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SYSTEM AN UNMANNED AERIAL VEHICLE TRAJECTORY GENERATION IN REAL TIME

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Abstract**—***This paper addresses the problem of real-time trajectory generation for unmanned aerial vehicles, emphasizing its importance for various applications such as search and rescue operations, environmental monitoring, and precision agriculture. The challenges associated with dynamic trajectory generation, including obstacle avoidance, adherence to mission constraints, and computational efficiency, are analyzed. A hybrid approach is proposed that integrates advanced path planning algorithms with real-time optimization techniques to ensure safe and efficient unmanned aerial vehicle navigation in complex environments. The system leverages onboard sensors and external data sources, such as GPS and LiDAR, for situational awareness and dynamic obstacle detection. A key feature of the proposed system is the ability to adapt the trajectory in response to real-time changes in the environment, ensuring robustness and reliability during autonomous flight. The implementation utilizes the PX4 autopilot platform, AirSim simulation environment, and QGroundControl software to validate the effectiveness of the proposed approach. The results demonstrate that the system achieves a balance between computational efficiency and trajectory accuracy, enabling its deployment in practical unmanned aerial vehicle applications.*

Index Terms—Real-time trajectory generation; AirSim; unmanned aerial vehicles; PX4 autopilot platform; R-CNN; QGroundControl.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are increasingly being deployed across a wide range of applications, including disaster response, environmental monitoring, infrastructure inspection, and agriculture. Their ability to operate in complex and hazardous environments, coupled with advancements in autonomy and real-time processing, has positioned UAVs as critical tools for modern problem-solving.

A fundamental requirement for UAV operation is trajectory generation-planning and executing a safe, efficient, and dynamically adaptive path to achieve mission objectives. Traditional trajectory generation approaches often assume static environments or rely on precomputed paths, which limits their applicability in real-world scenarios where conditions can change rapidly. Real-time trajectory generation addresses these challenges by allowing UAVs [1] to adapt their flight paths dynamically in response to environmental changes, such as the appearance of obstacles, shifting mission parameters, or evolving weather conditions.

This paper focuses on developing a real-time trajectory generation system that integrates advanced computational algorithms, real-world constraints, and high-performance hardware. By leveraging tools such as the PX4 autopilot platform, AirSim simulation environment, and QGroundControl mission planner, the proposed system is designed to enable autonomous UAV operations in dynamic environments.

The primary contributions of this study include the development of a hybrid algorithm combining global path planning and real-time local adjustments, the incorporation of sensory data for obstacle detection and avoidance, and a robust validation framework using simulation and field experiments. This research aims to bridge the gap between theoretical trajectory planning models and their practical deployment, enabling UAVs to operate safely [2] and efficiently in complex scenarios.

The remainder of this paper is organized as follows: Section II provides an overview of related work, highlighting existing approaches to UAV trajectory generation. Section III describes the system architecture and algorithmic framework. Section IV presents simulation and experimental results, demonstrating the system's performance.

II. NECESSITY OF REAL-TIME TRAJECTORY GENERATION SYSTEMS

The rapid expansion of UAV applications across diverse fields highlights the necessity for systems capable of ensuring safe, efficient, and autonomous operation in dynamic environments. Traditional navigation methods, which rely on pre-planned trajectories or manual control, often fall short in scenarios where real-time adaptability [3] is crucial.

UAVs frequently operate in settings where conditions can change unpredictably, such as urban areas with moving obstacles, forests with shifting weather patterns, or disaster zones with evolving hazards [4]. In such situations, the inability to adapt trajectories in real-time can lead to increased risks or mission failure.

Autonomous UAVs must also prioritize safety by effectively navigating around obstacles, avoiding collisions, and adhering to airspace regulations. Real-time trajectory generation systems [5] provide continuous environmental awareness by utilizing onboard sensors and external data, enabling UAVs to make immediate adjustments for safe operation. Moreover, efficiency is critical in many UAV missions, such as search and rescue, where precise and optimized movements can save time and resources. A real-time trajectory generation system minimizes unnecessary detours [6], reduces energy consumption, and ensures mission completion within required time frames.

As UAV usage expands to multi-UAV [7] systems for coordinated missions, the complexity of managing inter-UAV collision avoidance and synchronization increases. Real-time trajectory generation systems facilitate seamless coordination by dynamically updating each UAV's path in response to others' movements. Furthermore, advancements in artificial intelligence and machine learning have created opportunities to enhance UAV autonomy. These technologies enable real-time systems to predict environmental changes [8], optimize paths, and continuously improve through learning from previous missions.

In conclusion, the development of real-time trajectory generation systems is essential to address the challenges of dynamic environments, safety, efficiency, and scalability [9]. These systems not only enhance the reliability and performance of UAVs but also unlock their potential for more complex and high-stakes applications.

III. Justification of the Use of Development of a System for Generating UAV Flight Trajectory in Real Time

In the modern world, the use of UAVs is rapidly expanding across various fields, including military and rescue operations, logistics, agriculture, environmental protection, and infrastructure monitoring[10]. The high efficiency and versatility of drones enable them to perform complex tasks in hard-to-reach and hazardous conditions, which are often inaccessible to conventional aircraft and humans. However, with the increasing use of UAVs, there is a growing need to develop systems capable of generating optimal flight trajectories in real time, taking into account dynamic changes in the surrounding environment.

The purpose of this study is to substantiate the importance and relevance of developing a UAV real-time trajectory generation system and to analyze why such a system is essential for efficient task execution across various domains.

The main objectives of the study are as follows:

1) to demonstrate the necessity of autonomous solutions for enhancing UAV safety and cost-effectiveness;

2) to explore the importance of high trajectory accuracy and adaptability for ensuring safe navigation;

3) to determine the impact of trajectory generation systems on the efficiency and resource consumption of UAVs;

4) to highlight the role of modern artificial intelligence and machine learning technologies in enabling UAV autonomy.

Maintaining stability and accuracy during UAV flight is critical, particularly in challenging environmental conditions. Crosswinds and sudden gusts can significantly alter a UAV's trajectory, requiring adaptive algorithms to compensate for wind drift. Such algorithms must adjust the UAV's position and pitch angle in real time, counteracting wind forces to ensure the aircraft remains on its predefined path.

Altitude control becomes increasingly complex in environments with varying air density, such as at high altitudes where changes in air pressure and temperature can affect lift force. To address this, sensors and automated algorithms are necessary to dynamically adjust altitude, ensuring that the UAV remains on course without deviating from its trajectory.

Turbulent air poses additional challenges, causing irregular oscillations and vibrations that can destabilize flight. A robust correction mechanism is essential to counteract these disturbances. By filtering data from inertial sensors (IMU) to detect deviations, the UAV can promptly stabilize its trajectory by adjusting its pitch angle.

Weather conditions, including rain and snow, introduce unique obstacles to trajectory maintenance. These elements increase air resistance and add weight to the UAV's body and wings, potentially causing deviations from the intended path. Engine power compensation mechanisms are needed to offset these effects, allowing the UAV to maintain its trajectory despite the additional loads [11].

Flights over varied terrain, such as mountainous regions, forests, or water bodies, require careful adjustment to maintain consistent altitude relative to the ground. Terrain elevation changes demand the use of barometric sensor readings combined with altimeter data to dynamically adjust altitude, ensuring the UAV remains at a stable height above ground while following its intended trajectory.

Addressing these challenges is fundamental to the design of a reliable and efficient UAV trajectory generation system capable of operating effectively in diverse and dynamic environments.

IV. Proposed Approach

Unmanned aerial vehicles have attracted the attention of the research community due to their ability to obtain information about the environment; UAVs can be effectively used for search and rescue operations, inspection work, surveillance and information, but this requires the UAV to be highly maneuverable and resilient to unexpected system failures [12], such as GPS errors [13]. resilience to unexpected system failures, such as GPS errors. Current autonomous navigation systems for UAVs rely heavily on GPS, but this signal is unavailable in underground environments or under GPS jamming conditions, and is also weakened or unavailable in certain geographical regions. Providing autonomous navigation of UAVs in such environments requires geolocation solutions that work without GPS [14].

With the development of computer vision algorithms, many researchers have become interested in visual information-based navigation systems to overcome these challenges: in the framework of the DARPA Grand Challenge project, analyzing video information from cameras installed on mobile platforms, they demonstrated the effectiveness of using visual sensors for autonomous navigation. The effective use of video sensors for navigation is a long-standing goal of ground robotics. In recent years, a number of algorithms have been developed, which can be divided into methods using single cameras and methods using stereo cameras [15].

Successful examples have been obtained in the last decade using both perspective and omnidirectional cameras with single cameras with a large range of action. These approaches can be divided into those that use keypoint matching between consecutive images and those that track features in a sequence of images [16]. The main steps of keypoint-based methods include keypoint detection, matching, constructing epipolar radiometry based on these points, and finally estimating the relative position between frames. Feature tracking methods require tracking a certain number of feature frames (e.g., angles).

Due to the unavailability of video sequences captured by commercial medium-altitude UAVs, a video simulator was created using the Vricon 3D surface model to generate simulated video sequences for testing. The method first extracts key features and descriptors from continuous images of the simulated video sequence. Then, the key points are matched by similarity to the SURF descriptors.

A rejection procedure based on displacement RANSAC is used to remove anomalies. 6 Degrees of Freedom (6DoF) of motion are estimated only from the image matching points. Since the degrees of freedom are not limited to a specific motion model, the approach is universal [17]. The performance of the proposed system is evaluated in terms of both speed and accuracy relative to reference data.

As a result of the work, an imitation of UAVs was created and several important functions were implemented for testing and improving route formation methods. Various technical solutions were integrated within the framework of the simulation to effectively test different approaches to navigation, adaptation to changing weather conditions, and the use of cameras and lidars to assess the behavior of unmanned aerial vehicles. Below is a detailed description of the main results achieved during the work.

1) Building routes for unmanned aerial vehicles.
2) Testing the route formation method.
3) Creating different weather conditions.
4) Evaluating Route Generation Results.

A. Building routes for unmanned aerial vehicles

One of the main achievements is the ability to interactively build routes for unmanned aerial vehicles. This allows you to:

- Determine the flight point on the map and its coordinates, specifying the necessary parameters such as altitude, speed and direction of flight.
- The ability to test different route planning strategies, including algorithms based on depth search, A*, D*, etc., and adapt routes as the environment changes.
- Change the route structure in real time using a user-friendly interface, such as *q* ground control, for visualization and management.

B. Testing the route formation method

To improve the accuracy and reliability of UAV navigation during the simulation, several route formation methods were tested using different sensors:

Camera: Using a camera in the simulation allows you to obtain images of the environment and apply computer vision techniques, such as image segmentation, to recognize obstacles and important route points.

- The camera generates segmented images that allow you to accurately determine the presence of obstacles, such as buildings, trees, vehicles and other objects in the path of the drone.
- The camera also allows you to use the optical flow method to detect movement and change the status of the route (Fig. 1).

Lidar: Lidar is used to detect and map the environment in real time, which allows you to create detailed 3D maps of regions. This allows you to:

- Determine the distance to an object with high accuracy.
- It is used to create topographic maps and adjust the route when new obstacles are detected.
- The route formation method based on camera and lidar data can be used separately or in combination, which allows you to increase the adaptability of the UAV and optimize the route (Fig. 2).

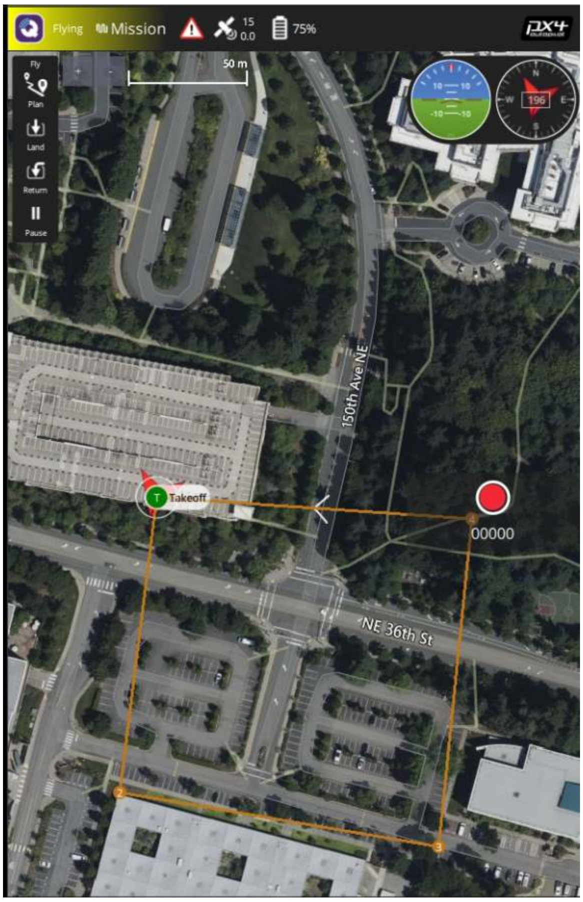

Fig. 1. UAV route construction map

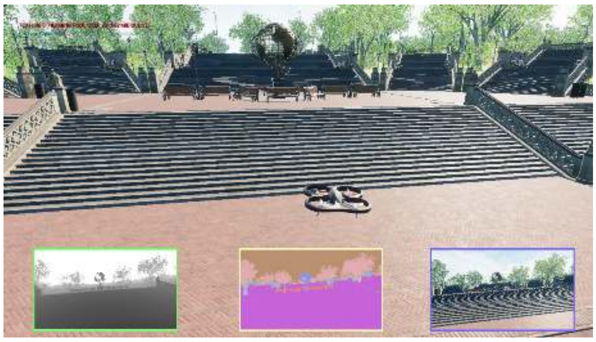

Fig. 2. Route construction methods

C. Creating different weather conditions

One of the key features implemented in the simulator is the creation of different weather conditions for testing drones in different scenarios. This allows you to simulate different situations that can affect navigation, such as the following:

- *Wind load:* Simulate different wind speeds and directions that affect flight stability and accuracy.
- *Precipitation:* Rain, snow, or fog can significantly reduce visibility and require orbit adjustments to continue a safe landing or flight.
- *Temperature fluctuations:* Changes in temperature can affect the aerodynamic characteristics of the drone, and these changes can be simulated to test the drone's response.

In this way, the ability to adjust weather conditions allows you to create more realistic conditions for testing drone navigation and safety algorithms in different external conditions (Fig. 3).

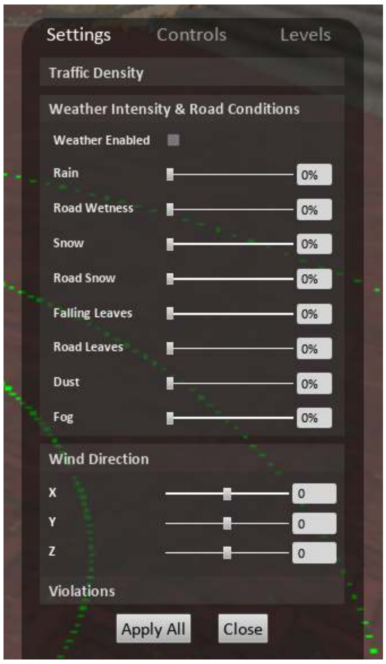

Fig. 3. Weather settings panel

D. Evaluating Route Generation Results

After running the route test in the simulator, the user can obtain the following UAV route generation results:

- *Route accuracy:* compares the planned route and the actual path the UAV traveled. This allows you to evaluate the effectiveness of the route generation algorithm.
- *Obstacle detection:* report on obstacles encountered by the UAV during flight and adjust the route in real time.
- *Efficiency analysis:* determine the time required to complete the route and compare it with the optimal time to determine the effectiveness of the selected route generation method.
- *Flight safety:* ensure compliance with safety conditions on the route, for example, do not approach prohibited areas or dangerous obstacles (Fig. 4).

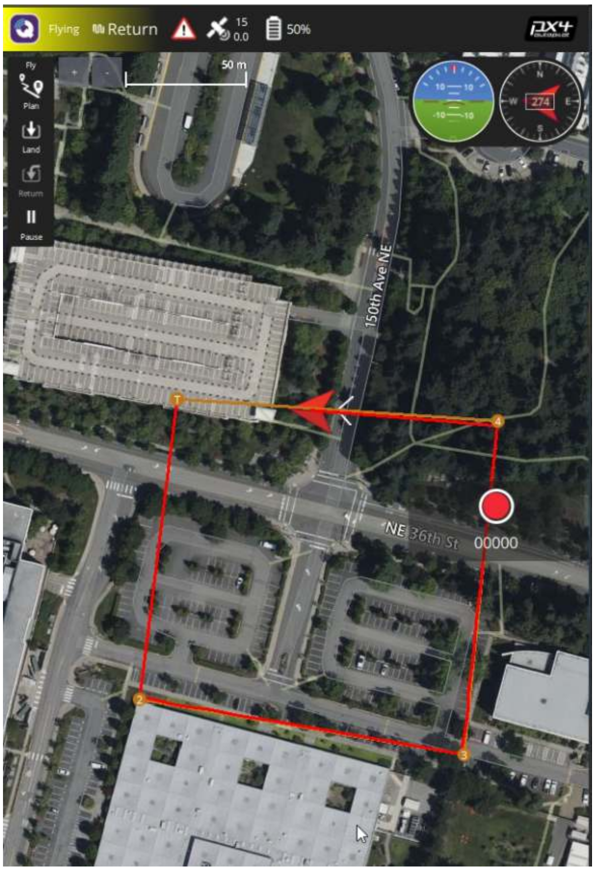

Fig. 4. Map of UAV route generation

V. CONCLUSIONS

As a result of the work, a powerful and flexible modeling platform was created for testing and improving methods for forming routes for unmanned aerial vehicles. The integration of various sensors, such as cameras and lidars, as well as the ability to create different weather conditions allow us to evaluate in detail the effectiveness of navigation algorithms and their ability to adapt to changing environmental conditions. The results obtained will allow us to draw conclusions about the accuracy and safety of the route and determine the best way to ensure effective and safe navigation of the drone in real situation.

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В. М. Синєглазов, А. І. Нікулін. Система генерації траєкторії безпілотних літальних апаратів у реальному часі

У роботі розглянуто проблему створення траєкторії в реальному часі для безпілотних літальних апаратів, підкреслюючи її важливість для різних застосувань, таких як пошуково-рятувальні операції, моніторинг навколишнього середовища та точне землеробство. Аналізуються проблеми, пов'язані з формуванням динамічної траєкторії, включаючи уникнення перешкод, дотримання обмежень місії та ефективність обчислень. Пропонується гібридний підхід, який об'єднує розширені алгоритми планування шляху з методами оптимізації в реальному часі для забезпечення безпечної та ефективної навігації безпілотних літальних апаратів в складних середовищах. Система використовує бортові датчики та зовнішні джерела даних, такі як GPS і LiDAR, для визначення ситуації та динамічного виявлення перешкод. Ключовою особливістю запропонованої системи є здатність адаптувати траєкторію у відповідь на зміни навколишнього середовища в реальному часі, забезпечуючи міцність і надійність під час автономного польоту. У реалізації використовується платформа автопілота PX4, середовище моделювання AirSim і програмне забезпечення QGroundControl для перевірки ефективності запропонованого підходу. Результати демонструють, що система досягає балансу між

обчислювальною ефективністю та точністю траєкторії, що дозволяє її розгортати в практичних застосуваннях безпілотних літальних апаратів.
Ключові слова: генерація траєкторії в реальному часі; AirSim; безпілотні літальні апарати; платформа автопілота PX4; R-CNN; QGroundControl.

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