Drone-Car Collaboration: An Emerging Domain for Intelligent Transportation Systems

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***Abstract*—In recent years, there has been an increased focus from within both the automotive industry and research communities on exploring the potential of drones (also known as Unmanned Aerial Vehicles, or *UAVs*) to enhance the capabilities of ground vehicles. This opens up a new avenue, the "*Drone-Car Collaboration*", presenting exciting possibilities for joint operations. The prospects that the drone-car collaboration bring include increased situational awareness and expanded capabilities, which will accordingly enhance driving safety, fuel efficiency, and enable novel applications. However, a detailed yet concise study is vital to better understand the current research progresses in the drone-car domain as well as the challenges for further advancement. Hence, this paper presents the first comprehensive survey on drone-car collaboration, which has many potential benefits to the community. We first introduce the technologies that make such collaboration possible and the general benefits a drone adds to ground vehicles. This is followed by the possible use cases of a drone within vehicle networks, single-car driving, infrastructure, and special-use vehicles. Finally, we discuss the possible future directions to realistically use drones in collaboration with ground vehicles.**

***Index Terms*—unmanned aerial vehicles, unmanned ground vehicles, vehicle-to-vehicle networks, edge computing**

I. Introduction

In recent years, there has been a surge of interest and attention dedicated to investigating the potential benefits of utilizing UAVs to augment the capabilities of ground vehicles. This exploration has revealed promising prospects for "**drone-car collaboration**", leading to the emergence of 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.

The growing interest in drone-car collaboration stems from the recognition that their integration can yield significant advantages in various fields. This integration allows for a more comprehensive and dynamic operational approach, where drones serve as valuable aerial assets that complement the mobility and maneuverability of ground vehicles. 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, an autonomous car 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.

One area where drone-car collaboration shows great potential is in strategic surveillance and reconnaissance operations. Drones equipped with advanced sensors and cameras can provide aerial perspectives, capturing real-time imagery data from vantage points that may be inaccessible or challenging for ground vehicles. By collaborating with drones, ground vehicles gain an elevated situational awareness, enabling them to make informed decisions, respond effectively to emerging scenarios, and improve the overall effectiveness of their missions.

Moreover, the fusion of UAVs and ground vehicles expands the operational range and reach of both platforms. Drones can cover large distances, explore remote areas, and gather information that can be transmitted to cars in real-time. This collaboration allows cars to benefit from the timely delivery of critical data, such as terrain conditions, potential obstacles, or even threats, which facilitates more efficient route planning and hazard avoidance. The combined capabilities of drones and ground vehicles contribute to safer and more effective operations, particularly in fields such as military missions, disaster response, or law enforcement activities; their combined efforts will also revolutionize various industries, shaping the future of intelligent transportation systems.

Considering the aforementioned potential applications of drone-car collaboration, this survey paper comprehensively investigates the enabling technologies, state-of-the-art usage scenarios, and anticipated advancements that are crucial in shaping the future of drone-car collaboration. We cover and categorize the existing literature on drone-car collaboration usage scenarios into 4 broad relevant categories, each having multiple sub-categories, to fully apprehend the existing works and their limitations in a clear and concise manner. Examining these categories provides a holistic understanding of the current landscape and sheds light on the pathways for further development in this technology. Overall, this paper presents the first overview of the current progress, potential, and limitations of drone-car collaboration – an emerging but overlooked application domain which is becoming prominent with the rapid advances of drones, autonomous driving, and vehicle computing technologies.

The rest of this paper is organized as follows: Section II focuses on enabling technologies that make drone-car collaboration possible. Section III delves into the potential applications, including its use in vehicle networks, assisted

The * authors are currently in alphabetical order. For the final draft, authors will be properly ordered by contributions made.

vehicle driving, providing infrastructure, and use with special-purpose vehicles. Section IV discusses the necessary future advancements needed to fully realize the potential of this technology; and finally, Section V concludes this work.

II. Enabling Technologies

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

1) Communication Systems: 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 [1], [2]. Reliable and low-latency communication ensures efficient coordination and enhances the overall collaboration.

2) Energy and Power Management: 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 [3]. Other solutions might include advanced batteries, energy harvesting systems, or wireless charging, to ensure prolonged operation and reduced downtime.

3) 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) [4]. In scenarios where video analysis is unhelpful, drones can also use RFID (radio frequency identification) tags to find nearby tagged objects [5]. 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 [6].

4) Accurate Localization: Successful drone-car collaboration requires precise localization and mapping of the drone, the car, and other objects in the environment. This can be determined by obtaining sensor data collected from the GPS system, the inertial measuring units (IMUs), camera, and other sensors; then, a computer vision technique such as *optical odometry* is used to estimate the motion of a camera or a vehicle by analyzing the camera data. Finally, the fusion of such techniques with the the rest of the sensor data is what constitutes the simultaneous localization and mapping algorithm – also known as *SLAM* – that many autonomous vehicle systems rely on. Overall, SLAM technology is what enables precise coordination, navigation, and synchronization between autonomous vehicular platforms.

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 landing on a vehicle. For example, Ford filed patents for a vehicle-mounted aerial drone container [7], a drone close-proximity operating system [8], a UAV integration system, and a UAV sanitation system.

III. State-of-the-Art Usage Scenarios

We divide state-of-the-art usage scenarios of drone-car collaboration into the four categories discussed below.

A. Vehicular Networks

1) UAVs for Edge Computing: UAVs are ideal for vehicular networks due to their adaptability and support for wireless communication [9]. 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 [10]. 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 [11], [12]. 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 [13]. For example, during rush hours, there may be more offloading requests from one area, which would require more UAVs to fulfill the requests [14].

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 [14]. 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.

Another system based on dedicated short-range communications (DSRC) is the IEEE 802.11p V2X standard, which encompasses drone-to-drone (D2D) and drone-to-infrastructure(D2X) [15]. 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 [16]. 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 rapid progress in drone and automotive technology has fostered innovative collaborations between UAVs and ground vehicles, resulting in significant advancements in transportation and safety. These collaborations, specifically 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 [12], 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 [17], 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 [18] .

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 [19]. 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 [20]. As a final example, in [21], 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 [22]. 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 [23]. 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 [18] and [17], by capturing visual data from an aerial viewpoint, drones enable a more comprehensive understanding of the driving environment for a human driver which rely 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).

Finally, in another paper, researchers discuss the case of how UAVs are employed to inspect aircraft wing panels. The collaboration between the 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 [24]. This paper was included because it can be applicable to cars, for example, using the vision system of the drone to help a human driver diagnose a potential issues of a ground vehicle such as a misalignment or deflated tires.

Driving Explorations: Drones can also be employed by a human driver for other purposes besides driving assistance. This makes a drone's ability to land on a car invaluable. For instance, in the study conducted by [1], authors explore the autonomous landing of a UAV on a moving ground vehicle, showcasing how drones can integrate with a car with a human driver who might use the drone for various other purposes. The collaboration between the UAV and the car enhances the visual capabilities of the system, allowing the UAV to precisely identify the landing platform on the moving vehicle and successfully land. Of course, this would benefit fully autonomous ground vehicles as well, however, the key here is that the drone can be deployed for additional driver assistance from a smart car with a human driver or retrieved seamlessly for use in a future task. When the drone is deployed for driving assistance, then the human driver can use it to enhance the ADAS (advanced vehicle assistance system) system of the vehicle as mentioned in [18] and [17].

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 [4], [25]–[28]. 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 [29]. 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 [30], [31]. 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 the ability to conduct infrastructure inspections [32]. Many pieces of infrastructure are vital to city life but are hard to inspect to ensure safety. Bridges, tall buildings, and dams are examples of infrastructure that could utilize a UAV for visual confirmation of structural integrity. A single inspector could do a routine check using a live video feed and also record said video for a more thorough or cross inspection later. Of course, ground vehicles would benefit from safer infrastructure, and the ground vehicles can collaborate with drones in this effort.

Last but not least, drones can provide parking assistance. One common source of congestion in cities are cars slowing down or even coming to a stop while looking for open parking. One way to relieve this is by deploying a UAV to identify open spaces for parking [32]. Using an embedded or even offloaded model, cities could find open curb-side or public lot spaces and then send directions to smart vehicles looking for a parking spot. This would make the search for parking much more efficient and cause less blockages for drivers and autonomous vehicles that are providing some services. Another place where drones could be used for parking assistance is in enclosed parking lots and parking structures [33]. For example, a parking structure could employ a drone to search for open spots and communicate them to the ticket machine for an incoming car. In addition to locating spots, the drone could also assist the vehicle or driver with parking by providing a camera feed from another perspective, which would also improve parking lot and parking structure safety and efficiency.

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 [34]. Drones can also be used in fully autonomous delivery systems by pairing them with a UGV [35]. The issue with drone delivery is the 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 [30]. 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 [6].

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 [35]. 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 [30].

IV. Possible Future Directions

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, aiming to shed light on the indispensable future directions that must be pursued for the complete realization of drone-car collaboration.

A. Enhancing Sensing and Processing Capabilities for UAV

As UAVs continue to address practical issues in various industries, it is becoming increasingly clear that future advancements will be necessary to fully realize their potential. 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 [34], [36]–[38]. 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

The potential for drone-car collaboration is immense, but there are some applications that have yet to come about that could potentially brighten the future for the technology. Here are four possible novel applications that could make drone-car collaboration a practical everyday reality:

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 [24].

3) Anti-theft Drone System: When a car is parked, a drone can function as an advanced anti-theft system, capable of detecting and recording any unauthorized access to the vehicle. In the event of such an incident, the drone promptly sends an alert to the car owner, providing them with real-time information. This innovative approach not only captures more comprehensive details about the criminals involved but also ensures that the surveillance footage remains secure, as it cannot be easily destroyed or tampered with. In fact, the drone could store the video data locally and also transmit to the cloud in a private, secure location in the event that the drone data cannot be recovered locally.

4) Drone for Enhanced Exploration: Drones can be used for enhanced exploration, such as mapping the local area around Recreational Vehicles (RV) or travel vehicles where network connectivity is limited or available map imaging is more sparse. RVs can be outfitted with drones that can explore and map the surrounding areas, providing a unique perspective and enhancing the travel experience.

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. Additionally, there are many novel applications for drone-car collaboration yet to be explored, such as drone detection and identification, anti-theft drone systems, and enhanced exploration. 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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