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Dead Reckoning Method for an Unmanned Aerial Vehicle in Conditions of Limited GPS Signal

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ABSTRACT: The article presents a dead reckoning navigation method dedicated to unmanned aerial vehicles (UAVs), enabling position determination under limited GNSS signal access. The method is based on the analysis of data from inertial measurement units (IMUs) and mathematical algorithms, allowing for precise monitoring of UAV trajectories. The study outlines the theoretical foundations of dead reckoning navigation, the derivation of key formulas, and the results of simulation tests of the method based on real inertial sensor data logs. The tests demonstrated promising effectiveness, highlighting its potential in military and civilian applications. The method can serve as a complement to traditional navigation systems.

1 INTRODUCTION

The dead reckoning navigation method offers an innovative approach to localising unmanned aerial vehicles (UAVs) in environments where GPS signals are disrupted or unavailable. Utilising data from inertial measurement units (IMUs) and advanced mathematical algorithms enables the estimation of UAV positions and trajectories, eliminating the reliance solely on external signals. As a result, it becomes an essential tool in scenarios where traditional navigation systems fail, such as military operations or missions in remote and challenging areas.

This study aims to demonstrate the effectiveness of the dead reckoning navigation method in UAV applications. The research compares various sensor data processing algorithms and evaluates their performance in real-world test scenarios. The experiments are intended to demonstrate the potential of the dead reckoning method as a reliable navigation tool under conditions of limited GNSS access. Furthermore, the study explores integrating this method with other navigation techniques to enhance the accuracy and reliability of autonomous UAV systems.

2 RELATED WORKS

Hou and Bergmann [1] introduced a pedestrian dead reckoning (PDR) method designed for head-mounted sensors, utilising the natural stabilisation of the head during movement to enhance accuracy. Their solution achieved an average positional error of 0.88 m, demonstrating the potential of head-mounted devices in applications such as sports, rescue operations, and smart environments.

At the 2024 International Conference on Indoor Positioning and Indoor Navigation [2], a comparative analysis of pedestrian dead reckoning algorithms highlighted the challenges and opportunities of using inertial data for accurate localisation. The study underscored the limitations of dead reckoning in GNSS-denied environments due to cumulative errors and explored methods for mitigating these inaccuracies. The authors emphasised the critical role of algorithm adaptability in optimising performance across varying operational conditions. Their findings underscore the potential of integrating dead reckoning with complementary technologies to enhance positioning accuracy in diverse environments, offering insights highly relevant to UAV navigation.

This study applies the dead reckoning method to UAV systems, extending its use beyond pedestrian localisation. Unlike the previous studies, which emphasise wearable sensors and pedestrian dynamics, this research employs the Madgwick filter, offering a computationally efficient solution suitable for UAV operations under dynamic conditions and limited GNSS availability.

3 DEAD RECKONING

3.1 *Definition of dead reckoning*

Dead reckoning navigation is a method for determining the current position of an object based on its last known location, the direction of movement, and the distance travelled, taking into account speed and time. This process relies on iterative calculations of successive positions without needing external navigation systems like GPS.

This navigation model is applicable in mobile sensor networks, where localization must be determined autonomously, and navigation data are calculated using the available motion parameters. This technique is particularly useful in mobile systems, such as UAVs, where external signals are disrupted [3].

In dead reckoning navigation for UAVs, it is crucial to account for the influence of wind on positional accuracy. Wind can cause the vehicle to drift from its planned trajectory, accumulating errors in position estimation. To correct these deviations, velocity vectors are used. The current position P(t) can be determined based on the previous position P(t-1), time Δt, and the sum of these vectors:

$$P_{(t)} = P_{(t-1)} + \Delta t \cdot \left(\overrightarrow{v_a} + \overrightarrow{v_w} \right) \quad (1)$$

where:
$P_{(t)}$ – current position of the object
$P_{(t-1)}$ – last known position of the object
Δt – time difference between position measurements
$\overrightarrow{v_a}$ – velocity vector of the object relative to the air
v_w – velocity vector of the wind

The accuracy of this method depends on precise measurements of both the velocity relative to the air and the wind's speed and direction. Therefore, in practical navigation, continuously monitoring atmospheric conditions and updating input data are essential to ensure the highest possible accuracy of dead reckoning navigation under variable environmental conditions.

3.2 *Inertial sensors*

To ensure the precision of dead reckoning navigation under limited GPS signal conditions, using accurate measurement data provided by onboard systems is crucial. Inertial sensors play a fundamental role, enabling the monitoring of motion and orientation of UAVs in space.

The inertial measurement unit (IMU), an integral component of the dead reckoning navigation system, consists of several key elements, each providing unique data that supports the estimation of an object's position and trajectory:

- A gyroscope measures angular velocities around axes, allowing the determination of changes in the UAV's orientation in space.
- An accelerometer records linear accelerations along three axes, enabling the calculation of the object's velocity and displacement.
- A magnetometer measures the Earth's magnetic field, facilitating the determination of spatial direction and orientation relative to the magnetic pole.
- A barometer measures atmospheric pressure, aiding in altitude determination based on pressure variations.

The data provided by these sensors are subsequently integrated and processed using advanced mathematical algorithms, allowing precise tracking of UAV trajectories even under dynamically changing environmental conditions.

4 METHODOLOGY

4.1 *Sensor fusion*

The sensor fusion process is a critical component of data processing in inertial systems, enabling consistent and precise information about an object's state in space. Each sensor generates data with distinct characteristics and noise levels; thus, their integration ensures mutual compensation of imperfections and enhances result quality.

In dead reckoning navigation, this process involves filtering and integrating data from the gyroscope, accelerometer, magnetometer, and barometer to determine parameters such as orientation, linear acceleration, and angular velocities. Complementary filtering, a widely used approach, combines measurements from various sensors, reducing the impact of noise and drift.

This study employs the Madgwick filter, known for its rapid convergence and stable system state estimations. This algorithm is based on gradient optimisation of the object's orientation using inertial data. Although its implementation is more complex than traditional methods, it offers significant advantages in systems requiring high precision, such as UAV navigation [4].

Data fusion allows for precisely determining an object's tilt angles, enabling accurate trajectory control and navigation in challenging conditions.

4.2 *Linear acceleration*

The linear acceleration of the platform is calculated using data from inertial sensors. These sensors provide raw acceleration data along the XYZ axes, which are trans-formed into a one-dimensional linear acceleration value using mathematical formulas. The coordinate system (Fig. 1) is centred at the UAV's centre of mass, with the X-axis aligned with the drone's movement direction, the Y-axis perpendicular in the horizontal plane, and the Z-axis aligned with gravitational acceleration. This system moves with the platform as the reference for all acceleration measurements.

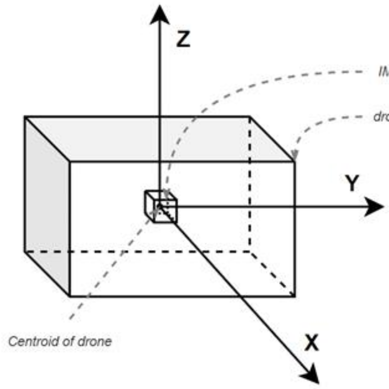

Figure 1. Coordinate system for UAV and IMU

One of the fundamental methods involves using the sum of the squares of acceleration components along each axis:

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{2}$$

where:
a – linear acceleration
a_x, a_y, a_z – acceleration along the individual axes of the XYZ coordinate system

This value represents the resultant acceleration of the object in space; however, accelerometer data also include a component related to gravitational attraction. To accurately determine the drone's displacement relative to the Earth's surface, it is necessary to compensate for the effect of gravity on accelerometer readings. This is achieved by using a gyroscope and magnetometer to determine the object's orientation relative to gravity's direction, separating motion-induced acceleration from the gravitational force [5]. This process involves transforming accelerometer readings along the XYZ axes using appropriate corrections:

$$\begin{cases} a_{xc} = a_x - g \cdot \sin\left(\theta_{pitch}\right) \\ a_{yc} = a_y + g \cdot \sin\left(\theta_{roll}\right) \cdot \cos\left(\theta_{pitch}\right) \\ a_{zc} = a_z + g \cdot \cos\left(\theta_{roll}\right) \cdot \sin\left(\theta_{pitch}\right) \end{cases} \tag{3}$$

where:
a_{xc}, a_{yc}, a_{zc} – compensated accelerations along the XYZ axes
g – gravitational acceleration constant
θ_{pitch} – pitch angle in the XY plane
θ_{roll} – roll angle in the YZ plane

This compensation eliminates the effect of gravity, which is crucial for accurately determining motion-induced acceleration. As a result, the input data for dead reckoning navigation algorithms are more precise, leading to more accurate trajectory estimations. Moreover, this approach in UAV systems enhances their reliability in environments with dynamically changing conditions, such as wind gusts or rapid manoeuvres.

4.3 *Determination of displacement*

To apply the dead reckoning navigation method, precise determination of linear acceleration a (Formula 2) is essential, including compensation for the effect of gravitational acceleration on the XYZ axes (Formula 3).

Linear velocity v is calculated through discrete integration of linear acceleration a. The navigation system reads inertial sensor data at equal time intervals Δt, necessitating an iterative integration process expressed by the formula:

$$v\left(t_k\right) = v\left(t_{k-1}\right) + a\left(t_k\right) \cdot \Delta t \tag{4}$$

where:
$v(t_k)$ – velocity at time t_k
$a(t_k)$ –acceleration at the time t_k
Δt – time interval between date readings

It is important to emphasise that onboard inertial sensors provide information only about the object's velocity relative to the surrounding medium, which in the case of aerial vehicles refers to airspeed. The omission of the wind velocity vector in such calculations leads to the accumulation of measurement errors, especially during long-duration operations.

The integrated linear velocity allows for the subsequent calculation of the distance travelled by the object over a specified period. For aerial vehicles, a critical aspect is the separation of horizontal displacement from altitude changes, eliminating the influence of altitude variation on the total distance. The horizontal distance can be calculated using the relation derived from the Pythagorean theorem:

$$s = \sqrt{\left(v \cdot t\right)^2 - \Delta h^2} \tag{5}$$

where:
s – horizontal distance travelled
Δh – altitude difference

Separately addressing horizontal and vertical components in calculations increases the precision of trajectory estimation, particularly in dynamically changing flight conditions. However, uncertainties stemming from the lack of wind velocity vector information remain a challenge.

4.4 *Angular calculations*

The displacement in meters is converted into geographic coordinates by transforming the heading into radians and calculating the divisors for latitude and longitude. In dead reckoning navigation, this process requires accounting for the variability of the metric length of a degree of latitude and longitude depending on the Earth's position. This consideration is critical because the Earth's shape as a geoid causes the metric length of a degree of longitude to decrease with increasing distance from the equator [6].

For the calculation of divisors of longitude and latitude, you can use the following formula:

$$\begin{cases} D_s = \left(\dfrac{2\pi \cdot R_M}{360}\right) \cdot P_s \\ D_d = \left(\dfrac{2\pi \cdot R_E}{360}\right) \cdot \dfrac{90 - P_d}{90} \end{cases} \tag{6}$$

where:
D_s, D_d – divisors for latitude and longitude, respectively
R_M, R_E – radii of the meridian and equator, respectively
P_s, P_d – previous latitude and longitude, respectively

Based on these values, you can determine geographic coordinates for the final location with the formulas:

$$\begin{cases} L_s = P_s + \dfrac{s}{D_s} \cdot \cos(\theta) \\ L_d = P_d + \dfrac{s}{D_d} \cdot \sin(\theta) \end{cases} \tag{7}$$

where:
L_s, L_d – current location (latitude and longitude, respectively)
θ – heading expressed in radians

These formulas allow for the precise determination of the object's current position, considering the impact of local geographic conditions and trajectory.

5 EXPERIMENT

5.1 *Procedure*

To evaluate the effectiveness of the dead reckoning algorithm, test flights were con-ducted using a DJI Mini 3 drone with an IMU and GPS module. The experiment simulated diverse navigation conditions to ensure the GPS signal stability, including environmental variations and flight dynamics, in areas with minimal terrain obstacles.

The recorded flight data included IMU readings, altitude information from the barometer, and GPS coordinates as a reference for accuracy evaluation.

The algorithm processed real-time data, integrating acceleration to calculate velocity and position. Simulations covered ideal conditions and disruptions, such as wind effects and sensor errors. For data analysis, a Python script was developed to integrate sensor data and process it using the following libraries:
– NumPy - numerical operations,
– pandas - managing and analysing log data,
– Matplotlib - visualising results, including flight trajectories, deviations from reference coordinates, and error histograms.

5.2 *Test cases*

The experiment included two main scenarios to examine the impact of different data processing strategies on the accuracy of dead reckoning navigation:

1. Scenario without GPS updates: The navigation algorithm operated solely based on inertial sensor data, starting from known initial coordinates. In this case, calculations were performed without subsequent GPS updates, simulating a complete loss of GNSS signal. This scenario assessed the error accumulation rate due to sensor drift and its effect on final accuracy.
2. Scenario with periodic GPS updates: The algorithm started from the same initial coordinates but updated its position every 15 seconds using GPS data to correct deviations from the actual trajectory. This scenario aimed to evaluate the effectiveness of GPS data integration in minimising navigation errors.

Three experiments were conducted for each scenario. Fig. 2, Fig. 3 and Fig. 4 illustrate the results for Scenario 1, while Fig. 5, Fig. 6 and Fig. 7 present the results for Scenario 2.

5.3 *Experiment results*

5.3.1 *Scenario without GPS updates - Flight No. 1*

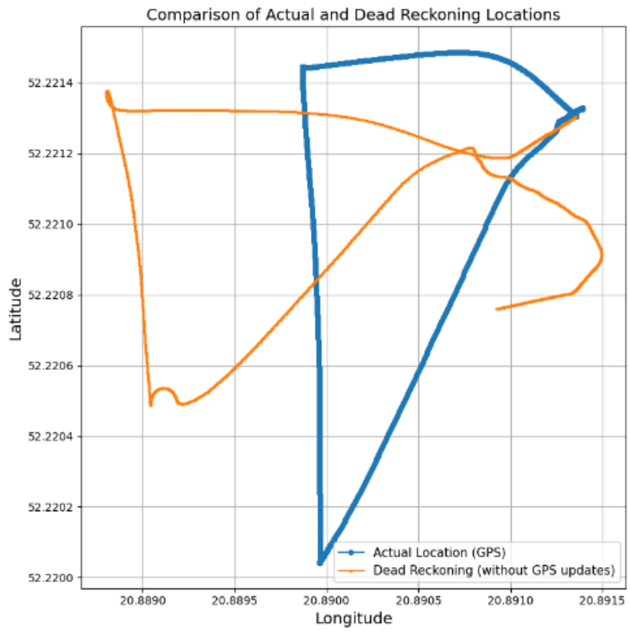

Figure 2. Comparison of the actual and computed trajectory for Flight No. 1 in the scenario without GPS updates

Table 1. MSE, MAE, and Maximum Error for Flight No. 1 in the Scenario 1

Error	Value	
MSE	0.000704 [°]	78.32 [m]
MAE	0.000592 [°]	65.95 [m]
Maximum Error	0.001209 [°]	134.59 [m]

5.3.2 *Scenario without GPS updates - Flight No. 2*

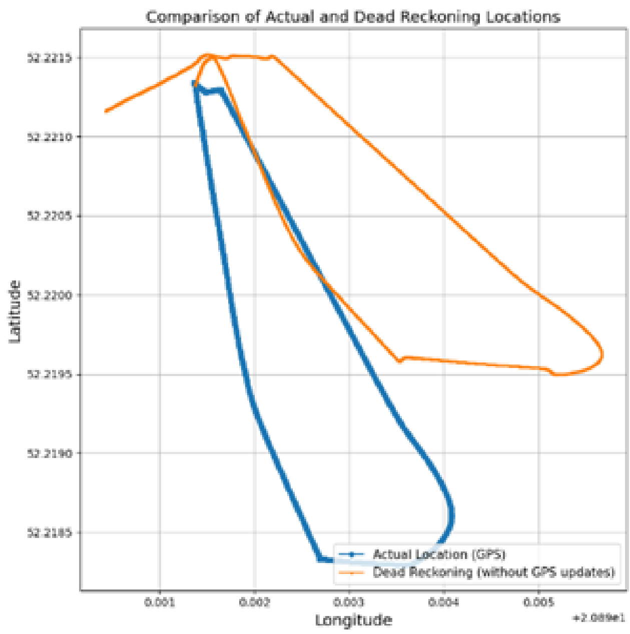

Figure 3. Comparison of the actual and computed trajectory for Flight No. 2 in the scenario without GPS updates

Table 2. MSE, MAE, and Maximum Error for Flight No. 2 in the Scenario 1

Error	Value	
MSE	0.001188 [°]	132.24 [m]
MAE	0.000988 [°]	110.04 [m]
Maximum Error	0.002209 [°]	245.95 [m]

5.3.3 *Scenario without GPS updates - Flight No. 3*

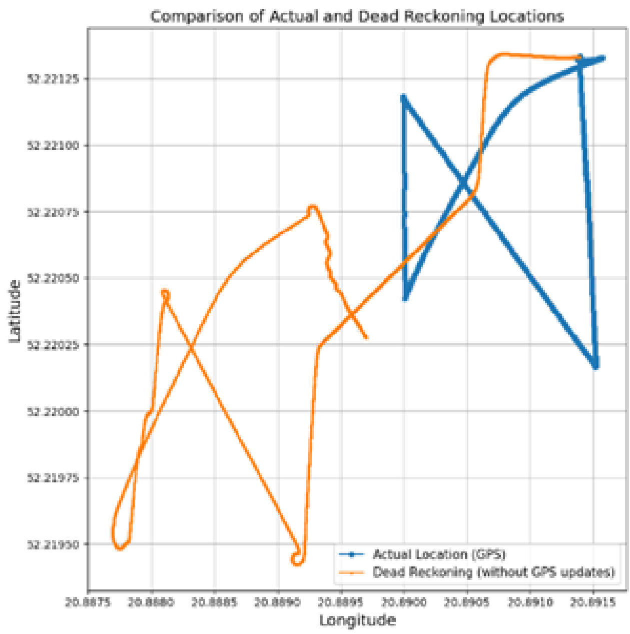

Figure 4. Comparison of the actual and computed trajectory for Flight No. 3 in the scenario without GPS updates

Table 3. MSE, MAE, and Maximum Error for Flight No. 3 in the Scenario 1

Error	Value	
MSE	0.000704 [°]	78.32 [m]
MAE	0.000592 [°]	65.95 [m]
Maximum Error	0.001209 [°]	134.59 [m]

5.3.4 *Scenario with periodic GPS updates - Flight No. 1*

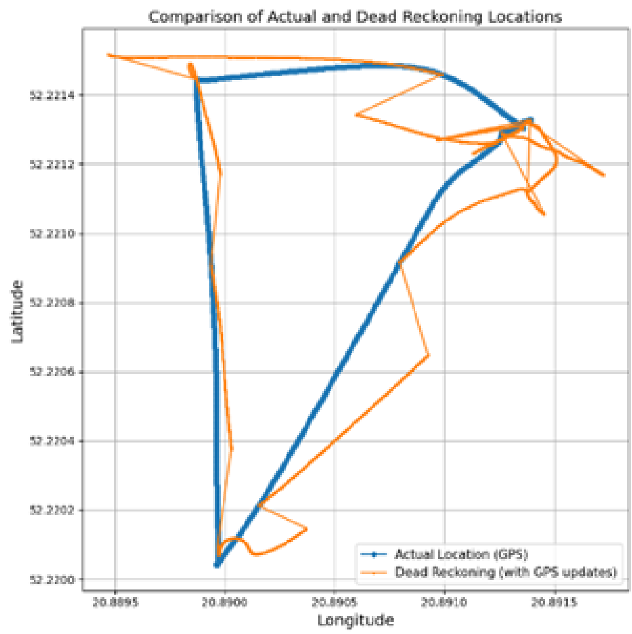

Figure 5. Comparison of the actual and computed trajectory for Flight No. 1 in the scenario with periodic GPS updates

Table 4. MSE, MAE, and Maximum Error for Flight No. 1 in the Scenario 2

Error	Value	
MSE	0.000191 [°]	21.24 [m]
MAE	0.000144 [°]	16.05 [m]
Maximum Error	0.000499 [°]	55.58 [m]

5.3.5 *Scenario with periodic GPS updates - Flight No. 2*

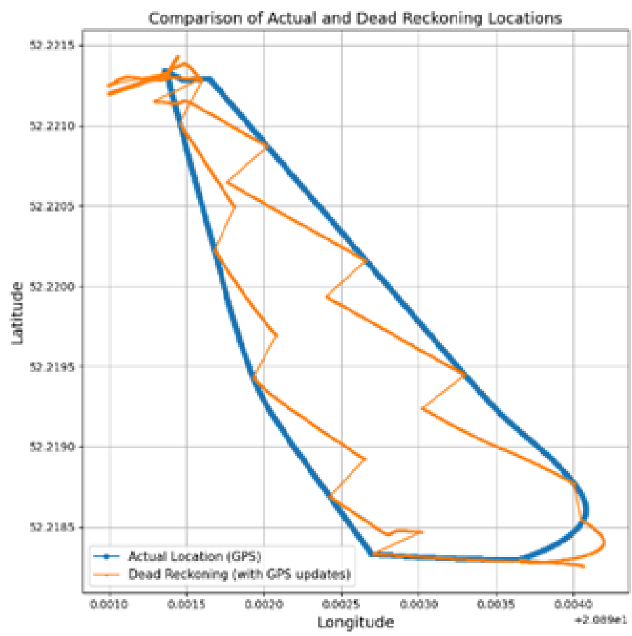

Figure 6. Comparison of the actual and computed trajectory for Flight No. 1 in the scenario with periodic GPS updates

Table 5. MSE, MAE, and Maximum Error for Flight No. 2 in the Scenario 2

Error	Value	
MSE	0.000196 [°]	21.86 [m]
MAE	0.000158 [°]	17.59 [m]
Maximum Error	0.000489 [°]	54.42 [m]

5.3.6 *Scenario with periodic GPS updates - Flight No. 3*

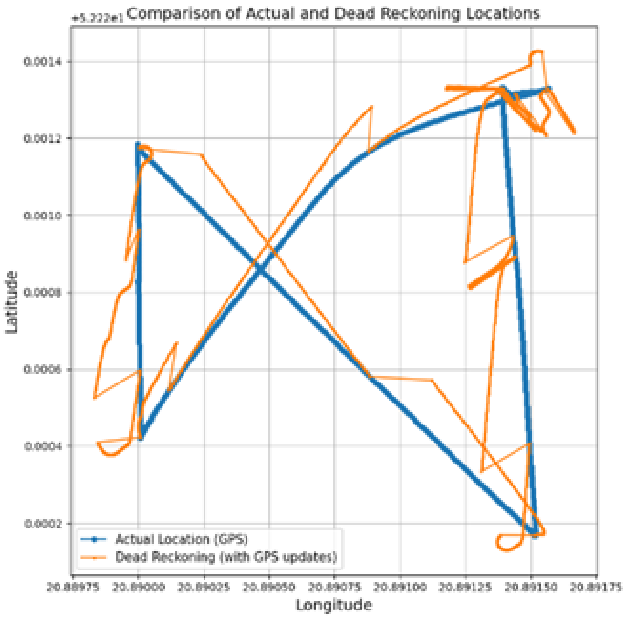

Figure 7. Comparison of the actual and computed trajectory for Flight No. 3 in the scenario with periodic GPS updates

Table 6. MSE, MAE, and Maximum Error for Flight No. 3 in the Scenario 2

Error	Value	
MSE	0.000106 [°]	11.82 [m]
MAE	0.000085 [°]	9.51 [m]
Maximum Error	0.000268 [°]	29.87 [m]

5.4 *Analysis of results*

The studies that were conducted revealed significant limitations of the dead reckoning navigation system, particularly in scenarios without GPS updates. Based on the results, including MSE, MAE, and maximum deviations, noticeable differences in positional estimation accuracy were observed depending on the availability of external reference data. For Flight No. 1 in the scenario without GPS updates, the mean squared error (MSE) was 78.32 m (Table 1), whereas, in the analogous scenario with periodic updates, it decreased to 21.24 m (Table 4), representing a reduction of over 70%.

The trajectory comparison plots (Fig. 2, …, Fig. 7) clearly show that navigation errors increase significantly over time in scenarios without GPS updates. In contrast, cases with periodic GPS updates demonstrate much greater alignment between computed and actual trajectories. This approach indicates that reliance on dead reckoning without external reference data, such as GPS, is infeasible. While dead reckoning is helpful for short durations, it does not provide sufficient accuracy for long-term operations without regular support from external systems like GNSS.

Notably, maximum errors in scenarios without GPS updates (Table 1, …, Table 3) pose significant risks in operations requiring high precision. During test flights, maxi-mum deviations reached 291.33 m in Flight No. 3 (Table 3), which could negatively impact tasks demanding precise positioning.

The circular test trajectories may have partially compensated for wind effects, as the drone alternated between moving with and against the wind, potentially distorting results and producing lower average errors than expected for longer linear flights.

6 CONCLUSION

The dead reckoning navigation method is moderately effective for UAV position estimation under limited GPS conditions, performing well over short distances and timeframes where error accumulation is minimal. It is a valuable complement to traditional systems during temporary GNSS signal loss.

However, a key challenge remains the impact of wind, which prevents the complete independence of dead reckoning from external data sources. Due to the limitations of IMU data, which only provides airspeed, additional solutions are needed to determine ground speed. In this context, optical flow technology, which analyses images to determine relative motion concerning the Earth's surface, is worth considering. Alternatively, other instruments, such as Doppler radar or advanced weather models, could be utilized to estimate the relative wind vector.

In conclusion, despite its limitations, the method shows potential for development. Integrating it with other measurement systems could enhance precision and resilience, benefiting industrial and military applications under challenging conditions.

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