Drone Situation Awareness and Path Planning Based on Deep Learning

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Abstract. With the rapid development of artificial intelligence and drone technology, drones are increasingly being used in military reconnaissance, disaster monitoring and rescue, agriculture, logistics and distribution, and other fields. Situational awareness and path planning, as key capabilities of drones, are critical to their ability to perform efficient and autonomous operations. This paper reviews the current application of deep learning in drone situational awareness and path planning, analyses its advantages and challenges, and discusses future development directions. Deep learning technology, through its powerful data processing and feature extraction capabilities, significantly improves the accuracy of situational awareness and the efficiency of path planning for drones in complex environments. However, current deep learning applications in drones still face challenges such as high data requirements, insufficient model generalization ability, limited computing resources, and security and robustness issues. Future research directions should focus on developing more efficient deep learning models, improving the interpretability and generalization ability of models, and optimizing drone hardware systems to meet real-time requirements. The introduction of interdisciplinary research will further promote the development of drone technology, enabling it to achieve efficient and safe applications in more fields.

Keywords: Situational awareness, path planning, Deep learning, drone technology.

1. Introduction

With the rapid development of artificial intelligence and the low-altitude economy of drones, drones have gradually integrated into people's production and life [1]. As an unmanned aerial vehicle capable of carrying various devices and remotely controlled [2], Unmanned Aerial Vehicles (UAVs) are widely used in military reconnaissance [3], disaster monitoring and rescue, agriculture, logistics and distribution, and other fields. Situational awareness refers to the drone's perception and understanding of various elements of the environment and itself, as well as the prediction of future states, and is a key capability to help the system make correct decisions [4]. Effective path planning can enable drones to effectively avoid obstacles and improve efficiency, so that resources can be maximized [5].

However, with the increasing complexity of application scenarios, a large amount of target information and environmental information are intertwined, which brings great challenges to the perception and path planning performance of drones. Complex environments (such as fire scenes, urban canyons, forests, etc.) usually require drones to have the ability to accurately identify and quickly respond to dynamic changes in the scene and adjust their trajectories in real time. Traditional perception methods rely on the evaluation algorithm analysis of multiple sensor data. In target-intensive environments, data interference is serious, which greatly affects the normal perception of drones [2]. Traditional path planning methods mainly rely on preset paths and rules, which are difficult to cope with complex and dynamically changing scenarios.

The introduction of deep learning technology has brought revolutionary changes to the situational awareness and path planning of drones. Relying on deep learning algorithms (Convolutional Neural Networks, CNN, etc.), drones can learn complex patterns and features from a large amount of data, thereby achieving faster and more accurate environmental perception and more reasonable and rapid path planning [6, 7]. Compared with traditional methods of calculating a large number of formulas to analyse the current situation, deep learning has higher speed and accuracy, and can reduce the shortcomings of drone hardware.

This article aims to review the current application status of deep learning in drone situational awareness and path planning, analyse the advantages and challenges of the integration of deep learning in drone perception and path planning, and explore future development directions.

2. Basic concepts and methods of traditional situation awareness and path planning

2.1. Traditional situational awareness

The concept of Situational Awareness (SA) was first proposed by Dr. Endsley in 1988, referring to a subjective perception of the environment by an intelligent agent [8]. Its core lies in achieving a comprehensive understanding of the environmental situation through perception, analysis, reasoning, and other processes. Traditional situational awareness mainly relies on conventional physical sensors (such as radar) to obtain information and uses the Endsley three-level model or the OODA loop model for analysis [3]. Taking the air combat situation analysis model proposed by Wang Guoyan et al. as an example, this model is a hierarchical decision-making model based on OODA, which characterizes the air combat situation by constructing a spatially multi-dimensional threat index, thereby enhancing the autonomous decision-making ability of UAVs in air combat scenarios [3].

However, this traditional model shows obvious limitations in complex environments. First, the perception accuracy of UAVs is limited by the physical performance of sensors, making it difficult to cope with changing environmental conditions. Moreover, the analysis and reasoning process relies on preset rules and expert knowledge, lacking adaptability and flexibility [8]. In addition, traditional models mostly have slow response speeds, making it difficult to meet the real-time requirements of tasks. When facing complex and changeable battlefield environments, its prediction ability is also insufficient to accurately predict future development trends.

In contrast, deep learning-based situational awareness models can automatically learn environmental features through data-driven methods, have higher accuracy, faster response speeds, and stronger prediction capabilities, providing more powerful support for UAVs' autonomous decision-making in complex environments.

2.2. Traditional path planning

UAV Path Planning is an important branch of robot motion planning, aiming to generate a three-dimensional spatial path for UAVs that meets task requirements and safely avoids obstacles (such as terrain, radar, and no-fly zones). Traditional path planning algorithms mainly include the A* algorithm, Dijkstra algorithm, and Ant Colony Optimization (ACO) algorithm. Among them, the ant colony algorithm is a heuristic search algorithm that introduces the concept of pheromones and makes random selections in each step of path selection (the probability of selection is positively correlated with the pheromone concentration), and finally selects the optimal path through pheromone concentration [9].

However, traditional path planning algorithms still have many shortcomings in complex environments. The A* algorithm and Dijkstra algorithm have high computational complexity in large-scale maps, which leads to excessive calculation time and makes it difficult to meet real-time requirements. Although the ant colony algorithm has a certain degree of adaptability, it still needs a large number of iterations to find a better solution when facing large-scale complex environments, which is time-consuming and requires high hardware resources [1, 9]. In addition, these traditional algorithms have poor adaptability in dynamic environments and cannot quickly respond to environmental changes [1].

In contrast, deep learning-based path planning methods can automatically generate optimal paths that adapt to complex dynamic environments by learning environmental features and path planning patterns, and have higher efficiency and adaptability.

3. Application of Deep Learning in Situation Awareness

The application of deep learning technology in UAV situational awareness is mainly reflected in its powerful data processing and feature extraction capabilities. Through deep learning algorithms, UAVs can automatically learn environmental features from a large amount of sensor data, thereby achieving faster and more accurate environmental awareness. Deep learning models can automatically extract high-level features from raw data without the need for manual design of feature extraction algorithms. This capability enables UAVs to quickly adapt and extract key environmental information when facing complex environments [6, 7]. At the same time, through training with a large amount of data, deep learning models can automatically learn complex patterns in the environment and adapt to different scene changes. For example, in dynamic environments such as fire scenes or urban canyons, deep learning models can adjust perception strategies based on real-time data, thereby improving the autonomous decision-making ability of UAVs [8, 9]. Deep learning algorithms (especially lightweight models such as MobileNet, EfficientNet, etc.) have fast inference speeds while ensuring high accuracy, which can meet the real-time perception needs of UAVs in complex environments. In addition, deep learning models can be continuously updated through online learning techniques to adapt to dynamic changes in the environment [3, 9].

The application of deep learning in UAV situational awareness mainly focuses on target detection and recognition, environmental perception and scene understanding, and multi-sensor data fusion:

Convolutional Neural Networks (CNNs) in deep learning perform well in target detection and recognition tasks. By training CNN models, UAVs can automatically identify target objects (such as vehicles, buildings, pedestrians, etc.) from image or video data, and classify and locate them. For example, algorithms such as YOLO (You Only Look Once) and Faster R-CNN have been widely used in UAV target detection, significantly improving the accuracy and real-time performance of target recognition [6, 7].

Situational awareness of UAVs in complex environments requires not only the identification of individual targets, but also the understanding of the entire scene. Semantic segmentation techniques in deep learning (such as U-Net, DeepLab, etc.) can help UAVs classify different objects in the scene at the pixel level, thereby achieving comprehensive perception of the environment. For example, in complex environments such as urban canyons or forests, UAVs can use semantic segmentation techniques to identify key elements such as buildings, trees, and roads, thereby better planning paths [8, 9].

UAVs are usually equipped with multiple sensors (such as cameras, radar, lidar, etc.). Deep learning can use multi-modal learning techniques to fuse data from different sensors, thereby improving the accuracy and robustness of perception. For example, deep learning-based multi-sensor fusion algorithms can combine visual data with radar data to achieve three-dimensional localization and tracking of targets [2, 3].

4. Application of Deep Learning in Path Planning

With the rapid development of drone technology, the demand for its application in complex environments is increasing. Traditional path planning methods exhibit obvious limitations when dealing with large-scale, dynamically complex environments, such as high computational complexity, slow response speed, and high hardware resource requirements. These problems undoubtedly severely limit the performance of drones in real-time dynamic planning. In recent years, the rapid development of deep learning technology has brought new solutions to path planning. This section will review the current application status of deep learning in drone path planning, analyze its advantages and challenges, and explore future development directions.

4.1. Advantages of deep learning in path planning

Deep learning models (such as convolutional neural networks (CNNs) and graph neural networks (GNNs)) can automatically extract high-level features from complex environmental data, such as the shape, position, dynamic change trends, and spatial structure of obstacles. This capability enables UAVs to understand the environment more quickly and accurately and generate optimal paths. Through deep learning, UAVs can construct high-precision environmental models from sensor data (such as images and LiDAR point clouds). For example, CNN-based models can extract the edges and contours of obstacles from images, while GNN-based models can capture the spatial relationships between objects in the environment [6, 7]. Deep learning models can learn patterns in historical path data, such as common optimal path shapes and obstacle avoidance strategies. This learning ability enables UAVs to quickly generate reasonable paths when facing new environments [1, 10].

Deep learning models (especially reinforcement learning algorithms) can continuously optimize path planning strategies through interaction with the environment, thereby adapting to changes in complex dynamic environments. Deep Reinforcement Learning (DRL) algorithms (such as Deep Q-Network, DQN) allow UAVs to autonomously learn obstacle avoidance and path optimization strategies during flight. For example, in dynamic environments, DRL models can adjust paths based on real-time sensor data to avoid suddenly appearing obstacles [6, 7]. Deep learning models can be continuously updated through online learning techniques to adapt to dynamic changes in the environment. For example, in fire rescue missions, UAVs can dynamically adjust flight paths by learning the trend of fire spread in real time [2, 3].

Deep learning models (especially lightweight models such as MobileNet and EfficientNet) ensure path planning accuracy while maintaining fast inference speeds, which can meet the real-time requirements of UAVs in complex environments. Real-time path planning algorithms based on deep learning can dynamically adjust paths during UAV flight to cope with sudden obstacles or environmental changes. For example, in urban canyons, UAVs can quickly generate obstacle avoidance paths by real-time sensing the location of buildings and pedestrians [8, 9]. Deep learning models can handle uncertainty in dynamic environments. For example, in logistics and distribution tasks, UAVs can predict changes in traffic flow through deep learning models and dynamically adjust delivery routes [1, 10].

4.2. Challenges of deep learning in path planning

Despite the significant advantages that deep learning has demonstrated in UAV path planning, it still faces many challenges in practical applications. The following is a detailed analysis of these challenges from four aspects: data requirements, model generalization ability, computing resources and reliability, and security and robustness.

The training of deep learning models relies on a large amount of high-quality labeled data, but in the field of UAV path planning, the cost of obtaining this data is high, and the labeling process is complex. UAV path planning requires a large amount of environmental data (such as topographic maps, obstacle distribution, dynamic target trajectories, etc.), and the acquisition of this data usually requires complex sensor equipment and long-term flight experiments [1, 10]. The labeling of path planning data requires professionals to mark every detail of the environment, such as the location, shape, and dynamic change trends of obstacles, which is time-consuming and labor-intensive [6, 7].

Deep learning models perform well in path planning in specific environments, but their generalization ability may be insufficient when facing unknown environments. UAVs may need to perform tasks in a variety of complex environments (such as cities, forests, fire scenes, etc.), and deep learning models may perform poorly in environments not present in the training data [3, 7]. In dynamic environments, deep learning models may find it difficult to quickly adapt to sudden changes (such as suddenly appearing obstacles or drastic changes in environmental conditions) [2, 3].

Deep learning models usually require high computing resources, while UAV hardware resources are limited. How to reduce computational complexity while ensuring path planning performance is an urgent problem to be solved. The training and inference process of deep learning models (especially deep reinforcement learning models) requires a lot of computing resources, but the airborne computing power of UAVs is limited and cannot meet real-time requirements [1, 10]. The black-box nature of deep learning models makes their decision-making process difficult to explain, which may bring risks in safety-critical tasks. For example, the model may generate unreasonable paths in some extreme cases, leading to UAV collisions [6, 7].

Deep learning models are vulnerable to adversarial sample attacks, which may lead to path planning failures or UAV out of control. By adding tiny noise or interference data, attackers can cause deep learning models to generate incorrect path planning results. For example, in logistics and distribution tasks, attackers may interfere with sensor data to cause the UAV to deviate from the planned path [2, 3]. When facing complex and changeable environments, deep learning models may exhibit insufficient robustness. For example, in extreme weather conditions (such as heavy fog, heavy rain), the path planning performance of the model may be significantly reduced [8, 9].

5. Conclusion

This paper mainly explores the current application status of deep learning in unmanned aerial vehicle (UAV) situational awareness and path planning, deeply analyzes its advantages and challenges, and discusses future development directions. Studies have shown that deep learning technology can significantly improve the accuracy of situational awareness and the efficiency of path planning for UAVs in complex environments, providing strong support for UAV autonomous decision-making. However, the current application of deep learning in UAVs still faces many challenges, such as high data requirements, insufficient model generalization ability, limited computing resources, and security and robustness issues. Future research directions should focus on developing more efficient deep learning models, improving the interpretability and generalization ability of models, and optimizing UAV hardware systems to meet real-time requirements. In addition, the introduction of interdisciplinary research, such as combining control theory and applied mathematics, will further promote the development of UAV technology. Through continuous technological innovation and optimization, UAVs are expected to achieve efficient and safe applications in more fields, providing important support for socio-economic development and emergency rescue missions.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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