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AUTONOMOUS UAV NAVIGATION WITHOUT GNSS

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ABSTRACT

Reliable navigation in GNSS-denied environments remains a major challenge for small unmanned aerial vehicles. When satellite signals are lost or degraded, the vehicle must rely entirely on onboard sensing to maintain control and return safely. This work presents a lightweight fallback navigation framework that combines inertial dead reckoning and optical flow-based velocity estimation. Both methods were implemented and tested in the PX4 Software-in-the-Loop environment with Gazebo, allowing safe and repeatable evaluation under simulated wind and signal-loss conditions. Results show that dead reckoning ensures short-term stability but accumulates large drift over distance, while optical flow navigation provides meter-level accuracy over multi-kilometer trajectories. Together, they offer a practical and fully autonomous alternative to GNSS for small UAVs operating in constrained or adversarial environments.

Keywords: GNSS-denied navigation, UAV, dead reckoning, optical flow, PX4, Gazebo simulation.

Introduction

Unmanned aerial vehicles (UAVs) rely primarily on the Global Navigation Satellite System (GNSS) to obtain absolute position and

velocity estimates for flight control. However, GNSS signals are easily degraded or lost in many real-world environments, such as dense urban areas, forests, or indoor spaces, and can be intentionally disrupted through jamming or spoofing. When this occurs, a UAV rapidly loses its ability to maintain global position control and execute autonomous missions. Ensuring continued operation under such conditions requires fallback navigation methods that function entirely onboard and without external references.

Modern open-source autopilots, such as PX4 [1] and ArduPilot [2], maintain a stable attitude and altitude using inertial and barometric feedback, but disable position-controlled modes once GNSS data is lost. The vehicle remains flyable but effectively blind in the horizontal plane. To restore autonomous behavior, alternative sources of motion information must replace GNSS in the state estimator. Among available options, dead reckoning and optical flow-based navigation stand out for their simplicity, low cost, and real-time feasibility on lightweight UAV hardware. Both methods can operate within the computational and sensor constraints of standard flight controllers, providing short to mid-range navigation capability without any external infrastructure.

This article presents a compact, fully onboard fallback navigation framework that integrates dead reckoning and optical flow velocity estimation within open-source autopilot systems. The framework enables seamless transitions between GNSS-available and GNSS-denied flight, maintaining control continuity and allowing the UAV to return safely or continue its mission when satellite positioning fails.

Related Work

A wide range of methods have been explored for GNSS-denied navigation, generally falling into four categories: inertial dead reckoning, optical flow navigation, visual-inertial odometry (VIO), and simultaneous localization and mapping (SLAM).

dead reckoning estimates position by integrating inertial sensor data – accelerations and angular rates – from the onboard IMU [3], [4]. It offers very low computational cost but suffers from unbounded drift due to sensor

bias and noise accumulation. Various improvements, including bias-compensated Kalman filters and recurrent neural network models [5], have been proposed to slow error growth, though they remain sensitive to long-term integration.

Optical flow navigation determines ground-relative velocity by measuring pixel displacements between consecutive image frames [6]. When combined with altitude data from a barometer or range sensor, it yields metric-scale velocity that can substitute GNSS velocity inputs in the estimator. This approach is lightweight and effective at low altitude but limited by lighting and surface texture.

Visual-inertial odometry and SLAM methods achieve higher accuracy and long-term consistency by jointly optimizing visual and inertial constraints [7]–[14]. However, they depend on continuous visual features and high-performance hardware, restricting real-time onboard use in open-source flight stacks.

Proposed Method

The proposed fallback navigation framework activates when GNSS updates are unavailable and replaces global positioning data with internally estimated motion cues. It relies on two complementary sources of information: inertial measurements for short-term motion prediction and optical flow for ground-referenced velocity estimation. These methods operate independently but can be combined in a layered structure to maintain continuous control during GNSS loss.

A. Inertial dead reckoning

When GNSS becomes unavailable, a UAV can still estimate its motion by integrating inertial and heading measurements over time. This process—known as *dead reckoning*—relies solely on data from the inertial measurement unit (IMU), magnetometer, and barometer. The IMU provides accelerations and angular rates, the magnetometer constrains yaw, and the barometer supplies altitude. These signals are fused in the autopilot's Extended Kalman Filter (EKF) [15], which continues to predict the vehicle's state even without external position updates.

Because integration errors grow rapidly, conventional dead reckoning becomes unreliable after only a short distance. To extend its usable range, the proposed framework augments the estimator with a calibrated speed model and mission-aware vector tracking.

During nominal (GNSS-available) flight, the UAV performs a short calibration sequence in which it flies at constant pitch angles while its true ground speed is recorded. This produces a mapping between commanded pitch angle and forward velocity. Once GNSS is lost, the UAV can approximate its displacement by multiplying this stored velocity with elapsed time, while maintaining heading from the magnetometer.

Two modes of operation are supported:

- **Direct Return-to-Launch (DirectRTL):** the UAV aligns to the home azimuth and flies straight using dead-reckoned distance estimation;
- **Path Return-to-Launch (PathRTL):** the UAV retraces its logged outbound path using stored inter-waypoint vectors, reducing accumulated drift.

B. Optical Flow-Based Navigation

Optical flow navigation estimates the vehicle's horizontal motion by observing how surface patterns move within consecutive camera frames. A downward-looking camera captures the apparent displacement of visual features as the UAV moves; from these displacements, image-plane velocities are computed. When the altitude above ground is known, these angular motions can be converted into metric ground-relative velocities.

This method effectively replaces the need for GNSS-based velocity or position updates during flight. Because the camera measures motion directly relative to the ground, it provides drift-free short-term information that allows the vehicle to stabilize or retrace recent trajectories. optical flow sensors typically include a small processor and a rangefinder, enabling onboard calculation of two-dimensional velocity without heavy computation.

In operation, horizontal velocity derived from optical flow is combined with barometric altitude and inertial orientation to reconstruct the

UAV's motion in local coordinates. As long as the ground surface exhibits sufficient texture and lighting, these measurements remain consistent over time. Unlike dead reckoning, where integration errors grow rapidly, optical flow navigation constrains drift to a near-linear rate and can maintain meter-level accuracy over hundreds of meters of travel.

The method's performance degrades over uniform surfaces, water, or at high altitude, where ground features become indistinct. Wind and rapid attitude changes can also distort apparent motion. Nevertheless, within moderate altitude and lighting conditions, optical flow navigation offers a lightweight and robust fallback option that extends autonomous flight well beyond the limits of inertial dead reckoning.

Results

A. Simulation environment

All experiments were conducted in simulation to ensure repeatability and safety during GNSS-denied flight. The evaluation used the PX4 Software-in-the-Loop (SITL) [16] environment with Gazebo Classic [17] as the physics simulator. Both dead reckoning and optical flow navigation modes were implemented using the same control logic and vehicle model. The simulated quadrotor reproduced the sensor suite of a typical field platform, including IMU, magnetometer, barometer, and a downward-facing optical flow sensor with a rangefinder.

GNSS data were disabled after takeoff to emulate the loss of satellite signals. The vehicle then executed return-to-launch maneuvers at different distances (0.1km - 3km) and under varying wind conditions (0m/s, 2m/s, and 5m/s). Each test was repeated twice for consistency. The mean deviation from the starting point was used as the error metric.

B. Dead reckoning performance

In dead reckoning mode, the UAV estimated its displacement by integrating calibrated forward velocity and heading over time.

Results showed that the error grows rapidly with both distance and wind intensity. For short-range returns ($\leq 100\text{m}$), position error remained

below 20m even with mild wind, but at larger scales it became dominant, exceeding 1.5km at 3km flight distance. The key driver of error was heading drift from the magnetometer, amplified by uncompensated wind effects.

Table 1.

Mean return-to-launch error for dead reckoning simulation tests in Gazebo SITL

Distance		0.1km			0.5km			1km			3km		
Wind speed		0m/s	2m/s	5m/s	0m/s	2m/s	5m/s	0m/s	2m/s	5m/s	0m/s	2m/s	5m/s
Pitch	5°	15m	45m	>50m	40m	>250m	>250m	81m	>500m	>500m	178m	>1.5km	>1.5km
	10°	14m	39m	>50m	44m	180m	>250m	66m	>500m	>500m	192m	>1.5km	>1.5km
	15°	12m	33m	48m	30m	74m	150m	63m	204m	>500m	167m	>1.5km	>1.5km
	25°	17m	22m	38m	25m	33m	106m	71m	152m	400m	194m	307m	>1.5km

These results indicate that while dead reckoning ensures controllability after GNSS loss, it can only support short-range recovery or bridging until another aiding source becomes available.

C. Optical Flow Performance

When optical flow measurements were enabled, the UAV replaced inertial velocity estimation with image-based ground-relative motion. This significantly constrained drift and allowed accurate return trajectories even over kilometer-scale flights.

Table 2 summarizes mean position errors for both DirectRTL and PathRTL strategies under identical conditions. The optical flow-based navigation reduced errors by nearly an order of magnitude compared to dead reckoning. Even with moderate wind, deviations remained within 5-7% of the traveled distance.

Table 2.

DirectRTL and PathRTL errors for Optical Flow Navigation

Distance	0.1km			0.5km			1km			3km		
Wind speed	0m/s	2m/s	5m/s	0m/s	2m/s	5m/s	0m/s	2m/s	5m/s	0m/s	2m/s	5m/s
Direct RTL error	1m	4m	19m	6m	21m	28m	13m	43m	82m	32m	74m	113m
Path RTL error	1m	7m	26m	8m	31m	47m	27m	67m	94m	66m	105m	146m

Table 2 summarizes mean position errors for both DirectRTL and PathRTL strategies under identical conditions. The optical flow-based navigation reduced errors by nearly an order of magnitude compared to dead reckoning. Even with moderate wind, deviations remained within 5-7% of the traveled distance.

The results show near-linear drift growth and consistent convergence toward the launch point. Path retracing produced slightly larger cumulative error due to multiple short segments, but provided smoother overall flight behavior. At higher altitudes or over visually uniform terrain, performance degraded as the simulated flow sensor lost feature contrast

Conclusion

This study presented a lightweight fallback navigation framework for unmanned aerial vehicles operating in GNSS-denied conditions. Two complementary methods—dead reckoning and optical flow navigation—were implemented and evaluated entirely in simulation using the PX4 SITL environment with Gazebo.

Dead reckoning, based on inertial and magnetic sensing, provided short-term controllability but exhibited rapid drift growth with distance and wind. optical flow navigation, which derives ground-relative velocity from image motion and altitude, achieved an order-of-magnitude improvement in accuracy and enabled reliable return-to-launch maneuvers over distances up to several kilometers. The results confirm that combining these techniques forms a practical, fully onboard solution for maintaining UAV autonomy during temporary or extended GNSS outages. Future work will focus on adaptive fusion between optical and inertial cues, as well as validation in real-world outdoor flights.

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АВТОНОМНАЯ НАВИГАЦИЯ БПЛА БЕЗ GNSS

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АННОТАЦИЯ

Надежная навигация в условиях отсутствия сигналов спутниковых навигационных систем остаётся серьёзной задачей для малых беспилотных летательных аппаратов. При потере или ухудшении сигнала GNSS аппарат должен полностью полагаться на бортовые датчики для поддержания управления и безопасного возвращения. В работе представлен облегченный резервный навигационный комплекс, объединяющий инерциальный метод счисления пути и определение скорости по оптическому потоку. Оба метода реализованы и протестированы в среде программной симуляции PX4 (SITL) с использованием физического моделирования Gazebo, что позволило проводить безопасные и воспроизводимые испытания при имитации ветра и потери сигналов. Результаты показывают, что инерциальное счисление пути обеспечивает кратковременную устойчивость, но быстро накапливает погрешность, тогда как навигация по оптическому потоку обеспечивает метровую точность на многокилометровых дистанциях. Совместное использование этих подходов обеспечивает практичную и полностью автономную альтернативу GNSS для малых БПЛА, работающих в сложных условиях.

Ключевые слова: навигация без GNSS, беспилотный летательный аппарат, счисление пути, оптический поток, PX4, симулятор Gazebo.