POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)

URL: http://dergipark.org.tr/politeknik

Collision avoidance for autonomous unmanned aerial vehicles with dynamic and stationary obstacles

Otonom insansiz hava araçları için dinamik ve sabit engellerle çarpışmayı önleme

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To cite to this article: Elmas E. E. ve Alkan M.,"Collision Avoidance for Autonomous Unmanned Aerial Vehicles with Dynamic and Stationary Obstacles", ***Journal of Polytechnic***, 28(1): 297-308, (2025).

Bu makaleye şu şekilde atıfta bulunabilirsiniz: Elmas E.E. ve Alkan M.,"Collision Avoidance for Autonomous Unmanned Aerial Vehicles with Dynamic and Stationary Obstacles", ***Politeknik Dergisi***, 28(1): 297-308, (2025).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.1474359

Collision Avoidance for Autonomous Unmanned Aerial Vehicles with Dynamic and Stationary Obstacles

Highlights

- *Dynamic obstacle detection*
- *Static obstacle detection*
- *Collision avoidance system in UAVs*

Graphical Abstract

An approach using optical flow and lidar sensors is recommended to avoid dynamic and static obstacles in unmanned aerial vehicles.

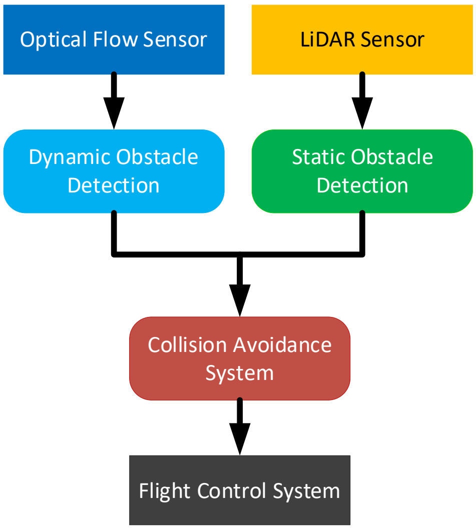

Figure. The block diagram of Collision Avoidance System

Aim

It is aimed to ensure safe navigation in unmanned aerial vehicles by avoiding dynamic and static obstacles.

Design & Methodology

Simulation tests using MATLAB Simulink show that the proposed obstacle avoidance system works efficiently with the real-time use of LiDAR and Optical Flow.

Originality

The originality of the study is that the designed system detects dynamic and static objects in UAVs using optical flow and lidar sensors and plans an obstacle-free path.

Findings

Experiment and simulation results show that the system creates the obstacle-free flight path of the UAV in different operating conditions.

Conclusion

The study presents a new collision avoidance system that involves the use of LiDAR to detect static obstacles and OF to detect dynamic obstacles during flight in an unmanned aerial vehicle. By combining LiDAR's high-resolution spatial data with OF's relative motion detection capability, the proposed system enables the detection and avoidance of both static and dynamic objects while in motion.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Collision Avoidance for Autonomous Unmanned Aerial Vehicles with Dynamic and Stationary Obstacles

Araştırma Makalesi / Research Article

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(Geliş/Received : 26.04.2024 ; Kabul/Accepted : 19.06.2024 ; Erken Görünüm/Early View : 22.07.2024)

ABSTRACT

The use of autonomous unmanned aerial vehicles (UAVs) has become one of the most used in many sectors in the last few years. This growing reliance on UAVs necessitates advanced navigation systems to ensure their safe and efficient operation, particularly in environments dense with both static and dynamic objects. Collision avoidance is a fundamental requirement in such scenarios. This study introduces a novel collision avoidance system for an UAV that incorporates the use of LiDAR for the identification of stationary and an optical flow (OF) for the identification of dynamic obstructions in their path. By fusing LiDAR's high-resolution spatial data with the relative motion detection capability of the OF, proposed system enables detection and avoidance of both static and dynamic objects on-the-fly. To evaluate the efficacy of the proposed system, various simulation and experiment were conducted. The results indicate that the system successfully avoids either stationary or dynamic obstacles.

Keywords: LiDAR, Optical flow, UAV, Sensor Fusion, Trajectory Planning, Collision Avoidance.

Otonom İnsansız Hava Araçları için Dinamik ve Sabit Engellerle Çarpışmayı Önleme

ÖZ

Otonom insansız hava araçlarının (İHA) kullanımı son yıllarda birçok sektörde çok yaygın kullanım alanı bulmuştur. İHA'ların kullanımının artması, özellikle sabit ve dinamik nesnelerle dolu ortamlarda, güvenli ve verimli bir şekilde çalışabilmeleri için gelişmiş navigasyon sistemlerini gerektirmektedir. Bu tür senaryolarda çarpışmadan kaçınmak temel bir gerekliliktir. Bu çalışma, bir İHA için, yollarındaki dinamik engellerin tanımlanması için sabit ve optik akışın (OF) tanımlanması için LiDAR kullanımını içeren yeni bir çarpışma önleme sistemi sunmaktadır. LiDAR'ın yüksek çözünürlüklü mekansal verilerini OF'nin göreceli hareket algılama yeteneğiyle birleştirerek önerilen sistem, hareket halindeyken hem statik hem de dinamik nesnelerin algılanmasını ve bunlardan kaçınılmasını sağlamaktadır. Önerilen sistemin etkinliğini değerlendirmek için çeşitli simülasyon ve deneyler yapılmıştır. Sonuçlar sistemin hem sabit hem de dinamik engellerden başarılı bir şekilde kaçındığını göstermektedir.

Anahtar Kelimeler: LiDAR, Optik akış, İHA, Sensör Füzyonu, Yörünge Planlama, Çarpışma Önleme

1. INTRODUCTION

The use of autonomous unmanned aerial vehicles (UAVs) has become one of the most used in many sectors in the last few years. Due to their unique flying capabilities, state-of-the-art air-borne drones have transformed fields such as precision agriculture, infrastructure inspection, search and rescue missions, and last-mile deliveries, making them more efficient and successful than ever before. Despite all these advances in UAV technology, problems with safety and reliability in practical operational situations still remain.Among other things, one major challenge is connected with an avoidance system that must reliably detect every potential obstruction posing a hazard to the flight path.

The main focus of detection sensors with the purpose of detecting stationary obstacles belongs to a typical radar unit, camera system, and ultrasonic devices in this research area. Another challenge, however, is avoiding contact with birds, or other flying objects. There are two major reasons why this happens first, their movements are very unpredictable, making tracking them even harder than stationary structures.

In addition, the dimensions and weight of the UAV, its energy consumption, and its computing power impose certain restraints regarding the choice of sensors and

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algorithms that can be used on board, meaning that their application is limited. The creation of an environment where automated flight would be unsafe in most obstruction cases is highly significant to protect lives as well as property from hazardous incidents. One approach to achieve this goal is by developing systems that are computationally efficient and capable of reliably avoiding collisions with stationary obstacles like buildings or trees as well as moving ones such as vehicles. The aim of this study is to address a problem that many researchers overlook real-time avoidance of dynamic obstacles using stationary UAVs.

The topic under consideration now relates to a technique of creating a drone system that involves LiDAR and optical flow algorithms for motion estimation. Through this combination, we obtain a system that not only detects objects around the UAV but also recognizes possible threats ahead.

One of the applications for these technologies is to detect stationary or moving threats, facilitating their avoidance and thereby preventing reactive evasion, which usually ends up with an attack. In addition, such a system will greatly enhance the safety level of unmanned aerial vehicle operations, especially in the implementation of light or low-powered airplanes.

There are two main research goals we are trying to achieve in this study:

Creating a cutting-edge real-time system that enables autonomous UAVs to detect obstacles using a LiDAR and track motion using an optical flow (OF).

Developing an avoidance algorithm that can initiate immediate manoeuvres when potential collisions with either moving or stationary obstacles are predicted.

2. MATERIAL AND METHOD

The increasing adoption and integration of UAVs into the airspace pose significant challenges in ensuring their safe operation without human intervention. Nevertheless, remarkable advancements have been achieved in tackling these challenges by incorporating cutting-edge technologies. The incorporation of Collision Avoidance Systems (CAS), Geo-Fencing, AI and ML, Path Planning and Optimization, and Sensor-Based CAS has brought about a revolutionary improvement in the safety and effectiveness of UAV operations [1, 2].

The safety of UAV operations in urban areas with a large population has been greatly enhanced through the implementation of CAS. In the research, Wang et al. [3] and others [4, 5] thoroughly discuss the algorithms and methods employed in these systems, focusing on the crucial role of real-time communication between UAVs in avoiding encounters that occur during the mid-air. The enactment of pre-programmed no fly areas and geographic encouragement is essential to this regard.

The idea of geo-fencing is derived from the creation of virtual boundaries that isolate the behaviour of aerial vehicles. This simple and effective method is used to prevent UAVs from flying in areas that are restricted. However, it does not address the issues caused by dynamic obstacles or the avoidance of other unplanned aerial vehicles. The commonplace implementation of geo-fencing technology in the management of UAVs has been observed in the control of security-related areas, this is particularly true of areas with a significant security or accessibility concerns. In their study, Torens et al. [6] investigate the practicality of the geo-fencing principles that prohibit UAVs from entering areas with no fly, such as airports or military bases. Additionally, Kim and Atkins [7] documented the creation of dynamic geo-fencing, this technology enables immediate updates to restrictions based on environmental changes or specific event-related necessities.

The advances in the field of AI and ML have led to the creation of complex CAS that are derived from the knowledge that is gained through practice. Through the analysis of data from previous flights and computer simulations, AI can prevent potential collision and determine the most effective evasive actions. These systems can adapt to different habitats and obstacles, this increases their effectiveness over time. However, the necessity of large amounts of data and computational power may preclude the immediate implementation of these ideas on smaller UAVs. Elmas and Alkan [8] stated the important elements for the design, simulation and implementation of the Unmanned Aerial Vehicle System. Günay and Korkut [9], Canpolat Tosun [10] state important issues in the fields of drone design and orbit control in their studies.

The combination of AI and ML in UAV operations has led to the development of autonomous flight capabilities, this has had the effect of increasing efficiency and safety. Wu et al. [11] conducted a comprehensive study that employed machine-learning-based methods to predict and reduce the probability of human error, ultimately decreasing the error rate. Also, Teixeira et al. [12] conducted a research study that demonstrates the value of deep learning in increasing the capacity of UAVs to recognize images, this is important for missions like search and rescue or agricultural monitoring.

The path planning and the optimization are both vital to the mission. The procedure of finding the shortest path and safest way for a UAV to travel to its intended destination while also avoiding obstacles is called path planning and optimization. Various algorithms, such as A* (A-star), Rapidly-exploring Random Trees (RRT), and their variants, are often used for this purpose. These algorithms can immediately alter the flight path of the UAV, considering any new obstacles or environmental changes. However, the computational complexity of these algorithms can have a significant impact, particularly on the rapid planning of paths in complex environments. The safe and efficient flight of UAVs is primarily supported by effective path planning and optimization. Huang et al. [13] present a cutting-edge algorithm that creates paths that are dynamic and take into account environmental variables that are unpredictable like erratic weather. Similarly, Chen et al. [14] focus on methods that have a balanced duration of flight and expenditure of energy; while also maintaining safety, this increases the overall effectiveness of UAVs in practice.

2.1. Sensor-Based Collision Avoidance Systems

One of the CAS for UAVs is the utilization of sensors-based systems. These systems are primarily dependent on the sensors on the UAV that recognize and detect obstacles as well as other aircraft, this guarantees the safety of the UAV around its intended area.

The investigation of LiDAR-based mapping and localization methods for UAVs in GPS-disabled environments has been studied in depth. Notably, Christiansen et al. [15] and Youn et al. [16] created a system that employs LiDARs and other sensors to estimate the state of small air vehicles. Their findings demonstrated a remarkable degree of accuracy, this led to the development of autonomous flight in complex environments. Droeschel et al. and Qian et al. [17, 18] also developed a method of combining LiDAR scans, RGB-D images, and inertial data on a quadrotor UAV and a robotic platform. This method facilitated the identification and mapping of a platform without necessitating external assistance. Through their experiments, they showed that unmanned aerial vehicles with LiDAR were capable of flying without supervision. The practical application of LiDAR technology to recognize obstacles and avoid them on UAVs has been studied in greater detail. In their research, Park and Cho [19] created a practical method of obtaining information regarding obstacles in LiDAR-based point clouds and avoiding interactions when using UAVs. Similarly, Ramasamy et al. [20] proposed a method that utilizes 3D LiDAR data that is separated by distance, the data is then classified as obstacles, this method allows humans to be automatically travelled through areas that are unfamiliar without the use of GPS. These investigations show the potential of combining LiDAR with specialized software that can be employed to process point clouds in order to ensure safe flying around obstacles [21, 22].

With their superior spatial resolution and precise measurement of distance, LiDAR has become a significant component of the detection of obstacles. In their research, Alonso-Mora et al. [23] developed a CAS that is proactive and employs 3D LiDAR. This innovative system visualizes the surrounding environment as a series of points that represent obstacles. By sampling a space with velocity, the system generates potential paths that avoid collisions, this ensures that the UAV maintains a safe distance from obstacles. In CAS domain, OF methods are similar to LiDAR in that they both rely on visual information from cameras to estimate the motion of objects [24]. Through the analysis of the patterns of motion in pixels between different frames, their system was able to differentiate between objects that are moving and stationary, this information was then used to alter the flight path of the UAV.

Deng et al. [25] Investigated the creation of a plan for regulating UAVs that utilize OF. By analysing the OF vectors from a single-lens camera that has a lens with a fixed focal length, the system can deduce the distance and velocity of objects. This methodology effectively demonstrated the capacity of OF in avoiding collisions in real time, this was especially true of situations where GPS was not accessible. The implementation of OF has been facilitated by the addition of machine-learning algorithms, this has led to an increase in the capacity to avoid and recognize obstacles. Recent research, such as the one conducted by Gandhi et al., and Kalidas et al. [26,27], have demonstrated a deep learning-based method that is successful in predicting and responding to the motion of dynamic obstacles.

The utilization of OF and deep learning aided the creation of a system of design-based vision by Cho et al. [28] Separate investigation. This system demonstrated the capacity to recognize and observe objects moving around them, this altered the course of the UAV in order to avoid any potential conflicts. The authors demonstrated the effectiveness of their approach by conducting both theoretical and practical experiments in the real world.

In their study, Florence et al. [29] developed a system of perception that is specifically designed to be used with UAVs, this system combines LiDAR point clouds with a deep-learning-based approach to OF. Their system has the ability to avoid from dynamic objects as well as the capacity to create safe flight paths in complex urban areas. The successful combination of machine learning with sensor fusion is a demonstration of the likely benefits of adaptive and intelligent CAS.

2.2. Horn-Schunck method

A cornerstone technique in computer vision applications is the Horn-Schunck method, which is used to estimate OF by addressing the aperture problem through the enforcement of a global smoothness constraint. The Horn-Schunck method has been recognized for its capacity to produce smooth OF fields. This method is derived from the assumption that the motion in the image plane is typically consistent, this promotes uniformity and decreases the probability of anomalous patterns of flow [30]. By considering motion as a form of global energy, the algorithm attempts to reduce it, which leads to a more uniform distribution of flow across two dimensional images.

The minimization of a global energy functional defines the flow. This functional is specifically designed for two-dimensional image sequences and can be described as follows:

$$E = \iint \left[(I_x u + I_y v + I_t)^2 + \alpha^2 (\|\nabla u\|^2 + \|\nabla v\|^2) \right] dxdy \qquad (1)$$

where I_x, I_y and I_t are the derivatives of the image intensity values along the x, y and time dimensions respectively, and the parameter α is a regularization constant.

Increasing α values result in a more uniform flow. Minimization of this functional is achieved through solving the corresponding multi-dimensional Euler–Lagrange equations. These are;

$$\frac{\partial L}{\partial u} - \frac{\partial}{\partial x}\frac{\partial L}{\partial u_x} - \frac{\partial}{\partial y}\frac{\partial L}{\partial u_y} = 0 \quad (2)$$

$$\frac{\partial L}{\partial v} - \frac{\partial}{\partial x}\frac{\partial L}{\partial v_x} - \frac{\partial}{\partial y}\frac{\partial L}{\partial v_y} = 0 \quad (3)$$

Where L is the integrand of the energy expression, giving

$$I_x(I_x u + I_y v + I_t) - \alpha^2 \Delta u = 0 \quad (4)$$

$$I_y(I_x v + I_y v + I_t) - \alpha^2 \Delta v = 0 \quad (5)$$

where subscripts again denote partial differentiation and $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ denotes the Laplace operator. In practice the Laplacian is approximated numerically using finite differences, and may be written $\Delta u(x,y) = (\bar{u}(x,y) - u(x,y))$ where $\bar{u}(x,y)$ is a weighted average of u calculated in a neighbourhood around the pixel at location (x,y) Using this notation the above equation system may be written;

$$(I_x^2 + \alpha^2)u + I_x I_y v = \alpha^2 \bar{u} - I_x I_t \quad (6)$$

$$I_x I_y u + (I_y^2 + \alpha^2)v = \alpha^2 \bar{v} - I_y I_t \quad (7)$$

which is linear in u and v and may be solved for each pixel in the image. However, as the solution is contingent on the adjacent values of the flow field, it necessitates repetition after the neighbouring values are updated. This iterative scheme is formulated by employing Cramer's rule:

$$u^{k+1} = u^{-k} - \frac{I_x(I_x\bar{u}^k + I_y\bar{v}^k + I_t)}{\alpha^2 + I_x^2 + I_y^2} \quad (8)$$

$$v^{k+1} = v^{-k} - \frac{I_y(I_x\bar{u}^k + I_y\bar{v}^k + I_t)}{\alpha^2 + I_x^2 + I_y^2} \quad (9)$$

where the superscript $k+1$ denotes the subsequent iteration to be calculated, with k representing the last computed result. Essentially, this is a matrix splitting technique akin to the Jacobi method, utilized for the extensive, sparse system that emerges when solving for all pixels in unison.

The Horn-Schunck method offers the advantage of producing a dense array of flow vectors, effectively interpolating the flow information within the inner regions of uniform objects from the motion boundaries. However, it has the drawback of being more susceptible to noise compared to local techniques.

3. PROPOSED SYSTEM ARCHITECTURE

To guarantee the safety and effectiveness of autonomous UAVs in complex settings, a CAS has been proposed that is combined LiDAR, OF, and IMUs to effectively navigate through intricate surroundings and avoid collisions as shown in Figure 1. The system employs sensor fusion technology to combine multiple, carefully chosen hardware components that together contribute to the overall effectiveness and dependability of the system. Among these components are LiDAR and cameras, which continuously provide real-time information about the UAV's surroundings.

Additionally, the system has a processor to run algorithm to calculate potential crash risks and appropriate avoidance actions in real time. It also has a communication module to provide effective monitoring and control by transferring data between the UAV and ground control stations.

3.1. Detailed Overview of System Hardware Components

The block diagram of the proposed UAV system is shown in Figure 1. The system consists of three parts Navigation Unit, Communication Module, and Collision Avoidance System. The sensors in each unit are crucial for enabling the UAV to navigate its surroundings and ensure a safe flight.

3.1.1. Navigation unit

The unit comprises three components;

Global Positioning System (GPS): GPS is one of the most vital technologies that help drones achieve accurate geographical positioning. In proposed system, the time period of the GPS module is 1 s.

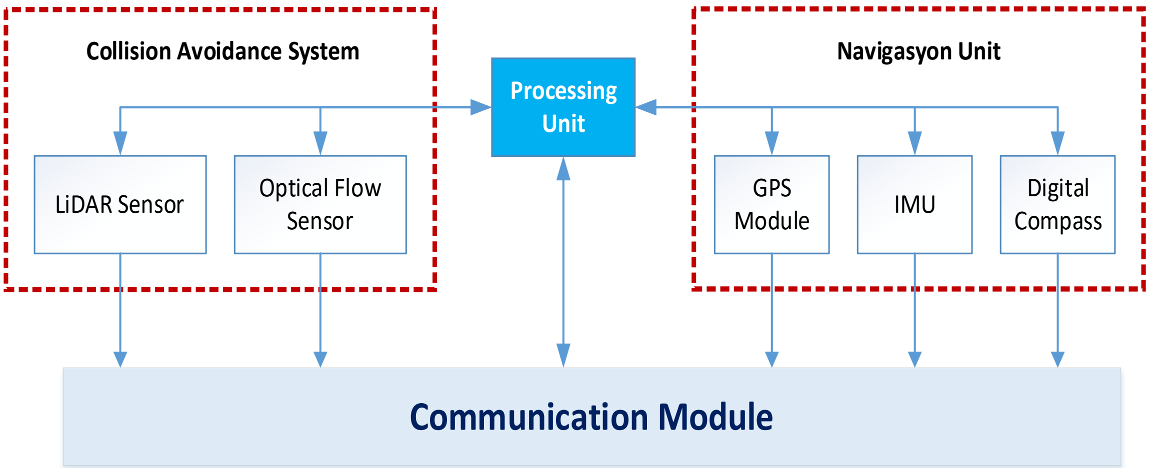


Figure 1. The system block diagram of the proposed UAV system

Inertial Measurement Unit (IMU): The IMU provides accurate information regarding the UAV's attitude, velocity, and acceleration that ensure consistent flight and precise guidance. The IMU typically provides readings at a higher rate, for example 0.02 s, and the average of these values in 1 s has been incorporated into the system.

Digital Compass: The Digital Compass is a modern technology that employs magnetometers to detect Earth's magnetic field, determining the direction of the UAV from magnetic north. When included in the UAV systems, such compasses contribute to the enhancement of control systems, making them much more accurate and therefore usable for sophisticated and subtle flight missions.

3.1.2. Communication module

The inclusion of a communication module in the UAV facilitates the exchange of data between the UAV and ground control stations or neighbouring UAVs. This functionality enables remote monitoring and control, as well as the implementation of cooperative collision avoidance measures.

3.1.3. Collision avoidance system

The collision avoidance system is crucial for ensuring the UAV's safety and the safety of the environment it operates in. It is equipped with an array of sensors designed to detect both dynamic (moving) and static (stationary) obstacles that may lie in the UAV's path. These sensors include a LiDAR and an OF. The block diagram of the CAS that contains two components is shown in Figure 2.

LiDAR: To ensure the precise and immediate recognition of obstacles near the UAV, a cutting-edge LiDAR sensor is employed. This advanced sensor produces laser waves and calculates the amount of time it takes for the waves to return, this creates a detailed 3D representation of the area around it.

Optical Flow: The OF has a significant impact on the motion and orientation of the UAV in relation to its surroundings. The Horn-Schunck method is used to produce smooth OF fields. By taking a series of pictures and analysing the motion of specific features within each picture, the OF can deduce the velocity and rotary rate of the UAV.

Figure 2 demonstrates the placement of various sensory devices, including cameras, and communication antennae, the landing gear, payload spaces, and other components that are crucial to the UAV's capacity to move, gather information, and maintain communication with the ground station. The on-board computer has primary purpose is to analyse and interpret a consistent series of sensor data to determine the most effective way to avoid collisions.

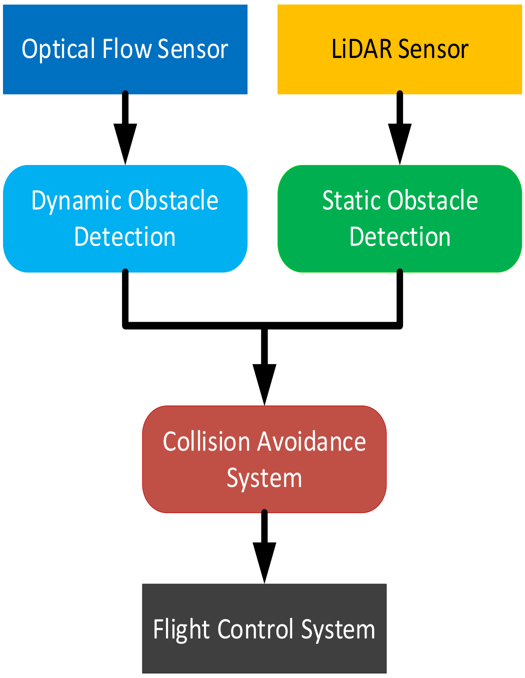


Figure 2. The block diagram of Collision Avoidance System

3.2. Overview of the Autonomous UAV

The state-of-the-art system comprises an extensive collection of software and hardware elements, meticulously crafted to fulfil distinct tasks and synergistically enhance the system's overall efficiency.

In Figure 3, a detailed visual representation of the autonomous UAV is provided, showcasing both its external architecture and the integrated systems that are crucial for its operation.

Figure 3. The comprehensive external representation of the autonomous UAV

The features of the autonomous UAV shown in Figure 3. are given in Table 1.

Table 1. The features of the autonomous UAV

Product	Features
Wheelbase	630mm
Sizen(LxWxH)	510x510x255mm
Weight	5kg
Brushless DC Motor	700KV
Carbon Fiber Propellers	155mm
Working current	30A
Input voltage	2-4S
LiPo Battery	11.1 V 4400 mAh 30C

The software encompasses a range of essential components, including trajectory planning, obstacle detection and classification algorithms, motion estimation algorithms, collision avoidance algorithms, and the flight control system, as depicted in Figure 4. The crucial function of each module is to guarantee the safe navigation of UAVs in their environment.

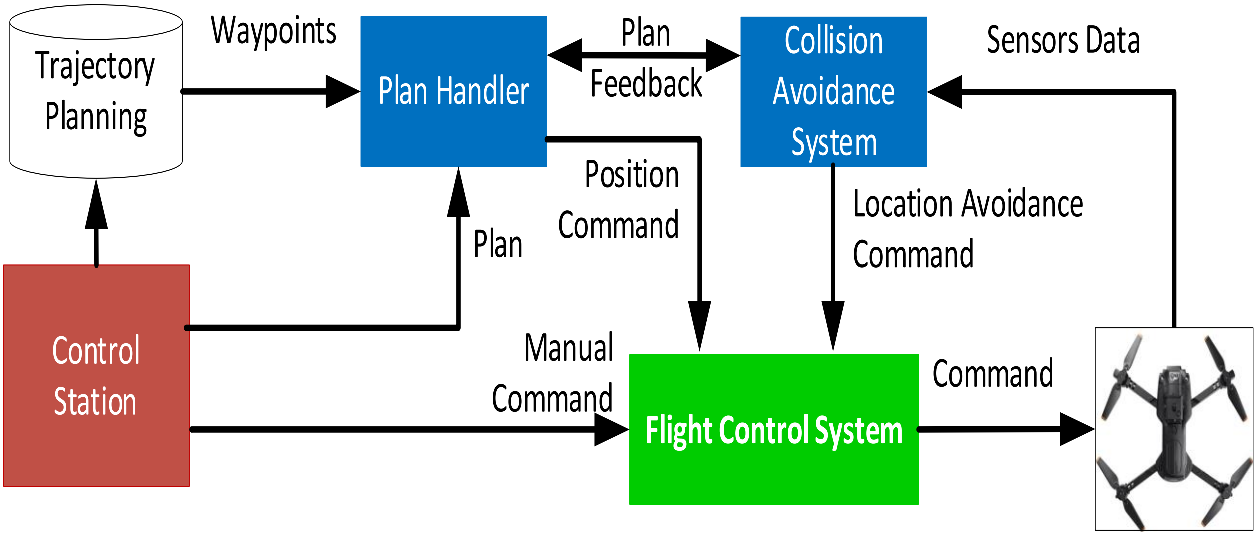


Figure 4. Detailed overview of system software components

Flight Control System: The collision avoidance algorithm provides collision avoidance manoeuvres to the flight control system, which then converts them into control commands for the actuators of the UAV. The flight control system enables the execution of the desired manoeuvres and prevents collisions by adjusting the attitude, throttle, and control surfaces. The follow chart of the flight control system is shown in Figure 5.

Trajectory Planning: Once obstacles have been detected and classified, the UAV is tasked with devising a secure trajectory in order to circumvent any potential collisions. To accomplish this, path planning algorithms are employed, taking into account the UAV's present location, the positions of obstacles, and the UAV's dynamic limitations (e.g., top speed and turning radius).

Collision Avoidance Algorithm: At the heart of the system lies the collision avoidance algorithm, which serves as its foundation. This algorithm takes into account the UAV's estimated motion and the obstacles detected, and then generates the necessary collision avoidance manoeuvres.

Several factors are considered in order to determine the most effective method of avoiding obstacles, the distance to obstacles, the speed and agility of the UAV, and the nature of the surroundings.

The collision avoidance algorithm is composed of two distinct units;

Obstacle Detection and Classification Algorithm: This algorithm is a software module that utilizes LiDAR to detect and categorize obstacles along the path of the UAV. It can recognize different types of obstacles such as buildings, trees, other aircraft and moving objects.

Motion Estimation Algorithm: This algorithm uses the Optical Flow data to determine the motion and orientation of the UAV. It can calculate the velocity and angular rates of the UAV by tracking feature points in consecutive images. This information plays a crucial role in predicting the UAV's future path and identifying any potential risks of collision.

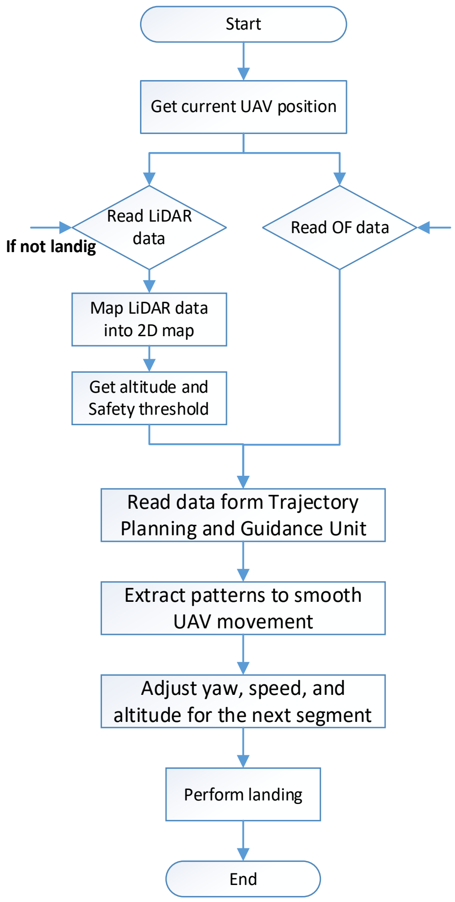


Figure 5. The flow chart of the flight control system

4. EXPERIMENTAL EVALUATION

4.1. Simulation Tests

MATLAB Simulink was employed to simulate the system as given in Figure 6. An extensive simulation tests was done using in order to evaluate the efficiency of CAS that incorporate LiDAR and OF in real-time.

4.1.1. Results and performance metrics from simulation tests

Various metrics were employed in order to evaluate the performance of the UAVs during the simulation such as collision rate, response time and path efficiency. The collision rate, which directly measured the system's primary goal of avoiding collisions, indicated the percentage of flights that involved a UAV coming into contact with an obstacle.

In order to make a comprehensive evaluation, various simulation scenarios, some relatively simple and some complex, were tried. Some scenarios were relatively simple, with few obstacles that made navigation straightforward. On the other hand, there were highly intricate environments with densely packed and unpredictably moving obstacles.

Throughout these simulations, a UAV successfully identified objects of different sizes and locations, whether they were stationary or in motion.

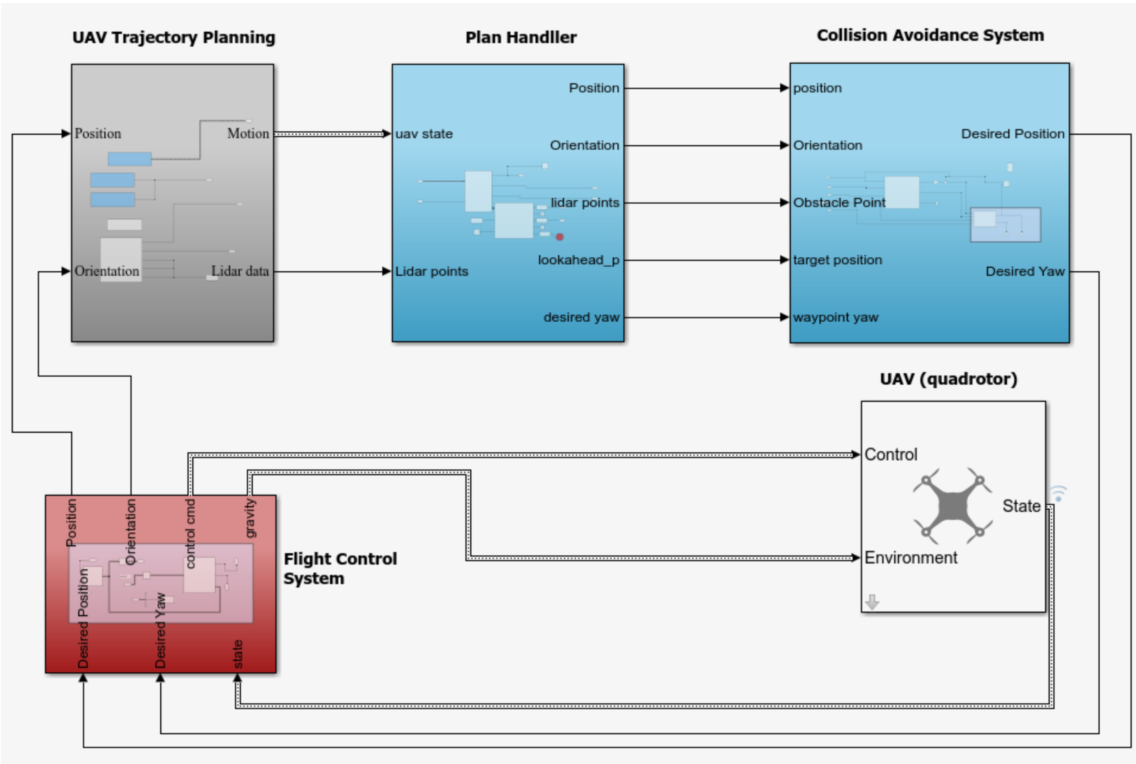


Figure 6. Block diagram of the system simulated in MATLAB Simulink

To fulfil its mission, the UAV followed a predetermined path that included intermediate waypoints. If the UAV encountered an obstacle while following its designated course, it utilized its LiDAR sensor to detect and recognize the obstacle. Once the obstacle was bypassed, the UAV resumed its journey, adhering to the established waypoints until the mission was accomplished. Figure 7 showcases the quadcopter's ability to detect both stationary and mobile obstacles using LiDAR during its flight.

To accurately simulate real-world flight scenarios, obstacles of varying sizes have been strategically positioned at random locations within the simulation environment.

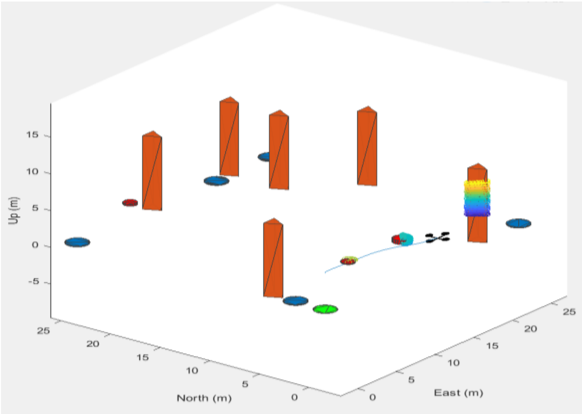
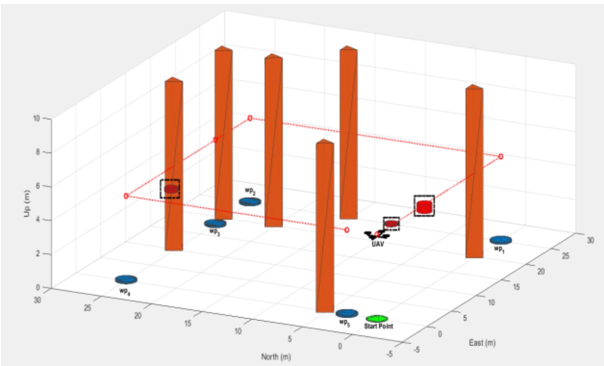


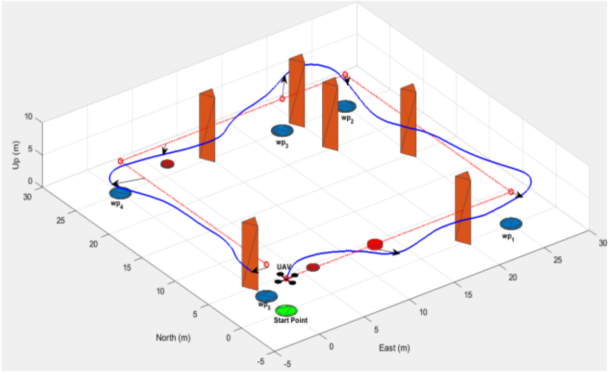
Figure 7. Detection of obstacles with LiDAR during the flight of the UAV

In Figure 8a, the simulation results showcase successful navigation along the obstacle-free path by following the designated waypoints. On the other hand, Figure 8b depicts the path followed when both dynamic obstacles were detected using the OF method and stationary obstacles were detected using LiDAR.



(a)

Figure 8. Detailed simulation results (a) obstacle-free path obtained by following the way (b) route followed as a result of detecting dynamic and stationary obstacles

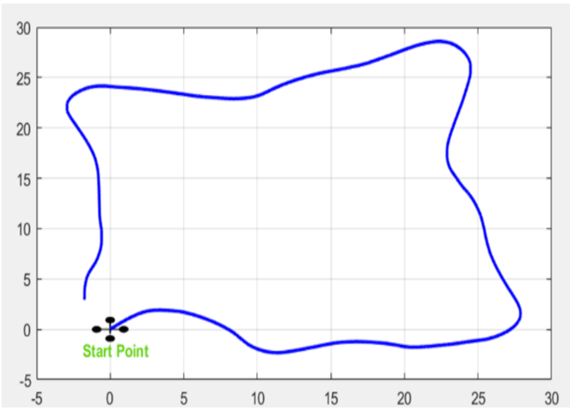


(b)

Figure 8.(Cont.). Detailed simulation results (a) obstacle-free path obtained by following the way (b) route followed as a result of detecting dynamic and stationary obstacles

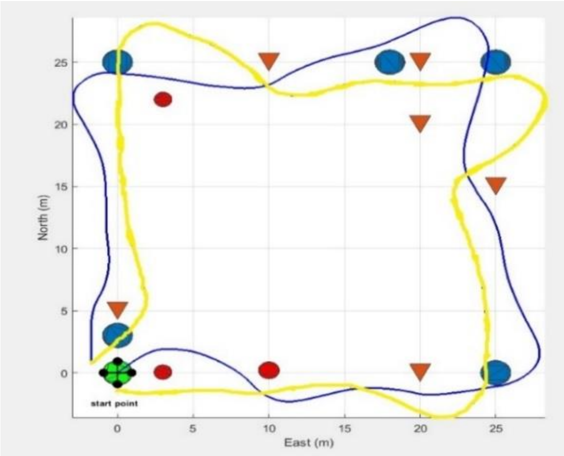
Figures 9a and 9b illustrate the flight paths of the UAV in the simulation. The UAV travels from the starting point to the target point, covering a distance of 97 m while manoeuvring around 3D triangular obstacles. Additionally, it follows the intermediate points and avoids obstacles represented by red balls, resulting in a path length of 108.3612 m. The outcomes of the simulation are affected by factors such as the position, quantity, and size of the intermediate points, as well as the location, size, and number of stationary and dynamic obstacles.

Table 2 provides comprehensive information on the path lengths for both cylindrical and triangular obstacles. Initially, the round-trip distance from the start to the target and back is determined by calculating obstacle-free paths. However, this distance may vary as the shortest route is determined by navigating through the intermediate points.



(a)

Figure 9. The results of the route (a) The UAV travels from the starting point to the target point (b) The route it follows when returning from the target to the starting point



(b)

Figure 9. (Cont.). The results of the route (a) The UAV travels from the starting point to the target point (b) The route it follows when returning from the target to the starting point

The agility of the UAVs' avoidance manoeuvres when faced with obstacles was assessed through response time. This metric measured how quickly the UAVs reacted upon detecting a potential collision. To evaluate the impact of avoidance behaviour on mission efficiency, path efficiency was analysed. It examined the deviation from the optimal path taken to avoid obstacles. Additionally, the computational load was monitored to ensure that the system did not overwhelm the UAVs' on-board processing capabilities. The simulation tests yielded promising results, with a significantly low collision rate observed in all scenarios. The UAVs displayed rapid response times, especially in dynamic environments where obstacle movements were unpredictable. While path efficiency was slightly compromised in highly complex scenarios, it did not undermine the achievement of mission objectives. Furthermore, the computational load remained within acceptable limits, confirming the system's suitability for real-time application.

Table 2. Path lengths for both cylindrical and triangular obstacles

Distance	**Triangular Obstacle**	**Cylinder Obstacle**
Way Point (Start to Target) meters	97	97
Obstacle Avoidance Enable (Start to Target) meters	108.3612	109.1072
Way Point (Start - Target -Start) meters	194	194
Obstacle Avoidance (Start -Target- Start) meters	221.7968	222.2466

Figure 10 shows the difference between the desired and current position of the UAV in the X, Y and Z axes, respectively, throughout the simulation. Figure 11 shows the desired yaw angle values in radians, calculated according to the obstacle and waypoints in the X, Y and Z axes of the UAV, respectively.

Upon encountering an obstacle, the UAV undergoes a shift in its position, accompanied by a corresponding adjustment in the yaw angle, which plays a vital role in steering the vehicle.

By evaluating the distances to both the obstacle and the waypoints, the UAV is directed towards its intended destination, successfully attaining the designated positions and yaw angles at specified intermediate points. The manipulation of the yaw angle is crucial for executing manoeuvres or adhering to a pre-established trajectory.

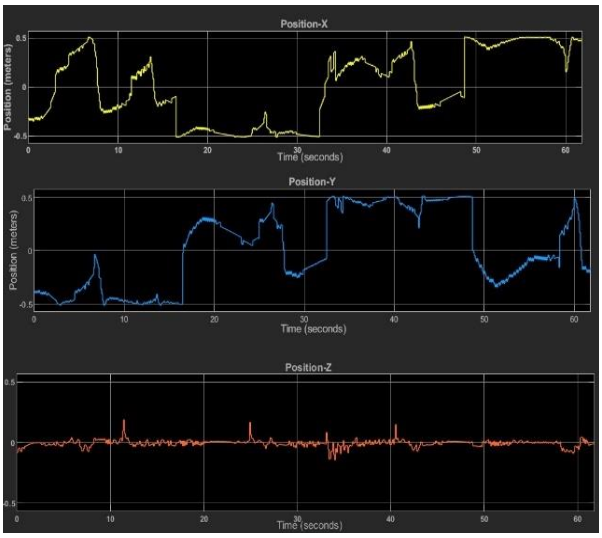


Figure 10. Position errors in the UAV's X Y Z axes

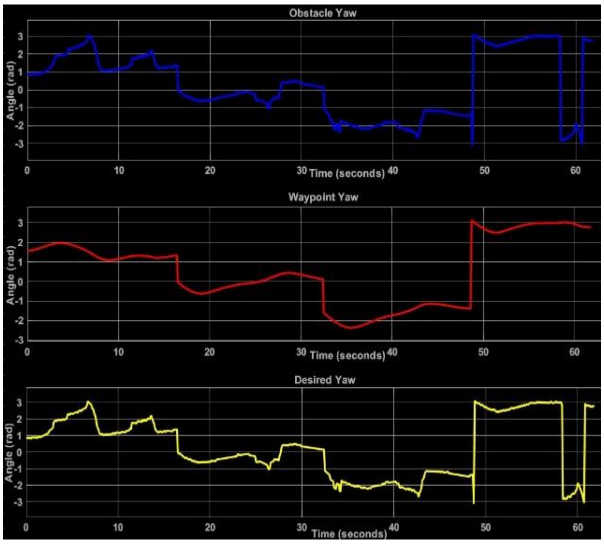


Figure 11. Desired yaw of the UAV according to obstacles and waypoints

4.2. Experiments

4.2.1. Setup and execution of real-world tests

Many experiments were conducted to verify the validity of the simulation results and assess the system's effectiveness in actual scenarios. The UAVs had LiDAR and camera (used by optical flow), both of which were used to detect obstacles.

Several tests were conducted that covered the entire spectrum of basic waypoint navigation in areas that were devoid of obstacles to intricate manoeuvres around objects that were moving.

The safety protocols were consistently followed, as evidenced by the presence of emergency override manuals and the constant monitoring of UAV flights by observers.

4.2.2. Case study: Avoiding a thrown ball

To assess the real-world capabilities of a UAV, a demanding test was conducted where the objective was for the UAV to evade a ball hurled into its trajectory. This specific scenario was carefully crafted to replicate the presence of an unforeseen and rapidly moving obstacle, thereby evaluating the UAV's capacity to swiftly respond in real-time.

While following its predetermined flight path, the UAV unexpectedly encountered the ball, which crossed its trajectory. The LiDAR and OF swiftly detected the presence of the ball, prompting the UAV's collision avoidance algorithms to activate. In response, the UAV swiftly manoeuvred to evade the ball and ensure a secure separation between the two.

The Horn-Schunck method, known for its effectiveness in handling sparse feature sets, has been utilized to determine the motion vectors that depict the trajectory and velocity of moving objects in frames captured at two distinct time points (t0 and t+1).

The OF result, displayed in Figure 12, illustrates the analysis of movement between Frames (a) and (b). This visual representation often manifests as a collection of arrows or vectors, with each arrow denoting the direction and magnitude of motion for specific points or patches within the images. The arrow's direction indicates the motion's direction, while its length signifies the speed of the motion.

(a) **(b)** **(c)**

Figure 12. The result of the OF from frames (a) First Image at t0 time; (b) Second Image at t+1 time, (c) OF result between images 11a and 11b

To assess the real-world capabilities of a UAV, a demanding test was conducted where the objective was for the UAV to evade a ball hurled into its trajectory. In its designated flight path, the unmanned aerial vehicle came upon an errant ball that was not supposed to be there. The avoidance system in the UAV sprang into action, immediately after the LiDAR and the OF identified the ball. Thus, the UAV precisely calculated a deviation from its route so as not to collide with the ball using this input data, ensuring a sufficient distance between them.

In this work, we employed the Horn-Schunck algorithm as one of the well-known techniques in solving a sparse set of features to estimate motion vectors which are used to track moving objects. These motion vectors present the direction and speed of each object from two consecutive frames (t0 and t+1). The optical flow output in Figure 12a, obtained by applying the Horn-Schunck algorithm on image pair (a) and (b), provides an analysis of movement between frames. A typical visual representation is composed of a cluster of arrows or vectors indicating directions and magnitudes of movements in various points or patches within images. The direction reveals where a motion was coming from, whereas its length indicates how fast it has been.

Employing a method that relies on computers allows for a more extensive analysis of the patterns of motion. This advanced understanding is aided by the graphical representation of OF vectors, these are represented by arrows that are colourful red. These arrows have the purpose of demonstrating the direction and magnitude of the motion of objects, they also provide a means to evaluate the motion. The significance of this dual representation is significant, as it helps to differentiate between different speeds and directions in a particular scene, this will allow a more detailed understanding of the underlying principles.

In a series of carefully planned experiments, collision avoidance with Unmanned Aerial Vehicles (UAVs) was successfully achieved during flight tests carried out on courses with different obstacles and in varying weather conditions. These experiments aimed to evaluate the ability of UAVs to overcome various obstacles and how they react in different weather conditions. The results highlight the importance of using UAV technology effectively in environments where it may encounter various challenges. The system is efficient at handling both stationary obstacles, such as trees and bridges, and mobile ones, including birds and other aerial vehicles. However, it's noteworthy that in areas with many obstacles and a lack of visible light, the effectiveness of optical flow may be diminished. Despite this, this solution provides alternative navigational options in inhospitable environments.

5. CONCLUSION

This study introduces a novel collision avoidance system for an UAV that incorporates the use of LiDAR for the identification of stationary and an OF for the identification of dynamic obstructions in their path. By fusing LiDAR's high-resolution spatial data with the relative motion detection capability of the OF, proposed system enables detection and avoidance of both static and dynamic objects on-the-fly. To evaluate the efficacy of the proposed system, various simulation and experiment were conducted. The results indicate that the system successfully avoids either stationary or dynamic obstacles.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Elif Ece ELMAS: Contributed to the study conception and design. Material preparation, data collection and analysis were performed. The first draft of the manuscript was written

Mustafa ALKAN: Contributed to the study conception and design. Material preparation, data collection and analysis were performed.

All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

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