QuaSAR: Quantum Sensing Aerial Reporting

FINAL PAPER

University of Georgia

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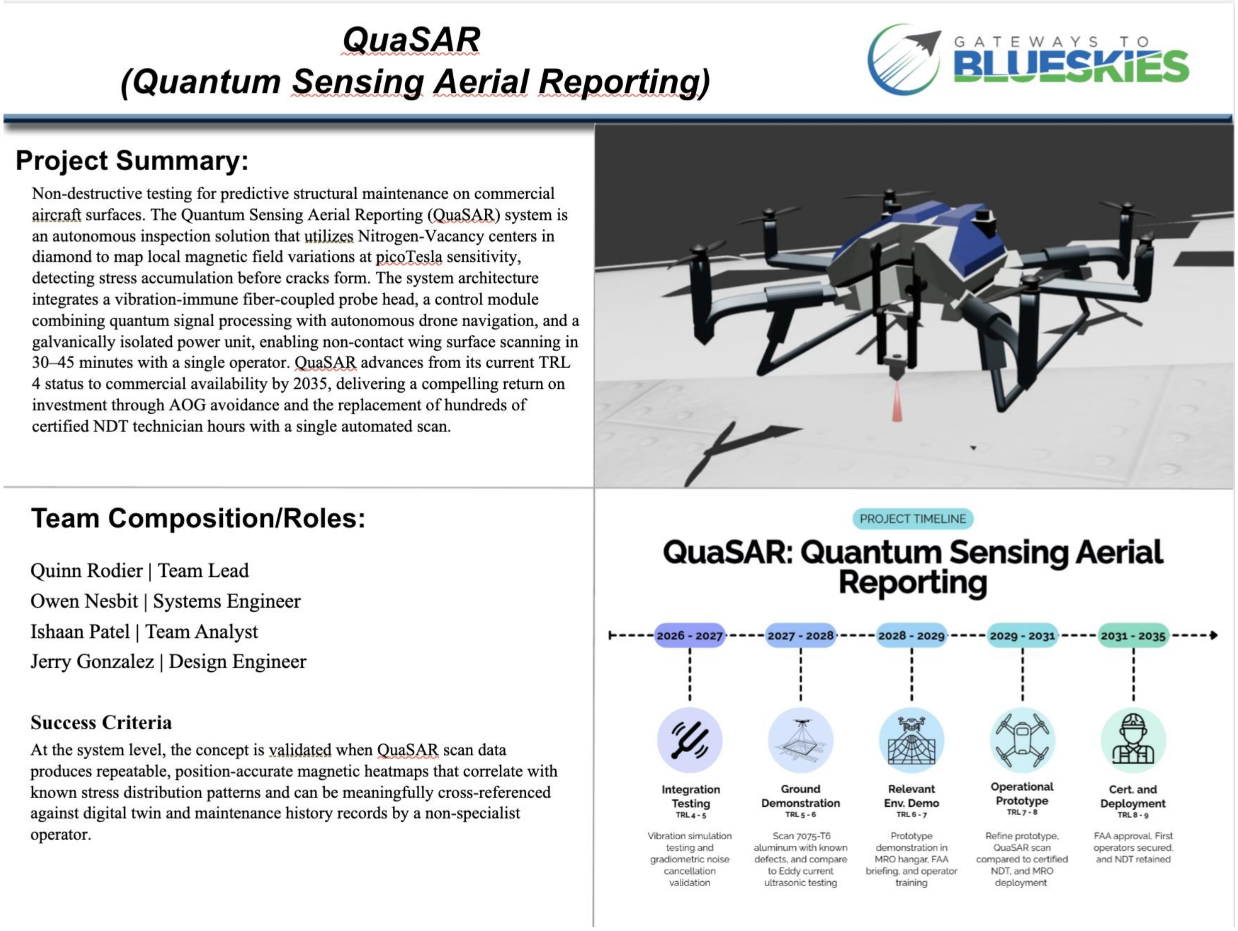
QUAD CHART



QuaSAR
(Quantum Sensing Aerial Reporting)

Project Summary:

Non-destructive testing for predictive structural maintenance on commercial aircraft surfaces. The Quantum Sensing Aerial Reporting (QuaSAR) system is an autonomous inspection solution that utilizes Nitrogen-Vacancy centers in diamond to map local magnetic field variations at picoTesla sensitivity, detecting stress accumulation before cracks form. The system architecture integrates a vibration-immune fiber-coupled probe head, a control module combining quantum signal processing with autonomous drone navigation, and a galvanically isolated power unit, enabling non-contact wing surface scanning in 30–45 minutes with a single operator. QuaSAR advances from its current TRL 4 status to commercial availability by 2035, delivering a compelling return on investment through AOG avoidance and the replacement of hundreds of certified NDT technician hours with a single automated scan.

Team Composition/Roles:

Quinn Rodier | Team Lead
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Success Criteria

At the system level, the concept is validated when QuaSAR scan data produces repeatable, position-accurate magnetic heatmaps that correlate with known stress distribution patterns and can be meaningfully cross-referenced against digital twin and maintenance history records by a non-specialist operator.

PROJECT TIMELINE

QuaSAR: Quantum Sensing Aerial Reporting

2026 - 2027	**Integration Testing**	TRL 4 - 5	Vibration simulation testing and gradiometric noise cancellation validation
2027 - 2028	**Ground Demonstration**	TRL 5 - 6	Scan 7075-T6 aluminum with known defects, and compare to Eddy current ultrasonic testing
2028 - 2029	**Relevant Env. Demo**	TRL 6 - 7	Prototype demonstration in MRO hangar, FAA briefing, and operator training
2029 - 2031	**Operational Prototype**	TRL 7 - 8	Refine prototype, QuaSAR scan compared to certified NDT, and MRO deployment
2031 - 2035	**Cert. and Deployment**	TRL 8 - 9	FAA approval. First operators secured, and NDT retained

ABSTRACT

Reliance on traditional non-destructive testing (NDT) methods has created significant bottlenecks in aircraft maintenance operations. Current procedures are labor intensive and limited in precision, unable to detect early-stage material degradation before structural damage progresses to a detectable scale. This final paper presents the Quantum Sensing Aerial Reporting (QuaSAR) system, an autonomous inspection solution that utilizes Nitrogen-Vacancy (NV) centers in diamonds to detect structural fatigue at the atomic level. Expanding substantially upon the original proposal, this paper provides a direct contrast of current NDT practices against the QuaSAR approach, a step-by-step concept of operations with explicit data flow, a Technology Readiness Level–based deployment roadmap with yearly milestones and completion criteria, and a return on investment assessment grounded in commercial aviation maintenance economics.

The system integrates a vibration-immune fiber-coupled probe head, a specialized control and avionics module, and a power distribution unit, operating as a drone-mounted autonomous inspector that generates magnetic heatmaps of aircraft wing surfaces. Key improvements over the proposal include a practical description of the system's unique benefits: picoTesla-level magnetic field sensitivity, non-contact operation, and autonomous single-operator workflow presented in direct comparison with visual inspection, eddy current testing, and ultrasonic testing. The economic analysis demonstrates a compelling return on investment driven by unscheduled aircraft-on-ground event avoidance and structural inspection labor reduction. The deployment roadmap advances the integrated system from its current TRL 4 status to commercial availability by 2035 through a structured sequence of milestones, with FAA regulatory engagement integrated from the outset.

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SITUATION ASSESSMENT

The structural integrity of commercial aircraft depends on a continuous cycle of non-destructive testing (NDT) carried out by certified maintenance crews following schedules prescribed by manufacturer maintenance manuals and FAA airworthiness directives. At present, the three most prevalent structural NDT methods in commercial aviation are visual inspection, eddy current testing, and ultrasonic testing. [25] Visual inspection requires technicians to physically examine airframe surfaces and accessible internal structure for cracks, corrosion, or deformation. While straightforward to administer, this method cannot reliably detect cracks below approximately one millimeter in length, is dependent on technician attention and environmental lighting, and requires unobstructed line-of-sight access to all surfaces. Eddy current testing improves on this detection floor by using electromagnetic induction to identify surface and near-surface discontinuities in conductive materials, but it requires direct probe contact with the surface, is sensitive to probe lift-off and orientation, and demands highly trained operators to separate genuine indications from noise. Ultrasonic testing extends detection into the internal structure of the material but similarly requires surface contact with a coupling medium and is relatively slow across the large surface areas that constitute a commercial aircraft wing. [25]

Limitations of Current Approaches

The most significant limitation shared by all three methods is that they are reactive. Each identifies damage that has already formed rather than detecting the material state conditions that precede structural failure. A crack detectable by eddy current testing at 0.1–1 mm has been accumulating internal fatigue for many thousands of flight cycles. The interval between crack nucleation and detectable flaw size is where material vulnerability is highest and where an early-detection system could enable the most consequential interventions. Beyond sensitivity, all three methods are labor intensive. A standard C-check for a commercial narrow-body aircraft requires the aircraft to be grounded for two to three weeks and demands between 6,000 and 12,000 man-hours of maintenance labor, with the structural NDT component alone accounting for hundreds of certified technician hours. [25][26] FAA regulations require that many structural inspections recur at fixed intervals regardless of actual aircraft condition, meaning that aircraft in good condition are grounded on schedule while potentially fatigued aircraft remain in service until the next prescribed interval.

The Demand Gap

The pressure on this inspection paradigm is increasing on multiple fronts simultaneously. The commercial aviation fleet is projected to require more than 40,000 new aircraft globally through 2040, driving an enormous expansion in the volume of maintenance activity required across the MRO sector. [27] At the same time, the aviation maintenance workforce faces a projected shortfall, with retirements outpacing new entries into the field and reducing the pool of certified technicians available to perform these procedures. [25] The industry has responded with incremental improvements—the adoption of FPV drones for visual inspection, the introduction of digital twins to supplement scheduled maintenance data, and a growing push toward sensor networks and predictive maintenance platforms—but the underlying inspection paradigm remains reactive, manual, and sensitivity-limited. [24][23] The convergence of a growing fleet, a shrinking workforce, and a regulatory framework built on fixed-interval manual inspection represents a structural constraint that incremental refinements to existing NDT methods are unlikely to resolve.

The QuaSAR system addresses this gap by offering a fundamentally different detection mechanism, using quantum-level magnetic field sensing that operates autonomously, requires no surface contact, and is capable of identifying the early precursors to structural fatigue before crack nucleation occurs. The contrast is not one of marginal improvement. NV center magnetometry operates two to three orders of magnitude more sensitive than conventional eddy current inspection, applied through an autonomous drone platform that reduces the labor requirement from hundreds of certified technician hours to a single operator overseeing a 30 to 45-minute automated scan.

USE CASE AND PROPOSED SOLUTION

The QuaSAR system is designed for one specific and well-defined use case: the autonomous detection of early-stage structural fatigue in commercial aircraft wing structures during scheduled and unscheduled maintenance events. The system addresses the limitations of current NDT practices not through incremental improvement but through a different detection mechanism. Structural fatigue in aluminum alloys alters the local magnetic susceptibility at the crystal lattice level, producing magnetic field perturbations that are measurable before any crack forms. By mapping the local magnetic field at each position along the wing surface, QuaSAR identifies regions of elevated stress accumulation indicative of fatigue risk, enabling truly predictive maintenance decisions based on the actual condition of the material rather than fixed inspection intervals.

Practical Advantages Over Conventional NDT

Table 1 summarizes the key operational differences between QuaSAR and the three conventional NDT methods currently in primary use. Four specific capabilities represent the most operationally significant advantages of the QuaSAR approach.

Attribute	Visual Inspection	Eddy Current	Ultrasonic Testing	QuaSAR
Detection Threshold	~1 mm crack visible	~0.1–1 mm crack	~0.1 mm internal flaw	Pre-crack stress accumulation (picoTesla sensitivity)
Surface Contact	Not required (visual)	Required	Required (coupling medium)	Not required (1–5 mm standoff)
Operator Certification	Certified A&P technician	Specialized NDT cert.	Specialized NDT cert.	14 CFR Part 107 + supplemental module
Wing Scan Time	4–12 hrs per wing	Hours per area	Hours per area	~30–45 min per wing (estimated)
Operation Mode	Manual	Manual	Manual	Autonomous
Detection Timing	Reactive	Reactive	Reactive	Predictive (pre-crack)

Table 1: QuaSAR vs. Current NDT Methods – Operational Comparison

Sensitivity and Early Detection: NV center magnetometers measure magnetic field variations on the order of picoTesla (10^{-12} T), a sensitivity level that enables detection of diffuse stress accumulation zones that precede crack nucleation. [1][18] Conventional eddy current inspection detects cracks in the range of 0.1–1 mm, at which point significant internal damage has already occurred. QuaSAR's detection threshold is fundamentally earlier in the fatigue life cycle, providing maintenance crews with the ability to schedule targeted structural interventions during planned downtime rather than responding to unexpected findings during scheduled checks.

Non-Contact Operation: All current contact-based NDT methods require either direct probe contact with the aircraft surface or physical technician access to the inspection area. The QuaSAR probe operates at a standoff distance of 1–5 mm, maintained by the LiDAR altimeter feedback loop, scanning the wing surface without contact. This eliminates the risk of probe-induced surface marking and enables inspection of areas that are difficult or time-consuming for technicians to access manually.

Automation and Reduced Labor: A QuaSAR wing scan requires one operator with basic 14 CFR Part 107 UAS certification and a supplemental training module. The quantum sensor data processing is handled autonomously by the onboard System-on-Chip (SoC), and the magnetic heatmap is generated automatically at the ground control station. No background in quantum physics is required of the operator, as the complex sensing mechanics are abstracted entirely by the onboard electronics. Total scan time for a complete wing surface is estimated at 30–45 minutes, a substantial reduction from the hundreds of certified technician hours required for structural NDT during a conventional C-check.

Predictive Maintenance Enablement: The magnetic field data generated by each QuaSAR scan can be archived and compared across inspection cycles, enabling trend analysis of fatigue accumulation over the aircraft's service life. This creates the data foundation for condition-based maintenance scheduling, reducing unnecessary groundings of airworthy aircraft and providing earlier warning for units accumulating stress above expected thresholds.

Technical Approach

The NV center sensing mechanism operates through Optically Detected Magnetic Resonance (ODMR). When NV centers in the diamond are illuminated by a 532 nm laser, they emit fluorescence proportional to their quantum spin state. Applying a microwave field near the NV resonant frequency (~2.87 GHz) produces a measurable reduction in fluorescence, and the precise frequency of this dip shifts in the presence of an external magnetic field. Simplifying from the full spin Hamiltonian, the magnetic field at the probe location is determined by:

$$B = (f_+ - f_-) / 2\gamma e \qquad \text{(Eq. 1)}$$

where f_+ and f_- are the upper and lower resonance dip frequencies and γe is the electron gyromagnetic ratio (28×10^9 Hz/T). [18] By measuring this quantity at each spatial location along the wing surface, the system generates a direct, non-contact map of the local mechanical stress state of the material beneath the probe, without requiring any of the coupling media, surface contact, or crack-scale damage associated with conventional NDT methods.

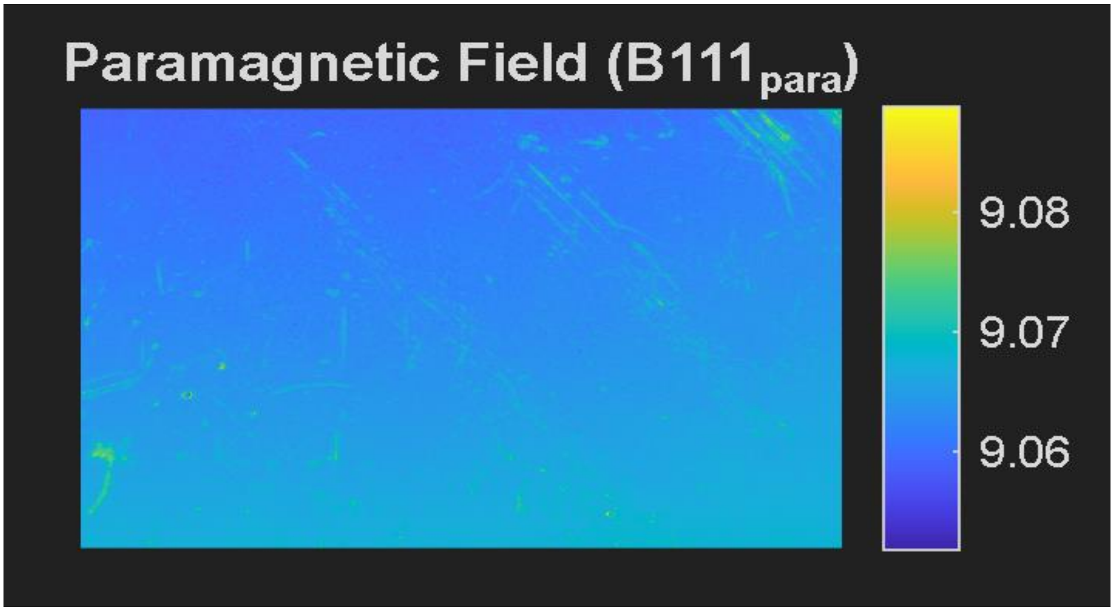

Figure 1: Paramagnetic Field Readings from Magnetic Vector Data

Figure 1 demonstrates a potential reading using vector data from a paramagnetic field captured with a Quantum Diamond Microscope (QDM) and processed using Harvard's QDMLab MATLAB tool, demonstrating feasible magnetic field readings that represent physical flaws. [28]

System Architecture

The QuaSAR system is comprised of three integrated subsystem modules, each designed to address a specific set of operational and technical requirements.

Module A – Probe Head: A synthetic High-Pressure High Temperature (HPHT) diamond microcrystal, cut along the [111] axis and containing high-density Nitrogen-Vacancy ensembles, [1] is connected via two sets of fiber couplers to a Laser Driver and a Multi-Pixel Photon Counter (MPPC) in Module B. The fiber coupler is a ceramic optical ferrule that fuses single-mode fiber directly to the diamond surface, eliminating free-space optics and the precision alignment hardware they require. This design is vibration-immune, a critical characteristic given the high-frequency vibration environment of a drone airframe. [3] A planar microwave antenna integrated onto the probe PCB delivers the required 2.87 GHz field with low power consumption, [4] and a Samarium-Cobalt permanent magnet provides the static bias field required to split the NV quantum states. [2] A micro-Peltier cooler with closed-loop PID control maintains the NV diamond at a stable operating temperature throughout the scan, eliminating thermally induced drift in the resonance frequency. [6] A motorized 3-axis gimbal decouples the probe head from flight attitude changes, and the LiDAR altimeter provides real-time standoff distance feedback for error characterization and calibration. [17]

Module B – Control Unit: The RF-SoC combines an FPGA with advanced processors to generate nanosecond-precision microwave pulses and perform real-time charge-state readout. [7] The Multi-Pixel Photon Counter (MPPC), connected to the probe via fiber optics, detects and measures NV fluorescence and transmits the signal to the FPGA for quantification. [8] A reference magnetometer located within the fuselage implements a gradiometric configuration that models and subtracts the drone's own magnetic signature from the NV sensor reading, isolating the wing material's field contribution. [10] The laser driver sends 532 nm laser pulses through the fiber optic cable to excite the NV centers, handling the synchronization between laser and photon counter. [9] The onboard computer manages autonomous navigation, data logging, and telemetry to the ground station via a long-range radio modem. [11][12] Navigation cameras provide forward depth, RGB, and vertical distance data to support autonomous tracking and obstacle avoidance without reliance on satellite positioning. [11]

Module C – Power Unit: Lithium polymer batteries provide the primary power source, offering the best power-to-weight ratio available for current UAV battery technology. [14] Electronic Speed Controllers are connected directly to raw battery voltage, with a galvanically isolated DC/DC converter separating the quantum payload power line from the propulsion system to prevent conducted electromagnetic interference from degrading sensor performance. [15][16] Low-Noise Low-Dropout Regulators provide a flat, regulated output voltage to the control module. [20]

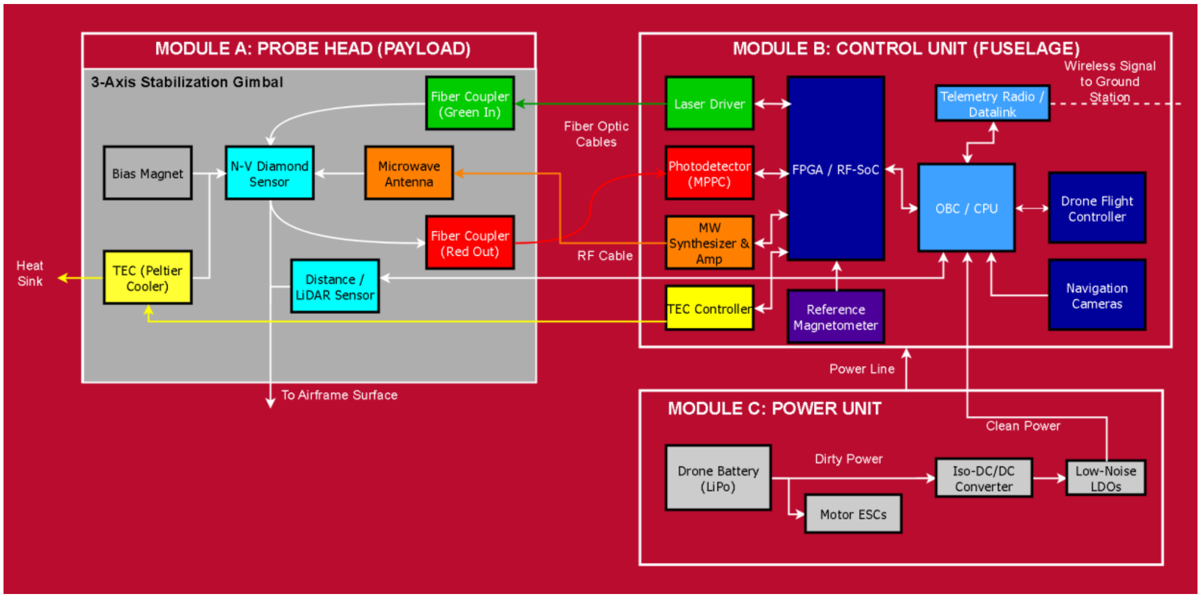

Figure 2: QuaSAR System Architecture

CONCEPT OF OPERATIONS

The operational concept for the QuaSAR system is designed to integrate into the existing aircraft maintenance workflow with minimal disruption to current procedures. The system is not intended to replace certified NDT inspectors but to function as an autonomous first-pass screening tool that directs inspector attention to regions of genuine concern, reducing total inspection time and improving the probability of detecting early-stage fatigue. A central design objective is a low training threshold: the system operator requires only 14 CFR Part 107 UAS certification, a supplemental module covering NV sensor operating principles and laser safety (Class 1–3R awareness), and basic pre-flight familiarity with the drone and quantum payload hardware. [19][21]

Operational Sequence and Data Flow

Step 1 – Pre-Mission Setup: The maintenance operator loads the aircraft tail number into the Ground Control Station (GCS) software, which retrieves the wing geometry profile from the maintenance management database. The operator defines the inspection boundary on the graphical interface, and the GCS generates the drone flight path automatically. The operator reviews the path and completes the pre-flight checklist, including confirmation that the Peltier cooler has reached its operating temperature setpoint and that fiber optic coupling integrity is confirmed.

Step 2 – Deployment and Baseline Calibration: The drone is launched from the hangar floor. During the initial positioning pass, the reference magnetometer in Module B characterizes the ambient magnetic environment of the specific hangar location and the aircraft's own static magnetic signature. This calibration baseline is established before any inspection data is collected, enabling the gradiometric subtraction algorithm to isolate wing material field contributions from environmental noise in all subsequent scan passes.

Step 3 – Wing Surface Scan: The drone follows the pre-planned flight path at a standoff distance of 1–5 mm from the wing surface, as maintained by the LiDAR altimeter feedback loop. The probe head illuminates the NV diamond via the 532 nm fiber optic, applies the 2.87 GHz microwave field, and the MPPC detects the resulting fluorescence. The fiber-coupled optical design ensures that high-frequency vibration from the propulsion system does not disrupt the optical path, [3] and the motorized gimbal decouples the probe from pitch and roll changes. The Peltier cooler maintains diamond temperature within ±0.1°C throughout the scan to eliminate temperature-induced frequency drift. [6]

Step 4 – GPS-Denied Navigation: Commercial maintenance operations frequently occur inside metal hangars where GPS signals are unreliable or unavailable. The QuaSAR system addresses this constraint by relying on the forward-looking depth camera and down-looking camera in Module B for simultaneous localization and mapping, and on the LiDAR altimeter for proximity sensing and obstacle avoidance. [11] Satellite positioning is not required for any phase of the inspection operation.

Step 5 – Real-Time Processing and Noise Subtraction: As the drone scans each section of the airframe, the RF-SoC processes the ODMR spectrum in real time and extracts the local magnetic field vector at each probe position using Equation 1. Simultaneously, the reference magnetometer data is used to subtract the drone's electromagnetic signature from the NV reading, isolating the wing material's contribution. The onboard computer logs the position-tagged magnetic field data throughout the scan.

Step 6 – Transmission, Visualization, and Documentation: Upon completing the scan, the onboard computer transmits the position-tagged magnetic field dataset to the GCS via the long-range telemetry modem. [12] The GCS software generates a 2D magnetic field heatmap overlaid on the wing geometry, with anomalous regions flagged by threshold comparison to the calibration baseline and to archived data from prior inspection cycles. Maintenance crews cross-reference flagged zones with the aircraft's maintenance history and digital twin data, and dispatch conventional NDT confirmation on the specific areas identified. Results are automatically exported to the maintenance management system, maintaining the FAA-required documentation chain.

Interoperability and Operational Constraints

The QuaSAR system is designed as a complementary tool within the existing maintenance infrastructure. Conventional eddy current, visual or ultrasonic inspection is still required to characterize any anomalies flagged by QuaSAR, maintaining the regulatory chain of inspection authority. The magnetic heatmap output is structured for integration with digital twin platforms and maintenance management systems that airlines and MRO operators already operate, lowering the adoption barrier by fitting into existing data workflows rather than requiring new infrastructure.

The system's current configuration is optimized for wing surface inspection during scheduled maintenance events when the aircraft is stationary in the hangar. The fiber-coupled design and active temperature control address the two primary environmental challenges of this setting: vibration from the drone propulsion system and ambient temperature fluctuation. The gradiometric noise cancellation architecture addresses the complex electromagnetic environment of an active maintenance facility, where electrical equipment, power tools, and aircraft systems all contribute to the local magnetic field. The support infrastructure is intentionally minimal as the GCS operates on a standard ground station laptop, battery charging infrastructure is commercial off-the-shelf, and the drone platform is based on established modular autopilot hardware, which limits the cost required at each deployment site and reducing the integration burden on adopting MRO operators.

PATH TO DEPLOYMENT

The NV quantum sensing subsystem has been demonstrated under controlled laboratory conditions, with published results confirming the ability to detect magnetic and strain fields at the sensitivity levels claimed. [18] The integrated QuaSAR system consisting of a NV payload mounted to an autonomous drone represents a new configuration that has not yet been flight-tested, placing the integrated system at Technology Readiness Level 4. The drone platform, navigation cameras, ground station laptop, and battery charging infrastructure represent commercial off-the-shelf technology at TRL 9. The following roadmap defines the milestones and completion criteria required to advance from the current integrated TRL to commercial deployment by 2035.

TRL Development Roadmap

Phase	Timeline	TRL	Key Milestones	Completion Criteria
Integration Testing	2026–2027	**4 → 5**	Vibration simulation testing (10–500 Hz, 5g peak) of fiber-coupled optical path; gradiometric noise cancellation algorithm characterization; Peltier temperature control validation (10–40°C ambient cycling)	Optical coupling loss <3 dB under vibration; noise floor <1 nT/√Hz; temperature stability within ±0.5°C
Ground Demonstration	2027–2028	**5 → 6**	First integrated system scan of 7075-T6 aluminum specimens with manufactured defects of known geometry and fatigue severity; direct comparison against eddy current and ultrasonic findings; MRO industry partner engagement	Quantitative sensitivity benchmark established; minimum detectable anomaly characterized and documented
Relevant Environment Demo	2028–2029	**6 → 7**	Prototype demonstration on retired aircraft wing inside commercial maintenance hangar; FAA engineering briefing under SAIT or equivalent framework; operator training protocols and safety procedures formalized; GCS software refined with user input	Regulatory dialogue initiated; operator training curriculum validated; no GPS dependency confirmed operationally
Operational Prototype	2029–2031	**7 → 8**	Refined prototype deployed at MRO facility under FAA-certified inspector supervision; QuaSAR scan data systematically correlated with conventional NDT findings; real-world labor savings quantified; regulatory submission data generated	Detection accuracy validated against certified NDT; statistical performance baseline established for certification submission
Certification & Deployment	2031–2035	**8 → 9**	FAA certification as supplemental inspection tool; commercial licensing launched 2033 under service-based deployment model; full commercial availability targeted 2035	FAA approval obtained; first commercial operators contracted; conventional NDT retained as dispositioning authority

Table 2: QuaSAR TRL Development Roadmap (2026–2035)

The regulatory engagement strategy is built progressively into the roadmap rather than deferred to the final phases. Initial FAA briefings at TRL 6/7 establish a regulatory dialogue early, allowing the agency to observe system performance data as it is generated and to identify the certification pathway appropriate for a novel inspection technology. The service-based commercial model, where MRO operators contract per inspection event rather than purchasing hardware outright, reduces the capital barrier for initial adopters and aligns the provider's incentive with sustained system performance and reliability.

Training Requirements

Operator certification for the QuaSAR system requires 14 CFR Part 107 licensure for small UAS operations, along with a supplemental training module covering NV center operating principles (magnetic and strain sensitivities, sources of sensor error), laser safety awareness (Class 1–3R), pre-flight hardware checks for the quantum payload, and GCS software operation. [19][21] Alignment re-calibration procedures and basic payload mounting and dismounting are also included, an area where the mechanical background of typical maintenance crew personnel provides a natural advantage. Total supplemental training is estimated at approximately 40 hours, a fraction of the multi-year certification path for FAA-authorized NDT inspectors, substantially broadening the pool of personnel capable of operating the system and reducing the per-inspection labor cost at each deployment site.

Return on Investment and Economic Impact

The economic justification for QuaSAR adoption rests on two principal value drivers: reduction of unscheduled aircraft-on-ground (AOG) events attributable to structural findings, and optimization of scheduled maintenance inspection labor.

Aircraft-on-ground costs for commercial narrow-body aircraft can reach tens of thousands of dollars per hour in lost revenue, crew accommodation, and operational disruption. [26] Unscheduled AOG events driven by structural findings discovered during or after scheduled maintenance, particularly those requiring additional documentation, re-inspection, or engineering disposition, are among the most costly maintenance outcomes airlines face. QuaSAR's predictive capability, detecting fatigue accumulation before crack nucleation, enables airlines to schedule targeted structural interventions during planned downtime rather than responding to unexpected findings that force unscheduled groundings. For a medium-sized carrier operating 100 narrow-body aircraft, even a modest reduction in structural-related AOG events translates to substantial annual savings at current AOG cost levels.

On the labor side, the shift from 200–400 certified NDT technician hours for the structural inspection component of a C-check to a single 30–45 minute QuaSAR scan, requiring one operator rather than multiple certified inspectors, represents a significant reduction in direct inspection labor cost. The estimated production system cost for a QuaSAR unit, including the drone platform, NV center payload, and GCS software, is projected at $150,000–$250,000. Given the labor savings per inspection cycle and the AOG avoidance benefit, the system is projected to achieve payback within the first year of operational use at an active MRO facility.

The stakeholder adoption case extends beyond direct cost savings. Airlines benefit from improved safety margins and data-driven maintenance scheduling that can ultimately inform condition-based interval adjustments. MRO facilities gain competitive differentiation through the ability to offer predictive structural health assessment as part of their service portfolio. Regulatory authorities gain access to richer and more frequent structural health data that may inform risk-based adjustments to inspection interval requirements as the technology matures and a performance track record is established. Original equipment manufacturers benefit from fleet-wide fatigue accumulation data that can feed back into future structural design and material selection decisions. These adoption incentives, layered across multiple stakeholder categories, present a compelling argument for investment that extends well beyond the direct financial return to any single operator.

CHANGES AND IMPROVEMENTS SINCE PROPOSAL

This final paper addresses each area of feedback identified by the proposal review panel and incorporates the positive elements of the panel's evaluation.

The situation assessment has been substantially expanded to provide a clear and specific contrast between current NDT methods and the QuaSAR approach. Where the proposal described the importance of early detection without detailing how current methods fall short, this paper specifies the detection thresholds, labor requirements, and reactive timing limitations of visual inspection, eddy current testing, and ultrasonic testing, establishing a concrete operational baseline against which QuaSAR's advantages are measured.

The use case section has been restructured to lead with the practical operational benefits of the system: sensitivity, non-contact operation, automation, and predictive maintenance enablement before introducing the underlying physics, and the Hamiltonian derivation from the proposal has been reduced to its essential operational result (Eq. 1) to maintain narrative clarity. Table 1 provides a direct side-by-side comparison that makes the system's advantages concrete and accessible without requiring familiarity with quantum sensing principles.

The concept of operations has been expanded from a general description of system behavior to a step-by-step operational sequence with explicit data flow, connecting each system module to its specific role in the inspection workflow. The constraints addressed by the system architecture: GPS-denied navigation, electromagnetic interference, vibration, and temperature drift are now linked directly to the corresponding module-level solutions, clarifying why the architecture takes the form it does.

The path to deployment section is entirely new relative to the proposal. A comprehensive TRL roadmap with yearly milestones, completion criteria, regulatory engagement checkpoints, and a defined commercial deployment model has been developed to address the judges' observation that feasibility and planning were not demonstrated. The ROI and stakeholder impact analysis, also new, addresses the economic dimension that was absent from the proposal. Together, these additions establish the practical and financial case for QuaSAR adoption that the proposal's technical focus did not include.

The overall narrative has been reorganized throughout to maintain a consistent focus on the core problem, the specific innovation, and why it matters to the aviation maintenance industry, in response to the judges' observation that the central storyline had been obscured by technical content in the proposal.

Figure 3 shows the updated CAD, created to show the preliminary design and containing all three modules and their harnessing. Detailed design is omitted to be determined during the prototyping and R&D phase.

Figure 3: Conceptual Design CAD

CONCLUSIONS AND KEY FINDINGS

The QuaSAR system proposes a technically grounded and operationally viable advancement in non-destructive testing for commercial aviation structural maintenance. The core finding of this analysis is that NV center quantum magnetometry, deployed on an autonomous drone platform, offers a qualitative improvement over existing NDT methods rather than a marginal one. The combination of picoTesla-level magnetic field sensitivity, non-contact operation, and autonomous single-operator workflow addresses the three primary limitations of the current inspection paradigm: insufficient early-detection sensitivity, high labor intensity, and reactive maintenance timing that depends on damage already having formed.

The system architecture is specifically designed to function within real maintenance environments. The fiber-coupled optical design provides vibration immunity, the gradiometric noise cancellation addresses the complex electromagnetic environment of an active hangar, and GPS-independent navigation enables reliable operation inside metal structures where satellite positioning is unavailable. The operational sequence integrates naturally into existing maintenance management workflows, and the low training requirement broadens the pool of personnel capable of operating the system relative to the specialized certification requirements of conventional NDT methods.

The economic analysis demonstrates a compelling return on investment for airlines and MRO operators. AOG avoidance savings and the labor reduction from automated scanning are each independently significant, and together they project a payback period well within the first year of operational use at an active facility. The deployment roadmap advances the integrated QuaSAR system from its current TRL 4 status to commercial availability by 2035, with FAA regulatory engagement built into the plan from TRL 6 onward and a service-based commercial model designed to minimize the capital barrier for early adopters.

Aviation safety ultimately depends on the ability to identify structural problems before they become failures. The QuaSAR system advances that capability to the atomic level, and the analysis presented in this paper establishes both the technical feasibility and the operational and economic case for its development and deployment within the commercial aviation maintenance sector.

APPENDICES

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