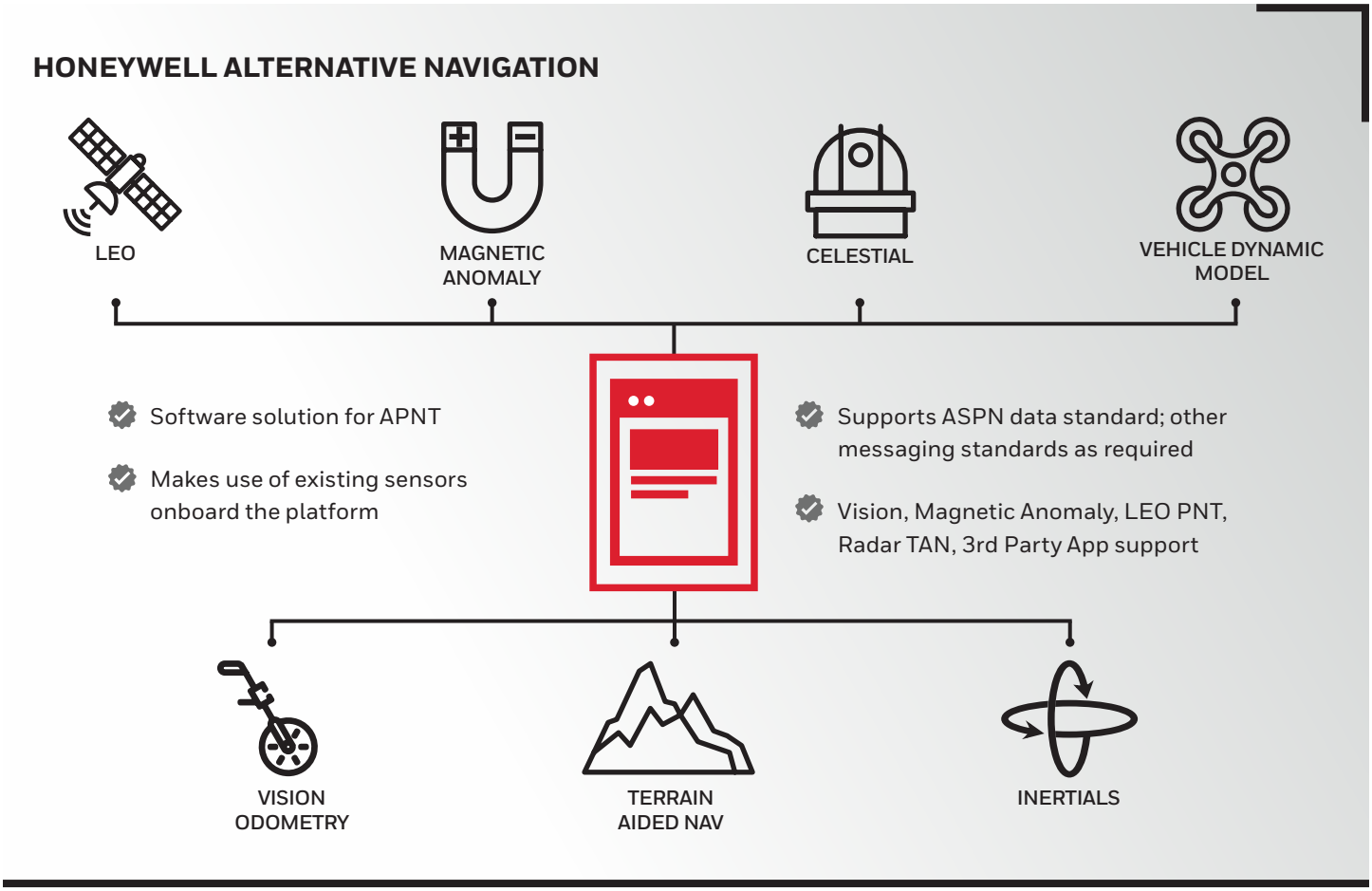


When satellite signals are fully denied or corrupted, additional aiding sources are needed to bound inertial drift and sustain long-duration accuracy, according to Ben Mohr, Offering Director for alternative navigation products at Honeywell Aerospace.

"There is value in having access to a variety of aiding sources because each modality has unique advantages and limitations," he said. "Our Honeywell Alternative Navigation Architecture (HANA) is an ever-expanding software framework that intelligently integrates inputs from several non-GNSS sources to determine position and velocity and correct drift errors, essentially playing the same role as GNSS."

Honeywell Aerospace's current focus is on vision-aided navigation (VAN), magnetic anomaly-aided navigation (MagNav) and LEO satellite navigation, but the company also continues to develop other potential HANA technologies. These include celestial navigation, which draws on the enduring constancy of the sun, moon, stars and planets to support assured positioning, navigation and timing (APNT). Vision odometry interprets motion by tracking how features shift across sequential images, while radar terrain-aided navigation (TAN) correlates observed terrain with digital maps to determine position and correct drift.

Together, these modalities reflect a fundamental shift from reliance on a single signal to a layered, resilient approach. HANA builds on this foundation by using a vehicle dynamic model to predict motion, validate sensor inputs and maintain accuracy when GNSS is degraded or unavailable. By intelligently fusing diverse sources, HANA delivers a trusted, all-source navigation solution designed for the realities of today's contested and congested environments.



VISION-AIDED NAVIGATION (VAN)

Vision-aided navigation uses onboard cameras, infrared sensors and thermal imagers to detect and track visual features on the ground, such as landmarks, structures and runways. The VAN software compares live images with stored maps and uses visual odometry to analyze sequential images.

What the cameras and sensors "see" can be tracked and compared frame by frame in real time to estimate motion, velocity, attitude and relative position. These inputs provide an independent source of precise navigation data to the INS when GNSS signals are unavailable or unreliable.

When fused with INS sensor data, the VAN inputs provide a passive source of position and timing that cannot be jammed. They can eliminate INS drift, enhance accuracy and support safer, more precise operations in complex and contested environments – making this approach particularly valuable for military operations.



MAGNETIC ANOMALY–AIDED NAVIGATION (MAGNAV)

Earth's crust contains naturally occurring magnetic signatures that vary by geography, creating a stable magnetic map that can be measured and compared against onboard reference data. Magnetic anomaly–aided navigation uses highly sensitive magnetometers to detect these subtle variations in the Earth's magnetic field to provide position updates independent of satellite signals.

When fused with an INS, magnetic aiding helps bound drift during extended GNSS outages, particularly over land or seabed regions with well-defined magnetic structures.

Because it is entirely passive and does not rely on external transmissions, MagNav is resistant to jamming and spoofing. While performance depends on the quality of magnetic maps and local field variability, it serves as a powerful complementary modality within a resilient, multi-layered navigation architecture.

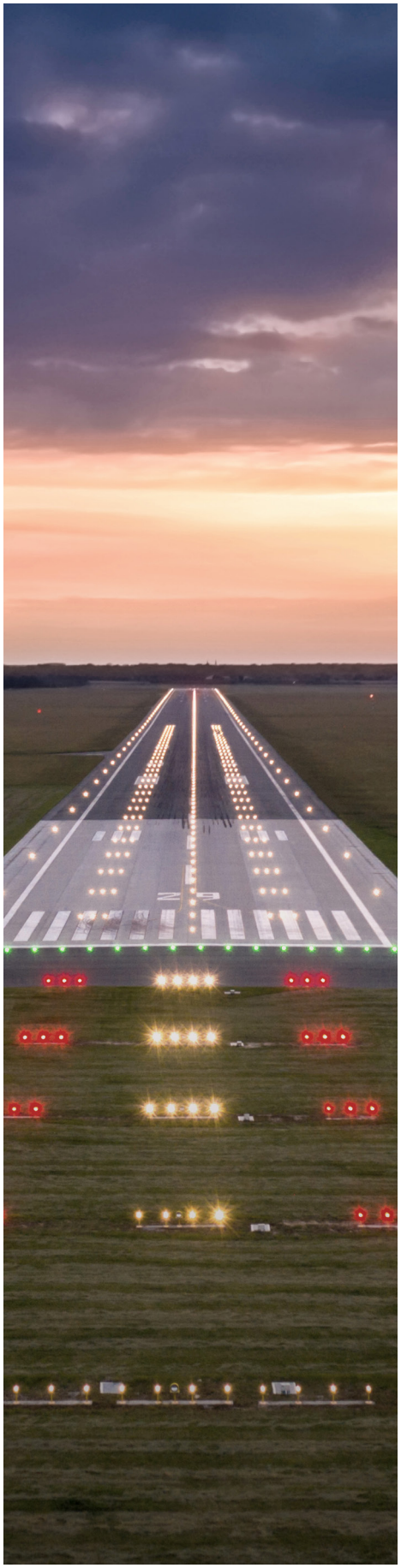


LOW EARTH ORBIT (LEO) SATELLITE NAVIGATION

LEO satellites are poised to become complementary sources of positioning and timing. Unlike today's GNSS satellites, which orbit at medium Earth orbit (MEO) altitudes of roughly 20,000 kilometers, LEO satellites operate much closer to Earth at altitudes of between 500 and 1,500 kilometers.

Because of this proximity, their signals arrive at the surface significantly stronger. That higher received power makes them inherently more resistant to jamming, since an interferer must generate substantially more energy to overpower the signal.

"LEO is not a replacement for existing navigation technologies," said Julie Heck. "It's an enabler of resilience, adding diversity and robustness to the overall navigation solution. While the LEO constellations are still evolving, they will no doubt provide us with another powerful signal to fuse into the navigation ecosystem."



VIEW OF THE FUTURE: QUANTUM-BASED NAVIGATION

Quantum sensing is becoming a foundational layer in the next generation of resilient, GNSS-independent navigation systems, according to Trevor Stephens, Senior R&D Manager for Honeywell Aerospace.

"Utilizing quantum sensors enables a breakthrough for resilient navigation because it allows us to leverage fundamental quantum properties of matter to provide an unprecedented level of stability, precision and trust," he said. "This allows us to deliver highly accurate navigation in GNSS-denied environments using intrinsic physical references that are inherently immune to jamming and spoofing.

Moving Quantum Beyond the Lab

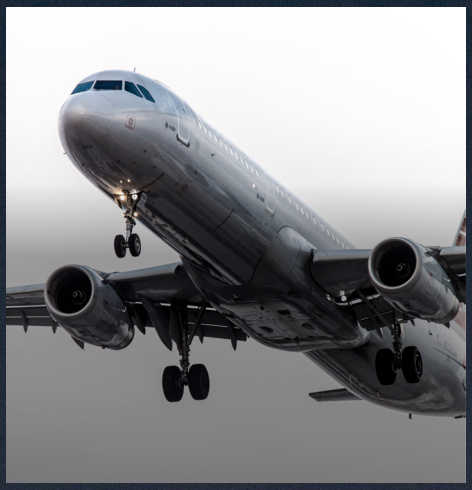
"At Honeywell Aerospace, we are moving this exciting technology beyond the laboratory and into real-world demonstrations on operational aircraft, including larger crewed platforms as well as smaller uncrewed systems," Stephens added. "We have successfully demonstrated quantum sensors in flight, and they have delivered highly resilient navigation performance in GNSS-denied environments."

According to Stephens, "Tight integration between teams of quantum sensor experts, navigation engineers and in-house flight operations lets us accelerate the development of quantum solutions and transition them to operational use faster."

He noted that Honeywell Aerospace is working with U.S. government researchers on quantum inertial measurement units and quantum magnetic anomaly–aided navigation.7

Quantum-based navigation represents a meaningful advance in inertial navigation systems for a wide range of potential applications, including aircraft, submarines and spacecraft operating in contested or signal-denied environments.

TRUSTED NAVIGATION MATTERS ACROSS MULTIPLE DOMAINS



Long before mechanical gyroscopes were installed on early airplanes, inertial navigation was at home on seagoing vessels. Gyroscopic instruments gave sailors reliable heading information independent of magnetic compasses or celestial fixes.

The reach of inertial technology expanded over the decades. In the 2020s, solid-state inertial navigation systems guide vehicles ranging from commercial airliners and military aircraft to ground combat vehicles, autonomous drones, naval vessels, submarines, precision munitions and spacecraft.

While the needs of each domain are unique, they all demand trusted, continuous navigation performance, especially when GNSS satellite signals are degraded, denied or unavailable.

COMMERCIAL AND BUSINESS AVIATION

In commercial air transport and business aviation, inertial navigation delivers continuous position, velocity and attitude data to pilots and onboard systems, independent of external signals.

Integrated with GNSS, flight management systems and air data computers, INS enables precise en route navigation, performance-based navigation procedures and accurate approaches in all weather conditions. At the core of these systems, inertial sensors also provide attitude and heading reference system (AHRS) functionality to primary flight displays and autopilot systems to ensure stable, controlled flight.

In business aviation, where aircraft often fly into smaller or more complex airports, high-integrity navigation is extremely important. Advanced inertial systems support smoother flight path control, improved situational awareness and reliable operation during temporary satellite signal disruptions.

When fused with weather radar, terrain awareness and traffic surveillance systems, INS and AHRS technologies contribute to safer, more efficient operations and help crews maintain confidence and precision from takeoff through landing.

ADVANCED AIR MOBILITY (AAM)

The coming age of advanced air mobility will introduce a new set of navigation challenges as urban air mobility (UAM) aircraft, autonomous delivery drones, and civilian and military unmanned aerial vehicles (UAVs) take to the skies we share.

"Resilient navigation is foundational to safety and operational confidence regardless of the AAM aircraft's purpose or mission," said Phil Robinson, Chief Technology Officer for critical unmanned systems and AAM at Honeywell Aerospace.

"Whether it is an electric vertical takeoff and landing (eVTOL) aircraft ferrying passengers through constrained urban corridors or an autonomous military UAV flying a mission beyond visual line of sight (BVLOS), AAM aircraft require resilient, high-integrity navigation to ensure precise positioning and safe separation," he continued. "That level of performance must be maintained whether or not GNSS signals are available to support mission success."

Size, weight and power (SWaP) come at a premium in the world of AAM aircraft, so Honeywell Aerospace has scaled inertial navigation capabilities to meet the specific needs of electric and highly autonomous platforms. Offerings include the HGuide family of inertial measurement units (IMUs), which delivers tactical-grade performance in the low-SWaP configuration AAM platforms require.

URBAN AIR MOBILITY (UAM)

Urban air mobility creates a new transportation layer in congested urban centers and underserved remote regions. This layer includes eVTOL aircraft designed to efficiently move people and cargo from Point A to Point B.

"UAM pilots rely heavily on visual cues when flying in urban environments," Robinson said. "But they still need blended navigation solutions that are really small, really lightweight and yet really capable to provide consistent, accurate PNT, especially during takeoff and landing operations at tight urban airports." As scale and autonomy increase, those compact, high-integrity systems will become foundational to maintaining safe separation, repeatable precision and passenger confidence in increasingly dense urban airspace.

UNMANNED AERIAL VEHICLES (UAV)

Unmanned aerial vehicles routinely operate beyond visual line of sight and into complex, congested and contested environments where trustworthy, uninterrupted navigation is vital. Layered and multimodal navigation can mean the difference between mission success and mission failure.

Resilient navigation enables everything from commercial inspection and cargo delivery missions to tactical ISR (intelligence, surveillance and reconnaissance) and precision engagement. But UAVs remain vulnerable to GNSS degradation from interference, multipath and deliberate jamming or spoofing.

"Military forces are relying more heavily than ever on uncrewed systems operating in contested environments where operators can't take reliable navigation for granted," said Mike Vallillo. "Conflicts like Russia-Ukraine have shown that jamming and spoofing are now routine, especially against drones operating beyond line of sight. That reality is driving an urgent need for resilient navigation systems designed to maintain accuracy, continuity and trust."



"Resilient navigation is foundational to safety and operational confidence regardless of the AAM aircraft's purpose or mission,"

Phil Robinson
Chief Technology Officer,
Critical Unmanned Systems and AAM
Honeywell Aerospace

MILITARY GROUND VEHICLES



Military operators depend on resilient navigation to maintain precise positioning, orientation and targeting capabilities for armored vehicles maneuvering across complex terrain and dynamic battlefield environments. Inertial systems provide continuous location and heading data independent of external signals, enabling accurate movement, stabilized sensor alignment and precise weapon pointing.

Mike Vallillo emphasizes that inertial navigation and other independent navigation methods are critical to success on today's battlefield, where adversaries routinely employ electronic warfare tactics to jam, spoof or otherwise disrupt satellite signals. "In modern warfare, resilient navigation isn't just about accuracy, it's about giving commanders and operators the positioning data they need to act quickly and decisively under pressure," he said.

Advanced ground navigation systems like the Honeywell Aerospace TALIN (Tactical Advanced Land Inertial Navigator) and Civitanavi PETRA provide military land vehicles with precise, self-contained positioning and pointing capability independent of external signals. Designed for harsh, high-dynamic environments, these inertial systems enable accurate maneuvering, stabilized sensor alignment and weapon targeting.

GUIDED AND LOITERING MUNITIONS

Guided and loitering munitions rely on INS to maintain precise trajectory control and stable maneuvering when GNSS is degraded or denied. By continuously measuring motion and updating position in real time, INS enables highly accurate targeting, ensuring munitions strike their intended targets with minimal deviation and reducing collateral damage.



CREWED AND UNCREWED SPACECRAFT

Whether supporting human spaceflight, planetary exploration or on-orbit science experiments, inertial technology ensures spacecraft know their orientation and motion with the accuracy required to accomplish complex missions in space.

GNSS does not exist in deep space or on planetary surfaces, so future travelers to the moon and Mars will rely on IMUs, star trackers, terrain-relative navigation and other onboard sensors to determine orientation and control trajectory. Inertial sensing is particularly critical during powered descent and landing phases, where real-time navigation performance directly affects mission success.

For satellites and scientific spacecraft, inertial sensors are critical to attitude determination and control. They help maintain precise pointing for communication antennas, Earth-observation instruments and space telescopes. High-precision inertial data allows platforms to stabilize imagery, align sensors with celestial targets and execute fine orbital adjustments.

Honeywell is providing key guidance and navigation components for NASA's Orion spacecraft fleet, which is supporting the Artemis lunar missions.[8]

SURFACE AND SUBSEA MARINE

Inertial navigation systems have a role to play on the high seas and beneath them. Surface vessels depend on precise heading, position and motion data to support safe navigation, collision avoidance, dynamic positioning and sensor stabilization. While GNSS is commonly used at sea, it remains vulnerable to interference and spoofing, making inertial systems an essential complementary layer to ensure continuous, trusted navigation.

Subsea operations present a different challenge because GNSS signals cannot penetrate seawater beyond a few centimeters, rendering satellite navigation unusable for submarines, autonomous underwater vehicles (AUVs) and offshore platforms operating below the surface.

In these environments, high-performance inertial navigation systems provide self-contained positioning, often augmented by Doppler velocity logs, acoustic positioning and pressure sensors to bound drift over time. Honeywell offers a full line of inertial solutions for marine surface ships, subsea vehicles and offshore applications that require reliable navigation independent of external signals.



WHAT HONEYWELL AEROSPACE BRINGS TO RESILIENT NAVIGATION

"The realities of today's operating environment shape our approach to navigation. Airspace is becoming more complex, AI and autonomy are expanding mission roles, and the RF environment is increasingly more contested. The objective is not to replace GNSS, but to augment it with complementary technologies that sustain reliable performance when GNSS is compromised."

Trevor Stephens Senior Research and Development Manager
Honeywell Aerospace, Navigation & Sensors Enterprise

In a world that increasingly relies on GNSS for navigation, Honeywell Aerospace is at the forefront of reinforcing satellite-based positioning with resilient, multi-layered navigation solutions that perform when signals are degraded, denied or unavailable.

"Honeywell Aerospace's strength lies not only in the unequaled quality and performance of our sensors, but in our unique ability to fuse inertial data with GNSS and alternative navigation sources in a practical and certifiable way," said Matt Picchetti. "We set the standard for blended inertial navigation solutions, which are proving their value at a time when GNSS signals are so vulnerable to jamming and spoofing."

Honeywell Aerospace is advancing a flexible, multimodal navigation architecture that incorporates a range of complementary technologies. These include an innovative portfolio of HANA technologies, including vision-aided navigation, magnetic anomaly-aided navigation and low Earth orbit satellite navigation. Each modality brings unique strengths and limitations, and Honeywell's expertise is in combining them intelligently and layering dissimilar technologies to validate position, manage drift and maintain operational confidence across environments.

Honeywell Aerospace's expertise in resilient navigation relies on a combination of outstanding engineering and research and development capabilities, a strong and motivated core of engineers and scientists, and a century-long legacy of innovation that traces back to the earliest days of aviation and the evolution of navigation and flight control.

That foundation is reinforced by dedicated navigation research centers in the United States and the Czech Republic, where teams focus specifically on advancing inertial sensing, alternative positioning technologies and intelligent sensor fusion. Coupled with deep systems-integration experience and a broad portfolio spanning inertial sensors, integrated navigation systems and emerging quantum technologies, Honeywell delivers mission-ready solutions built for real-world, high-consequence environments.


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FUTURE OF AVIATION NAVIGATION RESILIENCE

As the aerospace and defense industry moves toward greater automation and autonomy, Honeywell Aerospace's role in resilient navigation becomes even more critical. Honeywell Aerospace is actively preparing for current and future requirements, leveraging its breadth of sensor technologies and system-level integration expertise to enable resilient navigation today and into the future.

Honeywell Aerospace's resilient navigation solutions can support your platform or mission, contact a Honeywell Aerospace representative or visit our navigation website to explore our full portfolio of inertial, integrated and alternative positioning technologies.

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1 https://www.aahs-online.org/pubs/journals/files/644300.pdf

2 NIHF Inductee Elmer Sperry Invented the Gyroscopic Compass

3 EU chief von der Leyen's plane hit by suspected Russian GPS interference

4 Jamming and Spoofing of Civilian Airspace: Are the Days of GPS-Based Navigation Over – Insightful Geopolitics

5 https://boltflight.com/sperry-company-a-legacy-of-precision-and-innovation/

6 GNSS-Enabled Consumer Device XX CAGR Growth to Drive Market Size to XXX million by 2034

7 Honeywell Awarded U.S. Government Contracts to Develop Quantum Sensor-Based Navigation Systems

8 Honeywell Proudly Supports Nasa's Artemis I Launch and Orion Spacecraft with Key Technologies to Bring Humans to the Moon and Mars

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