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Overview Study of the Applications of Unmanned Aerial Vehicles in the Transportation Sector [†]

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Abstract: This study examines the use of Unmanned Aerial Vehicles (UAVs) in transportation, focusing on traffic monitoring and accident prevention. UAVs provide a cost-effective means for traffic surveillance, route planning, and accident analysis, enhancing data accuracy and timeliness. The paper discusses autonomous and human-intervention-supported drone systems for traffic surveillance, addressing technological and operational challenges and the balance needed for practical implementation. It also presents recent advancements, including a forerunner drone model, and references research on UAVs for maritime navigation safety, underscoring the need for their safe and efficient integration into transportation systems.

Keywords: unmanned aerial vehicle; road traffic monitoring; UAVs in maritime traffic; forerunner drone; drone autonomous operation

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1. Introduction

The use of UAVs has become widespread in various industries, such as agriculture, disaster management, transportation, and entertainment [1–9]. Researchers are continuously working on increasing UAV autonomy, as it reduces human error and improves flight accuracy [5,7,10]. Autonomous operations, such as takeoff and landing, are exposed to external disturbances, which can be mitigated by appropriate sensors and well-tuned control algorithms [5,9]. A thorough understanding of the UAV dynamics and models is essential for successful control design, which necessitates a multidisciplinary approach [9–13].

The sustainability advantages of UAVs are also significant. It was demonstrated by Loh et al. [14] that drones powered by gasoline generators achieved a high sustainability index, while, according to Sarghini and De Vivo [15], more precise pesticide application when using drones reduces environmental impact. Drone-based package delivery was proven to be energy-efficient in a study by Chiang et al. [16], and the role of drones in monitoring atmospheric pollution was emphasized by Jonca et al. [17]. The article of Wang et al. [18] is aimed to study hybrid renewable energy-powered drones, which offer longer operating times and a lower environmental impact.

This study provides a comprehensive analysis of the use of unmanned aerial vehicles in the transportation sector, with a particular focus on traffic monitoring, detection, the prevention of maritime accidents, and enhancing the safety of emergency vehicles. The paper thoroughly reviews and synthesizes the literature related to the subject. The aim of the article is to present the current state of drone technology in the transportation sector by summarizing the existing literature and research findings.

2. The Application of Unmanned Aerial Vehicles in Road Traffic Monitoring

UAVs are widely researched, including in-traffic monitoring applications [19,20]. According to Puri [21], numerous universities conduct research and tests using various types of UAVs to measure traffic-related data.

In the paper of Niu et al. [22], the UAV-based traffic monitoring systems are examined in urban areas, which utilize camera-equipped drones to record vehicle traffic. The videos are processed in a cloud-based system, and statistics are accessible through a web application. It is pointed out that traditional, fixed cameras are costly (USD 125.000) and less accurate (50–75%), whereas aerial camera systems achieve an accuracy of over 80%, do not have blind spots, and are also more cost-effective. The research of the authors involved tests with a 3DR Solo quadcopter and GoPro 4 camera, achieving high accuracy even with low-resolution images. UAVs can be stored in remote hangars located on building rooftops or poles, and temporary trailers can also be used as an alternative. UAVs can alternately fly over different streets and recharge periodically.

In the study of Niu et al. [22], the footage captured by the UAV in real-time is transmitted via wireless connection to a processing center, which allows for the avoidance of local, energy-intensive processing on the UAV, which increases flight time. A Haar cascade model is used for vehicle detection, which is a machine learning-based method also used for human face recognition. The model was tested with a training set ranging from 300 to 3750 images, with detected vehicles being marked by rectangles. A nearly 100% tracking accuracy and 90% detection accuracy at costs under USD 1000 was achieved by the authors. This is a higher accuracy than fixed-position traffic monitoring systems have achieved and can be further improved by increasing the number of training images.

Regarding Khan et al. [23], the challenges of traffic data collection on large road networks, where methods require significant infrastructure or labor, can be challenging. Previously, satellites and manned aircraft were used for traffic monitoring, but these methods proved unsuccessful due to quality, cost, and safety issues.

Recently, unmanned aerial systems are coming to the forefront in terms of traffic monitoring, management, and control. One reason for this is that UAVs can cover large areas quickly at extremely low costs [21,23,24].

A framework for traffic monitoring was used by Khan et al. [23] that incorporates flight planning, flight execution, data collection, data processing, data analysis, and optimization components within the framework.

It is mentioned by Khan et al. [23] that the flight planning stage includes preparing UAV flights in order to collect the necessary data. The UAV flight planning process is grouped into three main categories: safety, environmental, and route planning.

According to Khan et al. [23], successful execution of UAV flight operations first requires evaluating the flight zone of the area to be examined using local zone maps, ensuring a safe distance from active airports and drone-free zones. Additionally, it is necessary to obtain a flight permit, to consider the weather conditions and wind patterns of the area, and to choose the optimal time of day for operations; for instance, drone operations were conducted by Salvo et al. [25] during midday to minimize shadows, which improved video quality. Furthermore, electromagnetic interference and the status of GPS satellites must be monitored, especially for automated flights [23,26]. Advanced technologies allow UAV flight planning tools to designate waypoints and plan automated flights; however, even then, the presence of a remote pilot and operation within a visual line of sight of the UAV are mandatory [27].

During the flight execution phase, the UAV traverses the monitoring area along a predefined flight path. The trajectory is either flown by the remote pilot or autonomously followed by the UAV. Both methods require obtaining permits and clarifying legal matters, especially due to safety regulations [23]. During the flight, it is important that the video is stable; a gimbal is often used to mitigate image stability problems caused by maneuvers or wind [23,28].

UAV flights over a low-traffic intersection were conducted by Barmpounakis et al. [28]. The UAV hovered at a point where the intersection was visible from all directions. The maximum flight altitude was 70 m, and a 14 min video was recorded during the operation. The flight took place in sunny weather with moderate wind conditions during midday when shadows were minimized, ensuring effective vehicle identification during the analysis phase.

In the study of Salvo et al. [25], UAVs were used to collect traffic data in the suburbs of Palermo, where HD-quality, 15 min recordings were made during multiple flights to achieve the desired video length despite technical limitations. Data collection took place under ideal conditions during midday to minimize the impact of shadows. According to Khan et al. [23], data collection from UAVs is a critical component of the system that involves the collection of high-quality videos and other sensor data during flight.

Real-time data collection and processing was applied by Zheng et al. [29] and Sekmen et al. [30], where a ground station performs the image processing of live videos. A real-time vehicle tracking system was proposed by Zheng et al. [29] that serves to observe and study the behaviors of the drivers in order to prevent accidents and enhance highway safety. The system proposed by the authors is based on the live broadcasting of videos made by the UAV. A ground station, a computer, performs real-time image processing, followed by statistical analysis.

As opposed to this, offline processing is preferred by Salvo et al. [25] and Barmpounakis et al. [28], where video data are collected and analyzed after the flight.

Two main approaches to video analytics are described by Khan et al. [23]: partially automated and fully automated video analysis. The former provides high accuracy but requires significant human resources, while the latter is fast and requires less manpower; however, its accuracy can vary depending on environmental factors and demands a high computational capacity.

In terms of data analysis, various types of graphs and diagrams were used by the authors that emerge as outputs of data analysis procedures.

During the analysis, the trajectories of vehicles or other road users are displayed on x–y plane graphs to understand the behaviors and habits of road users. These trajectories are also graphically represented to illustrate traffic movement, for example, through an intersection or roundabout. The main focus of the work of Barmpounakis et al. [28] is trajectories that may compromise traffic safety. According to Khan et al. [23], the last step in the UAV-based traffic analysis framework is optimization tailored to the objectives of the study. In this phase, traffic parameters determined during the analysis are used to improve existing traffic models in order to support the management of real traffic situations. The optimization includes, among other things, the analysis of driver behavior and the monitoring of lane-changing maneuvers [23].

A comprehensive framework for analyzing road traffic with UAVs is presented by Khan et al. [23]. Additionally, it is highlighted that UAV technology is becoming more widespread for collecting detailed and accurate traffic data, and, although it has many advantages, it also has technical and safety limitations. The framework proposed by the authors enables more efficient use of UAVs for traffic data collection, especially in locations where fixed cameras are not feasible. Moreover, the framework can help improve the management of traffic incidents.

3. Application of Unmanned Aerial Vehicles in Maritime Transportation

According to Gorobetz et al. [31], maritime transportation accidents have become commonplace, with the demand for sea transport continuously increasing.

In the research, unmanned aerial vehicles are used in maritime shipping, particularly in transportation safety tasks in cases where the Automatic Identification System (AIS) does not function. The AIS is an automatic system that provides information on the identification, position, speed, and route of ships to maritime transportation safety services. The AIS is designed to assist in the safety of navigation and the management of maritime traffic [32].

The research of Gorobetz et al. [31] aims to propose UAVs as a maritime safety aid that allows for the visual detection of maritime units, preventing collisions of sea vessels. A further goal of the authors is to optimize the UAV's energy consumption in order to ensure that the unmanned aerial vehicle can continue performing its flight tasks effectively. It is mentioned that UAVs include object recognition tools and software to detect obstacles and other units or objects. This could improve the potential deficiencies of AIS systems in maritime units.

4. Forerunner Drone

A forerunner UAV concept that enhances the safety of emergency ground vehicles (EGVs), such as ambulances and fire trucks, is proposed by Nagy et al. [33] and Bauer et al. [34]. The UAV flies ahead of the EGV, monitors the road, and informs the EGV driver of any approaching hazards, such as vehicles in intersections that are traveling too fast and may not yield. The development was conducted by Bauer et al. [34] in Hungary at the ZalaZONE Automotive Test Track in Zalaegerszeg using a DJI M600 hexacopter equipped with a gimbaled camera to monitor the surroundings and communicate with the EGV via a 5 GHz WiFi connection.

During the experiments, three scenarios were tested at an intersection: the approaching vehicle stops in time, stops late, or does not stop at all. In the latter case, the UAV's warning prevented the EGV from a potential collision. The maximum speed of the DJI M600 was 20–25 km/h [34]. Faster maneuvers were tested by Hiba et al. [35] using software-in-the-loop (SIL) simulations where a fire truck was controlled with a game controller and the UAV was simulated in Matlab Simulink R2021a. The goal of the simulation was to test the autopilot and AI-based object detection [35].

5. Summary and Conclusions

The advantages of UAV applications in the transportation sector were presented in this study, particularly in cases of in-traffic monitoring, accident prevention, and data collection. Technological and operational challenges, as well as the multidisciplinary approach, were highlighted. The importance of rapid and cost-effective data collection is emphasized by the authors to optimize the role of UAVs in the transportation sector, with a particular focus being placed on how these tools can significantly contribute to improving the efficiency and safety of transportation systems.

In this article, the key references discussed in Sections 2–4 have been summarized by the authors in a comprehensive format for better clarity and easier understanding of the information. The summary and comparison of the main processed articles are illustrated in Table 1.

The development of autonomous functions, especially the capability for precision landing, is a key direction for the future. Precision landing is essential in critical situations where drones must land in confined spaces, on docking stations, or moving platforms, such as in emergency locations or on transport vehicles. Challenging weather conditions, such as strong winds, fog, and low visibility, further increase the complexity. Solving precision landing would significantly enhance the safety and reliability of drones, facilitating their wider use. Research has shown that landing is one of the most complex and critical tasks for UAVs, with the majority of accidents occurring during this phase. Achieving precise, even millimeter-level landings in harsh weather conditions remains a challenge for researchers. This can be achieved through well-chosen and properly tuned controllers. Future research by the authors aims to examine and compare the effectiveness of different controllers in achieving precise landings, with a focus being placed on linear quadratic regulators (LQRs) and $H\infty$ controllers. The tests are planned to be conducted mainly in strong wind conditions on a platform. This would significantly enhance the autonomy and safety of drones, particularly for tasks requiring extremely precise landings in adverse weather conditions.

Table 1. Comparison of the key references mentioned in Sections 2–4.

Study	Purpose of Application	Data Processing	Flight Mode	Image Processing	Observation Altitude
Niu et al. [22]	Traffic monitoring, vehicle detection	Real-time	Hovering	Haar Cascade Model	Not specified
Khan et al. [23]	Traffic monitoring, vehicle tracking	Real-time and offline	Moving and hovering	Automated image processing	Below 150 m
Salvo et al. [25]	Urban traffic analysis	Offline	Hovering (70 m)	Tracker open-source software	70 m, HD video
Barmpounakis et al. [28]	Traffic analysis	Offline	Hovering	Post-processed image analysis	70 m
Zheng et al. [29]	Driving behavior analysis, risk assessment	Real-time	Hovering and tracking	Kalman-filter-supported tracking	Not specified
Gorobetz et al. [31]	Enhancing maritime traffic safety	Real-time	Moving	Object detection	Not specified
Bauer et al. [34]	Accident prevention	Real-time	Moving (20–25 km/h)	YOLOv5, object detection	Not specified

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