WHITE PAPER

GNSS-Denied Navigation: Engineering Resilient Autonomy

The New Reality of Autonomous Navigation

Autonomous systems are no longer sitting at the edge of infrastructure, they're embedded within it.

Urban density, radio frequency (RF) congestion, canopy interference, indoor-outdoor transitions, and contested spectrum aren't edge cases anymore. They're everyday operating conditions.

The physics of inertial navigation hasn't changed. What has changed is the amount of uncertainty we can afford.

Global Navigation Satellite System (GNSS) degradation is now a design condition, not an anomaly. When satellite positioning fails, autonomy doesn't stop – it adapts, shifting from external reference to internal propagation. In that moment, inertial architecture determines everything.

Defence and security applications are increasingly driving this shift. Autonomous drones operating in contested environments must function even when satellite signals are degraded, denied, or intentionally disrupted. As a result, defence programmes are accelerating investment in resilient navigation architectures capable of maintaining positioning, navigation, and timing without continuous GNSS availability.

GNSS fades. Inertial navigation takes control

GNSS-Denied Is a Stress Test of Architecture

Most modern autonomous systems rely on tightly coupled GNSS/INS navigation architectures, where satellite updates, inertial propagation, and estimation filters operate as a unified system rather than independent components.

When GNSS is available, inertial drift is continuously corrected. When GNSS is interrupted, however, the inertial subsystem must temporarily sustain navigation on its own.

Drift is not a failure of inertial navigation. It is an inherent consequence of integrating sensor measurements over time.

The real engineering challenge is therefore not eliminating drift, but controlling its growth and ensuring predictable behavior during GNSS outages.

Navigation resilience depends on bias stability, thermal consistency, noise behaviour, timing integrity, and fusion robustness, all of which become observable when external corrections disappear.

The IMU: From Sensor to Structural Element

Within autonomy architectures, the IMU is often perceived as a component. In reality, it is foundational to overall system performance.

All Micro-Electro-Mechanical Systems (MEMS) inertial systems contain both deterministic and stochastic (random) error sources. Bias, scale factor variation, misalignment, and temperature sensitivity coexist with random walk and long-term instability. During nominal GNSS correction, these errors remain bounded. During GNSS interruption, they surface.

The resulting error cascade unfolds progressively:

- Gyroscope bias influences attitude
- Attitude deviation alters gravity projection
- Gravity projection affects velocity estimation
- Velocity error accumulates into position deviation

This progression is gradual but unavoidable.

Tactical-grade MEMS architectures enhance predictability not by changing sensor physics, but by deepening implementation.

These improvements typically involve:

- Deep multi-axis thermal calibration
- High-resolution compensation modelling
- Synchronised multi-IMU arrays
- Calibration-informed weighting
- Hardware-level timestamp alignment

The result is extended stability within realistic size, weight and power (SWaP) constraints.

The Consequence of N Seconds Without GNSS

GNSS outages must be understood in temporal context. Short interruptions of only a few seconds rarely destabilise well-designed inertial systems. Attitude remains stable and control loops continue to operate normally.

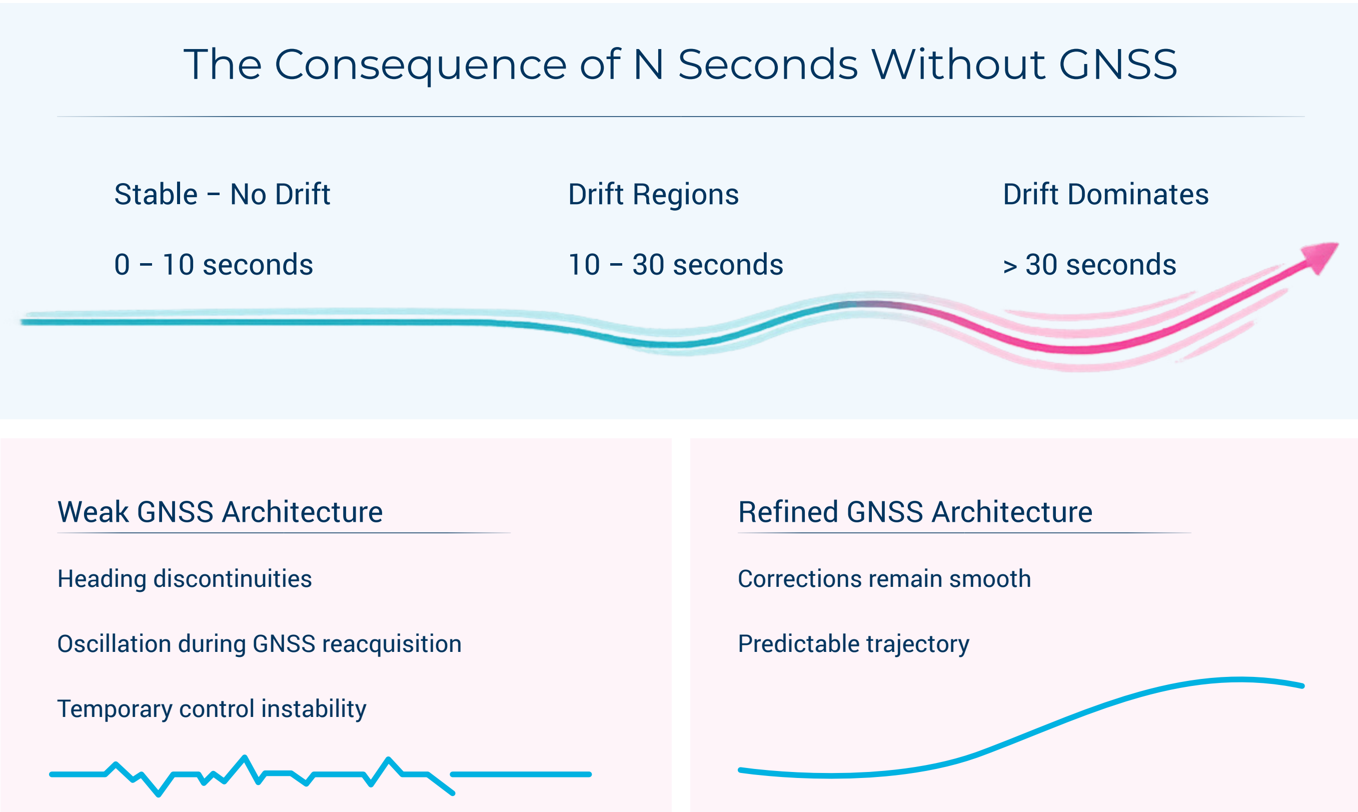
As interruption extends into tens of seconds, bias stability begins to influence behaviour. Velocity drift accumulates and position deviation becomes measurable.

Beyond thirty seconds, long-term bias characteristics dominate error growth.

In weaker inertial architectures, this phase may introduce:

- Heading discontinuities
- Oscillation during GNSS reacquisition
- Temporary control instability

In refined inertial architectures, corrections remain smooth and predictable. Outage duration alone does not determine the outcome. Drift growth rate does.



Impact of GNSS outages on inertial navigation performance, showing the transition from stable operation to drift-dominated behaviour over time

Timing: Precision Beyond Accuracy

Autonomous systems operate through continuous fusion of multiple sensors. Typical autonomy stacks combine:

- GNSS receivers
- Inertial sensors
- Cameras
- LiDAR (Light Detection and Ranging)
- Wheel odometry
- SLAM (Simultaneous Localisation and Mapping) algorithms

Temporal coherence is therefore critical.

Microsecond-level timestamp precision ensures that all sensors describe the same physical event.

Even millisecond misalignment can introduce measurable spatial distortion.

This requirement becomes particularly important in modern visual navigation architectures, where camera frames must remain precisely synchronised with inertial motion estimates.

Visual-Based Navigation Architectures

To improve navigation resilience, many modern drones combine GNSS and inertial sensing with visual navigation.These architectures may include:

- Visual-Inertial Navigation Systems (VINS)
- Visual-Based Navigation (VBN)
- Vision-based localisation using preloaded maps

In these architectures, cameras provide environmental observations while the IMU provides motion estimates.

The navigation system continuously fuses these data streams to estimate the drone's pose relative to the environment. Visual navigation is particularly valuable in environments where external positioning signals are unreliable, such as indoor spaces, dense urban areas, or natural environments with limited visibility of the sky. However, visual navigation performance depends heavily on accurate motion propagation and precise synchronisation between sensing modalities. The IMU therefore plays a critical role in stabilising visual navigation solutions.

Controlled Transition: Architecture Under Stress

The true test of a navigation system occurs during transitions between GNSS-available and GNSS-denied conditions. When GNSS signals degrade, the navigation filter relies more heavily on inertial propagation, and uncertainty in the position estimate increases. When GNSS signals return, corrections must be introduced gradually to avoid abrupt state discontinuities.

Poorly designed systems often exhibit oscillations or sudden jumps in navigation estimates during this phase. Robust architectures maintain stable behaviour and smoothly converge to the corrected position estimate. The ability to manage this transition smoothly is a defining characteristic of a mature navigation system.

Resilient PNT Architectures

In defence and security applications, navigation resilience is often described in terms of Position, Navigation, and Timing (PNT).

Modern PNT architectures combine multiple information sources including:

- GNSS measurements
- Inertial sensing
- Visual navigation
- External aiding sensors

Through sensor fusion frameworks such as EKFs, these inputs contribute to a navigation solution capable of maintaining operational continuity even when GNSS signals degrade.

Integrated Scenario: Urban Mapping UAV

Consider a mapping Unmanned Aerial Vehicle (UAV) operating in dense urban infrastructure.

GNSS is nominal at takeoff. As the aircraft approaches a bridge, multipath increases.

Under the structure, GNSS becomes unavailable for approximately forty-five seconds while LiDAR mapping continues.

In a system built around a stable tactical MEMS architecture attitude remains stable, velocity drift accumulates slowly, and mapping alignment remains coherent.

When GNSS returns, corrections are reintroduced gradually.

Navigation continuity is preserved.

Landscape of Alternative Navigation Technologies

When GNSS becomes unreliable, autonomous systems increasingly rely on complementary navigation techniques.

Common alternative navigation methods include:

- Visual navigation (VINS/VBN)
- LiDAR-based SLAM
- Terrain referenced navigation
- Signals-of-opportunity navigation
- Inertial dead-reckoning

Each method offers strengths but also limitations. Visual navigation depends on environmental texture. LiDAR SLAM requires processing resources. Signals-of-opportunity rely on RF infrastructure.

Inertial navigation remains the only navigation method that is completely self-contained and environment independent.

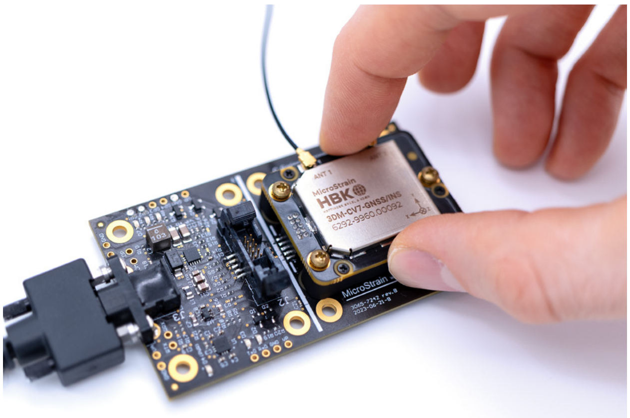
Technical Illustration: The 3DM-CV7 Architecture

A representative example of tactical MEMS refinement is the 3DM-CV7 IMU architecture.

The system integrates four independent MEMS IMUs within a synchronised array. Each sensor undergoes deep multi-axis thermal calibration across the operating temperature range. Calibration-informed weighting optimises the contribution of each IMU. Opposing mechanical orientation improves vibration resilience.

With a motion-to-message latency around 1.9 ms, and an event-based synchronisation system capable of aligning inertial measurements with external sensors such as cameras, the architecture supports high-integrity visual-inertial navigation.

MicroStrain by HBK's inertial engineering heritage dates back to the late 1980s, with decades of focus on compact inertial sensing and SWaP-efficient architectures for autonomous systems.



3DM-CV7-GNSS/INS – GNSS-Aided Inertial Navigation System

Environmental Robustness

Laboratory accuracy alone does not guarantee operational performance. Autonomous platforms operate in environments characterised by temperature variation, sustained vibration, mechanical shock, and continuous exposure to real-world conditions.

To ensure reliable navigation, inertial systems must be validated beyond controlled settings. This includes thermal cycling, long-duration bias stability evaluation, power-cycle repeatability, and cross-axis sensitivity testing.

Consistency across units is essential.

Customisation as Engineering Alignment

High-performance inertial integration rarely ends at default configuration.

Engineering alignment may involve:

- EKF tuning for mission dynamics
- GNSS outage optimisation
- Extended thermal characterisation
- Mechanical packaging adaptation
- Pulse-per-second (PPS) synchronisation

Modern autonomy programmes increasingly adopt Modular Open Systems Architecture (MOSA). Navigation components must therefore integrate seamlessly with existing autonomy frameworks such as PX4, ArduPilot, and ROS. Compatibility with these ecosystems significantly accelerates integration and reduces development effort.

Selecting Inertial Architecture: An OEM Framework

Choosing an inertial system for GNSS-degraded autonomy requires structured evaluation.

Key considerations include:

- Bias stability over realistic outage durations
- Thermal calibration methodology
- Architecture design (single IMU vs synchronised array)
- Timestamp precision and latency
- Environmental robustness
- Integration ecosystem maturity
- SWaP compatibility

Inertial selection is not a component decision. It is an autonomy architecture decision.

Designing Multi-Layer Navigation Architectures

Modern autonomous systems rarely rely on a single navigation technique.

Instead, resilient navigation architectures combine multiple complementary layers:

Primary navigation layer
GNSS positioning when signals are available.

Secondary navigation layer
Inertial propagation maintaining position, velocity, and attitude.

Complementary navigation layers
Visual navigation, LiDAR SLAM, terrain matching, or other aiding sources.

Sensor fusion frameworks continuously integrate these inputs to maintain a coherent navigation solution. This layered architecture enables autonomy systems to remain operational even when individual navigation sources degrade.

Why IMU Performance Matters More Than Ever

Autonomy density is increasing. RF complexity is rising. GNSS reliability cannot be assumed.

At the same time, defence programmes increasingly prioritise attritable autonomous systems, platforms capable enough for demanding missions yet affordable enough to be deployed at scale.

This shift places strong emphasis on SWaP-C efficiency:

Size	Weight	Power	Cost

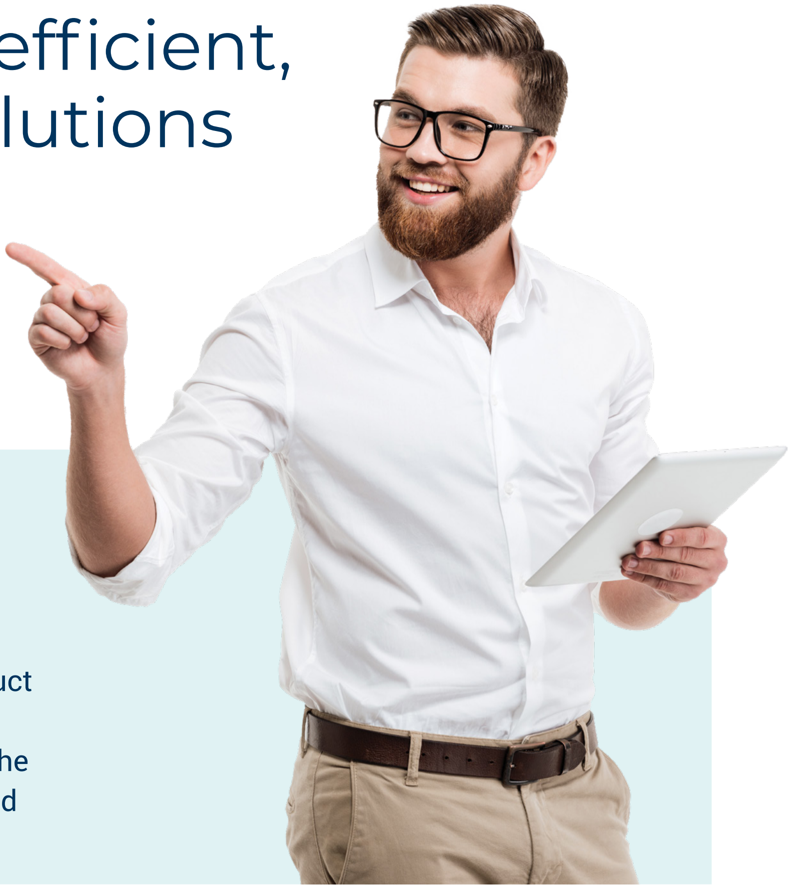
Navigation solutions must therefore deliver high performance within extremely constrained system budgets.

Conclusion

GNSS-denied does not mean navigation-denied. It means inertial-performance-dependent.

High-performance tactical MEMS architectures engineered through calibration depth, synchronisation precision, and architectural discipline, provide a credible and scalable foundation for resilient UAV, Unmanned Ground Vehicles (UGV), and robotic autonomy. When external reference becomes uncertain, internal stability defines outcome. And in modern operational environments, uncertainty is no longer exceptional. It is expected.

We provide exceptional sensing and insights to create safer, more efficient, and sustainable solutions



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