Unmanned Systems, Vol. 9, No. 1 (2020) 1–21

DOI: 10.1142/S2301385021500084

UNMANNED SYSTEMS
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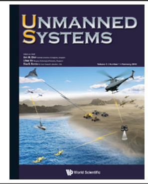

A Review of Recent Advances in Coordination Between Unmanned Aerial and Ground Vehicles

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Coordination between unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) has received increasing attention in recent years. The list of successful applications of UAV–UGV coordination systems is growing and demonstrates that UAV–UGV coordination can provide real-world solutions that other types of coordination cannot offer. This paper systematically reviews the advances in UAV–UGV coordination systems during the period of 2015–2020 and offers a comprehensive investigation and analysis of the recent research. First, the essential elements in the UAV–UGV coordination systems are analyzed, and four key functional roles are identified. The close collaboration among functional roles can achieve the UAV–UGV coordination on perception, task, and motion. From the perspective of functional roles, UAV–UGV coordination systems can be further classified into eight categories. The functional-role-based category provides novel insights into analyzing various patterns of UAV–UGV coordination. This paper also discusses the challenges related to UAV–UGV coordination.

Keywords: UAV–UGV coordination systems, air–ground collaboration; unmanned aerial vehicle; unmanned ground vehicle.

1. Introduction

In the last decade, an increasing variety of applications of unmanned aerial vehicles (UAVs)–unmanned ground vehicles (UGVs) coordination systems in the military and civilian areas demonstrates the capabilities of UAV–UGV coordination in providing solutions that other types of coordination cannot offer. The UAV–UGV coordination systems are used in many applications (both individually and collectively), including exploration [1], surveillance [2], rescue [3], and agriculture [4].

The UAV–UGV coordination system involves UGVs and UAVs working together to achieve a common goal and coordinating their actions in order to make full use of their individual capabilities or skills. The strong complementarities between UAVs and UGVs provide a new breakthrough for the application of UAV–UGV coordination systems. UAVs can move rapidly from one place to another, can provide global as well as precise views on the environment, and are less prone to communication and GPS signal outages than UGVs. UGVs can carry larger payloads and endure longer missions. They operate closer to the environment and provide the capacities to intervene on the environment, to deploy sensing and communicating devices, and to perceive details that a UAV might miss [5].

Table 1 lists the characteristics with respect to UAVs and UGVs. It can be observed from the table that, both UAVs and UGVs have their own limitations, which notably reduce their efficiency in performing tasks to some extent [6]. On the other hand, the great heterogeneity and complementaries between UAVs and UGVs in dynamics, speed, sensing, communication, functions, and so forth, make the UAGVSs powerful to complete a variety of complicated task. The UAV–UGV coordination system combines the strengths of

Received 7 March 2020; Revised 12 August 2020; Accepted 12 August 2020; Published xx xx xx. This paper was recommended for publication in its revised form by editorial board member, Xiang Chen.
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Table 1. Comparison between different types of UAVs and UGVs.

Vehicle types	Mobility	Adaptability	Sensing	Endurance	Payload	Others
Multirotor UAV	low speed	can land in very small area	precise inspection	short	small	easy of use
	VTOL and hover	land on rough surfaces				
Helicopter UAV	quick speed VTOL and hover	can land in small area land on rough surfaces	precise inspection	long	middle	hard to control
Fixed-wing UAV	high speed	large landing space needed	large area coverage	long	Large	
	no VTOL/hover	great stability in wind				
Tracked UGV	low speed maneuver in tight places	can move on rough terrain	small field of view	short	very large	
Wheeled UGV	Quick speed high maneuverability	easily slide on slopes sink into soil and wet ground	small field of view	long	quite large	light weight

Note: VTOL stands for vertical take-off and landing.

ground and aerial robots to provide on-demand sensing capabilities.

The topic of UAV–UGV coordination falls under the field of multi-robot coordination. Due to the great heterogeneity between UAV and UGV, the current research results on multi-robot system (MRS) cannot be directly used to the UAV–UGV coordination system. Special attention needs to be given to new features presented in the UAV–UGV coordination system. Unlike the existing MRS which mainly focuses on UAVs or UGVs, the UAV–UGV coordination system needs to process information from totally different platforms and effectively coordinate the behaviors of UAVs and UGVs, which make the research on UAV–UGV coordination systems more challenging.

The closest survey to UAV–UGV coordination systems is published almost five years ago. Chen *et al.* [6] reviewed a number of influential and successful types of UAV–UGV coordination systems and proposed a taxonomy for classification of existing UAV–UGV coordination systems in which different types of UAV–UGV coordination systems could be described in a consistent manner. In the strict sense, the paper is just a taxonomy and does not review related research works.

Other surveys had a narrower scope than our work and focused on revealing multiple technical aspects of UAV–UGV coordination systems. Duan and Liu [7] analyzed the key issues in multiple unmanned air/ground vehicles heterogeneous cooperation, including heterogeneous flocking, formation control, formation stability, network control, and actual applications. Waslander [8] surveyed six technical challenges in UAV/UGV team coordination: relative tracking, coordinated landing, formation control, target detection/tracking, task assignment, and localization/mapping. Çaşka and Gayrette [9] reviewed various UAV/UGV collaboration frameworks and approaches according to system application. In a recent survey by Cajo *et al.* [10], the authors focused on the control problems of the UAVs and UGVs that have been addressed by the fractional-order techniques over the last decade.

The innovations and main contributions of the paper are the following.

- This paper provides an overview of the recent advances in UAV–UGV coordination systems from 2015 to 2020. The UAV–UGV coordination systems are classified into eight different settings, from the perspective of the functional roles that UGVs and UAVs have in a system.
- We present several open research issues that call for the attention of the researchers involving UAV–UGV coordination.

The rest of the paper is organized as follows. Section 2 provides an overview of the four essential elements of the UAV–UGV coordination system and introduces various functional roles in a UAV–UGV coordination system. We categorize UAV–UGV coordination systems into two different settings, depending on whether the functional roles between UGVs and UAVs are the same, and survey them in Secs. 3 and 4, respectively. For each setting, different categories are identified and reviewed according to the functional roles of UGVs and UAVs in a UAV–UGV coordination system. Section 5 discusses the identified eight categories of

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UAV–UGV coordination systems. Section 6 discusses the remaining challenges. Section 7 concludes the paper.

2. Essential Elements and Categorization

This section will analyze the essential elements in a UAV–UGV coordination system: UGVs, UAVs, tasks, and environments, as shown Fig. 1. In addition, according to the skills and activities of UGVs and UAVs in a UAV–UGV coordination system, four key functional roles are identified. Since the close collaboration among these roles is necessary in order to achieve the UAV–UGV coordination. Sections 3 and 4 will use the functional roles as the criteria of the classification to review the recent advances in UAV–UGV coordination systems.

2.1. *UGV and UAV*

UGVs can take on various configurations in different UAV–UGV coordination systems. Two propulsion configurations for UGVs are commonly used: tracked vehicles and wheeled vehicles. Tracked configurations consist of continuous treads powered by two or more wheels and increase the contact area of the vehicle with the ground. This can improve traction in difficult terrains. When difficult terrain is to be navigated for a specific application, tracked UGVs may be preferred [11]. Wheeled vehicles can be characterized by the type of wheel used and the number of wheels used, each with advantages and disadvantages for different wheel configurations in terms of stability, maneuverability, and controllability, as discussed by Siegwart *et al.* [12]. Wheeled UGVs often allow for higher speeds than tracked UGVs.

UAV features in the UAV–UGV coordination system may vary depending on the application, in order for them to fulfill their specific task. The use of UAVs in the UAV–UGV coordination system can be categorized as fixed wing, multirotor, or single rotor.

- **Fixed wing:** The fixed-wing UAV has lower energy requirements and longer flight time than multi-rotor. However, it cannot hover or make tight turns, which limits its deployment in certain applications. In recent years, a new hybrid category has received special attention: convertible UAV [13]. They combine rotorcraft for take-off and landing maneuvers with fixed wing for energy-efficient long-range flights.
- **Multirotor:** These vehicles have one or more rotors (e.g. quadrotor [14, 15]) and can achieve stable hovering and precise flight by adjusting rotor speed and balancing different forces. The multirotor can operate in a wide speed range and can take off and land vertically.
- **Single rotor (Helicopter):** The single rotor can take off and land vertically, hover, and fly forward and backward. It is more efficient and stable than multirotor. However, a helicopter with a single giant rotor has a higher mechanical complexity.

2.2. *Task*

The UAV–UGV coordination system is assigned a wide variety of tasks with varying degrees of complexity. Task complexity determines the difficulty of the task, which

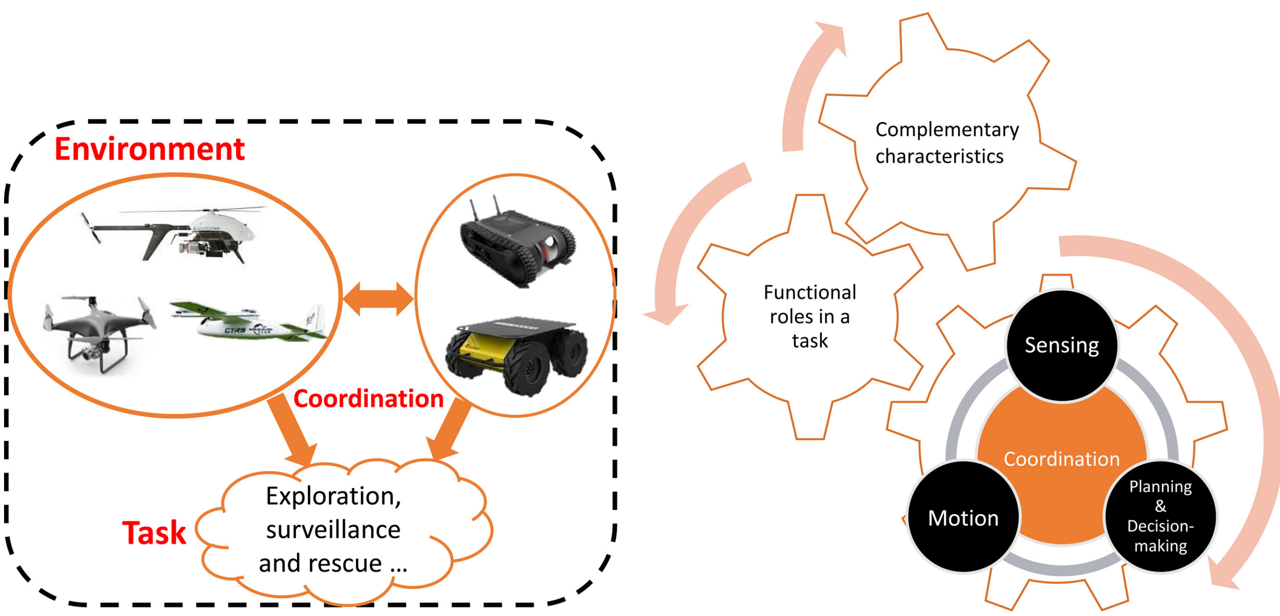

Fig. 1. Essential elements of UAV–UGV coordination system.

affects the number and type of vehicles needed to complete it and which may be composed of multiple simpler sub-tasks. Single-vehicle tasks can be accomplished by one vehicle, such as small-scale mapping, pick and place, and navigation problems. Multi-vehicle tasks require multiple cooperating vehicles. Multi-vehicle tasks can be further distinguished based on the required level of cooperation for successful completion, ranging from loosely to tightly coordinated. Loosely coordinated tasks can be decomposed into sub-tasks that can be independently executed with minimum interaction among vehicles. Examples include large-scale exploration and mapping, hazardous material collection, tracking, and surveillance. In such scenarios, the environment can be divided into disjoint areas, and the vehicles operate within their specified areas. Tightly coupled tasks are not decomposable and require coordinated execution with significant interaction among vehicles. Examples include formation and large-scale construction.

Metrics are crucial for tracking, assessing, and comparing a process, task, or system with respect to performance, usability, efficiency, quality, and reliability, as defined by the system performance goals. Metrics can also be used to evaluate the effectiveness of a UAV–UGV coordination system and its members on various levels. Some evaluation criteria in the UAV–UGV coordination system are domain-specific. For exploration and mapping, performance measures include navigation accuracy or error of the object position [16]. In addition to domain-specific criteria, there are several common metrics in the UAV–UGV coordination system, including solution optimality, algorithm time complexity, load balancing, resource utilization, robustness to noise, scalability and so on.

2.3. *Environment*

An environment is everything in the world that surrounds UGVs and UAVs. An environment provides UGVs and UAVs with something to perceive or change and somewhere to "live" and collaborate.

The environments confronted by UGVs and UAVs can greatly differ. The ground environments confronted by UGVs are complex and diverse and may contain positive obstacles such as rocks or trees (or indoors obstacles like furniture) and a negative obstacle such as a ditch, which can restrict the behavior of UGVs or force them to change their behavior. In addition, structured and unstructured roads are contained from those designed to standards and range from well-marked to barely perceptible dirt tracks. Structured roads have known, constant geometries (e.g. lane width, radius of curvature) and clear lane and boundary markings. Unstructured roads may be of variable geometry, have abrupt changes in curvature, and may be difficult to distinguish from the background (e.g. may be paved or unpaved). The dynamic objects (e.g. humans or animals) in an environment may change trajectory suddenly and without warning pose challenges for motion planning of UGVs. Complex environments (e.g. occlusion, cluttered background, or partial and full changing illuminations) can make the detection of objects in the environment difficult [17]. Detecting obstacles on unstructured roads, in particular, may be more difficult because curves or dips may restrict the ability to see far ahead.

Compared with ground environments, airspace confronted by UAVs is relatively simple. According to the International Civil Aviation Organization classification, airspace can be broadly classified as controlled or uncontrolled. Controlled refers to an area within current air traffic control in which the flight shall be flown at a level that is not below 300 m above the highest obstacle of the area. Therefore, the controlled airspace is mainly obstacle-free. Uncontrolled airspace may contain positive obstacles, such as buildings [18]. In addition, complex environmental conditions in airspace (e.g. foliage or haze) can make it difficult for a UAV to detect objects in the environment.

2.4. *A categorization of UAV–UGV coordination system*

The capabilities of UGVs and UAVs determine their functional roles in a UAV–UGV coordination system for a specific task [19]. The biggest challenge for UAV–UGV collaboration is how to best leverage the complementary functional roles of UGVs and UAVs to implement tasks that are difficult for other types of coordination to complete. The four main functional roles in the UAV–UGV coordination system are identified and defined as follows from a control system viewpoint.

- **Sensors** are responsible for detecting events or changes in their environment and sending the information to other components or vehicles;
- **Actuators** are responsible for performing some actions or activities;
- **Decision makers** are responsible for making decision (e.g. determining task plans or motion planning) for other components or vehicles;
- **Auxiliary Facilities** are responsible for providing chief agents with energy, communication, computation, and other services other than the function of sensors, actuators, and decision makers.

Figure 2 illustrates the blocks of functional roles. The interactions between the blocks and the required functionality from each block are dependent on the goal of the system (i.e. the application). Existing UAV–UGV

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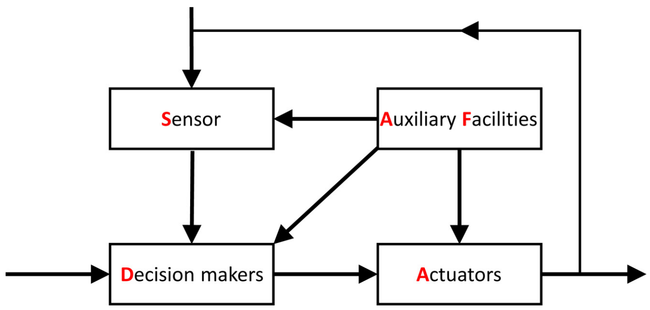


Fig. 2. Functional roles in UAV–UGV coordination systems.

coordination systems focus on the design of one or more of these blocks for different applications.

We categorize UAV–UGV coordination systems according to the functional roles of UGVs and UAVs in such a system and denote as $\langle X|Y\rangle$ with $X, Y \subseteq \{S, A, D, AF\}$, where X and Y represent the functional role of UAVs and UGVs, respectively. For example, $\langle S, D|A\rangle$ refers to the category of the UAV–UGV coordination system in which UAVs take the sensor and decision-maker roles, and UGVs take the actuator role.

Figure 3 illustrates an overview of the taxonomy that our review follows according to functional roles in a UAV–UGV coordination system. The UAV–UGV coordination systems can be classified into two categories: the systems with different functional roles of UAV/UGV and the systems with same functional roles. In UAV–UGV coordination systems with different functional roles, UAVs and UGVs take different but complementary functional roles, which provides widely application prospects in navigation, surveillance, formation and so on. On the other hand, in UAV–UGV coordination systems with same functional role, by virtue of the difference in observation accuracy/angles or mechanical structure, the cooperation among UGVs and UAVs can obtain better results in navigation, inspection and target tracking.

3. UAV–UGV Coordination Systems with Different Functional Roles of UAV/UGV

Since the characteristics of UAVs and UGVs are strongly complementary, the combination of different functional roles makes cooperative UAV–UGV coordination systems promising. First, when capturing ground features, UGVs acting as actuators are usually limited by their speed and environmental occlusion, while UAVs acting as sensors can be deployed to quickly find ground targets. Second, because UAVs have the advantage of operating at high altitudes, their auxiliary communication links are less prone to being blocked by obstacles than those of UGVs. Therefore, unconnected UGVs located at different positions can be connected indirectly with the support of UAVs serving as communication relays [20, 21]. Finally, UAVs (especially smaller ones) are usually restricted by their short voyage due to the limitation of carried energies, while UGVs acting as carriers (auxiliary facilities) have larger payload capability.

3.1. *UAVs acting as actuators and UGVs acting as auxiliary facilities*

This type of the UAV–UGV coordination system can be represented as $\langle A|AF\rangle$, in which the UGVs acting as auxiliary facilities assist UAVs in implementing tasks. On one hand, the UGV can act as a mobile carrier to carry the UAV near reconnaissance targets and change the UAVs battery. On the other hand, the UGV can be a mobile differential Global

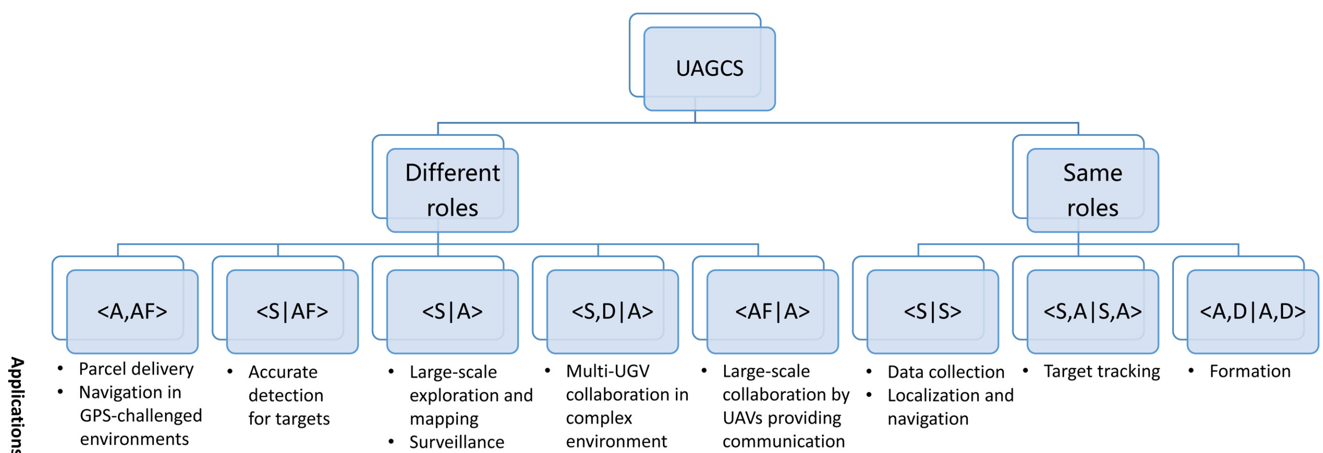
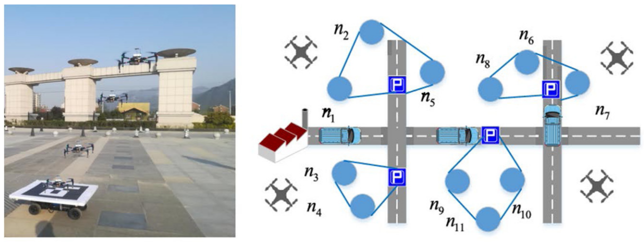


Fig. 3. The taxonomy for UAV–UGV coordination system and applications for each kind of the UAV–UGV coordination systems.



(a) (b)

Fig. 4. UGV acting as mobile carrier. (a) UGV acting as landing platform from Yang *et al.* [23] (b) UGVs acting as the carriers of UAVs and parcels from Peng *et al.* [24].

Navigation Satellite System (GNSS) reference station to help reduce the navigation uncertainty of the UAV.

3.1.1. *UGV acting as mobile carrier*

Because a UAV can fly over congested roads, it can provide fast, cost-efficient delivery of goods ordered online or rapid disaster relief operations [22]. However, because of their limited battery capacities, the hovering time of UAVs is quite short, hindering them from performing various remote jobs. In this case, UGVs can be utilized to carry and assist UAVs in various applications. Fig. 4 shows two examples for this kind of UAV-UGV coordination system.

A. UAV docking on UGV

Their vertical take-off and landing capability makes UAVs (mainly quadrotors) particularly suitable for docking onto UGVs, where the runway for take-off and landing is often very short. Many studies have focused on the precise landing ability of UAVs. This capability is important for autonomous docking of a UAV platform into a moving recharging station in missions requiring repeated flight operations and also in information-gathering and -delivery applications, where the UAV is required to reach a precise, desired position and then return to a base. Table 2 lists the approaches for UAV docking on UGV.

Many indoor experiments on autonomous landing on a slow-moving target are presented in works by the indoor positioning system. More recently, Rodriguez *et al.* [25] presented a vision-based autonomous UAV landing maneuver on top of a moving platform. The maneuver can be completely learned in simulation without prior human knowledge and by means of deep reinforcement learning techniques. Daly *et al.* [26] presented a novel decentralized coordination method for the autonomous rendezvous of a UAV and a UGV, which uses feedback linearization for each vehicle controller to render the input–output dynamics of each vehicle linear, and a decentralized linear relative position controller to drive the vehicles together from an arbitrary initial state.

Many studies describe systems capable of autonomous outdoor landing. Earlier studies were mostly concerned with precision landing on a static or slowly moving ground platform. For example, Lange *et al.* [27] proposed a vision-based landing approach in which a custom visual marker made of concentric rings allows a relative pose estimation between the UGV and the UAV, and UAV control is performed using optical flow measurements and velocity. Fu *et al.* [28] proposed a GPS-based navigation algorithm and an image-based visual control law to solve the autonomous landing problem. Yang *et al.* [23] presented a UAV autonomous landing system based on a hybrid camera array in a GPS-denied environment. This system combines fish eye images and stereo depth images, and the research proposes a novel state estimation algorithm to determine the motion state of the UGV. In addition, the authors proposed a nonlinear control strategy to achieve robust and precise control

Table 2. Approaches for UAV docking on UGV.

	UAV type	Reference	Approach
Indoor	Quadrotor	Rodriguez *et al.* [25]	Deep reinforcement learning
	Quadrotor	Daly *et al.* [26]	Decentralized coordination control
Outdoor	Quadrotor	Lange *et al.* [27]	Vision-based control
	Quadrotor	Yang *et al.* [23]	Nonlinear control
	Quadrotor	Fu *et al.* [28]	Vision-based control
	Quadrotor	Ghommam and Saad [29]	Adaptive tracking control
	Quadrotor	Rucco *et al.* [30]	Optimal control
	Quadrotor	Xu and Luo [31]	Control combined with tracking and
	Quadrotor		approaching based on the range distance
	Quadrotor	Baca *et al.* [33]	Model predictive control
	fixed-wing	Zheng *et al.* [34]	Sliding mode control
	VTOL UAV	Byun *et al.* [35]	Vision-based control
	Helicopter	Huang *et al.* [36]	Fixed-time control

of the UAV. Based on camera information extracted from the image plane, Ghommam and Saad [29] introduced a two-stage landing controller to ensure a safe landing on the moving platform. In order to reduce the fuel waste and improve the operation efficiency of UAV when carrying out low-cost aerial surveillance and mapping tasks, Rucco *et al.* [30] arranged UGVs as a mobile refueling unit, where the UAV will rendezvous with the UGV for refueling during very windy conditions.

Recent studies have demonstrated the autonomous landing of a UAV on a high-speed ground vehicle. Xu and Luo [31] presented a solution capable of landing on a moving car at speeds of 7 m/s. Borowczyk *et al.* [32] proposed a system that utilizes a vision-based approach combined with IMU and GPS measurements from a cell phone placed on the ground vehicle. Their proposed solution is able to track and land on a car moving at speeds of up to 50 km/h. Baca *et al.* [33] presented a complete system for the perception, control, and trajectory planning for a UAV to identify and land on a moving car at 15 km/h.

There are many studies for the autonomous docking problem for UAVs other than quadrotor. Zheng *et al.* [34] designed a sliding mode control law for autonomous landing missions for fixed-wing UAVs to track the desired landing trajectory and maintain constant relative pitch and roll angles. Byun *et al.* [35] developed a smart docking system for a vertical take-off and landing (VTOL) UAV. The VTOL UAV can dock on a UGV for their combined operation. A sphere-shaped mechanical docking interface between the UAV–UGV is proposed to allow for flexible and accurate positioning. A vision-based, target-tracking method to enhance the precision landing performance also was investigated. Huang *et al.* [36] presented a new fixed-time control algorithm to enable the autonomous landing of a helicopter onto a ships deck in the presence of parametric uncertainties and external disturbances.

Compared with landing on a UGV, an unmanned surface vehicle (USV) landing mission of the UAV with high accuracy is more difficult. Since a USV on an ocean is affected by wind and waves, the practical motion of a USV in rough sea conditions cannot be effectively formulated by a UGV. Huang *et al.*, studied a robust adaptive control approach [37]and a fixed time control approach [36] for autonomous shipboard landing by considering the 6 degree-of-freedom (6DOF) full motion of a USV. Xia *et al.* [38] proposed a complete solution, consisting of a mission planning and a nonsingular adaptive hierarchical control algorithm, to make UAVs land on the moving ship in rough ocean conditions.

B. Drone-assisted parcel delivery

A number of studies on drone-assisted parcel delivery for last-mile delivery have been proposed in the literature [39–42]. The ground vehicle (GV) departs carrying a UAV and all customer parcels. As the GV drives to a location near customers, the UAV is launched from the GV, carrying parcels for individual customers. The UAV then returns to the GV, which has moved to a new customer location. The GV is required to load packages, recharge batteries, and to recover the UAV so it can be secured aboard the UGV while in transit. In this case, by transporting the UAV closer to customer locations onboard the truck, the effective flight range of the UAV can be increased so that it can reach more customers. Table 3 lists the approaches for drone-assisted parcel delivery.

This application, although innovative, gives rise to several transportation planning problems. Murray and Chu [39] modeled the UAV-based cargo delivery problem as the Flying Sidekick Traveling Salesman Problem (FSTSP). The authors proposed the idea of having a drone attached to the top of a truck that can make a delivery at the same time when the truck is making another delivery. Once the drone finishes making a delivery, it needs to fly back to the truck at the current delivery location or along its route to the next delivery location. The authors designed heuristic algorithms for two UAV delivery VRP problems. Another work [40] presented a simulated-annealing-based heuristic algorithm to tackle FSTSP. Ferrandez *et al.* [41] proposed to first find the optimal launch locations through clustering and then determine the vehicle route by using a genetic algorithm. Campbell *et al.* [43] formulated and optimized models for drone delivery in collaboration with a truck. Wang *et al.* [42] derived a number of worst-case results on FSTSP, i.e. the maximum savings that can be obtained from using drones. Ha *et al.* [44] proposed a cluster-first, route-second and a route-first, cluster-second heuristic. More recently, the same authors [45] investigated a different objective function: the minimization of the total transportation cost for both the vehicle and the drone. They proposed a mixed-integer linear programming (MILP) model and two heuristics. Yu *et al.* [46] introduced a variant of FSTSP: TSP with mobile recharging stations (TSPMRS). They presented an algorithm that finds not only the most efficient order in which to visit the sites but also when and where to land on the charging stations to recharge.

Agatz *et al.* [48] developed another type of traveling salesman problem with drones (TSP-D), in which truck and drone are making deliveries in parallel. The authors presented the mixed-integer programming (MIP) model and proved the theoretical worst-case approximation bound by solving 12-node problems. They also developed a heuristic approach following a route first, cluster-second principle with local search afterward. More recently, the same authors [49] developed a precise solution for the TSP-D using the dynamic programming approaches based on the well-known Bellman–Held–Karp dynamic programming algorithm. This approach was able to find the optimal solution for problem instances with 10 customers much faster than the solution from the integer programming approach presented by Agatz *et al.* [48]. Kitjacharoenchai *et al.* [50] presented an MIP formulation for TSP-D and developed an algorithm based on insertion heuristics to solve problems containing up to 100 locations.

There are also two variants of TSP-D. One is called the Vehicle Routing Problem with Drone (VRP-D), which was proposed by Dorling *et al.* [51]. In VRP-D, a drone may travel with a truck, take off from its stop to serve customers, and land at a service hub to travel with another truck as long as the flying range and loading capacity limitations are satisfied. Poikonen *et al.* [52] extended the research and theoretically analyzed the maximum benefit under ideal circumstances. The second variant is the same-day delivery routing problem with heterogeneous fleets (SDDPHF) [53], in which two fleets of vehicles and drones deliver goods from the depot to customers who dynamically request services. When a new customer request arrives, a dispatcher has to decide whether to accept the customer for same-day delivery and, if so, determine the according assignment and routing decisions. The literature mentioned above typically considered only one UAV in vehicle-drone cooperative goods distribution, while more recent studies have proposed leveraging multiple UAVs to simultaneously deliver packages to customers. Peng *et al.* [24] used a novel hybrid genetic algorithm to support a GV and multiple UAVs working cooperatively for efficient parcel delivery. Murray and Raaj [55] proposed a heuristic approach to solve this problem. Wang *et al.* [54] proposed the simultaneous use of trucks, truck-carried drones, and independent drones to construct an efficient truck-drone parcel delivery system.

FSTSP and TSP-D restrict the UAV to serving only one customer per flight. Luo *et al.* [56] introduced the two-echelon cooperated routing (TECR) problem in which UAVs can access multiple targets in one flight and proposed two heuristics to solve the model. However, it was assumed that the GV can always find a rendezvous node to recycle the UAV wherever the UAV takes off. Liu *et al.* [57] proposed a two-stage route-based modeling approach to optimize both the truck's main route and the UAV's adjoint flying routes. A hybrid heuristic integrating nearest neighbor and cost saving strategies was developed to quickly construct a feasible solution. The simulated annealing algorithm was integrated with Tabu search, to improve the quality of the solution as well as the search efficiency.

3.1.2. *UGV act as mobile reference station*

UAVs are often confronted with GNSS-challenged environments when performing tasks. For example, a small quadrotor might be used for bridge inspection or structural health monitoring, for surveillance applications in urban environments, or for applications that require UAVs to transition from indoor-to-outdoor operations or vice versa.

Table 3. Different problems and solution approaches for drone-assisted parcel delivery.

Problem	Reference	Solution procedure
2E-VRP	Manyam *et al.* [47]	Branch-and-cut algorithm
FSTSP	Murray and Chu [39]	Greedy heuristic algorithm
	Ponza *et al.* [40]	Simulated-annealing (SA) algorithm
	Ferrandez *et al.* [41]	Genetic algorithm
	Wang *et al.* [42]	Deriving worst-case results
	Campbell *et al.* [43]	Deriving an approximation model
	Ha *et al.* [44]	TSP-LS and Greedy randomized adaptive search procedure
	Ha *et al.* [45]	Two heuristic rules
TSPMRS	Yu *et al.* [46]	Model transformation method
TSP-D	Agatz *et al.* [48]	Route-first, cluster-second heuristics
	Agatz *et al.* [49]	Dynamic programming approach
	Kitjacharoenchai *et al.* [50]	Insertion heuristics
VRP-D	Dorling *et al.* [51]	SA algorithm
	Poikonen *et al.* [52]	Extending the worst-case bounds
SDDPHF	Ulmer *et al.* [53]	Approximate dynamic programming
TSP-D with multiple UAVs	Peng *et al.* [24]	Hybrid genetic algorithm
	Wang *et al.* [54]	Hybrid truck-drone delivery algorithm
	Murray and Raaj [55]	Three-phase heuristic solution approach
TECR	Luo *et al.* [56]	Two heuristic rules
	Liu *et al.* [57]	Simulated annealing algorithm

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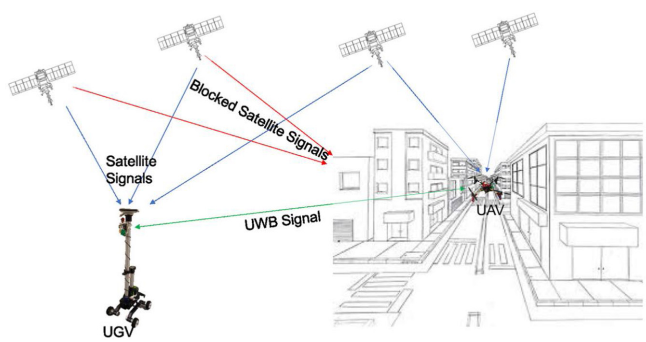

Fig. 5. UAV–UGV coordination system to improve positioning in challenging GNSS environments from Sivaneri and Gross [58].

Collaborative positioning techniques with UAV–UGV coordination use locally available or opportunistic measurements, such as measurements from UGVs, to help reduce navigation uncertainty, as shown in Fig. 5.

The UGV effectively assumes the role of a mobile differential GNSS reference station, while the UAV is the roving receiver. Furthermore, the UGV also acts as an additional GNSS satellite by providing a cooperative ranging measurement between the UAV and UGV. Sivaneri and Gross [58] focused on the design of the optimal motion of the UGV to best aid the UAVs navigation, and developed two novel cooperative strategies as well as two estimation strategies for the UGV to assist a UAV. Sivaneri and Gross [59] presented an experimental flight test evaluation of the proposed cooperative strategies. Jung and Ariyur [60] bolstered UAV GPS data accuracy through the use of relative positioning and GPS data of UGV. The multiple low-quality GPS modules on a UGV within line-of-sight (LoS) of the UAV are used to bolster UAV's GPS data accuracy.

3.2. *UAVs acting as sensors and UGVs acting as auxiliary facilities*

The UAV can hover in some crucial areas or fly at low altitude for making closer measurements, which means the versatility of smaller-scale UAVs enables them to make more accurate detection. However, the limited flight time of small UAVs means they have difficulty in inspecting long distances. Acting as a moving station, the UGV can offset the UAVs flight time disadvantage and enable it to collect data in a very large area.

This type of UAV–UGV coordination system, represented by $\langle S|AF \rangle$, is often deployed to inspect critical infrastructure, such as precision agriculture, target surveillance, and power line inspection. Tokekar *et al.* [4] built a UAV–UGV data collection system for precision agriculture, which uses the UAV for making measurements and the UGV for the transport of the UAV due to its limited energy. Ropero *et al.* [61] introduced a hybrid UGV-UAV system designed to achieve a set of target points distributed around an exploration area. Liu *et al.* [62] investigated a novel high-voltage power line inspection system that consisted of the GV and drone working cooperatively. The GV acts as a mobile platform that can launch and recycle the drone, while the drone can fly over the power line for making inspections within its limited flight time. Zhu and Wen [63] built an electronic patrol system consisting of the cruise vehicles and communication, detection, and command-and-control networks for the USV-UAV. Based on an analysis of the problems faced by collaborative USV-UAV systems, they established a model to evaluate the effectiveness of such synergistic cruises.

The studies mentioned above for UGV-assisted UAV inspection considered only one UAV, incapable of concurrently serving multiple targets distributed in an area. More recent work [64, 65] has employed multiple drones to serve multiple targets in parallel, which can significantly enhance efficiency and expand service areas. Hu *et al.* [65] proposed using a vehicle carrying multiple UAVs to perform sensing tasks over a target area. Another work [66] studied a UGV-assisted UAV inspection problem. Multiple UAVs were launched and recycled from the UGV in different locations, maximizing time efficiency for the UGV and the UAVs. Peng *et al.* [64] proposed a novel hybrid genetic algorithm, which supports the cooperation of one UGV and multiple drones for wide-area inspection applications.

3.3. *UAVs acting as sensors and UGVs acting as actuators*

In this type of the UAV–UGV coordination system, represented by $\langle S|A \rangle$, UAVs act as sensors to collect and transmit the information pertaining to the environment or tasks, while UGVs plan their paths to perform tasks according to the received information. UAVs can rapidly capture this information because of their speed and broader range of vision. Therefore, using UAVs to transmit the gathered environment and task information to UGVs can significantly accelerate the response to the changes in tasks and environments. Fig. 6 shows the type of $\langle S|A \rangle$ UAV–UGV coordination systems under different autonomy levels of UAV.

Earlier studies of this application relied on manual flight control of the air vehicle to collect data from the area before deploying the ground vehicle. For example, Stentz *et al.* [67] demonstrated that the precollected aerial data can improve the efficiency of planning for UGVs, even when the maps generated were out of date due to changes in the environment. Stentz *et al.* [68] and Vandapel *et al.* [69] introduced similar multi-robot systems in which the ground navigation capability of a UGV was enhanced by pre-collected LIDAR data obtained by the aerial vehicle.

As autonomous exploration technology becomes more advanced, the UAV can collect the ground image, which is

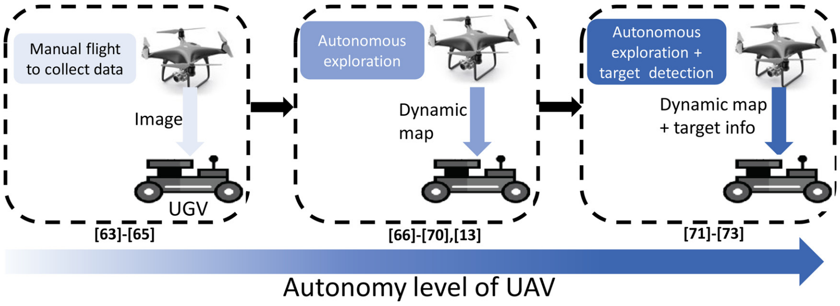

Fig. 6. The type of $\langle S|A\rangle$ UAV–UGV coordination system under different autonomy levels of UAV.

then processed with image denoising, image correction, and obstacle recognition to construct the ground map automatically, and the UGV can avoid obstacles and perform tasks [3]. Giakoumidis *et al.* [70] used a UAV to detect obstacles in an indoor environment. The UAV generated a slowness map, which represented the change in distance to the nearest obstacle at each point in the map, and decided on a minimum time trajectory for a UGV. Käslin *et al.* [71] presented a localization method based on elevation maps for UGVs. The method allows a UGV to find its relative position and orientation within the reference map provided by a UAV without relying on GPS. Zhang *et al.* [72] developed an autonomous air–ground cooperative field surveillance system, in which the UAV provides a birds eye view to the UGV for collision avoidance and path planning. When the task is finished, the UAV will land on the UGV. Peterson *et al.* [73] presented a UAV–UGV coordination system that utilized the overhead view of the UAV to determine the path plan for the UGV in real time.

Lazna *et al.* [16] utilized a UAV to not only generate a 2D map but also to create a 3D map of the region of interest via photogrammetric techniques. The map helps a UGV to plan a trajectory along which the regions of interest are searched. Kim *et al.* [74] showed how two UAVs can provide stereo vision to a UGV and compute altitude maps, which are then used by the UGV in its decision-making processes.

Advances in UAV technology can provide object identification and analysis, which has enabled studies proposing many novel applications for a UAV–UGV coordination system. MacArthur *et al.* [75] used a stereo system on a UAV to identify simulated land mines in images, localize marked points in the images of an open field, and send a UGV to those locations. Deusdado *et al.* [76] presented a robotic team suited for sampling and retrieving bottom sediment in mudflats. The robotic team included a UGV, equipped with a drilling tool designed to be able to retain wet soil, and a UAV for building a high-resolution geo-referenced mosaic from a set of aerial images. Jung *et al.* [77] introduced an algal-bloom UAV–USV coordination system named ARROS. The UAV flies over the surface of a river or lake for monitoring in order to rapidly detect and locate algal blooms, while the USV plans its path to remove harmful algal blooms according to the locations of algal blooms detected by the UAV.

3.4. *UAVs acting as sensors as well as decision makers and UGVs acting as actuators*

In this type of the UAV–UGV coordination system, represented by $\langle S, D|A\rangle$, UAVs provide UGVs with environmental information and monitor the UGVs. Therefore, the UAVs act as an "eye-in-the-sky" and decision maker for providing guidance for UGVs, as shown in Fig. 7.

Michael *et al.* [78,79] proposed an abstraction model for a UGV team that allows the UAV to control the team without any knowledge of the specificity of individual vehicles. The abstraction model includes a gross model of the shape of the formation of the team and information about the position and orientation of the team in the plane. Chaimowicz and Kumar [80] addressed the problem of deploying many UGVs in urban environments where a group of UAVs can be used to coordinate the UGVs. In the UAV–UGV coordination system, UAVs with aerial cameras can be used to monitor and command a swarm of UGVs, controlling the shape (distribution) and motion of each group. Similarly, Aranda *et al.* [81] proposed a vision-based control method to drive a set of robots moving on the ground to a desired formation using multiple camera-equipped UAVs as control units. Each camera views, and is used to control, a subset of the ground team. This method can be considered to be a

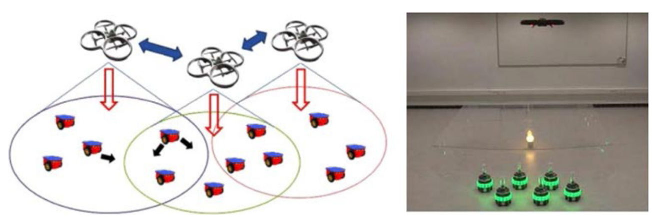

Fig. 7. UAVs acting as an "eye-in-the-sky"and decision maker to provide the guidance for UGVs from Aranda *et al.* [81] and from Mathews *et al.* [84].

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partially distributed solution, combining the simplicity of centralized schemes with the scalability and robustness of distributed strategies. More recently, the same authors [82] presented another vision-based control method that demands only simple resources from UGVs and does not need a complex coordination strategy for the UAVs. This method provides a flexible architecture and has useful decoupling properties and robustness to various typical sources of errors.

UAVs can serve as escorts for UGVs, providing privileged eye-in-the-sky data to avert potential problems on UGVs. Rao *et al.* [83] controlled the motion of a UGV along a desired trajectory using observations from a camera on a UAV. Mathews *et al.* [84] introduced supervised morphogenesis, which enables UAVs to provide assistance for self-assembling UGVs. The UAVs exploit their elevated position to characterize the environment and view the environment to supervise and control a morphology formation of UGVs. The UGVs rely on UAVs to act as an "eye-in-the-sky" to form new morphologies.

3.5. *UAVs acting as auxiliary facilities and UGVs acting as actuators*

In this type of the UAV–UGV coordination system, represented as $\langle AF|A \rangle$, the UAV, as an auxiliary facility, can provide communication to UGVs. When UGVs are required to decentralize the execution of tasks in a collective manner within a large area, they utilize a great deal of energy for communications. Hence, energy-efficient techniques that consider the constrained capacity of the batteries of UGVs are needed. Collecting a massive amount of data using traditional multi-hop forwarding will involve heavy use of the underlying energy-scarce nodes and inherently unreliable wireless links, leading to reduced network lifetimes and low data collection rates, respectively. Owing to their elevation, UAVs have more chances of LoS connections toward the users/UGVs, as shown in Fig. 8. Oubbati *et al.* [85] performed a comprehensive survey of position-based routing protocols for flying (UAV) ad hoc networks with their various categories and compared the advantages and weaknesses of each protocol. Oubbati *et al.* [86] presented the architecture, constraints, mobility models, routing techniques, and simulation tools dedicated to these flying ad hoc networks.

UAVs can hover at fixed locations to provide coverage of the areas requiring communication or to enhance the coverage of public safety communications. Oubbati *et al.* [87] characterized the properties of a UAV-assisted vehicular ad hoc network in urban environments and further proposed a network routing protocol for reliable data delivery. Mozaffari *et al.* [88] considered a UAV-assisted downlink network based on device-to-device communications.

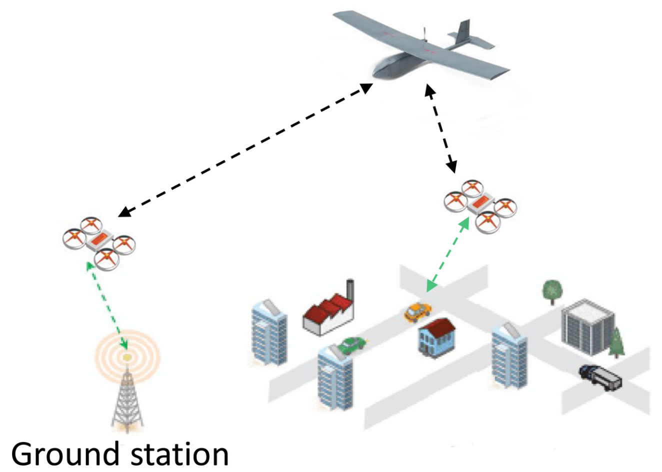

Fig. 8. UAVs to provide communication for UGVs.

Scenarios with static UAVs and mobile UAVs were each analyzed. For the static UAV scenario, the authors provided optimal settings for the UAV altitude to maximize the coverage probability and the system sum-rate. For the mobile UAV scenario, the authors provided a minimum UAV altitude (minimum transmit power) to completely cover the entire area.

Xiao *et al.* [89] formulated a UAV-aided vehicular ad hoc network (VANET) transmission game and derived the Nash equilibria of the game to determine the impacts of the UAV transmission costs and the radio channel condition on communication performance of the VANET against smart jamming. A hotbooting anti-jamming relay strategy is used for a UAV to select the optimal relay scheme without knowing the VANET model and the jamming model. Multiple UAVs, forming an aerial subnetwork, use relaying and multi-hop communication methods for extending the coverage. Zhou *et al.* [90] constructed a two-layer networking architecture to support the concept of multi-UGV coordination. This involved multiple UAVs forming an aerial subnetwork and aiding the ground vehicular subnetwork through air-to-air and air-to-ground communications. Cheng *et al.* [91] proposed an air–ground integrated mobile edge network. In the network, multiple drone cells were deployed in a flexible manner to provide agile radio access network coverage for the temporally and spatially changing users (UGVs) and data traffic.

Because of their mobility, UAVs can be an efficient way to provide temporary communication networks when conventional terrestrial networks are damaged or when UGVs are scattered in a large area. Shi *et al.* [92] proposed a comprehensive architecture of the drone-assisted vehicular networks and described their potential applications. Merwaday and Guvenc [93] analyzed the throughput gains of public safety communications brought about by UAVs through simulations. Zhang and Liu [94] used two cooperative UAVs to achieve the downlink transmission over a large number of emergency response rescue vehicles on the ground in post-disaster areas. Based on tools of stochastic geometry, a theoretical framework was developed to derive the coverage probability and average achievable rate in closed forms for the overlaying multi-UAV multi-channel downlink scenario. Jia and Zhang [95] modeled a UAV base station in ground-to-air cooperative networks to improve connectivity among vehicles in areas affected by disaster. A scenario involving multiple UAVs was analyzed to determine the minimum number of UAVs needed to guarantee a target connectivity threshold among vehicles for a given geographical area and vehicle density. Zhu *et al.* [96] proposed a 3D nonstationary geometry-based stochastic channel model for UAV-ground communication systems and investigated the computation and optimization methods of time-variant channel parameters, as well as analyzing the theoretical statistical properties.

Network performance and lifespan may be strongly affected by a UAVs moving trajectory, so some studies have focused on the UAV mobility model and energy consumption. Choi *et al.* [97] formulated an off-line trajectory optimization problem for determining the energy-efficient maneuvering of the UAV-based relay and solved it using a direct shooting method. Our previous work [21] investigated a path planning problem for the messenger UAV to support indirect communications among all UGVs. A heuristic method was introduced to find the shortest route for enabling the UAV to deliver information to all requesting UGVs. To enhance covert communication performance, Zhou *et al.* [98, 99] jointly optimized the UAVs trajectory and transmitted power in terms of maximizing the average covert transmission rate from the UAV to a UGV, subject to transmission outage constraints and covertness constraints.

4. UAV–UGV Coordination Systems with Same Functional Role of UAV/UGV

As heterogeneous robots, UGVs and UAVs have a significant difference in observation accuracy, observation angles, and mechanical structure. Therefore, better results in navigation, inspection and target tracking can be obtained by effectively coordinating UGVs and UAVs with the same functional role.

4.1. *UAVs and UGVs acting as sensors*

This type of UAV–UGV coordination systems can be represented as $\langle S|S\rangle$, in which UAVs and UGVs act as sensors to generally implement data collection and navigation tasks.

4.1.1. *Data collection*

UAV–UGV coordination systems have recently emerged as a tool for collecting spatial information in real time from natural environments. Since the UGVs can be delegated to collect the ground data while UAVs cover the air or the sea, the combination of data collected from the UAV and UGV can be used to conduct a thorough investigation of the environment.

Shkurti *et al.* [100] described a UAV–UGV coordination system for helping scientists to inspect marine ecosystems. In this system, UAVs and UGVs communicate with off-site scientists and operate in a hierarchical structure to autonomously collect visual footage of interesting underwater regions from multiple scales. Similarly, Reineman *et al.* [101] introduced a system of ship-launched fixed-wing UAVs for measuring the marine atmospheric boundary layer and ocean surface processes. The UAV measurements, including atmospheric momentum and radiative heat fluxes, are complemented by measurements from ship-based instrumentation. Maini *et al.* [102] proposed a heterogeneous team of aerial and ground robots that were tasked with monitoring a terrain along a given path. Both types of robots were equipped with cameras that can monitor the terrain within their fields-of-view. Nikolakopoulos *et al.* [103] presented the synergistic use of the UAV–UGV coordination system to investigate and map a beachrock formation on Syros Island, Greece.

UAV–UGV coordination systems can be used for automated monitoring in precision agriculture, thereby reducing cost and limiting human exposure to dangerous agricultural chemicals. For example, UAVs can provide information about crops such as unhealthy and stressed plants to UGVs, and the UGVs can then be used for care of crops such as removal of diseased plants, extraction of tissue samples, and water and fertilizer applications. Roldan *et al.* [104] proposed a UAV–UGV coordination system to monitor environmental variables in greenhouses. UAVs and UGVs are equipped with sensors for measuring temperature, humidity, luminosity, and carbon dioxide concentration, all of which are relevant variables for controlling and monitoring the conditions of crops.

The UAV–UGVs ability to cooperatively search for hazardous radiation sources provides a safer approach than what is possible with manned survey teams. Christie *et al.* [105] presented systems, algorithms, and experiments to perform a radiation search autonomously using a UAV–UGV coordination system. When searching for hazardous radiation sources, the UAV is capable of autonomously scanning large areas to collect radiation data, and the UGV could reach the radiological point of interest to collect additional radiation data, transmit video to operators at a remote base station, and update other unmanned systems simultaneously searching the area.

4.1.2. *Mapping and target location*

When UAVs and UGVs perform mapping and target location, there is a significant difference in the data types, observation angles, and observation accuracy each provides. Therefore, a better result on mapping and localization can be obtained by integrating these different data.

Qin *et al.* [1] introduced an autonomous exploration and mapping system using a UAV–UGV coordination system in GPS-denied environments. In this system, the UGV carried out fast autonomous exploration and active 2.5-D simultaneous localization and mapping (SLAM) to generate a coarse environment model, which serves as a navigation reference for subsequent complementary 3D fine-mapping conducted by a UAV. Hsieh *et al.* [106] assembled a team of aerial and ground robots to monitor a small village and search for and localize human targets. The UAVs generated the maps used to design navigation controllers and plan missions for the UGV team. The UGVs constructed a map of the radio signal strength for use as an aid in planning missions. Cai and Kousuke [107] proposed a method to achieve the cognitive sharing among UGVs and UAVs by identifying the same object. The same authors [108] proposed another cognitive sharing method based on edge-label subgraph matching for object recognition. This method was applied to the navigation system where a UAV directs a ground robot to the target position via cognitive sharing.

4.2. *UAVs and UGVs acting as sensors and actuators*

The complementary strengths of air-ground-based sensors and actuators encourage the cooperative use of both UAVs and UGVs for target tracking. This type of UAV–UGV coordination system can be represented as $\langle S, A | S, A \rangle$.

The main advantages of target tracking using UAVs are that they have a wide field of view and can cover large areas quickly [109]. However, sensors mounted on UAVs are unable to localize the target on the ground accurately due to the limits on altitude and airspeed. UGVs are slower and have a more limited field of view, but they are capable of getting closer to targets and resolving their relative locations with greater accuracy. In addition, in a pursuit-evasion scenario, a ground vehicle has the ability to "capture" a target, whereas the UAV can only observe and inform.

Tanner *et al.* [110] proposed a switched control architecture between UAVs and UGVs to track a moving target. In this work, the UAVs and the UGVs were deployed in groups to detect and track moving targets in certain regions. However, the UGV were modeled as point masses without differentiating their respective motion constraints. Furthermore, a localization approach was not provided [1]. Yu *et al.* [111] designed a cooperative path planning algorithm for tracking a moving target using both UGVs and UAVs. The authors extended the algorithm to multi-vehicle collaboration scenarios. In the algorithm, a decentralized planning algorithm relying on an auction scheme plans finite look-ahead paths that maximize the sum of the joint probability of detection over all vehicles. Similarly, vidal *et al.* [112] and Yu *et al.* [113] proposed probabilistic path planning algorithms for UAVs and UGVs to cooperatively track moving targets.

In addition to tracking a certain target, Minaeian *et al.* [114] used the complementary capabilities of UGVs and UAVs to track and control crowds on a border area. On the UAV, a customized motion detection algorithm is applied to follow the crowd from a mounted moving camera. Due to the UAVs lower resolution and broader detection range, UGVs with higher resolution and fidelity were used to detect individual humans, as well as moving landmarks to localize the detected crowds with unknown independently moving patterns at each time point.

4.3. *UAVs and UGVs acting as decision makers and actuators*

Cooperative formation in the UAV–UGV coordination systems, represented by $\langle A, D | A, D \rangle$, is a class of heterogeneous multi-agent collaboration. Due to the different characteristics of UAVs and UGVs, such as dynamic behavior, sensor capabilities, and computational power, the formation control in a UAV–UGV coordination system can be quite challenging. Current application areas of formation for UAV–UGV coordination systems include search and rescue operations, coverage tasks, and security patrols. Table 4 lists the approaches used in this type of the UAV–UGV coordination systems.

The formation studies for UAV–UGV coordination systems can be classified into two groups. The first group includes studies where the coordination is done by a centralized unit that can oversee the whole group and command the individual robots accordingly. For example, Santana *et al.* [115] proposed a centralized control structure for a leader-follower formation involving a UGV-UAV team. Rabelo *et al.* [116] proposed a centralized control for a heterogeneous line formation composed by a UAV and a UGV. The virtual structure is the approach chosen, where the structure considered is the line whose extremities are the two robots. The centralized algorithms rely on perfect communication but are prone to fail due to a connection failure or occurring fault in the controller.

The second group contains distributed formation methods for achieving the coordination. In decentralized approaches, a local controller is designated for each agent,

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Table 4. Coordination approaches in the $\langle A, D|A, D\rangle$ type of UAV–UGV coordination systems.

The way of coordination	Reference	Approach
Centralized coordination	Santana *et al.* [115]	Leader-follower formation control
	Rabelo *et al.* [116]	Formation control based on virtual structure
Decentralized coordination	Rahimi *et al.* [117]	Lyapunov-based control
	Ivancevic *et al.* [118]	Hamiltonian control
	Neto *et al.* [119]	Convoy control
	Tran *et al.* [120]	NI consensus control
	Xiong *et al.* [121]	$l_2 - l_\infty$ control
	Kamel *et al.* [122]	FTCC strategy

and the control signals are provided using local information of agents and their neighbors. This approach is better able to avoid communication failures, and also the local processors perform fewer processing routines. Rahimi *et al.* [117] studied a time-varying formation of UGVs and UAVs. By considering coupling between the individuals in a neighborhood and a synchronization method, a proper controller is proposed for each individual, which provides acceptable performance in a changing topology. Ivancevic *et al.* [118] proposed a decentralized framework for prediction and control of a large-scale joint swarm of UGVs and UAVs, performing a joint autonomous land–air operation. Neto *et al.* [119] designed a decentralized control law to govern UGVs in line formation, following the forward speed of the leading vehicle as UGVs and UAVs maintain a prescribed distance between each other. Tran *et al.* [120] proposed a switching formation control law based on the relative-position consensus for UGVs and UAVs moving in formation. All agents can automatically create a new safe formation to overcome obstacles, then restore the prototype formation once the obstacles are cleared. Xiong *et al.* [121] analyzed the dynamic output feedback consensus control problem of the UAV–UGV coordination system under the leader-follower formation with a dynamic quantizer.

Kamel *et al.* [122] investigated a fault-tolerant cooperative control strategy for a team of UAVs and UGVs in the presence of actuator faults. A broken UGV that cannot complete its assigned task will exit the formation mission, and a fault-tolerant cooperative control (FTCC) strategy is designed to reassign the mission to the remaining healthy vehicles. If the faulty UGV can continue the mission with degraded performance, the other team members will reconfigure their controllers, taking into consideration the capability of the faulty UGV.

5. Discussion

5.1. *Publication outlets for different types of UAV–UGV coordination systems*

The previous section reviewed existing studies of UAV–UGV coordination systems, according to the functional roles of UAVs and UGVs. Figure 9 illustrates the number of papers published during the period of 2015–2020 on the eight types of UAV–UGV coordination systems. It is quite clear that the studies for the UAV–UGV coordination systems with different functional roles, as opposed to those with the same roles, are receiving more attention. This may be because the combination of different roles can develop the advantages of the complementarities in the characteristics between UGVs and UAVs. For the UAV–UGV coordination systems with different functional roles, the studies on $\langle A|A F\rangle$ have drawn a great deal of attention, while the number of studies on $\langle S, D|A\rangle$ is still fairly limited. In $\langle S, D|A\rangle$, UAVs acting as decision makers require a high autonomy to make decisions on their own as well as UGVs and adapt to changes in the environment.

5.2. *Coordination mode in the UAV–UGV coordination systems*

5.2.1. *Perception coordination*

The coordination of perception between UAVs and UGVs allows the UAV–UGV coordination systems to precisely model their environment from sensory information and obtain knowledge of how their actions are affecting the environment. To measure variables in the environment or track objects, techniques of perception coordination using the UAV–UGV coordination systems are studied to obtain more accurate, more complete, or more dependable information. According to the coordination pattern of information flow between sensors, the type of perception

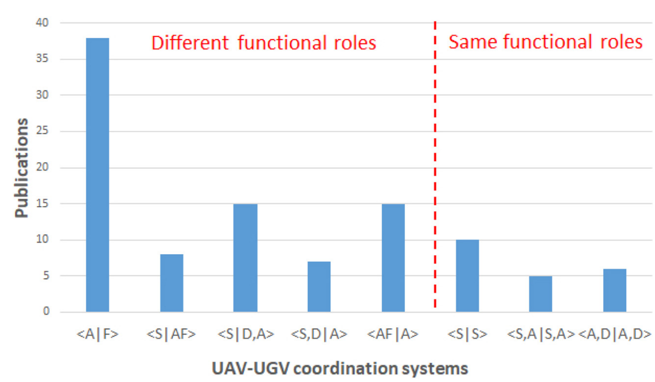

Fig. 9. The number of recent publications on the eight kinds of the UAV–UGV coordination systems.

coordination (sensor fusion) can mainly be divided into complementary and cooperative coordination. In the complementary coordination, multiple information sources supply different information about the same features, e.g. literature [102, 105]. Cooperative coordination uses the information extracted by multiple independent sensors to provide information that would not be available from a single sensor, e.g. literature [100, 101, 104]. SLAM for UAV–UGV coordination systems has been developed to simultaneously generate a map of the environment and localize themselves within this map. SLAM leverages heterogeneous robot cooperation to tackle complex environments. Distributed SLAM with sparse robot networks and decentralized active SLAM [106] that enabled robot teams to traverse and map the environment were also investigated.

In addition, to reduce the uncertainty of information, perception coordination in UAV–UGV coordination systems can extend the range of system perception. In $\langle S|AF\rangle$, UGVs acting as mobile carriers assist UAVs in inspecting the critical infrastructure in a large area, such as precision agriculture, target surveillance, and power line inspection.

5.2.2. *Planning and Decision-making coordination*

Planning and Decision-making are critical components of autonomy in UAV–UGV coordination systems. These components are responsible for making decisions that range from task planning, and path (motion) planning. Task planning is designed to solve the problem of which UGV/UAV should execute which task. This involves task decomposition and task allocation. Path (motion) planning is designed to generate the path of each robot [123]. So far, the research on planning and decision-making coordination has been mainly concentrated on the path (motion) planning problem, even though task allocation can directly influence the effect of path planning. Task allocation can be considered an instance of the well-known optimal assignment problem. A comprehensive taxonomy for task allocation of the multi-agent system can be found in [124]. Since the UAV–UGV coordination systems face constraints that heterogeneous multi-agent systems do not encounter, including spatial, temporal, sensing, and communication constraints, task allocation algorithms for UAV–UGV coordination systems have been developed. Examples include heuristics [55, 56], policy function approximation based on geographical districting [53], the K-means clustering method [125], and a hybrid genetic algorithm [24].

The path (motion) planning problem is to find optimal paths $\sigma(\alpha) : [0, 1] \to X$ in the configuration space X for individuals in a UAV–UGV coordination system that starts at the initial configuration and reaches the goal region while satisfying given global and local constraints (e.g. the differential constraints of vehicles). In addition, the path planning problem should consider not only any obstacles (whether static or dynamic) in the environment but also any possible interference between robots. There are several types of path problems defined in UAV–UGV coordination systems.

- Point-to-point path planning, that is, to find optimal paths that will drive vehicles from the start to the goal configuration. See, for example, the UGV path planning problem [16, 71, 72, 107, 108] with the map generated by UAV in $\langle S|D, A\rangle$ and $\langle S|S\rangle$.
- Coverage path planning, that is, to plan an optimal path that passes over all points of an area or volume of interest. See, for example, the target search problem [75, 77] in $\langle S|D, A\rangle$.
- Multiple waypoint path planning, that is, to find the shortest possible route that stops at each waypoint. See, for example, the Drone-UGV parcel delivery problem [39–43] in $\langle A|AF\rangle$, the UGV-assisted surveillance problem [4, 61–63] in $\langle S|AF\rangle$, and the messenger UAV path planning problem [21, 98, 99] in $\langle AF|A\rangle$.

5.2.3. *Motion coordination*

The object of motion coordination in UAV–UGV coordination systems is to have UAVs and UGVs move according to some constraints on the team as a whole [126], such as formation [127], manipulation [128], target search/tracking [129], and dispersion/aggregation. In these problems, the motions of individual robots are no longer independent of each other; instead, the group must move in synchrony according to predefined motion constraints for the entire team.

In general, two strategies can be adopted for motion coordination in UAV–UGV coordination systems: centralized coordination and distributed coordination. In centralized coordination, all computations and controls are performed in a global central station, which may result in a high communication burden, high computational load, and high memory requirements. Distributed coordination requires no central controller, and all measures and controls are performed by individuals in UAV–UGV coordination systems. Although both strategies are considered workable depending on the conditions of the real applications, the distributed motion coordination is considered the more promising of the two due to many physical constraints such as narrow communication bandwidths, limited computing/memory resources, and the large sizes of vehicles to manage and control.

Distributed motion coordination in UAV–UGV coordination systems requires robots to coordinate motions either (1) relative to other robots; (2) relative to the environment; (3) relative to external agents; or (4) relative to robots and the environment.

Table 5. Various motion coordination in UAV–UGV coordination systems.

Relative motion requirements	Tasks of UGVs and UAVs
Relative to other robots	Formations in $\langle A, D \| A, D\rangle$, Docking in $\langle A \| AF\rangle$
Relative to the environment	Search in $\langle S \| D, A\rangle$, Localization and mapping in $\langle S \| S\rangle$, Coverage, Deployment
Relative to external agents	Pursuit and target tracking in $\langle S, A \| S, A\rangle$
Relative to other robots and the environment	Escort in $\langle S, D \| A\rangle$

Much of the current research on motion coordination in UAV–UGV coordination systems is aimed at developing specific algorithms to one or more of the behaviors of UAVs and UGVs listed in Table 5. In general, most current work on motion coordination, especially for distributed coordination, is aimed at understanding the theoretical formal control principles that can predictably converge to the desired group behaviors and remain in stable states.

6. Challenges and Insights

The great heterogeneity and complementaries between UAVs and UGVs in dynamics, speed, sensing, communication, and functions enable UAV–UGV coordination systems to efficiently complete many complicated tasks [6]. These advantages lead to better performance than having a single powerful but complex robot or homogeneous robots performing the same task. However, it also increases the complexity of the design process. Many challenges still face the research community before UAV–UGV coordination systems that are able to perform complex tasks can be deployed. In this section, we discuss some of the challenges pertaining to designing UAV–UGV coordination systems and provide some insights on future research directions.

6.1. *Task modeling and identification*

Modeling and identifying the task scenarios lies at the root of UAV–UGV coordination systems. According to the system goal, tasks can be identified and modeled at multiple levels of abstraction as required to support the purpose of UAV–UGV cooperation. Analysis of the obtained models can reveal further information about the way in which a task is achieved, the task relevance, etc. However, current studies mostly require the system designer to manually model tasks. To aid UAV–UGV coordination systems in completing complex tasks in uncertain environments, the step of task modeling and identification should be automated as conditions change.

6.2. *Dynamic Functional Role Allocation*

Although there exist many studies for UAV–UGV coordination with the fixed functional roles, it seems still rare to see the UAV–UGV coordination systems with dynamic functional roles. The dynamic property for functional role is of particular importance to examine the adaptivity level of UAV–UGV coordination systems. The role assignments can be dynamic and time-variant to better cope with the complexity of tasks and variability in environments. Therefore, the functional roles of individual vehicles might have to be dynamically altered and assigned new roles before the completion of their assigned tasks. In addition, the role assignments should also take into consideration the tradeoff between the redundancy of vehicle capabilities and the fault tolerance or robustness to the failures of vehicles.

6.3. *Computational complexity*

UAV–UGV coordination approaches should be computationally efficient due to the need for real-time response in some applications or the lack of enough computational resources of robots. UAVs/UGVs generally are limited on computational capability due to size and weight constraints and might not be able to offload their computations to the cloud due to bandwidth scarcity, poor or unreliable connectivity, and minimum latency requirements. The interactions among UGVs and UAVs increase the computational cost per robot as the number of robots increases. Tightly coordinated tasks also increase the computational burden due to the large amount of communication and data exchange among robots [130]. This imposes the aforementioned challenge of developing efficient coordination approaches but should also encourage researchers to design more advanced embedded hardware technology.

6.4. *Scalability and heterogeneity tradeoff*

In order to operate effectively in different scenarios, a UAV–UGV coordination system needs to be scalable and adaptable in order to cope with the dynamic environment and complexity of tasks. Having UAVs and UGVs act on the environment simultaneously further increases the uncertainty in the system. Many decentralized planning and control algorithms for the UAV–UGV coordination system have been proposed in the literature but still face challenges when dealing with the tradeoff between scalability and robot heterogeneity in highly dynamic environments. Therefore, developing planning algorithms that strike a task-appropriate balance between scalability and heterogeneity will result in increased use of UAV–UGV coordination systems. Hierarchical approaches where local interactions are dense and global interactions are sparse could be adopted to improve system scalability.

6.5. *Human-in-the-loop*

The term human-in-the-loop refers to a system architecture that requires robots to interact with humans. Humans involvement can transmit the necessary intervention to an individual vehicle or a group of vehicles in order to execute actions alongside other vehicles. The benefits of such systems include improving task performance of the UAV–UGV coordination system, managing the UAV–UGV coordination system to support human beings, and improving system adaptability and resistance to environmental stochasticity. However, this system also faces challenges such as human factors and understanding the intention of humans. Therefore, determining whether human-in-the-loop is an asset or liability in a given scenario is key to choosing the system architecture that would be the most efficient in terms of completion of tasks.

7. Conclusion

The coordination between UAVs and UGVs has been attracting more and more attention. This paper systematically reviews the advances in UAV–UGV coordination systems from 2015 to 2020 and performs a comprehensive investigation and analysis on the recent research. We identify four key functional roles in the UAV–UGV coordination system: sensor, actuator, decision maker, and auxiliary facility. Close collaboration among these functional roles can increase the UAV–UGVs coordination as it pertains to perception, communication, task performance, and planning. Beyond the four functional roles, the UAV–UGV coordination system has been further classified into eight categories. The functional-role-based category has provided new insights into the analysis of the various patterns of UAV–UGV coordination. This paper also discusses challenges pertaining to UAV–UGV coordination that have yet to be sufficiently addressed.

Acknowledgments

This work was supported in part by the National Outstanding Youth Talents Support Program 61822304, in part by the National Natural Science Foundation of China under Grant 61673058, in part by the NSFC-Zhejiang Joint Fund for the Integration of Industrialization and Informatization under Grant U1609214, in part by Consulting Research Project of the Chinese Academy of Engineering (2019-XZ-7), in part by the Projects of Major International (Regional) Joint Research Program of NSFC under Grant 61720106011, in part by National Postdoctoral Program for Innovative Talent, in part by Beijing Advanced Innovation Center for Intelligent Robots and Systems and in part by China Postdoctoral Science Foundation under Grant 2020M672747.

References

[1] H. Qin, Z. Meng, W. Meng, X. Chen, H. Sun, F. Lin and M. H. Ang, Autonomous exploration and mapping system using heterogeneous UAVs and UGVs in GPS-denied environments, *IEEE Trans. Veh. Technol.* **68**(2) (2019) 1339–1350.

[2] Y. Liu, Z. Luo, Z. Liu, J. Shi and G. Cheng, Cooperative routing problem for ground vehicle and unmanned aerial vehicle: The application on intelligence, surveillance, and reconnaissance missions, *IEEE Access* **7** (2019) 63504–63518.

[3] J. Li, G. Deng, C. Luo, Q. Lin, Q. Yan and Z. Ming, A hybrid path planning method in unmanned air/ground vehicle (UAV/UGV) cooperative systems, *IEEE Trans. Veh. Technol.* **65**(12) (2016) 9585–9596.

[4] P. Tokekar, J. Vander Hook, D. Mulla and V. Isler, Sensor planning for a symbiotic UAV and UGV system for precision agriculture, *IEEE Trans. Robot.* **32**(6) (2016) 1498–1511.

[5] S. Lacroix and G. Le Besnerais, Issues in cooperative air/ground robotic systems, *Robotics Research*, (Springer, 2010), pp. 421–432.

[6] J. Chen, X. Zhang, B. Xin and H. Fang, Coordination between unmanned aerial and ground vehicles: A taxonomy and optimization perspective, *IEEE Trans. Cybern.* **46** (APR 2016) 959–972.

[7] H. Duan and S. Liu, Unmanned air/ground vehicles heterogeneous cooperative techniques: Current status and prospects, *Sci. China Technol. Sci.* **53**(5) (2010) 1349–1355.

[8] S. L. Waslander, Unmanned aerial and ground vehicle teams: Recent work and open problems, *Autonomous Control Systems and Vehicles* (Springer, 2013), pp. 21–36.

[9] S. Çaşka and A. Gayretli, A survey of UAV/UGV collaborative systems, *Proc. 44th Int. Conf. Computers and Industrial Engineering (CIE44)*, Vol. 14, Istanbul, Turkey, pp. 453–463.

[10] R. Cajo, T. T. Mac, D. Plaza, C. Copot, R. De Keyser and C. Ionescu, A survey on fractional order control techniques for unmanned aerial and ground vehicles, *IEEE Access* **7** (2019) 66864–66878.

[11] S. Sakai, M. Iida, K. Osuka and M. Umeda, Design and control of a heavy material handling manipulator for agricultural robots, *Autonom. Robots* **25**(3) (2008) 189–204.

[12] R. Siegwart, I. R. Nourbakhsh and D. Scaramuzza, *Introduction to Autonomous Mobile Robots* (MIT press, 2011).

[13] K. Wang, Y. Ke and B. M. Chen, Autonomous reconfigurable hybrid tail-sitter UAV u-lion, *Sci. China Inf. Sci.* **60**(3) (2017) 033201.

[14] W.-Y. Ruan and H. Duan, Multi-UAV obstacle avoidance control via multi-objective social learning pigeon-inspired optimization, *Front. Inf. Technol. Electron. Eng.* **21**(5) (2020) 740–748.

[15] T.-M. Wang, Y.-C. Zhang, J.-H. Liang, Y. Chen and C.-L. Wang, Multi-UAV collaborative system with a feature fast matching algorithm, *Front. Inf. Technol. Electron. Eng.* (2020) 1–18.

[16] T. Lazna, P. Gabrlik, T. Jilek and L. Zalud, Cooperation between an unmanned aerial vehicle and an unmanned ground vehicle in highly accurate localization of gamma radiation hotspots, *Int. J. Adv. Robot. Syst.* **15**(1) (2018) 1–16.
[17] National Research Council, *Technology Development for Army Unmanned Ground Vehicles* (National Academies Press, 2003).
[18] C. Hu, Y. Wang, R. Wang, T. Zhang, J. Cai and M. Liu, An improved radar detection and tracking method for small UAV under clutter environment, *Sci. China Inf. Sci.* **62**(2) (2019) 29306.
[19] M. Wooldridge, N. R. Jennings and D. Kinny, A methodology for agent-oriented analysis and design, *Proc. Third Annual Conf. Autonomous Agents* (New York, United States, 1999), pp. 69–76.
[20] Y. Ding, B. Xin and J. Chen, Precedence-constrained path planning of messenger UAV for air-ground coordination, *Control Theory Technol.* **17**(1) (2019) 13–23.
[21] Y. Ding, B. Xin, J. Chen, H. Fang, Y. Zhu, G. Gao and L. Dou, Path planning of messenger UAV in air-ground coordination, *IFAC-PapersOnLine***50**(1) (2017) 8045–8051.
[22] B. Rabta, C. Wankmuller and G. Reiner, A drone fleet model for last-mile distribution in disaster relief operations, *Int. J. Disast. Risk Reduct.* **28** (2018) 107–112.
[23] T. Yang, Q. Ren, F. Zhang, B. Xie, H. Ren, J. Li and Y. Zhang, Hybrid camera array-based UAV auto-landing on moving UGV in gps-denied environment, *Remote Sens.* **10**(11) (2018) 1829.
[24] K. Peng, J. Du, F. Lu, Q. Sun, Y. Dong, P. Zhou and M. Hu, A hybrid genetic algorithm on routing and scheduling for vehicle-assisted multi-drone parcel delivery, *IEEE Access* **7** (2019) 49191–49200.
[25] A. Rodriguez-Ramos, C. Sampedro, H. Bavle, I. G. Moreno and P. Campoy, A deep reinforcement learning technique for vision-based autonomous multirotor landing on a moving platform, *2018 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)* (IEEE, 2018), pp. 1010–1017.
[26] J. M. Daly, Y. Ma and S. L. Waslander, Coordinated landing of a quadrotor on a skid-steered ground vehicle in the presence of time delays, *Autonom. Robots* **38**(2) (2015) 179–191.
[27] S. Lange, N. Sunderhauf and P. Protzel, A vision based onboard approach for landing and position control of an autonomous multirotor UAV in gps-denied environments, *2009 Int. Conf. Advanced Robotics* (IEEE, 2009), pp. 1–6.
[28] M. Fu, K. Zhang, Y. Yi and C. Shi, Autonomous landing of a quadrotor on an UGV, *2016 IEEE Int. Conf. Mechatronics and Automation* (IEEE, 2016), pp. 988–993.
[29] J. Ghommam and M. Saad, Autonomous landing of a quadrotor on a moving platform, *IEEE Trans. Aerosp. Electron. Syst.* **53**(3) (2017) 1504–1519.
[30] A. Rucco, P. Sujit, A. P. Aguiar, J. B. De Sousa and F. L. Pereira, Optimal rendezvous trajectory for unmanned aerial-ground vehicles, *IEEE Trans. Aerosp. Electron. Syst.* **54**(2) (2017) 834–847.
[31] L. Xu and H. Luo, Towards autonomous tracking and landing on moving target, *2016 IEEE Int. Conf. Real-time Computing and Robotics (RCAR)* (IEEE, 2016) pp. 620–628.
[32] A. Borowczyk, D.-T. Nguyen, A. P.-V. Nguyen, D. Q. Nguyen, D. Saussié and J. Le Ny, Autonomous landing of a quadcopter on a high-speed ground vehicle, *J. Guid. Control, Dyn.* **40**(9) (2017) 2378–2385.
[33] T. Baca, P. Stepan, V. Spurny, D. Hert, R. Penicka, M. Saska, J. Thomas, G. Loianno and V. Kumar, Autonomous landing on a moving vehicle with an unmanned aerial vehicle, *J. Field Robot.* **36**(5) (2017) 874–891.
[34] Z. Zheng, Z. Jin, L. Sun and M. Zhu, Adaptive sliding mode relative motion control for autonomous carrier landing of fixed-wing unmanned aerial vehicles, *IEEE Access* **5** (2017) 5556–5565.
[35] Y. Byun, J. Song, W. Song and B. Kang, Conceptual study of a smart docking system for VTOL-UAV, *J. Aerosp. Eng.* **29**(2) (2015) p. 04015053.
[36] Y. Huang, M. Zhu, Z. Zheng and M. Feroskhan, Fixed-time autonomous shipboard landing control of a helicopter with external disturbances, *Aerosp. Sci. Technol.* **84** (2019) 18–30.
[37] Y. Huang, Z. Zheng, L. Sun and M. Zhu, Saturated adaptive sliding mode control for autonomous vessel landing of a quadrotor, *IET Control Theory Appl.* **12**(13) (2018) 1830–1842.
[38] K. Xia, S. Lee and H. Son, Adaptive control for multi-rotor UAVs autonomous ship landing with mission planning, *Aerosp. Sci. Technol.* **96** (2020) 105549.
[39] C. C. Murray and A. G. Chu, The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery, *Transport. Res. C, Emerg. Technol.* **54** (2015) 86–109.
[40] A. Ponza, Optimization of drone-assisted parcel delivery, Master's thesis, University of Padua (2016).
[41] S. M. Ferrandez, T. Harbison, T. Weber, R. Sturges and R. Rich, Optimization of a truck-drone in tandem delivery network using k-means and genetic algorithm, *J. Ind. Eng. Manage.* **9**(2) (2016) 374–388.
[42] X. Wang, S. Poikonen and B. Golden, The vehicle routing problem with drones: Several worst-case results, *Optimiz. Lett.* **11**(4) (2017) 679–697.
[43] J. F. Campbell, D. Sweeney and J. Zhang, Strategic design for delivery with trucks and drones, Supply Chain Analytics Report SCMA (2017).
[44] Q. M. Ha, Y. Deville, Q. D. Pham and M. H. Ha, Heuristic methods for the traveling salesman problem with drone, arXiv (2015).
[45] Q. M. Ha, Y. Deville, Q. D. Pham and M. H. Ha, On the min-cost traveling salesman problem with drone, *Transport. Res. C, Emerg. Technol.* **86** (2018) 597–621.
[46] K. Yu, A. K. Budhiraja, S. Buebel and P. Tokekar, Algorithms and experiments on routing of unmanned aerial vehicles with mobile recharging stations, *J. Field Robot.* **36**(3) (2019) 602–616.
[47] S. G. Manyam, D. W. Casbeer and K. Sundar, Path planning for cooperative routing of air-ground vehicles, *2016 American Control Conf. (ACC)* (IEEE, 2016), pp. 4630–4635.
[48] N. Agatz, P. Bouman and M. Schmidt, Optimization approaches for the traveling salesman problem with drone, *Transport. Sci.* **52**(4) (2018) 965–981.
[49] P. Bouman, N. Agatz and M. Schmidt, Dynamic programming approaches for the traveling salesman problem with drone, *Networks* **72**(4) (2018) 528–542.
[50] P. Kitjacharoenchai, M. Ventresca, M. Moshref-Javadi, S. Lee, J. M. Tanchoco and P. A. Brunese, Multiple traveling salesman problem with drones: Mathematical model and heuristic approach, *Comput. Ind. Eng.* **129** (2019) 14–30.
[51] K. Dorling, J. Heinrichs, G. G. Messier and S. Magierowski, Vehicle routing problems for drone delivery, *IEEE Trans. Syst. Man, Cybern., Syst.* **47**(1) (2016) 70–85.
[52] S. Poikonen, X. Wang and B. Golden, The vehicle routing problem with drones: Extended models and connections, *Networks* **70**(1) (2017) 34–43.
[53] M. W. Ulmer and B. W. Thomas, Same-day delivery with heterogeneous fleets of drones and vehicles, *Networks* **72**(4) (2018) 475–505.
[54] D. Wang, P. Hu, J. Du, P. Zhou, T. Deng and M. Hu, Routing and scheduling for hybrid truck-drone collaborative parcel delivery with independent and truck-carried drones, *IEEE Internet Things J.* **6**(6) (2019) 10483–10495.
[55] C. C. Murray and R. Raj, The multiple flying sidekicks traveling salesman problem: Parcel delivery with multiple drones, *Transport. Res. C, Emerg. Technol.* **110** (2020) 368–398.
[56] Z. Luo, Z. Liu and J. Shi, A two-echelon cooperated routing problem for a ground vehicle and its carried unmanned aerial vehicle, *Sensors* **17**(5) (2017) 1144.

October 1, 2020 8:46:31pm WSPC/284-US 2150008 ISSN: 2301-3850 2nd Reading

[57] Y. Liu, Z. Liu, J. Shi, G. Wu and W. Pedrycz, Two-echelon routing problem for parcel delivery by cooperated truck and drone, *IEEE Trans. Syst. Man, Cybern., Syst.* (2020) 1–16, Early access.

[58] V. O. Sivaneri and J. N. Gross, UGV-to-UAV cooperative ranging for robust navigation in gnss-challenged environments, *Aeros. Sci. Technol.* **71** (2017) 245–255.

[59] V. O. Sivaneri and J. N. Gross, Flight-testing of a cooperative UGV-to-UAV strategy for improved positioning in challenging GNSS environments, *Aerosp. Sci. Technol.* **82** (2018) 575–582.

[60] S. Jung and K. B. Ariyur, Compensating UAV GPS data accuracy through use of relative positioning and GPS data of UGV, *J. Mech. Sci. Technol.* **31**(9) (2017) 4471–4480.

[61] F. Ropero, P. Muñoz and M. D. R-Moreno, TERRA: A path planning algorithm for cooperative UGV–UAV exploration, *Eng. Appl. Artif. Intell.* **78** (2019) 260–272.

[62] Y. Liu, J. Shi, Z. Liu, J. Huang and T. Zhou, Two-layer routing for high-voltage powerline inspection by cooperated ground vehicle and drone, *Energies* **12**(7) (2019) 1385–1405.

[63] M. Zhu and Y. Wen, Design and analysis of collaborative unmanned surface-aerial vehicle cruise systems, *J. Adv. Transport.* **2019** (2019) 1–10.

[64] K. Peng, W. Liu, Q. Sun, X. Ma, M. Hu, D. Wang and J. Liu, Wide-area vehicle-drone cooperative sensing: Opportunities and approaches, *IEEE Access* **7** (2019) 1818–1828.

[65] M. Hu, W. Liu, K. Peng, X. Ma, W. Cheng, J. Liu and B. Li, Joint routing and scheduling for vehicle-assisted multidrone surveillance, *IEEE Internet Things J.* **6**(2) (2018) 1781–1790.

[66] M. Hu, W. Liu, J. Lu, R. Fu, K. Peng, X. Ma and J. Liu, On the joint design of routing and scheduling for vehicle-assisted multi-UAV inspection, *Future Gen. Comput. Syst.* **94** (2019) 214–223.

[67] T. Stentz, A. Kelly, H. Herman, P. Rander, O. Amidi and R. Mandelbaum, Integrated air/ground vehicle system for semi-autonomous off-road navigation, *Proc. AUVSI Unmanned Systems Symp. 2002* (Florida, United States, 2002), pp. 1–15.

[68] A. Stentz, A. Kelly, P. Rander, H. Herman, O. Amidi, R. Mandelbaum, G. Salgian and J. Pedersen, Real-time, multi-perspective perception for unmanned ground vehicles, *Proc. AUVSI Unmanned Systems Symp. 2003* (figshare, Baltimore, United States, 2003).

[69] N. Vandapel, R. R. Donamukkala and M. Hebert, Unmanned ground vehicle navigation using aerial ladar data, *Int. J. Robot. Res.* **25**(1) (2006) 31–51.

[70] N. Giakoumidis, J. U. Bak, J. V. Gómez, A. Llenga and N. Mavridis, Pilot-scale development of a UAV-UGV hybrid with air-based ugv path planning, *2012 10th Int. Conf. Frontiers of Information Technology* (IEEE, 2012), pp. 204–208.

[71] R. Käslin, P. Fankhauser, E. Stumm, Z. Taylor, E. Mueggler, J. Delmerico, D. Scaramuzza, R. Siegwart and M. Hutter, Collaborative localization of aerial and ground robots through elevation maps, *2016 IEEE Int. Symp. Safety, Security, and Rescue Robotics (SSRR)* (IEEE, 2016), pp. 284–290.

[72] S. Zhang, H. Wang, S. He, C. Zhang and J. Liu, An autonomous air-ground cooperative field surveillance system with quadrotor UAV and unmanned ATV robots, *2018 IEEE 8th Annual Int. Conf. CYBER Technology in Automation, Control, and Intelligent Systems (CYBER)* (IEEE, 2018), pp. 1527–1532.

[73] J. Peterson, H. Chaudhry, K. Abdelatty, J. Bird and K. Kochersberger, Online aerial terrain mapping for ground robot navigation, *Sensors* **18**(2) (2018) 630.

[74] J. H. Kim, J.-W. Kwon and J. Seo, Multi-UAV-based stereo vision system without gps for ground obstacle mapping to assist path planning of UGV, *Electron. Lett.* **50**(20) (2014) 1431–1432.

[75] E. Z. MacArthur, D. MacArthur and C. Crane, Use of cooperative unmanned air and ground vehicles for detection and disposal of simulated mines, *Proc. Intelligent Systems in Design and Manufacturing VI*, Vol. 5999, International Society for Optics and Photonics (Porto, Portugal, 2005), pp. 909–917.

[76] P. Deusdado, M. Guedes, A. Silva, F. Marques, E. Pinto, P. Rodrigues, A. Lourenço, R. Mendonça, P. Santana, J. Corisco *et al.*, Sediment sampling in estuarine mudflats with an aerial-ground robotic team, *Sensors* **16**(9) (2016) 1461.

[77] S. Jung, H. Cho, D. Kim, K. Kim, J.-I. Han and H. Myung, Development of algal bloom removal system using unmanned aerial vehicle and surface vehicle, *IEEE Access* **5** (2017) 22166–22176.

[78] N. Michael, J. Fink and V. Kumar, Controlling a team of ground robots via an aerial robot, *2007 IEEE/RSJ Int. Conf. Intelligent Robots and Systems* (IEEE, 2007), pp. 965–970.

[79] N. Michael, J. Fink and V. Kumar, Controlling ensembles of robots via a supervisory aerial robot, *Adv. Robot.* **22**(12) (2008) 1361–1377.

[80] L. Chaimowicz and V. Kumar, Aerial shepherds: Coordination among UAVs and swarms of robots, *Proc. Int. Symp. Distributed Autonomous Robotic Systems*, Citeseer (Toulouse, France, 2004), pp. 243–252.

[81] M. Aranda, G. López-Nicolás, C. Sagüés and Y. Mezouar, Formation control of mobile robots using multiple aerial cameras, *IEEE Trans. Robot.* **31** (2015) 1064–1071.

[82] M. Aranda, Y. Mezouar, G. López-Nicolás and C. Sagüés, Scale-free vision-based aerial control of a ground formation with hybrid topology, *IEEE Trans. Control Syst. Technol.* **27**(4) (2018) 1703–1711.

[83] R. Rao, V. Kumar and C. Taylor, Visual servoing of a UGV from a UAV using differential flatness, *Proc. 2003 IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, Vol. 1, (IEEE, 2003), pp. 743–748.

[84] N. Mathews, A. L. Christensen, A. Stranieri, A. Scheidler and M. Dorigo, Supervised morphogenesis: Exploiting morphological flexibility of self-assembling multirobot systems through cooperation with aerial robots, *Robot. Autonom. Syst.* **112** (2019) 154–167.

[85] O. S. Oubbati, A. Lakas, F. Zhou, M. Güneş and M. B. Yagoubi, A survey on position-based routing protocols for flying ad hoc networks (fanets), *Veh. Commun.* **10** (2017) 29–56.

[86] O. S. Oubbati, M. Atiquzzaman, P. Lorenz, H. Tareque and S. Hossain, Routing in flying ad hoc networks: Survey, constraints, and future challenge perspectives, *IEEE Access* **7** (2019) 81057–81105.

[87] O. S. Oubbati, A. Lakas, N. Lagraa and M. B. Yagoubi, Uvar: An intersection uav-assisted vanet routing protocol, *Proc. 2016 IEEE Wireless Communications and Networking Conf.* (IEEE, 2016), pp. 1–6.

[88] M. Mozaffari, W. Saad, M. Bennis and M. Debbah, Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs, *IEEE Trans. Wirel. Commun.* **15**(6) (2016) 3949–3963.

[89] L. Xiao, X. Lu, D. Xu, Y. Tang, L. Wang and W. Zhuang, UAV relay in vanets against smart jamming with reinforcement learning, *IEEE Trans. Veh. Technol.* **67**(5) (2018) 4087–4097.

[90] Y. Zhou, N. Cheng, N. Lu and X. S. Shen, Multi-UAV-aided networks: Aerial-ground cooperative vehicular networking architecture, *IEEE Veh. Technol. Mag.* **10**(4) (2015) 36–44.

[91] N. Cheng, W. Xu, W. Shi, Y. Zhou, N. Lu, H. Zhou and X. Shen, Air-ground integrated mobile edge networks: Architecture, challenges, and opportunities, *IEEE Commun. Mag.* **56** (2018) 26–32.

[92] W. Shi, H. Zhou, J. Li, W. Xu, N. Zhang and X. Shen, Drone assisted vehicular networks: Architecture, challenges and opportunities, *IEEE Netw.* **32**(3) (2018) 130–137.

[93] A. Merwaday and I. Guvenc, UAV assisted heterogeneous networks for public safety communications, *2015 IEEE Wireless Communications and Networking Conf. Workshops (WCNCW)* (IEEE, 2015), pp. 329–334.

[94] S. Zhang and J. Liu, Analysis and optimization of multiple unmanned aerial vehicle-assisted communications in post-disaster areas, *IEEE Trans. Veh. Technol.* **67**(12) (2018) 12049–12060.

[95] S. Jia and L. Zhang, Modelling unmanned aerial vehicles base station in ground-to-air cooperative networks, *IET Commun.* **11**(8) (2017) 1187–1194.

[96] Q. Zhu, Y. Wang, K. Jiang, X. Chen, W. Zhong and N. Ahmed, 3D non-stationary geometry-based multi-input multi-output channel model for UAV-ground communication systems, *IET Microw. Antennas Propag.* **13**(8) (2019) 1104–1112.

[97] D. H. Choi, B. H. Jung and D. K. Sung, Energy-aware path planning of an unmanned aerial vehicle acting as a communication relay for mobile ground nodes, *Proc. Inst. Mech. Eng. G, J. Aerosp. Eng.* **233**(3) (2019) 1124–1132.

[98] X. Zhou, S. Yan, J. Hu, J. Sun, J. Li and F. Shu, Joint optimization of a UAV's trajectory and transmit power for covert communications, *IEEE Trans. Signal Process.* **67**(16) (2019) 4276–4290.

[99] X. Zhou, Q. Wu, S. Yan, F. Shu and J. Li, UAV-enabled secure communications: Joint trajectory and transmit power optimization, *IEEE Trans. Veh. Technol.* **68**(4) (2019) 4069–4073.

[100] F. Shkurti, A. Xu, M. Meghjani, J. C. G. Higuera, Y. Girdhar, P. Giguere, B. B. Dey, J. Li, A. Kalmbach, C. Prahacs *et al.*, Multi-domain monitoring of marine environments using a heterogeneous robot team, *2012 IEEE/RSJ Int. Conf. Intelligent Robots and Systems* (IEEE, 2012), pp. 1747–1753.

[101] B. D. Reineman, L. Lenain and W. K. Melville, The use of ship-launched fixed-wing UAVs for measuring the marine atmospheric boundary layer and ocean surface processes, *J. Atmosph. Ocean. Technol.* **33**(9) (2016) 2029–2052.

[102] P. Maini, K. Yu, P. Sujit and P. Tokekar, Persistent monitoring with refueling on a terrain using a team of aerial and ground robots, *2018 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)* (IEEE, 2018), pp. 8493–8498.

[103] K. Nikolakopoulos, P. Lampropoulou, E. Fakiris, D. Sardelianos and G. Papatheodorou, Synergistic use of uav and usv data and petrographic analyses for the investigation of beachrock formations: A case study from syros island, aegean sea, greece, *Minerals* **8**(11) (2018) 534.

[104] J. Roldán, P. Garcia-Aunon, M. Garzón, J. de León, J. del Cerro and A. Barrientos, Heterogeneous multi-robot system for mapping environmental variables of greenhouses, *Sensors* **16**(7) (2016) 1018.

[105] G. Christie, A. Shoemaker, K. Kochersberger, P. Tokekar, L. McLean and A. Leonessa, Radiation search operations using scene understanding with autonomous UAV and UGV, *J. Field Robot.* **34**(8) (2017) 1450–1468.

[106] M. A. Hsieh, A. Cowley, J. F. Keller, L. Chaimowicz, B. Grocholsky, V. Kumar, C. J. Taylor, Y. Endo, R. C. Arkin, B. Jung *et al.*, Adaptive teams of autonomous aerial and ground robots for situational awareness, *J. Field Robot.* **24**(11–12) (2007) 991–1014.

[107] Y. Cai and S. Kousuke, Geometric relation matching based object identification for UAV and UGV cooperation, *2015 Conf. Technologies and Applications of Artificial Intelligence (TAAI)* (IEEE, 2015), pp. 478–483.

[108] Y. Cai and K. Sekiyama, Subgraph matching route navigation by UAV and ground robot cooperation, *2016 IEEE Congress Evolutionary Computation (CEC)* (IEEE, 2016), pp. 4881–4886.

[109] S. Liu, S. Wang, W. Shi, H. Liu, Z. Li and T. Mao, Vehicle tracking by detection in UAV aerial video, *Sci. China Inf. Sci.* **62**(2) (2019) p. 24101.

[110] H. G. Tanner, Switched UAV-UGV cooperation scheme for target detection, *Proc. 2007 IEEE Int. Conf. Robotics and Automation* (IEEE, 2007), pp. 3457–3462.

[111] H. Yu, K. Meier, M. Argyle and R. W. Beard, Cooperative path planning for target tracking in urban environments using unmanned air and ground vehicles, *IEEE/ASME Trans. Mechatron.* **20**(2) (2014) 541–552.

[112] R. Vidal, O. Shakernia, H. J. Kim, D. H. Shim and S. Sastry, Probabilistic pursuit-evasion games: Theory, implementation, and experimental evaluation, *IEEE Trans. Robot. Autom.* **18**(5) (2002) 662–669.

[113] H. Yu, R. W. Beard, M. Argyle and C. Chamberlain, Probabilistic path planning for cooperative target tracking using aerial and ground vehicles, *Proc. 2011 American Control Conf.* (IEEE, 2011), pp. 4673–4678.

[114] S. Minaeian, J. Liu and Y.-J. Son, Vision-based target detection and localization via a team of cooperative UAV and UGVs, *IEEE Trans. Syst. Man, Cybern., Syst.* **46**(7) (2015) 1005–1016.

[115] L. V. Santana, A. S. Brandão and M. Sarcinelli-Filho, Heterogeneous leader-follower formation based on kinematic models, *2016 Int. Conf. Unmanned Aircraft Systems (ICUAS)* (2016), pp. 342–346.

[116] M. F. S. Rabelo, A. S. Brandao and M. Sarcinelli-Filho, Centralized control for an heterogeneous line formation using virtual structure approach, *Proc. 2018 Latin American Robotic Symp.* (IEEE, 2018), pp. 135–140.

[117] R. Rahimi, F. Abdollahi and K. Naqshi, Time-varying formation control of a collaborative heterogeneous multi agent system, *Robot. Autonom. Syst.* **62**(12) (2014) 1799–1805.

[118] V. Ivancevic and Y. Yue, Hamiltonian dynamics and control of a joint autonomous land–air operation, *Nonlinear Dyn.* **84**(4) (2016) 1853–1865.

[119] A. A. Neto, L. A. Mozelli and F. O. Souza, Control of air-ground convoy subject to communication time delay, *Comput. Electric. Eng.* **76** (2019) 213–224.

[120] V. P. Tran, M. Garratt and I. R. Petersen, Switching time-invariant formation control of a collaborative multi-agent system using negative imaginary systems theory, *Control Eng. Pract.* **95** (2020) 104245.

[121] S. Xiong, Q. Wu and Y. Wang, Distributed coordination of heterogeneous multi-agent systems with dynamic quantization and l_2-l_∞ control, *Int. J. Control, Autom. Syst.* **18** (2020) 1–14.

[122] M. A. Kamel, K. A. Ghamry and Y. Zhang, Real-time fault-tolerant cooperative control of multiple UAVs-UGVs in the presence of actuator faults, *J. Intell. Robot. Syst.* **88**(2–4) (2017) 469–480.

[123] Z. Yan, N. Jouandeau and A. A. Cherif, A survey and analysis of multi-robot coordination, *Int. J. Adv. Robot. Syst.* **10**(12) (2013) 399.

[124] G. A. Korsah, A. Stentz and M. B. Dias, A comprehensive taxonomy for multi-robot task allocation, *Int. J. Robot. Res.* **32**(12) (2013) 1495–1512.

[125] R. Duan, J. Wang, C. Jiang, H. Yao, Y. Ren and Y. Qian, Resource allocation for multi-UAV aided iot noma uplink transmission systems, *IEEE Internet Things J.* **6** (2019) 7025–7037.

[126] L. E. Parker, Path planning and motion coordination in multiple mobile robot teams, *Encycl. Complexity Syst. Sci.*, Robert A. Meyers, ed. (Springer-Verlag New York, 2009), pp. 11–34.

[127] W. Xiao, J. Yu, R. Wang, X. Dong, Q. Li and Z. Ren, Time-varying formation control for time-delayed multi-agent systems with general linear dynamics and switching topologies, *Unmanned Syst.* **7** (01) (2019) 3–13.

[128] A. Mohiuddin, T. Taha, Y. H. Zweiri and D. Gan, A survey of single and multi-UAV aerial manipulation, *Unmanned Syst.* **8**(2) (2020) 119–147.

[129] Y. Zhang, Y. Wen, F. Li and Y. Chen, Distributed observer-based formation tracking control of multi-agent systems with multiple targets of unknown periodic inputs, *Unmanned Syst.* **7**(01) (2019) 15–23.

[130] Y. Rizk, M. Awad and E. W. Tunstel, Decision making in multiagent systems: A survey, *IEEE Trans. Cogn. Develop. Syst.* **10**(3) (2018) 514–529.

September 29, 2020 7:25:57pm WSPC/284-US 2150008 ISSN: 2301-3850 2nd Reading

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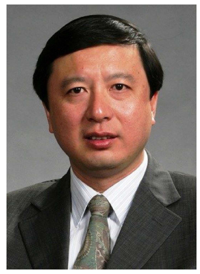

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