Progress in UAV Path Planning Technology based on Machine Vision Navigation

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Abstract. With the rapid development of Unmanned Aerial Vehicles (UAV) technology, their applications in agricultural monitoring, search and rescue, environmental monitoring and other fields are increasing. These application scenarios put forward higher requirements for the autonomous navigation and path planning capabilities of UAVs. UAV path planning technology based on machine vision is a key technology for UAV autonomous navigation. The technology also has received the widespread attention in recent years. This paper reviews the UAV path planning technology based on machine vision, and makes a comprehensive analysis from basic principles, key technologies to future development directions. First of all, this paper introduces the basic concept of UAV and the role of machine vision in UAV route planning. Secondly, the application of visual localization, environment perception, target detection and machine learning in path planning is discussed in detail. At the same time, the analysis of the main challenges facing the current technology, including environmental complexity and computing resource constraints and real-time data processing, etc. Finally, the development directions of future technologies are prospected, such as the application of advanced machine learning techniques, swarm UAV disaster response, and real-time obstacle avoidance.

Keywords: Unmanned Aerial Vehicle, Visual Navigation, Path Planning

1 Introduction

In the past ten years, the Unmanned Aerial Vehicles (UAV) technology has experienced explosive growth, its application range from the initial military reconnaissance extended to agriculture monitoring, disaster response, such as traffic management and civil fields [1]. The efficient deployment of UAVs relies heavily on their autonomous navigation capabilities, especially in unknown or hostile environments. In this context, machine vision-based path planning technology is particularly critical, which can provide real-time environmental perception capabilities, enabling UAVs to identify obstacles, plan paths, and safely reach their destinations. Although machine vision technology has shown great potential in UAV navigation, its implementation still faces various challenges, such as real-time processing in dynamic environments, accuracy and stability. The solution of these problems is crucial to promote the practicality and commercialization of UAV technology. At present, a large

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number of researches focus on improving the visual processing ability of UAVs. Ai et al. use distributed model prediction and visual field topology technology for environment perception and obstacle avoidance [2]. Al - Kaff et Al. was put forward based on the dimension of the feature point detection Expansion Algorithm (Size Expansion Algorithm) [3], although some progress has been made, but these studies are often ignored in the practical application of UAV facing the complex environment and the dynamic change [4]. Visual navigation system must deal with a large amount of image data, extraction of available information, and to estimate the states of the UAV, real-time algorithms exist in the process of the real-time [5], accuracy and complexity of environmental problems such as data fusion. Research gaps mainly focus on path planning for UAVs that are difficult to adapt to complex and dynamic environments in real time, and how machine learning can optimize the limited computing power and reduce the waste of UAV energy.

This study aims to fill the blank of the above research, through a new path planning framework based on machine vision, make the UAV can be more accurate, more efficient navigation in complex and dynamic environment. It opens up new possibilities for the deployment of UAVs in a wider range of application areas, such as swarm UAV disaster response.

2 The Current Research Background

UAV is a kind of aircraft that does not require direct human operation and is driven by autonomous power [6]. Table 1 shows the usual composition of UAV systems, including UAV platform, flight control system, communication system, mission load, and ground control station. These components allow UAVs to perform missions without direct human operation, adapt quickly to different mission requirements, and reduce personnel risk in hazardous areas.

Table 1. UAV systems are usually composed of the following main components

Composition name	Description
The UAV platforms	It is the UAV body, it can be a fixed-wing aircraft, helicopter, multi-rotor aircraft, etc.
Flight control system	It is responsible for the take-off, flight path control, stabilization and landing of drones.
communication system	It is used for data transmission between the drone and a ground control station.
Task load	It includes cameras, sensors, and other devices for performing specific tasks.
ground control station	It allows operators to monitor the state of the drone and control its flight.

Figure 1 shows a frontal view of a UAV, where structures such as the camera, wings and fuselage can be clearly seen. These structures endow the UAV with various functions required, such as visual recognition, etc.

Fig. 1. Front view of a UAV

The autonomous, flexible, and safe features of Uavs are shown in Table 2, which enable Uavs to perform missions efficiently without direct human control, can quickly adapt to different mission requirements, and minimize the risk to people in hazardous areas.

Table 2. The operation of UAV features include

Characteristic	Description
Autonomy	It is able to perform tasks without direct human control.
Flexibility	It can be deployed quickly to suit different task requirements.
Safety	It can reduce personnel risk when operating in dangerous or difficult to reach areas for humans.

Navigation path planning based on machine vision is refers to the use of UAV pick up camera and image processing technology, environmental perception and processing, and then planning out a match from the starting point to the target point constraints feasible flight path [7]. However, in the face of complex scenes, it is difficult for small UAVs to complete complex calculations in a short time, which requires more excellent image processing methods and navigation algorithms to efficiently complete the task.

3 Current Research Progress

3.1 UAV Environment Perception

UAV needs to be aware of its own location and environment before path planning. This requires the calculation and positioning of the incoming data from the sensors. According to Andy Couturier et al. [3], there are two main types of visual positioning way, is a kind of relative visual positioning (RVL), is a kind of absolute visual positioning (AVL).

RVL relies on real-time data to do calculations, which will make the errors that have been generated be reused again and again. This recursive way to solve the problem will make the problem more and more serious. Although the SLAM method can construct loop-back paths and eliminate errors, it loses its advantage when the paths are not closed. The combination of OV and INS proposed by Leutenegger S et al. has made the local positioning accurate enough [8], but it still does not completely solve the problem of error accumulation.

In AVL, UAV need to get the map data in advance, both from the airborne camera and satellite images. This way has a good performance in tackling the drift problem. However, the origin of the map data, the time of shooting, etc. are generally uncertain, and may not be the same in terms of clarity, brightness, white balance, etc. While various approaches have been suggested by scholars to enhance and optimize image matching, including template matching, feature point matching, deep learning-based matching, and visual odometry-based matching [3]. But in the face of the dynamic environment, such as earthquake, mud-rock flow, avalanche, typhoon disaster scenarios happens, such as image matching technology will be serious terrain changes. But some scholars put forward a kind of AVL and RVL combined navigation method, extended kalman filter (EKF) based on vision navigation system [9]. However, this method has no advantage when flying at low altitude, and it loses the ability of rapid response in disaster scenes.

Wu Y, etc for UAV system developed a perception can automatically initialize the tracker [10]. Concrete is in the kalman filter framework integrates a quick significant target detector. But it appears in the scene when the condition the effect not beautiful.

3.2 Optimization of UAV Path Planning Algorithm

In the path planning of UAV, in order to improve the problems of complex calculation and low accuracy in traditional three-dimensional path planning, Jiaproposed A path planning method based on the combination of improved genetic algorithm and sparse A* algorithm [7] . The method first establishes the mathematical model based on the environment, and then through the operation of the improved GA algorithm operator, make it more suitable for UAV flight. A suitable flight route is pre-calculated by the ground computer. For the environmental changes faced by the UAV after takeoff, Jia proposed a method combining GA algorithm and SAS algorithm [7]. Firstly, the optimized GA algorithm calculates the global path, and then the real-time performance of SAS algorithm is used to deal with the emergency situation, so that the UAV can make real-time feedback and avoidance actions to unexpected threats during flight. However, this method has not been verified on the real hardware platform, and it is difficult to deal with moving obstacles.

Babel L put forward an algorithm to determine the fixed-wing unmanned aircraft in the no-fly zone in the scene the shortest path [11]. The algorithm considers the UAV dynamics and navigation capabilities. Especially in the case of GPS is not available, the use of visual navigation based on landmarks. To set up a discretization algorithm based on airspace, and apply standard network algorithm to calculate the avoid the no-fly zone and adapt to the performance of UAV.

When UAV is mainly in the city, city map information often can be obtained through the network ahead of time, which makes the city map can be use drones. Shahoud and some researchers employ the Probabilistic Hough Transform (PHT) technique for identifying and extracting the street boundary [12], while others utilize it to detect and extract the street's perimeter. Enable UAV to match its position, and use visual odometer (VO) to modify the position offset of UAV.The algorithm idea about this method is also relatively clear (see Figure 2).

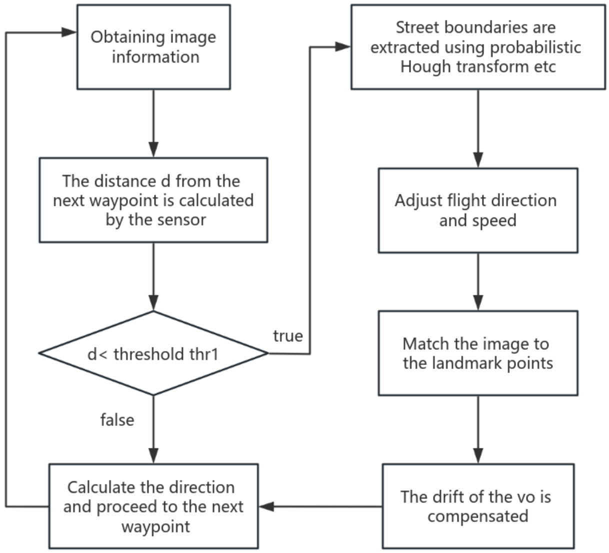

Fig. 2. Schematic route tracking algorithm

When the UAV encounters the problem of low GPS accuracy or failure, the UAV will be almost impossible to use in the vast majority of scenarios. Especially when there are valuables or complex obstacles in the working environment of the UAV, the UAV will rely heavily on high-precision GPS and other sensors. This will also increase the cost of the drone. And Warren M et al. proposed a path following algorithm for visual instruction and repetition (VT&R) [13]. The UAV is able to correct the route by using the pre-collected path map. And then the correction is made based on the real-time local feature map. The process of image segmentation is shown in Figure 3, and this process is crucial for UAV path planning through machine vision, as it allows the UAV to identify and distinguish different regions in the environment to make navigation decisions.

Fig. 3. A Schematic representation of the image segmentation

3.3 Machine Learning and Path Planning

UAV path planning needs to be based on existing maps in most cases. This map collection and processing for small UAV brings a huge challenge. Although the drone's onboard computer is capable of analyzing images in real time, it still suffers from low accuracy and a small number of frames. This is especially true when obstacles are no longer stationary. The utilization of artificial intelligence techniques has been widely proposed by numerous scholars to address the challenge of dynamic obstacle avoidance.

A novel approach to path planning in navigation, incorporating semantic segmentation, was introduced by Bartolomei L et al [14]. The method to avoid no texture area and other areas may cause the failure of positioning. This method using hierarchical planning at the same time, combining with the A * search and B - Spline trajectory optimization, to ensure the effectiveness of the path. Through a series of light realistic simulations, it is proved that the strategy is effective in improving the positioning and navigation accuracy of UAV. The deep learning framework was shown in Figure 4, and it illustrates the structure and working mechanism of the neural network used in reinforcement learning algorithms for UAV path planning.

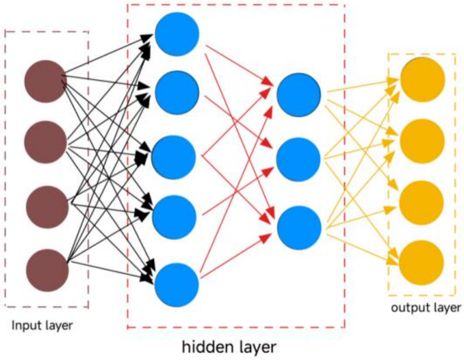

Fig. 4. Illustration of the deep learning framework

Duan Y put forward a new reinforcement learning algorithm [15], it will be the learning process as an optimization goal, and use the standard reinforcement learning algorithm to optimize. Through study rather than manual design to implement end-to-end optimization of the algorithm. Through coding algorithms into circulation RL2 weights of neural network (RNN), these weights through gm's (slow) reinforcement learning algorithm for learning. In small-scale set shows the method and theory of the optimal performance is considerable.

Zhu et al. proposed a unique idea to solve the problem that navigation strategies such as GPS are prone to poor accuracy in some cases [16]. They describe UAV navigation process as a markov decision process, and use the sensor observations as MDP state information input. The study adopted the Deep Reinforcement Learning (DRL) algorithm to learn directly from the original sensor input navigation strategy, and they discusses the DRL in the development and the challenges faced by these scenarios. In addition, we explore ways to transfer the policies trained by DRL algorithms from the simulation environment to the real world, and investigate ways to improve the robustness of sensors. Although DRL shows great potential in the field of UAV navigation, this study also points out some limitations, including partial observability problem, low training efficiency due to sparse reward, and insufficient generalization ability.

4 The Future Development Direction

Self-directed learning and dynamic route mapping: As artificial intelligence technology continues to evolve, the upcoming unmanned aerial vehicle (UAV) route planning system will increasingly emphasize autonomous learning capabilities and adaptability. This means that the system can automatically adjust and optimize the flight strategy according to the past flight experience and environmental changes to improve flight efficiency and flight safety.

Cluster UAV in response to emergencies: the UAV cluster in the application of the disaster response. For example, in emergency situations such as earthquakes, floods or fires, swarms of drones can be quickly deployed to perform rescue operations and damage assessment. This requires drones have highly coordination and stability under extreme conditions. Can even underwater environment should be brought into the scope of research, development and water empty amphibious UAV, thus the perils of the sea, floods and other wading environment for UAV to assist the rescue activities.

Deal with real-time obstacle avoiding to change position: the development of more advanced obstacle avoidance algorithm, combined with artificial intelligence and machine learning technology can make the UAV in the process of flying quickly identify and avoid sudden obstacles, such as aircraft, birds or sudden meteorological conditions, to ensure the flight safety. Improve the safety of UAVs that fly in crowded areas for a long time, such as film aerial shooting, air patrol, and drone delivery.

5 Discussion

Cluster UAV applications in the field of disaster response is a highly practical value. This field puts forward a series of challenging requirements for UAVs, including stability in extreme environments and accuracy of visual navigation. At present, the research of this field still needs more scholars delve into and creative thinking.

Traditional UAV navigation and decision method in the face of the mountain flood, earthquake, fire, these complex environment, such as landslides, may encounter many difficulties, such as visual identification difficult, complex path planning, real-time decision-making ability is insufficient, etc. Therefore, combining with machine learning, reinforcement learning techniques, in particular, for UAV to provide a more powerful perception, learning and decision-making, become the key to solve these problems.

Reinforcement learning allows drones in interaction with the environment, through the way of trial and error learning the behavior of the optimal strategy. In the disaster response, UAV by reinforcement learning, learning how to effective navigation in complex environment, how to accurately identify the target and how to optimize aid delivery, etc. At the same time, combined with deep learning and computer vision technology, UAVs can further improve their perception and decision-making ability in complex environments.

For the existing disaster response schemes, there are the space-ground integrated network combined with satellite and UAV [17], and the virtual combination scheduling scheme of heterogeneous network radio resources based on cross-population genetic algorithm. However, in the face of extreme environments, it may still face problems such as unstable communication and insufficient navigation accuracy. The most serious problem is that the path planning optimization of UAVs is poor after multiple disaster points appear. The potential solution to this problem lies in utilizing deep learning and reinforcement learning to enhance the optimization of intricate tasks, including multi-target points, thereby elevating the efficiency of disaster response.

However, the UAV disaster response system is a complex collection of multiple systems. It requires the effective integration of unmanned aerial vehicles (UAVs) or equipment modules with different functions. In the literature [18, 19], the authors presented their design scheme for the UAV disaster response system. By integrating various algorithms such as ant colony algorithm and annealing algorithm, they aim to develop a scheme that can maximize the rescue effect. However, in the field of UAV disaster response research, there is still a lack of a unified standard and method to calculate the rescue benefit, which limits the comprehensiveness and standardization of the research results.

Therefore, combining machine learning, especially reinforcement learning, to further improve the environment perception, path planning and real-time decision-making capabilities of UAVs will be a direction worthy of in-depth research.

In addition, due to the large theoretical span of this paper, the theoretical verification research has not been discussed in more depth, which may lead to the lack of exhaustive elaboration on the specific implementation details of the method. Future research needs to conduct more in-depth exploration in these aspects to promote the development and improvement of UAV disaster response technology.

6 Conclusion

Through a comprehensive review of UAV path planning technology based on machine vision, the author deeply discusses its application and development in the field of UAV autonomous navigation. With the wide application of UAV technology, such as agricultural monitoring, film and television media, and disaster relief, there is an increasing demand for advanced autonomous navigation and accurate path planning. The path planning technology based on machine vision not only improves the operation efficiency of UAV in complex environments, but also enhances its ability to adapt to dynamic changes.

Although machine vision technology has shown great potential in UAV navigation, it still faces many challenges, such as variable environmental changes, computational resource limitations, and real-time data processing. Solving these problems is crucial to promote the practicability and commercialization of UAV technology. Future research should focus more on developing advanced machine learning algorithms that can adapt to complex and dynamic environments in real time, optimize multi-sensor fusion technology, and improve the efficiency of UAV path planning.

The author not only provide researchers and engineers with an overview of machine vision-based UAV path planning techniques, but also highlight further research directions and potential application directions. Through continued technological innovation and algorithm optimization, future UAV navigation systems will be more intelligent and efficient, capable of safer and more reliable autonomous flight in a wider range of applications, thus opening up new business opportunities and bringing significant societal benefits.

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