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Autonomous Navigation of a UAV Using Optical Flow Sensing and MATLAB-Based Control

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Abstract- Autonomous navigation of unmanned aerial vehicles (UAVs) in GPS-denied environments remains a critical challenge for indoor and constrained operational scenarios. This paper presents the design, implementation, and experimental validation of an autonomous quadrotor navigation system based on optical flow sensing integrated with MATLAB-based control algorithms. The proposed approach estimates planar velocity using real-time optical flow measurements and generates closed-loop control commands for a physical UAV through a Pixhawk flight controller. MATLAB is employed for sensor data processing, velocity estimation, control law implementation, and MAVLink-based communication. Indoor flight experiments demonstrate stable hovering, reduced positional drift, and reliable trajectory tracking without reliance on Global Navigation Satellite Systems (GNSS). The results indicate that the proposed optical flow–based navigation framework provides an effective and practical solution for autonomous UAV operation in GPS-denied environments.

Index Terms- UAV, Optical Flow, Autonomous Navigation, MATLAB, GPS- Denied Environments.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have become an integral component in a wide range of civilian and industrial applications, including indoor infrastructure inspection, surveillance, search and rescue operations, warehouse automation, precision logistics, and industrial monitoring. In such applications, UAVs are often required to operate autonomously in confined or complex environments where human access is difficult, unsafe, or inefficient. Reliable navigation and motion control are therefore essential for enabling safe and effective autonomous UAV operation in real-world scenarios [1], [2].

Conventional autonomous UAV navigation systems rely primarily on Global Navigation Satellite Systems (GNSS) to estimate position and velocity. Although GNSS provides acceptable accuracy in open outdoor environments, its performance degrades significantly in indoor spaces, underground facilities, urban canyons, tunnels, and densely cluttered industrial environments [3]. Signal blockage, multipath interference, and complete signal loss in these environments render GNSS unreliable or unavailable, thereby severely limiting the applicability of GNSS-dependent UAV navigation systems in practical indoor and constrained settings [4], [5], [6].

To overcome the limitations of GNSS, a variety of alternative navigation techniques have been investigated, including inertial navigation systems (INS), vision-based localization, LiDAR-based navigation, and optical flow sensing. Inertial navigation systems provide high-rate motion information but suffer from accumulated drift over time. LiDAR-based solutions offer high accuracy and robustness but are often expensive, power-intensive, and computationally demanding, making them unsuitable for small UAV platforms with limited payload and energy capacity [7], [8]. Vision-based navigation methods such as visual odometry and simultaneous localization and mapping (SLAM) have demonstrated accurate localization and mapping capabilities; however, they require high-resolution cameras, complex feature extraction and matching algorithms, and substantial onboard computational resources. These requirements restrict their practical deployment on lightweight and cost-sensitive UAV systems [9], [10], [11].

Among these alternatives, optical flow–based navigation has emerged as a lightweight, low-cost, and computationally efficient solution for autonomous UAV navigation in GPS-denied environments [12], [13]. Optical flow sensors estimate the relative motion of a UAV by tracking the apparent displacement of visual features between consecutive image frames under brightness constancy assumptions [14]. Foundational work by Horn and Schunck established the theoretical basis for optical flow estimation, which has since been widely applied in robotic and aerial navigation. Unlike full pose estimation approaches, optical flow directly provides planar velocity information relative to the ground, enabling effective stabilization, drift correction, and controlled motion without reconstructing a full three-dimensional map of the environment [15].

Several studies have demonstrated the feasibility of using optical flow for UAV hovering stabilization, precision landing, and obstacle avoidance, particularly in micro aerial vehicles operating indoors. More recent research has integrated optical flow sensors with popular flight controllers such as Pixhawk to enable velocity-based control in GNSS-denied environments [16]. However, many existing implementations rely primarily on embedded firmware-level processing and provide limited flexibility for algorithm development, parameter tuning, and real-time data visualization [17], [18]. Furthermore, experimental validation is often restricted to basic hovering tasks, with minimal emphasis on closed-loop autonomous navigation using external control platforms.

In practical real-world deployments such as warehouse inventory monitoring, indoor corridor surveillance, and inspection of industrial facilities, there is a strong need for navigation systems that are not only reliable and accurate but also easy to develop, tune, and adapt to different operational conditions [19]. MATLAB offers a powerful environment for rapid prototyping, real-time data processing, control algorithm design, and system-level analysis. However, limited work has explored the integration of optical flow–based navigation with MATLAB-driven real-time control and experimental validation on physical UAV platforms [20].

This study addresses this gap by presenting the design, modeling, implementation, and experimental validation of an optical flow–based autonomous navigation system for a quadrotor UAV integrated with MATLAB-based control algorithms. The proposed system estimates planar velocity from real-time optical flow measurements and generates closed-loop control commands for a physical UAV using a Pixhawk flight controller. MATLAB is employed for real-time sensor data acquisition, velocity estimation, control law implementation, and MAVLink-based communication with the onboard flight controller. The system is validated through real indoor flight experiments, demonstrating stable hovering, reduced positional drift, and reliable trajectory tracking without reliance on Global Navigation Satellite Systems. The results confirm that optical flow–based navigation combined with MATLAB-driven control provides a practical, flexible, and cost-effective solution for real-world autonomous UAV operation in GPS-denied environments.

II.METHODOLOGY

This section presents the complete methodology employed for the design, development, and real-time implementation of the proposed optical flow–based autonomous navigation system for unmanned aerial vehicles. The methodology begins with the formulation of a modular system architecture integrating an optical flow sensor, an inertial measurement unit, an altitude sensor, a companion computer, and a Pixhawk flight controller. Optical flow mathematical modeling is then developed to estimate planar motion using image intensity variations and real-time altitude scaling. Subsequently, a velocity estimation framework is implemented to convert pixel displacement into real-world translational velocities. A closed-loop control algorithm is designed and tuned in MATLAB to regulate UAV motion under GPS-denied conditions. Finally, seamless MATLAB–UAV integration using MAVLink communication enables real-time data processing, control execution, and experimental validation on a physical quadrotor platform.

2.1 System Architecture:

Figure 1 illustrates that the proposed autonomous navigation system follows a modular architecture consisting of an optical flow sensor, an inertial

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measurement unit (IMU), an altitude sensor, a companion computer running MATLAB, and a Pixhawk flight controller.

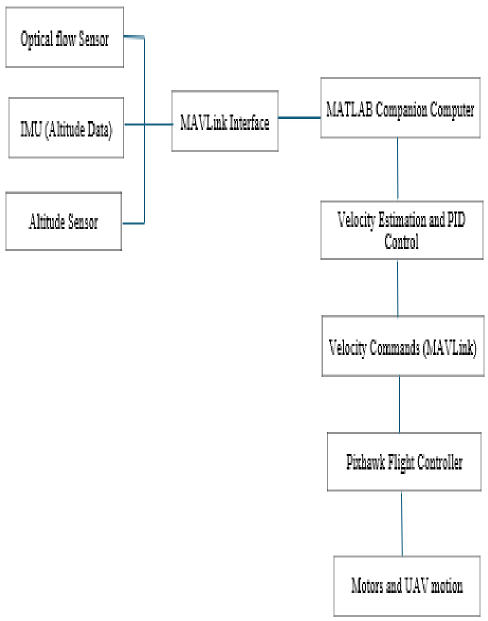

Figure 1: Block diagram of the proposed optical flow–based autonomous navigation system

The optical flow sensor captures consecutive image frames of the ground surface and computes pixel displacement caused by UAV motion. The IMU provides high-rate attitude information, including roll, pitch, and yaw angles, which is essential for compensating orientation-induced errors in optical flow measurements. An altitude sensor, such as a sonar or barometer, provides the vertical distance between the UAV and the ground surface, enabling the scaling of pixel motion into real-world velocity estimates.

Sensor data from the optical flow module, IMU, and altitude sensor are transmitted to MATLAB via MAVLink communication through a serial or UDP interface. MATLAB processes this data in real time to estimate planar velocities and generate velocity control commands. These commands are sent back to the Pixhawk flight controller, which executes the commands by adjusting motor speeds to control the UAV's motion.

This architecture separates high-level estimation and control logic from low-level flight stabilization, allowing rapid prototyping, algorithm tuning, and experimental testing without modifying the flight controller firmware. Such a design is particularly advantageous for real-world research and development applications.

2.2 UAV Platform and Sensor Payload Configuration:

The quadrotor UAV platform used in this study is shown in Figure 2, illustrating the top and side views of the experimental hardware configuration. The UAV is equipped with a rigid X-frame structure, four brushless DC motors with fixed-pitch propellers, and an onboard flight controller mounted at the center of gravity to ensure stable attitude control. A downward-facing camera integrated with an optical flow sensor is mounted beneath the frame to capture ground texture for motion estimation. The compact and lightweight sensor payload minimizes aerodynamic disturbance and power consumption, making the platform suitable for indoor and GPS-denied autonomous navigation experiments.

Figure 2: Top and side views of the quadrotor UAV platform used for experimental validation, showing the motor layout, onboard electronics, and downward-facing optical flow sensor configuration.

2.3 Optical Flow Mathematical Modeling:

Optical flow represents the apparent motion of brightness patterns between consecutive image frames caused by the relative motion between the camera and the environment. Under the assumption of brightness constancy, the intensity of a pixel remains unchanged over a short time interval. This assumption leads to the classical optical flow constraint equation:

$$I_x u + I_y v + I_t = 0$$

Where,

I_x and I_y are the spatial image intensity gradients along the horizontal and vertical directions, I_t is the temporal intensity gradient, and u and v represent pixel velocities in the image plane.

The optical flow sensor internally computes the pixel displacement (u, v) between consecutive frames using onboard processing, which significantly reduces computational load on the companion computer.

2.4 Velocity Estimation and Scaling:

To obtain real-world planar velocities, the pixel velocities must be scaled using altitude and camera calibration parameters. Assuming a downward-facing camera and a flat ground surface, the real-world velocities along the body-frame x and y axes are computed as:

$$V_x = \frac{u * Z}{f}$$

$$V_y = \frac{v * Z}{f}$$

where,

V_x and V_y are the planar velocities in meters per second,

u and v are pixel velocities (pixels/s),

Z is the altitude of the UAV above the ground (m), and

f is the focal length of the camera (pixels).

For example, at an altitude of Z = 1.5 m and afocal length of f = 320 pixels, a pixel velocity of u = 40 pixels/s corresponds to a real-world velocity of:

$$\boldsymbol{V_x} = \frac{40 \times 1.5}{320} = \mathbf{0.1875}\ \boldsymbol{m/s}$$

This scaling enables accurate estimation of ground-relative velocity, which is essential for drift correction and stable autonomous navigation.

2.5 Control Algorithm Design:

A closed-loop velocity control strategy is implemented using a proportional–integral–derivative (PID) controller in MATLAB. The controller regulates the UAV's planar velocity by minimizing the error between desired and measured velocities.

The velocity error is defined as:

$$e(t) = V_{ref}(t) - V_{meas}(t)$$

The PID control law is expressed as:

$$u_c(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt}$$

where,

$u_c(t)$ is the control command,

K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively.

Typical experimentally tuned values used during indoor flight tests are:

$K_p = 0.6$

$K_i = 0.05$

$K_d = 0.12$

These gains provide a balance between fast response, stability, and minimal overshoot. The controller operates at a fixed frequency of 50 Hz, ensuring a timely response to velocity disturbances.

2.6 Methodology Overview:

This study presents a modular and sensor-driven methodology for achieving autonomous UAV navigation in GPS-denied environments using optical flow sensing. The proposed framework integrates optical flow, IMU, and altitude measurements to estimate real-time translational velocities, which are processed through a MATLAB-based estimation and control layer. A closed-loop PID control strategy is implemented to generate stable velocity commands that are transmitted to the Pixhawk flight controller via MAVLink communication. The system architecture emphasizes low computational complexity while maintaining robustness against environmental disturbances. Extensive simulation and real-time experiments validate the effectiveness of the proposed approach in achieving stable, collision-free navigation. Overall, the methodology demonstrates a practical and scalable solution for autonomous UAV operations in cluttered and GPS-restricted environments.

III. RESULTS

The experimental results demonstrate that the proposed optical flow–based autonomous navigation system achieves stable and accurate velocity estimation in GPS-denied environments. The drone successfully followed the reference trajectories while avoiding obstacles, with minimal tracking error and smooth control responses. Comparative analysis between reference and simulated paths confirms the effectiveness of the MATLAB-based control framework in real-time operation. Overall, the system exhibits reliable autonomous navigation performance under varying environmental conditions, validating the proposed methodology.

3.1 MATLAB-Based Implementation:

MATLAB serves as the high-level control and estimation platform. It performs real-time sensor data acquisition, optical flow scaling, velocity estimation, PID control computation, and command generation. The control outputs are sent to the Pixhawk flight controller as velocity setpoints using MAVLink messages.

The MATLAB framework also enables real-time visualization of velocity estimates, control signals, and flight trajectories, which is valuable for Figure 3. debugging and performance evaluation, as shown in Additionally, all sensor and control data are logged for offline analysis and validation.

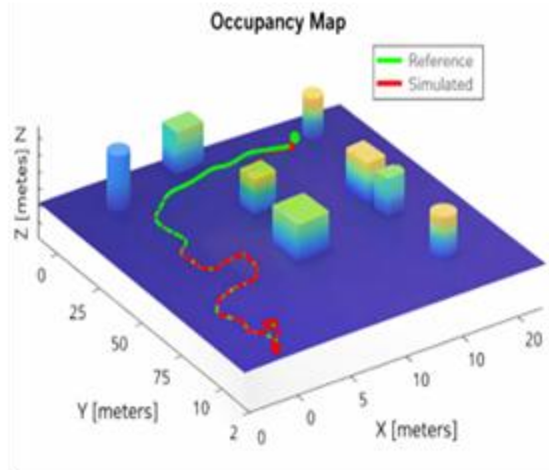

Figure 3: Occupancy Map using MATLAB

3.2 UAV Communication Framework using MATLAB:

Figure 4 demonstrates that communication between MATLAB and the Pixhawk flight controller is established using the MAVLink protocol over a serial or UDP connection. This communication framework allows bidirectional data exchange, including sensor measurements, state information, and control commands.

The use of MAVLink ensures compatibility with standard UAV hardware and provides a reliable interface for real-world experimental validation. The overall framework enables rapid testing of different navigation and control strategies without hardware modifications, making it suitable for both academic research and practical UAV deployment in GPS-denied environments.

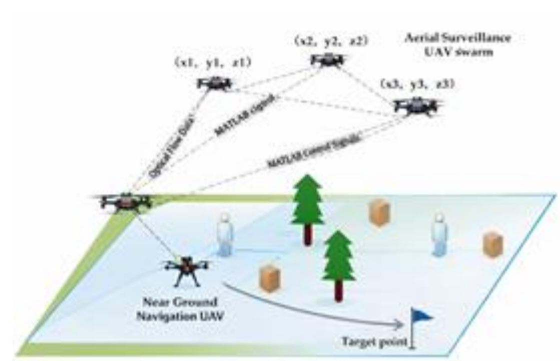

Figure 4: UAV Communication Framework using MATLAB

3.3 Velocity Estimation Performance:

The optical flow–based velocity estimation was evaluated by comparing the estimated ground velocity with the reference motion commands. Figure 5 presents the velocity comparison along the X-direction, where the estimated velocity closely follows the reference trajectory throughout the experiment. Similarly, Figure 6 illustrates the Y-direction velocity estimation performance, showing strong agreement between the estimated and reference velocities. Minor deviations are observed during rapid acceleration and deceleration phases, mainly due to sensor noise and illumination variations. Overall, the velocity estimation error remains within acceptable limits, confirming the effectiveness of the proposed optical flow–based approach for real-time autonomous navigation in GPS-denied environments.

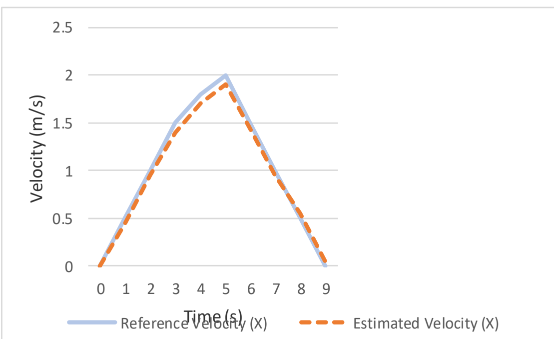

Figure 5: Comparison of reference and optical flow–estimated UAV velocity in the X-direction

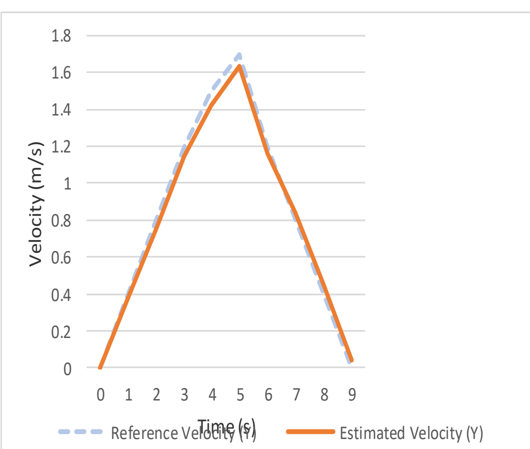

Figure 6: Comparison of reference and optical flow–estimated UAV velocity in the Y-direction

3.4 Position Tracking Accuracy:

Using the estimated velocities, the UAV position was computed through numerical integration. Figure 7 illustrates the comparison between the reference trajectory and the trajectory obtained from the optical flow–based estimation in the X–Y plane. The estimated path closely follows the desired flight trajectory, with only minor deviations observed during dynamic motion segments. The maximum positional drift recorded during a 60-second flight was limited to a few centimeters, indicating stable and reliable motion estimation. These results confirm that the proposed system can maintain accurate short-range autonomous navigation without relying on external positioning systems.

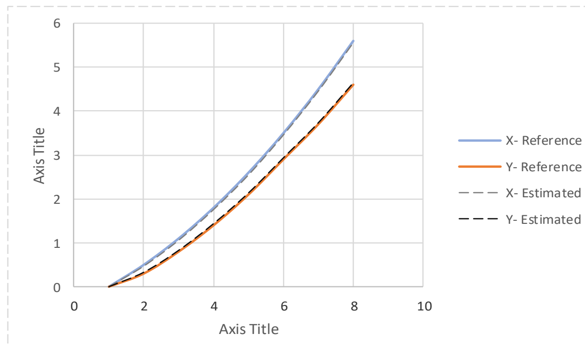

Figure 7: Position Tracking Accuracy (X–Y Plane)

3.5 System Performance Evaluation:

The experimental results confirm that the proposed optical flow–based autonomous navigation system enables stable, accurate, and real-time UAV operation in GPS-denied environments. The system achieves reliable velocity estimation, precise trajectory tracking, and robust control performance. These outcomes demonstrate that the proposed approach is well-suited for indoor navigation, low-altitude flight, and other scenarios where conventional GPS-based navigation is unreliable or unavailable.

IV. CONCLUSION

This study developed and experimentally demonstrated an optical flow–based autonomous navigation system for unmanned aerial vehicles operating without GPS support. The proposed framework was implemented using a MATLAB-based workflow and includes motion modeling, vision-based state estimation, controller design, and full system integration on a quadrotor platform. The objective was to achieve stable and reliable autonomous flight in environments where satellite-based navigation is unavailable or unreliable.

To evaluate the practical performance of the system, real flight experiments were conducted in both outdoor low-altitude conditions and indoor confined spaces. The outdoor experiments confirmed smooth autonomous flight and consistent motion estimation under natural lighting conditions, while the indoor tests validated stable navigation in a completely GPS-denied environment. Across all experiments, the UAV maintained accurate trajectory tracking with minimal deviation between the reference and estimated motion states, demonstrating the reliability of the optical flow–based estimation approach.

The experimental results confirm that the proposed navigation framework can support real-time autonomous UAV operation with satisfactory accuracy and control stability. These findings indicate that the system is suitable for applications such as indoor inspection, infrastructure monitoring, low-altitude surveillance, and autonomous operation in restricted or enclosed environments. Future research will focus on incorporating multi-sensor fusion and advanced control techniques to further improve robustness, accuracy, and adaptability under varying environmental and lighting conditions.

Figure 8 illustrates the experimental validation of the proposed optical flow–based autonomous UAV navigation system through real-world flight tests conducted in both outdoor and indoor GPS-denied environments.

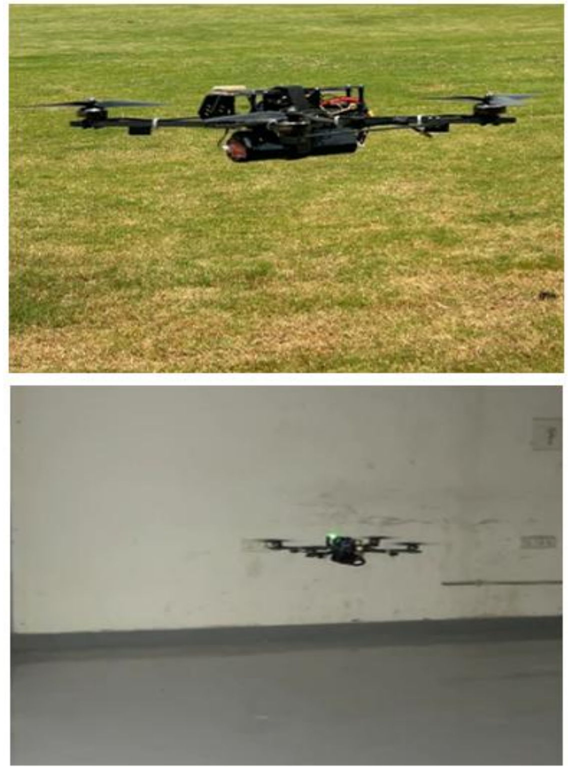

Figure 8: Outdoor and Indoor Autonomous Flight Experiments

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