Multi-modal Autonomous Obstacle Detection and Collision Avoidance System for UAVs

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***Abstract*—This article details the design, creation and testing of a multisensory self-flying drone system capable of spotting and dodging barriers independently. The system combines deep learning barrier finding, flexible flight planning, compact 3D mapping and cooperative accident prevention to help drones safely explore complicated areas. This paper will explain the equipment used, software developed, how parts were joined and checks done outdoors to establish this approach works well. Results show better safety and dependability for drone jobs and potential uses like monitoring land/buildings, checking worksites, efficient farming and fast disaster response.**

Keywords—UAVs, Autonomous Systems, computer vision, Obstacle Detection, Collision Avoidance, Deep Learning, Adaptive Control, Decentralized Algorithms

I. Introduction

Unmanned aerial vehicles (UAVs) have attracted interest across industries for their capability to access remote or hazardous areas and carry out tasks independently. Nonetheless a key challenge in UAV operations involves ensuring navigation in environments with obstacles. Conventional methods for detecting obstacles and avoiding collisions often depend on rules or manual intervention, which restrict the UAVs independence and flexibility. This study introduces a modal approach that combines deep learning, computer vision, adaptive control algorithms, lightweight depth estimation networks, Bézier curve model [5], bionic algorithms [5] and decentralized collision avoidance algorithms to improve UAV navigation capabilities in outdoor environments [6].

II. Research Contributions

Wu's research focuses on enhancing obstacle avoidance capabilities through flexible path planning in disturbed environments. They achieved fast adaptive path planning without maps in unknown environments. Zhou investigated the architecture of UAV swarms and achieved distributed autonomous navigation.[5]

Remaining Challenges:

Despite research progress, certain inadequacies persist, such as algorithms falling into local optima and the challenge of achieving full coverage in path planning.

Proposed Solution:

The study aims to address these challenges by proposing path planning methods for UAVs encountering both static and dynamic obstacles.[6]

III. Obstacle Detection and Collision avoidance

A. Problem Formulation

The problem addressed in the study involves UAVs used for urban applications and GIS data collection. The primary objective is obstacle avoidance during UAV flight, considering both stationary obstacles like buildings and variable obstacles like birds.

The difficulty lies in predicting the movements of variable obstacles like birds and efficiently avoiding them during high-speed UAV flight.[4]

The study also explores the development of adaptive obstacle avoidance control systems and lightweight depth estimation networks for obstacle avoidance on nano-drones, focusing on the Crazyflie platform. It also discusses the implementation and validation of decentralized algorithms for 3D collision avoidance with multiple UAVs, showcasing the effectiveness of the proposed algorithm in outdoor environments. The study introduces innovative approaches such as the Channel-Aware Distillation Transformer (CADiT) for knowledge transfer in lightweight depth estimation networks and the Circular arc Trajectory Geometric Avoidance (CTGA) algorithm for autonomous obstacle avoidance in complex flight environments. Additionally, the study discusses the use of neural control and synaptic plasticity for adaptive obstacle avoidance of autonomous drones, demonstrating the effectiveness of synaptic plasticity in enabling drones to navigate in diverse environments with varying obstacle densities, narrow corners, and deadlocks. The proposed methods and algorithms are supported by experimental results, simulations, and detailed analyses, providing valuable insights into their practical applicability and effectiveness in real-world scenarios.[6][10]

B. Technique Overview: The proposed technique involves several steps

- Image capturing
- Converting the captured image to grayscale
- Blurring the image to reduce noise
- Detecting edges using the Canny algorithm
- Finding contours to identify objects
- Drawing contours for visualization
- Identifying obstacles and free areas based on pixel color
- Commanding the UAV to move to the freer area
- Repetition of the process for continuous navigation.[1]

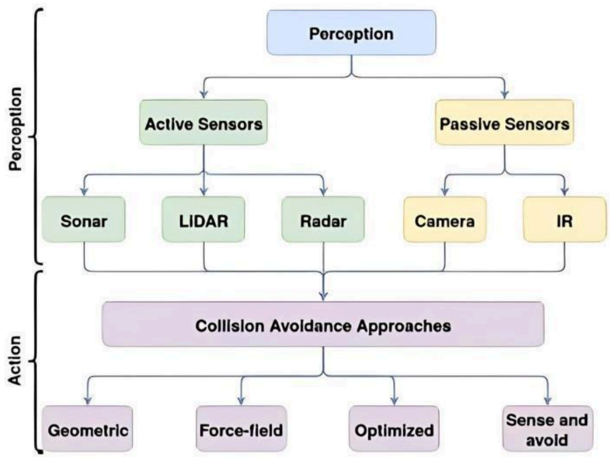

Fig. 1. Fig. 1. Collision avoidance system generalized modules[5]

C. Object Recognition Methods

Appearance-based methods: These methods use example images or templates of objects for recognition. However, objects can vary significantly under different conditions, making it challenging to rely solely on appearance for recognition.

Feature-based methods: These methods search for matches between object features and image features. Features such as surface patches, corners, and linear edges are extracted for recognition.

Obstacle Avoidance Importance: Obstacle avoidance is crucial for mobile robots, including UAVs, to navigate freely. Path planning relies on accurate mapping and obstacle detection.[4]

D. The study proposes three algorithms for obstacle avoidance

Brute force method: Compares cropped object images pixel by pixel with a database.

Modified Maximum Likelihood Estimation (MLE) approach: Compares defining features like color, size, and shape to identify the best match and Avoidance by Image Segmentation: Utilizes area calculation to identify and avoid obstacles.[3]

Collision avoidance systems are crucial for both autonomous and non-autonomous vehicles to prevent collisions due to various factors such as operator negligence, equipment malfunction, or adverse weather conditions.

These systems are particularly critical for UAVs, which are increasingly being used in various applications, as they can access difficult-to-reach or hazardous areas without risking human lives.[4]

E. Collision Detection and Avoidance

A collision is detected when the distance between the vehicle and an object is less than a predetermined collision radius. Collision avoidance involves calculating necessary maneuvers to avoid collisions based on real-time sensor data. Different approaches, such as geometric, force-field, optimized, and sense-and-avoid, are used for collision avoidance

1) Utilization of Bionic Algorithms

Researchers have utilized bionic algorithms such as particle swarm optimization (PSO), wolf swarm optimization (WSO), and ant colony optimization (ACO) to solve independent path planning for UAVs. Despite their robustness, these algorithms can become trapped in locally optimal solutions. [5]

a) Preference for Genetic Algorithms:

Genetic algorithms are favored for their continual directional adjustments, although they require significant computational resources.[6]

2) Modeling

The study models UAV motion and threat areas, including static and dynamic obstacles, to simulate real-world scenarios.

It focuses on medium and large fixed-wing UAVs and considers parameters like speed, acceleration, and obstacle characteristics.

$$uav = (vuav \times \cos\eta, vuav \times \sin\eta), \; UAV = (x,y) \quad (1)$$

where vuav is the speed, η is the heading angle, and (x, y) denotes the current coordinate position of the UAV. This research focuses on medium and large fixed-wing drones characterized by high aspect ratio. The drone tuning parameters investigated in this study were built according to the performance indicators mentioned previously, with a speed range of [100-150] km/h. and an acceleration range of $[-5, 5]$m/s.[6]

3) Path Planning Methods

The study describes path planning methods for UAVs encountering static full-coverage threats and dynamic obstacles.

It employs the Bézier curve model for path depiction, aiming to enhance flight performance and autonomous control.

It introduces an improved Bézier curve model to enhance UAV path planning in complex obstacle conditions.

Bézier bends show upgrading flight execution and moderating the complexities of independent control require the creation of a streamlined, nonstop flight way . With this in mind, the quadratic Bézier curve has been exploited as a model to represent the path, including the identification of data points and control points24. Notably, the efficiency and complexity of Bezier curve layout planning focuses on the number and location of control points. Therefore, applying the quadratic Bézier curve seems to be a wise choice for orbit modeling, due to its high accuracy and fast computational throughput25.

The formula for a second-order Bézier curve is:

$$B(t) = (1-t)^2 P_0 + 2t(1-t) P_1 + t^2 P_2,\ t \in [0, 1] \quad (2)$$

The data points P0 and P2 were coordinated, along with the control point P1, as illustrated below:

$$f(x(t), y(t)) = (1-t)^2 (x_0, y_0) + 2(1-t)(x_1, y_1) + t^2 (x_2, y_2),\ t \in [0, 1]. \quad [6] \quad (3)$$

4) Receding Planning Framework

The study introduces a backward planning framework to optimize control variables within finite intervals, ensuring efficient path planning while avoiding local optima.

In summary, the study contributes to the field of UAV path planning by proposing methods to address challenges like obstacle avoidance in complex environments, utilizing advanced modeling and planning techniques.[6]

5) Other Avoidance Algorithm

The study presents a study on a three-dimensional autonomous obstacle avoidance algorithm for unmanned aerial vehicles (UAVs) using circular arc trajectories. The algorithm aims to address the challenge of real-time autonomous obstacle avoidance in complex flight environments. It proposes a novel obstacle avoidance method based on the geometric relationship between UAVs and obstacles through obstacle modeling. The algorithm transforms the obstacle avoidance problem into a trajectory tracking strategy and is designed to generate circular arc avoidance trajectories to ensure safe flight.

The study discusses the obstacle avoidance problem, obstacle modeling, and the working mechanism of the proposed Circular arc Trajectory Geometric Avoidance (CTGA) algorithm. It also presents simulation results for static simple, complex, and dynamic obstacles, demonstrating the algorithm's effectiveness in avoiding obstacles and implementing obstacle avoidance missions for UAVs.[7]

The study discusses the use of neural control and synaptic plasticity for adaptive obstacle avoidance of autonomous drones. The study addresses the need for obstacle avoidance strategies for drones operating in complex environments with obstacles, corners, and deadlocks. It offers an alternative method using two ultrasound devices based on distance sensors, neural control, and synaptic plasticity. Neuronal control relies on feedback loops of two neurons, and synaptic plasticity is achieved through online rule-based learning and synaptic scaling. This approach allows the drone to navigate in diverse environments, adapting its turning angle to avoid obstacles effectively. The neural controller was developed and evaluated using a physical simulation environment, demonstrating its ability to successfully explore and navigate environments without collision.[8]

The study discusses the implementation and validation of a decentralized algorithm, 3D-SWAP, designed for 3D collision avoidance with multiple Unmanned Aerial Vehicles (UAVs). The algorithm extends ideas from previous work on ground robots and combines a similar strategy on a horizontal plane with control of the UAVs' altitude to navigate safely in 3D environments. It operates reactively, requires low computational load, is decentralized, and works with noisy sensors and restricted communication.[9]

The study details the system integration and experimental results to validate 3D-SWAP, including the use of Software-In-The-Loop simulations and outdoor field experiments with up to 3 UAVs. The UAVs used in the experiments are custom-designed hexarotors equipped with various sensors such as Lidar and 3DR uBlox GPS receiver, as well as communication systems.[9]

The algorithm's robustness is evaluated through simulations and field experiments, demonstrating its effectiveness in addressing 3D collision avoidance in outdoor environments. The study also discusses the integration of 3D-SWAP with the UAV Abstraction Layer (UAL) and the use of a simulator based on Gazebo for realistic simulations.

F. Collision Avoidance System Components and Architecture

CAS for unmanned vehicles typically include sense, detect, and collision avoidance modules. Perception or obstacle detection is the initial step, where sensors are used to perceive the environment and detect obstacles. Action or collision avoidance involves determining if an obstacle poses a risk of collision and performing maneuvers to avoid it.

Types of Sensors:

- Sensors used for obstacle detection can be categorized as passive or active.
- Passive sensors detect energy emitted by objects, such as visual cameras, thermal cameras, and spectrometers.
- Active sensors emit waves or light and detect their reflections, such as LiDAR.[5]

1) Selection of Wing and Material

e-ISSN No. 2584-1025

The paper explores different design configurations for the UAV's airframe, including wing type, fuselage material, and propeller location. It discusses the advantages of using delta wings for their lift effectiveness and structural rigidity. Additionally, it presents corrugated plastic (Coroplast) as a suitable material choice for its lightweight, shock-absorbent properties, and cost-effectiveness compared to traditional materials like foam board or balsa wood.[2]

2) Concept of Ultrasonic Sensor

The paper introduces ultrasonic sensors as a crucial component for obstacle detection and distance measurement. It explains how ultrasonic sensors work by emitting sound waves and analyzing the reflected signals to determine distances. The HC-SR04 ultrasonic sensor is specifically mentioned for its affordability, accuracy, and ease of use, making it suitable for the UAVs obstacle detection system.[2]

3) Design Configuration and Construction

The paper outlines the process of designing the UAV's flight plan, emphasizing the importance of scaling down real models for accurate construction. It discusses the construction materials and techniques, highlighting the use of Coroplast for its durability and resistance to environmental factors. Precision cutting, filing, and adhesive bonding are emphasized for quality assembly, with attention to aerodynamic properties to ensure optimal flight performance.[2]

4) Collision Detection Sensors

Various sensors are considered for collision detection, including active RADAR/LIDAR and passive visual electro-optical (EO) or forward-looking infrared (FLIR) sensors. Each type of sensor has its advantages and limitations in terms of resolution, covert operation, and power requirements.[2]

5) Visual Threat Awareness Avoidance (VISTA) System

The VISTA system is proposed for passive, stereo image-based obstacle detection. It utilizes block matching stereo computation and image segmentation for collision detection, inspired by human vision principles. The system aims to increase robustness to stereo correspondence errors and provide constraints for motion planning and avoidance.[3]

6) MATRIX System Architecture

The MATRIX system is developed as a multi-layer architecture for trajectory re-planning and intelligent plan execution. It integrates threat detection algorithms with path planning and trajectory generation to achieve real-time threat detection and avoidance, even under faults and failures.[3]

7) IMPACT System

The IMPACT system combines the MATRIX and VISTA systems to achieve integrated motion planning, awareness, and control. It enables aggressive maneuvering for UAVs to accomplish mission objectives under various threats and dynamic environmental changes.[3]

8) Failure Detection and Reconfiguration

A layer within the MATRIX architecture focuses on failure detection, identification, and reconfiguration. It monitors the health of UAV subsystems/components, detects faults/failures, and reconfigures controls to maintain desired flight performance.[3]

9) FLARE System

The FLARE system is designed for fast online actuator reconfiguration enhancement. It utilizes decentralized failure detection and re-configurable control algorithms to handle actuator failures, control effector damage, and disturbances while maintaining system stability.[3]

10) HeliCon Controller

The HeliCon controller is developed for helicopter UAVs, combining partial feedback linearization, sliding mode control, and outer-loop LQR control for stabilization. It includes a retrofit module for accommodating loss-of-effectiveness failure of flight control actuators.[3]

G. Integration of Image Processing with UAVs

Past research has demonstrated the integration of image processing techniques with quad-rotor aerial robots for tasks such as indoor positioning, object tracking, and obstacle detection.

Various experiments, like those conducted by Zou et al. and Courbon et al., have explored using cameras and sensors for image processing and reference point recognition during UAV navigation.

IFOR UAV Example: The IFOR (Intelligent Flying Object for Reconnaissance) UAV utilizes LIDAR for obstacle detection and two cameras for object identification and signboard reading. Image processing techniques like SURF descriptors and OCR are employed for object recognition.[4]

IV. Summary

This paper provides a detailed exploration of obstacle detection and collision avoidance systems for unmanned aerial vehicles (UAVs). It begins by outlining the problem formulation, emphasizing the challenges associated with predicting the movements of variable obstacles like birds and efficiently avoiding them during high-speed UAV flight. The study delves into various techniques and methodologies proposed to address these challenges, including adaptive obstacle avoidance control systems, lightweight depth estimation networks, and decentralized algorithms for 3D collision avoidance with multiple UAVs. The proposed techniques involve image processing steps such as image capturing, grayscale conversion, edge detection, and obstacle identification, supported by hardware and software components like the Linux OS, OpenCV library, ROS, and Pixhawk flight controller. Additionally, the text discusses object recognition methods, the importance of obstacle avoidance, and three algorithms proposed for obstacle avoidance. It highlights the critical role of collision avoidance systems in ensuring the safety of UAV operations, particularly in complex environments, and explores various sensor types and algorithms utilized for collision detection and avoidance. Furthermore, it presents advancements in system architecture, such as the MATRIX and VISTA systems, designed to enhance trajectory replanning, threat detection, and autonomous control. Finally, the text discusses the integration of image processing techniques with UAVs and provides examples of past research endeavors, showcasing the practical application of these systems in real-world scenarios.

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