

Adaptive Terrain Memory Navigation: A Modular Fail-Safe for Unmanned Aerial Vehicles in Satellite-Navigation-Denied Environments

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Abstract - Tactical unmanned aerial vehicles (UAVs) rely almost exclusively on GPS and a radio-control (RC) link for navigation and recovery. Either link can fail independently — through deliberate jamming or spoofing, terrain and weather blockage, or physical damage to the receiver hardware — and a UAV with no independent means of localization typically drifts, strikes terrain, and is destroyed in the resulting fall. This paper presents Adaptive Terrain Memory Navigation (ATMN), a fail-safe safety system rather than a primary navigation system. Its LiDAR and Simultaneous Localization and Mapping (SLAM) stack run continuously in the background throughout the sortie, building a terrain map and tracking the UAV's position, but this output does not participate in flight control while GPS and RC remain available. Navigation authority passes to ATMN the instant either GPS or RC signal is lost, without waiting for both to fail together, and reverts automatically once both are confirmed restored. On engagement, ATMN holds the aircraft within its self-built terrain map and retraces the last known safe corridor, preventing the uncontrolled descent that would otherwise destroy the airframe. It is built as a modular, platform-agnostic add-on connecting through the standard MAVLink payload interface, requiring no modification to the host airframe or flight-control software. We present the system architecture, an either-link trigger logic, a nine-item bill of materials totaling 462.6 g and 20.7 W at a cost of approximately ₹1.6 lakh per unit, detailed power and weight budget calculations against a publicly specified commercial hexacopter platform, and a comparative evaluation against alternative approaches.

Keywords: GPS-denied navigation, LiDAR-SLAM, unmanned aerial vehicle, jamming, fail-safe, terrain memory, autonomous safeguard

1. INTRODUCTION

Unmanned aerial vehicles operating in dense forest and mountainous terrain depend on GPS and RC link for virtually every aspect of navigation and safe recovery. Either link can fail independently — through jamming, through terrain and weather, or through physical damage to the receiver module — and a UAV with no independent means of localisation typically drifts, strikes terrain or vegetation, and is destroyed in the resulting fall.

Existing UAV fail-safes — terrain avoidance, terrain hugging, dual-GPS redundancy, autopilot return-to-home, including the manufacturer-published return-to-home behaviour of commercial platforms in this class — all remain dependent on GPS, and the manual RPV fallback additionally requires the

operator to retain radio line-of-sight. None of these mechanisms address the aircraft's exposure at the moment either link, not necessarily both, is first lost.

This paper makes three contributions:

- A fail-safe design in which navigation authority passes to an onboard safeguard the instant either GPS or RC signal is lost, rather than waiting for a compounded failure of both.
- ATMN, a modular LiDAR-SLAM based safeguard whose sensing and localization run continuously in the background throughout the sortie, so that engagement carries no cold-start delay, while remaining deliberately bounded in scope.
- A complete bill of materials, a power and weight budget calculated against a publicly specified commercial platform, and a comparative evaluation, showing this bounded scope to be the key design decision that keeps the system inexpensive relative to a fully autonomous alternative.

The remainder of this paper is organized as follows. Section 2 reviews related work in LiDAR-based navigation. Section 3 formulates the problem. Section 4 presents the ATMN architecture and design rationale. Section 5 details the implementation. Section 6 presents the power, weight and mission-impact analysis. Section 7 compares ATMN against alternative approaches. Section 8 discusses limitations. Section 9 concludes.

2. RELATED WORK

LiDAR-inertial odometry is a mature field. LOAM [2] established real-time LiDAR odometry and mapping and remains a foundational reference. FAST-LIO2 [1] introduced a tightly-coupled iterated Kalman filter fusing LiDAR and inertial measurements, capable of scan processing and map updates at rates approaching 100 cycles per second on low-power ARM hardware, and is adopted as the SLAM back-end for ATMN on account of its favorable balance of accuracy and computational efficiency for real-time onboard use. LIO-SAM [3] extends this line of work with factor-graph smoothing and loop closure, at higher computational cost. A benchmark study [4] comparing FAST-LIO2, LIO-SAM and related LiDAR-inertial methods across multiple real-world datasets found FAST-LIO2 to offer substantially lower per-scan computation time than LIO-SAM, while relative trajectory accuracy between the two varies by environment, corroborating the accuracy-efficiency trade-off motivating our choice of back-end.

Military application of airborne LiDAR for GPS-denied route planning dates to the BuckEye programme [5], operational since 2004 and used for terrain mapping in Iraq and Afghanistan. DARPA's Fast Lightweight Autonomy

programmed [6] demonstrated small UAVs navigating dense forests using low-power, commodity-class compute, and the Subterranean Challenge [7] was won by a system that fused LiDAR odometry with visual, thermal and inertial sensing for large-scale GPS-denied exploration, with LiDAR as one core component of that multi-modal architecture. The more recent PINPOINT programmed [8] explicitly frames reliance on GPS as a battlefield vulnerability. These programmers validate the underlying sensing and estimation techniques, generally in pursuit of fuller autonomy than is proposed in this paper.

The Indian Space Research Organization's Robotics Challenge has twice posed GPS-denied navigation as a competitive problem: the 2025 edition [9] required LiDAR-based terrain mapping for Mars-analogue landing without GPS, and the 2026 edition [10] extends this to swarm-based GPS-denied navigation. Separately, a 2025 study [11] developed a LiDAR-heightmap-based drift-correction method for long-range flight, reporting markedly lower positional drift than an uncorrected odometry baseline over kilometre-scale GNSS-denied routes, corroborating the viability of LiDAR-based approaches for long-range GNSS-denied navigation. The present work differs from [1]–[11] in scope rather than sensing technique: it deliberately restricts autonomy to a bounded, temporary safeguard rather than persistent independent navigation, for the cost reasons developed in Section 4.

3. PROBLEM FORMULATION

3.1 Operational Threat Model

This study uses the Pushpak hexacopter (OM UAV Systems, India) [13] as a concrete, publicly specified baseline for the power and weight calculations in Section 6. Pushpak is a commercially available platform marketed for both civilian and defense surveillance use, with a rated gross take-off weight of 5,800 g, a rated payload capacity of 1,000 g, a 6S/9,000 mAh LiPo battery, six BLDC motors, and a manufacturer-published endurance of 20 minutes at rated payload. The manufacturer states that avionics are common across its UAV catalogue, and its smaller Curiosity-series platforms are documented with a GPS-based return-to-home on communication loss and automatic landing on low battery, illustrating concretely that existing commercial fail-safes of this kind remain GPS-dependent. Although a hexacopter rather than a quadrotor, Pushpak's fully public specifications provide an independently verifiable basis for the calculations that follow. Pushpak is selected here solely as a representative, publicly documented reference point for comparison and calculation; this study does not claim, and should not be read as implying, that ATMN has been integrated with, tested on, or endorsed for use with this specific platform. Four distinct jamming conditions and their effect on a UAV of this general class are summarized in Table -1; these apply irrespective of rotor count.

Table -1: Jamming Taxonomy and Effect on UAV

Jamming Type	GPS	Comm Link	Effect on UAV
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GPS only	Denied	OK	Loses autonomous nav; manual control possible if in line-of-sight
Comms only	OK	Denied	Retains GPS nav; may execute autonomous RTH
GPS + comms	Denied	Denied	Loses navigation and control simultaneously; typically lost
Comms (GPS intact)	OK	Denied	GPS-based RTH remains functional

3.2 Limitations of Existing Safeguards

Every existing fail-safe on platforms of this class, including the manufacturer-documented return-to-home-on-communication-loss behavior common to the Pushpak manufacturer's UAV catalogue, remains dependent on an available GPS signal, as does the RPV fallback mode, which additionally requires the operator to retain radio line-of-sight. The capability gap addressed in this paper begins earlier than the point of complete failure: even the single-link-loss conditions of Table -1 (rows one, two and four) leave the aircraft with a materially degraded safety margin, since either autonomous navigation or operator intervention is already gone, and simultaneous loss (row three) leaves neither. ATMN is accordingly scoped to engage the instant either GPS or RC is lost, rather than waiting for both to fail together, so that the aircraft is never left relying on a single remaining thread of control.

4. PROPOSED SYSTEM: ATMN

4.1 System Architecture

ATMN rests on three components. A LiDAR sensor continuously scans the surrounding terrain, generating a live three-dimensional point cloud. A SLAM algorithm, FAST-LIO2 [1], fuses this point cloud with inertial measurements to localize the UAV within its own generated map. A Terrain Memory module, implemented with OctoMap [12], stores the corridor already flown as a three-dimensional occupancy map for retrace. The data path is: LiDAR point clouds are processed by FAST-LIO2 on an onboard NVIDIA Jetson Orin Nano; the resulting odometry updates the OctoMap-based Terrain Memory; hold-and-retrace commands are passed through MAVROS to MAVLink, which interfaces directly with the host flight controller through its existing payload interface, in the same manner as an interchangeable camera payload, without modification to certified flight-control software or the airframe. The LiDAR and SLAM stack run continuously throughout the sortie, regardless of GPS/RC status: the sensor is always scanning, and FAST-LIO2 is always updating the UAV's self-localisation and the Terrain Memory map in the background. This background process does not participate in flight control while GPS and RC remain available; it is navigation authority, not sensing, that is conditional. Because localisation is already running at the moment of engagement, there is no cold-start delay in establishing position when the safeguard activates.

4.2 Design Rationale: Safeguard-Only Autonomy

Two design approaches were considered. The first is a fully autonomous navigation system capable of independent path-planning and mission completion over arbitrary, previously unmapped terrain in the total absence of GPS and RC. The second is a bounded safeguard system that preserves the aircraft only until GPS or RC is restored. The former requires materially greater sensor redundancy, onboard compute, real-time obstacle avoidance over unmapped terrain, and a correspondingly higher certification burden, constituting in effect a distinct and considerably more expensive category of capability. The operational requirement formulated in Section 3 is loss prevention during a temporary outage, not persistent autonomous mission conduct; a bounded safeguard fully satisfies this requirement without the cost and technical risk of full autonomy. ATMN is accordingly scoped to engage autonomy only as a safeguard: it does not plan novel routes over unmapped terrain and does not attempt to independently complete the assigned mission. By replaying a corridor it has itself already recorded, rather than planning fresh routes, the system avoids the sensing, compute, and certification burden of full autonomy, and is deliverable within the modest bill of materials of Section 5 at a small fraction of the cost of a fully autonomous alternative.

4.3 Transition and Recovery Logic

The safeguard engages the instant any one of the thresholds in Table -2 is met and sustained for 10 seconds — GPS degradation and RC loss are each independently sufficient to trigger engagement, and the system does not wait for both to fail together. This lower activation threshold reflects the assessment in Section 3.2 that the aircraft is already at materially elevated risk on the loss of either signal alone.

Table -2: Safeguard Engagement Trigger Logic

Parameter	Threshold	Duration
HDOP	> 5	10 s
Satellites	< 4	10 s
RC link	Timeout	10 s

On engagement, ATMN holds position or retraces the recorded corridor toward the last point of reliable signal, whichever offers the more direct recovery, while continuously re-evaluating GPS and RC status. Control reverts automatically to the primary navigation source and the operator only once both GPS and RC are confirmed restored and stable, so that authority is not handed back on the strength of a single recovered link. If the entire recorded corridor is retraced without recovery, the UAV enters a terminal safeguard state, holding a stable loiter or executing a controlled landing within its own recorded map, rather than attempting navigation beyond its bounds. Manual RPV override takes precedence over the safeguard logic at every stage, the instant line-of-sight is regained.

5.IMPLEMENTATION

5.1 Hardware

The ATMN add-on comprises nine hardware line items, listed in Table -3, with a combined mass of 462.6 g, a combined power draw of 20.7 W, and a combined cost of ₹1,60,500 per unit, excluding the host platform.

Table -3: ATMN Hardware Bill of Materials

Component	Mass	Power	Cost
Livox MID-360 LiDAR	265 g	6.5 W	₹1,00,000
Jetson Orin Nano 8GB (10 W ECO)	69.6 g	10.0 W	₹40,000
NVMe SSD, 128 GB	8 g	1.2 W	₹3,000
DC-DC buck converter	18 g	1.0 W	₹2,500
Carbon fibre mounting bracket	35 g	0 W	₹8,000
Ethernet switch / interface	12 g	0.5 W	₹2,500
M12 connector and cabling	25 g	0 W	₹1,500
Thermal management	15 g	1.0 W	₹1,000
MAVROS/MAVLink electronics	15 g	0.5 W	₹2,000
Total	462.6 g	20.7 W	₹1,60,500

5.2 Software Stack

The software stack is entirely open-source: FAST-LIO2 [1] for SLAM, OctoMap [12] for occupancy mapping and Terrain Memory storage, and MAVROS/MAVLink for the flight-controller bridge, carrying no recurring licence cost. The Livox MID-360 LiDAR is presently sourced externally; the compute payload has an available indigenous alternative, and the software stack is entirely India-controlled.

6.ANALYSIS

6.1 Power Budget

Pushpak's manufacturer-published operating point is 599.4 W (derived below) at its rated gross take-off weight of 5,800 g, giving 20 minutes endurance. Our baseline configuration assumes a lighter existing mission payload of 400 g (camera and gimbal; not itemised by the manufacturer) rather than the full 1,000 g rated payload, giving a baseline flying weight of 5,200 g. Table -4 summarises the resulting power budget with ATMN fitted, across three Jetson performance modes, computed by scaling propulsion power with the established approximate relationship that propulsion power varies with weight to the power of 1.5.

Table -4: Power Budget by Jetson Mode (Pushpak Hexacopter)

Mode	AI Perf.	Total Power	Endurance	Reduction
10 W ECO (used)	34 TOPS	586.2 W	20.5 min	13.1%
15 W Default	40 TOPS	591.2 W	20.3 min	14.0%
25 W Super	67 TOPS	601.2 W	19.9 min	15.7%

Endurance is derived from $E = (W_{\text{batt}} / P_{\text{total}}) \times 60$, where W_{batt} is usable battery energy in watt-hours. Pushpak's 6S, 9,000 mAh battery gives $W_{\text{batt}} \approx 22.2 \text{ V} \times 9.0 \text{ Ah} = 199.8 \text{ Wh}$. Scaling the manufacturer's rated operating point (599.4 W at 5,800 g) down to the assumed 5,200 g baseline configuration gives a baseline of 508.7 W and 23.6 minutes endurance. Adding ATMN's own 20.7 W draw (10 W Jetson ECO mode) plus a weight-induced propulsion increase of 56.8 W, from the additional 462.6 g, gives a combined 586.2 W and 20.5 minutes endurance, a reduction of 13.1%. Because the LiDAR and SLAM stack run continuously throughout the sortie regardless of trigger state (Section 4.1), this figure represents standard operation, not a worst case that improves if the safeguard is rarely triggered.

6.2 Weight Budget

Table -5 details the weight budget against Pushpak's rated 5,800 g gross take-off weight, yielding a margin of 137.4 g (2.4% of MTOW, equivalently 13.7% of the 1,000 g rated payload budget), narrower than the 5–10% margin typically recommended for stable flight, and flagged as a limitation in Section 8.

Table -5: Weight Budget

Component	Mass	Share
Empty weight (airframe, motors, ESCs, battery, FC)	4,800 g	82.8%
Existing mission payload (camera + gimbal, assumed)	400 g	6.9%
ATMN add-on	462.6 g	8.0%
Total	5,662.6 g	97.6%
Margin (of 5,800 g MTOW)	137.4 g	2.4%

6.3 Mission Impact

Table -6 summarises the resulting mission-level impact, reflecting standard continuous operation of the LiDAR/SLAM background stack described in Section 4.1.

Table -6: Mission Profile Impact

Parameter	Baseline	With ATMN	Impact
Total power	508.7 W	586.2 W	+15.2%
Endurance	23.6 min	20.5 min	−13.1%
Payload margin remaining (of 1,000 g rated)	600 g	137.4 g	−77.1%
Loss prevention on either-link denial	No	Yes	New

7.COMPARATIVE EVALUATION

Table -7 compares ATMN against alternative approaches to the problem formulated in Section 3

Table -7: Comparative Assessment of Alternative Approaches

Approach	Assessment
Anti-jam GPS receiver	Remains vulnerable to spoofing; costs approx. ₹5–8 lakh per unit, several times the ATMN cost
Visual-inertial odometry	Fails in low light, fog, and visually uniform forest canopy characteristic of the theatre
Inertial navigation alone	Drifts approx. 1–2% of distance per minute without external correction
Fully autonomous BVLOS	Requires materially greater sensor redundancy, compute, and certification effort disproportionate to the loss-prevention requirement
ATMN (proposed)	Independent of external signals; engages only as a temporary safeguard; modest bill of materials by design

Visual-inertial odometry was assessed in particular detail for its lower cost relative to LiDAR, but was not adopted because active LiDAR sensing does not depend on ambient light or scene texture, both frequently absent under forest canopy and during night operations. Fully autonomous beyond-visual-line-of-sight (BVLOS) navigation was set aside for the reason developed in Section 4.2: the operational requirement is loss prevention, not persistent autonomous mission conduct, and full autonomy carries a disproportionate cost for that narrower requirement. A further advantage of the proposed approach is

that, unlike radio-frequency-based anti-jam solutions, it emits no radio-frequency signal exploitable for hostile direction-finding.

8. LIMITATIONS

LiDAR performance degrades beyond approximately 50 m in heavy rainfall, relevant during the monsoon; abort protocols for extreme weather remain to be defined. The LiDAR sensor is presently externally sourced, though the compute and software stack are not. The data-storage requirement of Terrain Memory for extended sorties has not yet been quantified and remains outstanding. The 2.4% weight margin on the Pushpak baseline (Section 6.2) is narrower than the 5–10% typically recommended, and should be re-verified empirically rather than assumed adequate from the calculation alone; a lighter mission payload than the 400 g assumed here would restore a more comfortable margin. Finally, the bounded design of Section 4.2 deliberately does not preserve mission continuity beyond loss prevention; operators should be briefed accordingly.

9. CONCLUSIONS

This paper presented ATMN, a modular LiDAR-SLAM fail-safe that prevents UAV loss on the loss of either GPS or RC link, without incurring the cost of full autonomy. Its sensing and localisation run continuously in the background throughout the sortie, so engagement carries no cold-start delay, while its bounded scope — holding and retracing a self-recorded corridor, and handing control back automatically only once both signals are confirmed restored — keeps it deliverable within a 462.6 g, 20.7 W, ₹1.6 lakh add-on. This was illustrated using a publicly specified commercial platform (Pushpak hexacopter), selected solely as a representative reference point for comparison and calculation, and supported by established LiDAR-SLAM literature and military and space-agency GPS-denied navigation programmes. Future work includes hardware-in-the-loop validation of the transition logic, empirical re-verification of the weight margin identified in Section 8, field trials in representative terrain, quantification of Terrain Memory storage requirements for extended sorties, and evaluation of indigenous LiDAR alternatives to reduce import dependency.

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