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Drone-Car Collaboration for Advanced Mobility: A Survey

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Abstract— **In recent years, the automotive industry and research communities have increasingly focused on exploring the potential of drones (also known as Unmanned Aerial Vehicles, or *UAVs*) to enhance ground vehicles. This exploration has opened a new avenue, termed ”Drone-Car Collaboration”, which presents exciting possibilities for joint operations. The collaboration between drones and cars promises increased situational awareness, expanded capabilities, enhanced driving safety, improved fuel efficiency, and novel applications. However, a detailed study is vital to understand the current progress and challenges in the drone-car domain. This paper presents the first comprehensive survey on drone-car collaboration, highlighting its many potential benefits. We explore state-of-the-art use cases and enabling technologies, and discuss future directions for realistically implementing drones in collaboration with ground vehicles.**

I. Introduction

Modern automobiles are now equipped with advanced sensing and computing capabilities due to technological advancements, transforming them from mere transportation devices into powerful computing hubs [1], [2]. Unmanned Aerial Vehicles (UAVs or drones) have also experienced rapid growth and rising popularity. Recently, there has been a surge of interest in exploring the potential benefits of utilizing UAVs to augment the capabilities of ground vehicles [3]. This exploration has unveiled promising prospects for ”drone-car collaboration,” leading to innovative joint operations. By combining the unique strengths and functionalities of drones and cars, exciting possibilities have arisen, paving the way for a new era of collaborative endeavors.

UAVs can significantly enhance the capabilities of ground vehicles (GV) by providing an aerial or birds-eye view (BEV) and various types of sensors integrated with it [4]. These unique features of drones allow them to capture sensing information from various heights and angles, thereby enriching the context awareness of the GVs. Such aerial support can effectively mitigate the sensory limitations caused by the fixed positioning and obstructed views inherent to GVs. Although a drone has an expansive visual range when compared to a ground vehicle’s limited site distance, it is typically much smaller in size and has a limited battery capacity and consequently, limited computational power. On the contrary, a GV can easily support the power demand required for consistent high-computational tasks because it is not constrained by its power output and availability. Thus, the collective efforts of drones and cars result in a synergistic partnership, enhancing their individual capabilities and extending the scope of what they can achieve together.

Since 2023, many EV manufacturers [5] consider drones as an important extension to cars [6] for extended mobility, expanded sensing capabilities, and enhanced safety. However, the research community is less aware of this direction, and no systematic survey summarizes the recent developments. Existing surveys mainly focus on either (1) drone-vehicle communication [7], [8], (2) applications of drones using machine learning [9]–[11], or (3) drone swarm interaction [12], [13]. This leaves a pressing need for comprehensive reviews that summarize existing application scenarios, enabling technologies, and challenges, as well as potential use cases and industry applications. Such reviews could help stakeholders from both the research and industry communities understand the gaps and opportunities in this evolving field, fostering further innovation and collaboration.

Hence, this paper presents the first overview of the current progress, potential, and limitations of drone-car collaboration – an emerging but overlooked application domain that is becoming prominent with the rapid advances of drones, autonomous driving, and vehicle computing technologies. By synthesizing existing research and identifying gaps, we aim to provide a foundational reference for future studies and innovations in this field. In particular, our paper makes three major contributions.

- We conduct a detailed analysis of the current state-of-the-art applications of drone-car collaboration, deriving a taxonomy and identifying their technical gaps. We anticipate that the taxonomy will help the application developers and researchers to better understand the diverse capabilities and limitations within the field of drone-car collaboration.
- We inspect the cross-domain technologies that enable the drone-car collaboration. This discussion motivates us for the possible future work direction.
- Building on our analysis of the existing literature and exploration of enabling technologies, we highlight several potential directions for future research, which will serve as guidelines for peers.

The rest of this paper is organized as follows: Section II investigates the potential applications, including its use in vehicle networks, assisted vehicle driving, providing infrastructure, and use with special-purpose vehicles. Section III focuses on enabling technologies that make drone-car collaboration possible. Section IV discusses the necessary future advancements needed to fully realize the potential of this technology; and finally, Section V concludes this work.

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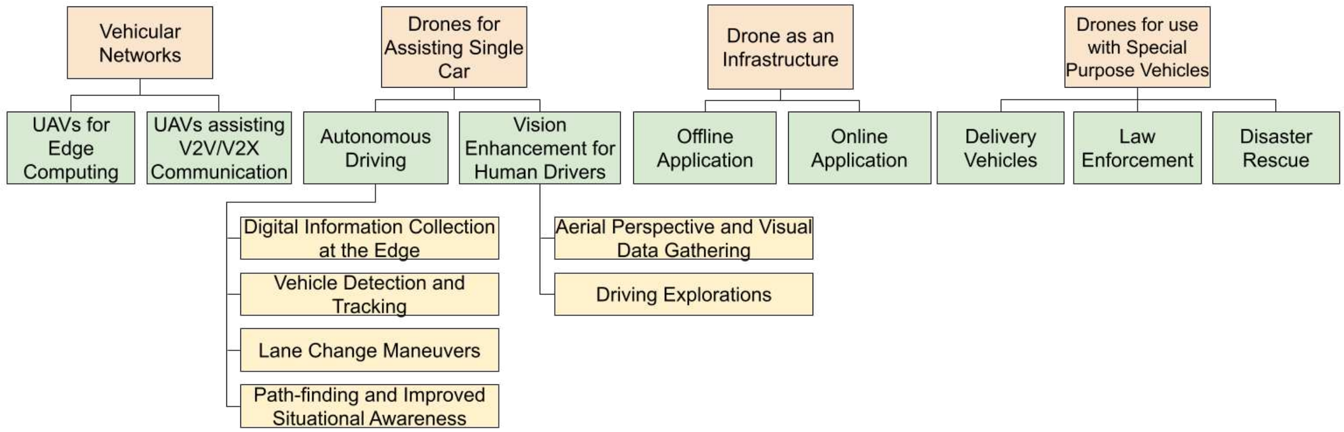

Fig. 1. Taxonomy of State-of-the-art Applications of Drone-car Collaboration

II. State-of-the-Art Applications

Fig.1 illustrates the taxonomy for this section, where we survey the state-of-the-art applications of drone-car collaboration.

A. *Drone-assisted Vehicular Networks*

1) UAVs for Edge Computing: UAVs are ideal for vehicular networks due to their adaptability and support for wireless communication [14]. They can help process events closer to the source of the data via edge computing. UAVs can handle offloaded high computational tasks from ground vehicles, as well as being used as a data storage device.

Offloading to UAVs has many benefits and proves to be efficient [15]. Efficiency can be measured by observing the throughput in densely populated areas, the amount of offloaded data, and the service satisfaction ratio. UAVs can allow coverage for offloading in areas that ground base stations are unable to reach, due to factors such as road layout, geography, etc. Offloading tasks from the car to the drone can allow the car to focus on completing other tasks that are time-sensitive.

Presently, UAVs are used as flying ad-hoc networks (FANETs) to help process events such as traffic monitoring and disaster management [16], [17]. Additionally, offloading with cache-enabled UAVs improves efficiency because it can determine patterns in mobility and content request distribution; they are able to be scheduled to a position at a certain time and location to guarantee enough resources for offloading requests. In order to achieve effective scheduling, three things must be taken into consideration: the scheduling times of UAVs to carry out a task, the number of UAVs to carry out a task, and efficient role-switching for better cooperation [18]. For example, during rush hours, there may be more offloading requests from one area, which would require more UAVs to fulfill the requests [19].

2) UAVs assisting V2V/V2X Communication: UAVs are supplied with 802.11-based WiFi modules enabling communication with ground vehicles in Vehicle-to-Vehicle (V2V) applications. The main benefit of allowing communication of UAVs with ground vehicles is their mobility. Vehicles have limited coverage, unlike UAVs, which are flexible and adaptive [19]. The UAVs have an excellent Line-of-Sight (LoS) for their communication antennas because of their ability to change altitude and position. UAVs can allow V2V communication to continue when interference from buildings, landscapes, or other objects get between two vehicles or base stations.

To support low-latency communication link and dedicated short-range communications (DSRC), [20] encompasses drone-to-drone (D2D) or UAV-to-UAV (U2U) and ground-to-UAV (G2U) or drone-to-infrastructure(D2X). With standards used in D2X, UAVs would be able to share vehicle information with other airspace users, such as other drones. D2X can improve car safety communication, such as collision avoidance.

In that regard, drones are vulnerable to attack because of a typically unsecured communication link where management frames are transmitted without encryption due to the overhead (latency) caused by the encryption and decryption process [21]. An attacker can inject a malicious frame into the communication between the UAV and ground vehicle. This could result in the attacker gaining control of the vehicle. Other possible attacks include Denial-of-Service attacks, eavesdropping, and routing attacks. As such, these security aspects need to be addressed before drone-car collaboration technology can be commercially adopted.

B. *Using Drones for Assisting a Single Car*

The collaborations between a drone (or multiple drones) and one car, can be grouped into two main categories: (1) Autonomous Driving, where drones can play a crucial role in supporting autonomous vehicles; and (2) Vision Enhancement and Integration with Human Drivers, where a drone can extend the line of sight beyond what ground-based sensors or human drivers can perceive, thereby enhancing situational awareness.

1) Autonomous Driving

Digital Information Collection at the Edge: Drones collect, analyze, and transmit data to autonomous driver assistance systems (ADAS), improving communication and decision-making processes right at the source of data generation (the edge). For example, in [17], the authors evaluate the performance of UAV-to-car communications through a combination of test-bed and simulation experiments. The study investigates the efficiency and reliability of data transmission between drones and ground vehicles, which is crucial for enabling collaboration and improving transportation systems which will increasingly incorporate vehicles of autonomy.

Vehicle Detection and Tracking: Drones provide an aerial perspective to identify, track, and analyze vehicle movements, enhancing the understanding of the driving environment for autonomous systems. For example, in [22], the authors propose a knowledge-based approach for perception enhancement in autonomous vehicles, where the drone gathers crucial information about the surroundings (such as nearby cars) and shares it with the ground vehicle. The additional knowledge provided to the car by the drone consequently enhances driving context recognition; an autonomous vehicle can keep track of the surrounding objects with greater accuracy, which improves its ability to navigate complex situations and make better decisions [23] .

Lane Change Maneuvers: Drones assist in optimizing lane change maneuvers by gathering information about the road environment and sharing it with autonomous driver assistance systems, improving the safety and efficiency of lane changes. In one study, high-resolution data from a swarm of drones are used for lane detection and lane-changing identification [24]. The aerial perspective provided by the drones helps to accurately identify lane markings and vehicle positions, enabling a more comprehensive understanding of the road environment. Another paper presents a deep learning approach to predict lane-changing maneuvers, where a drone can be used to gather data on vehicle positions and movements, which is then used to automatically label the data and train a deep learning model to predict when a vehicle is about to change lanes [25]. As a final example, in [26], vehicle trajectory data is used to develop a lane change risk index. The drone collects data on vehicle positions and trajectories, which is then processed to assess the risk associated with lane changes in real time, potentially preventing accidents and enhancing overall road safety when using autonomous vehicles.

Path-finding and Improved Situational Awareness: By improving situational awareness and mapping out paths, drones can help autonomous vehicles make better decisions, navigate complex situations, and ultimately enhance road safety. In another research paper, a path-following strategy is developed for a formation of an unmanned ground vehicle (UGV) and a UAV [27]. This collaborative approach ensures more efficient and accurate path-following as the aerial perspective provided by the UAV enhances the UGV's visual capabilities and understanding of the surrounding environment. Furthermore, a cooperative exploration strategy is presented in a separate study involving UGVs and UAVs [28]. Here, the UAV's bird's-eye view allows for more effective exploration and navigation in an unknown environment.

2) Vision Enhancement for Human Drivers

Aerial Perspective and Visual Data Gathering: Drones extend the line of sight beyond ground-based sensors or human drivers, capturing visual data that enhances the understanding of the driving environment. As mentioned in [23] and [22], by capturing visual data from an aerial viewpoint, drones enable a more comprehensive understanding of the driving environment for a human driver which relies especially on visual senses. In another study, one group of researchers used a virtual reality simulation to evaluate a UAV-based street lighting systems aimed at improving traffic safety by enhancing night visibility. In the simulation, drones gather information about the road environment, such as light conditions, and can effectively light up the area around a car to make it safer for other vehicles and pedestrians traveling at night. The light conditions in an area along a route can be transmitted to other vehicles to make decisions about lighting (such as increasing headlight brightness or using a drone to light the area when they arrive).

Researchers discuss on how UAVs are employed to inspect aircraft wing panels [29]. The collaboration between UAV and ground-based systems enables more accurate and efficient inspections, as the aerial perspective provided by the UAV allows for better visibility and access to the aircraft wing panels. Similarly, it can be applicable to cars, for example, using the vision system of the drone to help a human driver diagnose potential issues of a ground vehicle such as a misalignment or deflated tires.

Driving Explorations: Drones can be utilized by human drivers for tasks beyond driving assistance, such as the autonomous landing on moving vehicles demonstrated in the study by [30]. This capability enhances a car's visual system, allowing drones to accurately identify and land on a moving platform. Such technology is beneficial not only to autonomous vehicles but also enhances the functionality of cars with human drivers, who can use the drone to improve the vehicle's advanced driver-assistance systems (ADAS), as noted in [23] and [22]. This integration allows for drones to be swiftly deployed for additional tasks or retracted for future use.

C. Drone as an Infrastructure

Many tasks in cities today are labor intensive and require simple manpower such as traffic monitoring and inspections. Other activities such as parking and merging lanes can cause congestion which requires study and adjustments by local officials to improve. All of these tasks can be simplified and improved with the use of UAVs.

1) Offline Applications: Cameras and other sensors have become standard in our current smart cities. However, these sensors are limited to the areas where they can be mounted and returned to for data collection. Many current systems could be enhanced by the use of UAVs. For example, there has been some research into the use of drones for traffic and car monitoring [31]–[34]. However, many of the computer recognition systems are currently either too slow, inaccurate, or computationally intensive to be feasible for real-time use, but this does not stop them from still being valuable. The perspective that a drone's camera can obtain on the road compared to a stationary camera gives much better feedback for those looking to relieve congestion. With the freedom of movement for the camera combined with the ability to use more effective algorithms later, utilizing a drone for non-real-time applications is simple and effective.

2) Online Applications: In a future of smart cities, there are a plethora of real time needs that can be solved via the use of UAVs. With the increase in smart cars, the need for consistent and responsive edge computing is rapidly growing. In higher density areas, the need for dynamic roadside units could easily be alleviated with the use of UAVs as temporary additions to the existing stationary units [35]. Having a way to deploy additional computational and networking power dynamically to high-demand areas allows for resources and budgets to be utilized more efficiently.

Also, UAVs can be used for real-time applications with traffic monitoring [36], [37]. While they may be unable to do consistent high-demand computation, drones can still provide base-level computations and act as mobile cameras for workers looking to reduce traffic. This strategy can be deployed in the same manner as the roadside units. When there is a high volume of traffic or some stoppage, officials can deploy drones to monitor what is going on and get a more detailed view than pre-mounted, fixed cameras placed periodically along the road (often attached to street lights).

Another real-time drone-assisted application includes infrastructure inspections [38], vital for ensuring the safety of critical city structures like bridges, tall buildings, and dams. Using UAVs, an inspector can perform routine checks with a live video feed and record the footage for detailed later analysis. This process not only enhances safety but also enables collaboration between drones and ground vehicles to maintain robust infrastructure.

Drones can significantly streamline parking assistance in urban areas. A common source of city congestion is vehicles slowing down to find parking. By utilizing UAVs to identify available curb-side or public lot parking spaces, cities can direct smart vehicles to these spots efficiently [38]. This method reduces traffic blockages and improves parking efficiency, especially in enclosed lots and structures where drones can relay spot availability to ticket machines or assist with parking via additional camera perspectives, enhancing both safety and convenience [39].

D. Drones for use with Special Purpose Vehicles

In this section, three special purpose vehicle or application scenarios are discussed: Delivery Vehicles, Law Enforcement, and Disaster Rescue.

1) Delivery Vehicles: UAVs can be deployed with ground vehicles to assist with delivery services. For example, one or more drones can be deployed with a delivery truck. While the delivery driver delivers packages normally along their route, the drone delivers lightweight packages in the area [40]. Drones can also be used in fully autonomous delivery systems by pairing them with a UGV [41]. The issue with drone delivery is that drone's flight is limited by no-fly zones and the reduction of flight time caused by package weight. However, it is still possible for a drone to be used to reduce overall delivery time and/or assist a delivery vehicle.

2) Law Enforcement: UAVs can support law enforcement in preventing crime and capturing criminals. Unlike other traffic sensors, UAVs can follow individuals after detecting information such as a stolen car or running a light. A UAV can broadcast their approximate GPS location to dispatch vehicles so they can intercept the driver [36]. Drones could also potentially be used to clear a path for law enforcement or emergency vehicles in route to an emergency or hospital.

When dealing with terrorists, UAVs can be used for detection of explosives and weapons in the area. UAVs equipped with metal detectors can scan a wide area for suspicious objects. When something suspicious is detected, a GPS signal can be transmitted (such as to a ground vehicle) and the area can be thoroughly searched by the drone using X-ray [42].

3) Disaster Rescue: In disaster zones, a UAV guided by a UGV can use its enhanced aerial view to perform feature recognition to identify human features and actions. Once people in need are identified, GPS data can be sent to a rescue team. In areas where rescue teams cannot reach survivors, a UAV and UGV can be deployed to deliver emergency supplies [41]. The UAV will collect visual information about the environment to assist the UGV in reaching the survivors.

In smaller incidents, a UAV can fly ahead to the area and capture video and other data from the site. For example, if sensors at an intersection indicate a high likelihood of a crash, a UAV can be sent out to the scene to scan the area and send data to an emergency handling service [36].

III. Enabling Technologies

There are several technologies that facilitate drone-car collaboration. These technologies include:

1) Cutting-edge Communication Technologies: Effective communication between drones and ground vehicles is crucial for seamless collaboration. Real-time data interchange and command transmission between the two platforms are made possible via wireless communication protocols such as WiFi, cellular networks, or specialized communication systems [30], [43]. Reliable and low-latency communication ensures efficient coordination and enhances the overall collaboration.

2) Advanced Sensor Technologies: Drones and ground vehicles rely on a range of sensors to perceive their surroundings and gather essential data. The most common sensor is a video camera used to collect and analyze video frames to detect objects; other common sensors used to supplement or substitute camera data include rangefinders and LI-DAR (Light Detection and Ranging) [34]. In scenarios where video analysis is unhelpful, drones can also use RFID (radio frequency identification) tags to find nearby tagged objects [44]. For specific applications, it is possible to add unique sensors based on special requirements which are normally not attached to drones, for example, attaching metal detectors and x-ray machines to a drone for security purposes [42].

3) Robust Distributed Computing System: enhances the interaction between drones and cars. By leveraging edge computing, these systems process data directly on vehicles, drones, or both, as well as utilizing road infrastructure [11]. This approach significantly reduces latency and enables real-time decision-making, which is critical for the autonomous navigation of both drones and vehicles. Integrated data fusion combines sensory data from both drones and cars to improve environmental awareness, which is crucial for precise and safe autonomous operations [45]. These systems are designed to scale seamlessly, handling an increasing number of drones (drone swarm) and cars (car fleet) and more complex data interactions without loss of performance. Additionally, their built-in reliability and fault tolerance ensure continuous operation, even in the event of component failures during critical autonomous functions.

4) Energy-efficient Drone: Efficient power management enables extended flight times for drones and longer operational periods for ground vehicles. For applications requiring uninterrupted up-time, backup drones can be used to take the place of a drone that is low on battery power. When some downtime is allowed, drones can have their batteries swapped after landing [46]. Other solutions might include advanced batteries, energy harvesting systems, or wireless charging, to ensure prolonged operation and reduced downtime.

5) Drone Take-off and Landing on Vehicles: Many automotive companies such as Ford, General Motors(GM), Toyota, and Honda are already implementing hardware support for drones to take-off and land on a vehicle. For example, Ford filed patents for a vehicle-mounted aerial drone container [47], a drone close-proximity operating system [48], a UAV integration system, and a UAV sanitation system.

IV. Possible Future Directions

Despite advancements in technologies that facilitate drone-car collaboration, as discussed in Section III, there remains significant work to be done to fully realize the potential of drone-car systems. In this section, we explore the essential advancements required in both hardware and software to enhance the sensing and processing capabilities of drones. Additionally, we explore potential expansions of usage scenarios and CV algorithm for aerial image analysis as well as distributed task offloading system.

A. Enhancing Sensing and Processing Capabilities for UAV

Some applications that are helping much toward the future of drone-car collaboration include the use of drones as flying infrastructure or in hybrid delivery systems, which has demonstrated their potential to revolutionize wireless service and logistics, while their use in acoustic-based surveillance systems and compressive imaging technology has shown their potential for video analysis and energy conservation [40], [49]–[51]. However, to fully realize the potential of drones, advancements in battery life, flight range, and imaging technology will be necessary. As drone technology continues to improve, the range and effectiveness of their applications will continue to expand, further solidifying their place in various industries and help to realize a future where drones and cars work together to achieve safer roads and more vehicular autonomy.

B. Expanding Usage Scenarios for Drone-car Collaboration

To highlight the potential of drone-car collaboration, we discuss two innovative applications that could transform it into a practical part of daily life:

1) Swarm Intelligence: Swarm intelligence involves the coordination and collaboration of multiple drones and ground vehicles as a cohesive unit. By advancing swarm intelligence algorithms and control systems, both platforms will be able to collaborate more effectively, scale more efficiently and distribute decision-making. This could tackle complex tasks such as distributed surveillance, coordinated search and rescue operations, or distributed delivery systems.

2) Ground Vehicle Inspection: Drones can be used for vehicle inspection, both on ground and in air. Drones equipped with computer vision technology can inspect vehicles for damage and provide a detailed inspection report, making the inspection process faster and more efficient. This idea can be adapted from the use of drones to inspect aircraft [29].

C. Accelerated CV Algorithm for Aerial Image Analysis

Real-time processing of aerial image analysis needs acceleration, potentially through the development of more efficient algorithms tailored for edge computing or employing hardware accelerators like GPUs, TPUs, NPUs. Expanding capabilities in 3D mapping and environmental reconstruction is also crucial for drone-car collaboration, utilizing advanced techniques like SLAM to generate accurate, real-time maps from aerial data. Fusing multi-modal data, including LIDAR, radar, and ground-based sensor information with aerial imagery, represents a promising direction for future work. Geometric deep learning for spatial data is also a potential approach, focusing on developing algorithms that understand and manipulate data defined on non-Euclidean domains, such as graphs and manifolds. These are more natural representations for sensor data. Overall, the integration of sensory data with aerial imagery is expected to significantly enhance situational awareness and the accuracy of decision-making.

D. Dedicated Distributed Task Offloading System

Tasks that require intensive computation, like real-time video processing for object detection or path planning, can be offloaded from drones to nearby cars equipped with better computational capabilities or directly to roadside units that perform the computations and send back necessary instructions. There is a lack of dedicated algorithms for dynamic resource allocation and task scheduling based on the current network conditions, computational load, and priority level of tasks for drone-car collaboration. Reinforcement Learning (RL)-based resource allocation, Federated Learning for decentralized decision-making, and Genetic Algorithms for optimizing task distribution represent promising avenues for future research tailored only for drone-car distributed task processing systems. These methodologies are well-suited to enhance efficiency and effectiveness in complex, multi-agent environments.

V. Conclusion

In conclusion, the potential for drone-car collaboration is vast, and the applications are continually expanding. From assisting with edge computing and V2V/V2X communication to parking assistance and disaster rescue, drones and cars working together can lead to safer roads, enhanced situational awareness, and more efficient use of resources. The necessary advancements in hardware and software, such as improvements in battery life, flight range, and imaging technology, are already underway, further solidifying the role of drones in various industries. As technology continues to evolve, the future of drone-car collaboration is exciting, and we can expect to see more advancements in the field as drones become smaller, lighter, and more reliable. There is one particularly special thing to note: as technology becomes more advanced and cheaper to produce, we can expect the size and weight of the drone to decrease, while at the same time see improvements in battery life. These two key factors will likely be the driving force behind the future of drone-car collaboration.

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