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REVIEW PAPER

A Review of Collaborative Air-Ground Robots Research

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Abstract

The collaboration of heterogeneous robots is a hot topic in multi-intelligent agents, characterized by wide-area coverage and high environmental adaptability. Compared with a single-intelligent agent, multi-intelligent agent collaboration presents superior data matching, system redundancy, and robustness. At the same time, the complementarity of heterogeneous multi-robot is formed a cross-domain, which inherently improves its perception capability, execution capability, and operational efficiency in the complex environment. Therefore, multi-intelligent agents' organic coordination and cross-domain collaboration will lead to a new paradigm of future robotics and applications. This paper reviews air-ground collaboration, the Unmanned Ground Vehicles (UGVs), and Unmanned Aerial Vehicles (UAVs) collaborative system as the research targets. Firstly, the essential elements of UGVs and UAVs are introduced. Secondly, the types of equipment, sensors, missions, environments, metrics under heterogeneous robotic platforms, and how to make device selections in which tasks and scenarios are classified. Thirdly, several vital roles in the air-ground collaborative systems are identified. Finally, a multi-level classification of air-ground collaboration in funded projects, competitions, unique scenarios, inspirations, platforms, and challenges is discussed.

Keywords Multi-domain cooperation · Multi-intelligence · Air-ground collaboration · Mission planning

1 Introduction

In recent years, the rapid development in artificial intelligence and mobile robotics has brought great benefits, covering from auto-driving and medical services robots to smartphones, all of which are closely related to the lives of human beings. In scientific research, robotic collaboration became the hot spot in multi-intelligence agents' investigations. In industrial environments, collaborative robots are used in logistics and manufacturing industries, such as mobile robots for orderly handling in logistics warehouses and robotic arms for assembling in cooperation. However, there are still significant challenges for robotic collaboration in the civilian domain. For example, they need to interact with humans and deploy in unknown environments [1–3].

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1.1 Why to Study Air-ground Collaboration

In daily life and scientific research, a single-intelligent agent (e.g., UAVs/UGVs) as a standard robotic system usually requires independent control systems, which use associated control methodologies and theories to achieve pre-defined metrics when operated by humans or autonomously. Meanwhile, an efficient control system can be tuned adaptively to reach the objectives in the case of various environmental conditions [4, 5]. Unfortunately, due to environmental and physical limitations, multiple operators are required to carry out complicated manual coordination with each other. In the face of complex scenarios and multiple tasks, the "independent and irrelevant" characteristics of both are challenging to achieve numerous functions. It is also tough to resume a normal state in case of system failure. UAVs and UGVs, as typical representations, can work together to achieve their goals and collaborate to leverage their respective capabilities and strengths. Therefore, leveraging the strengths of both and their complementary can provide a breakthrough.

In civilian applications, search and rescue (SAR) is a crucial scene in which the collaboration of heterogeneous robots could leverage shorter response times to save lives [6, 7]. In SAR operations, multi-robot collaboration can significantly improve efficiency and accelerate the search for victims. First, UAVs are used to determine the SAR area and perform preliminary detection, real-time mapping, monitoring, or establishing communication networks in emergencies. Then, UGVs are used for path planning and material delivery. Therefore, the air-ground collaboration can significantly benefit SAR, as shown in Fig. 1.

1.2 Strengths and Weaknesses of UAVs/UGVs

Unmanned Aerial Vehicles (UAVs), particularly multi-rotor UAVs, have become a hot spot in robotics. Its characteristics are as follows: (1) Physical Advantages: UAVs are relatively lower manufacturing costs, compact, and highly flexible. Their long air-frame life characteristics also enhance survivability. (2) Functional Advantages: The novel architecture, unique flight patterns, excellent diversity, and adaptability onboard, which can quickly move through obstacles, rough terrain, and steep hillsides, provide a view from high altitudes [8], and feed information to the control center in real-time, etc. (3) System Characteristics: UAVs have a tiny appearance based on their physical characteristics, and the onboard systems are usually embedded platforms. Accordingly, highly efficient and low-consumption control methodologies are always more suitable for this kind of device, such as filtering [9], state estimation [10], and other robust algorithms are essential. (4) Restrictions: UAVs' load and battery life are limited, resulting in difficulty performing missions requiring heavy equipment. The low strain capability cannot cope with unexpected occurrences, and the Wi-Fi communication between UAVs and controllers could be affected by high-rise buildings which may block them, or in cities with many Wi-Fi signals causing interference. A relevant solution is also presented in [11] for the communication limitation by adopting a natural Bayesian formula representing the problem and investigating the perturbation of search performance by different prior belief probability distribution functions.

Unmanned Ground Vehicles (UGVs) are another current research hot spot in the field of automation, which characteristics are as follows: (1) Physical Advantages: UGVs have a larger payload, which means they can carry large devices, powerful computers, and complex operational equipment [12] on long-distance missions. (2) Functional Advantages: These devices have great potential to improve traffic safety, efficiency, convenience in road traffic, and a large variety of autonomous driving [13] applications and extensions, such as perception [14], planning [15], etc., could be implemented. (3) System Characteristics: UGVs mainly depend on their ability to carry higher consumption equipment. Compared with UAVs, the former has a more mature and advanced control system, which is stable and highly efficient [16]. (4) Restrictions: As described in [17], UGVs are often limited by the onboard sensors and their architecture when driving in complex environments, including narrow sensing range, poor terrain travel ability, climbing capabilities, convex and concave obstacles. These factors tend to reduce the efficiency of UGVs in performing missions. Accordingly, which proposes an autonomous system based on LiDAR and camera in GNSS-denied scenarios and an obstacle detection fusion strategy. This combination removed false detection to some degree.

1.3 Strengths and Weaknesses of UAVs/UGVs Collaboration

UAVs/UGVs collaboration belongs to the category of cross-domain. It has significant heterogeneity. The present studies on heterogeneous robot systems cannot be applied directly. Unlike the homogeneous robots, the UAVs/UGVs collaborative system will require processing data from different platforms and coordinating their behavior effectively. Therefore, the research of air-ground collaborative systems is imperative and challenging, which characteristics are as follows:

1. UGVs could identify ground targets at short distances. However, with unknown environments, there is a considerable limitation in the perception ability of the vehicle sensors, which can only achieve local path planning [18–20]. On the other hand, the UAVs have a wider field of view, provide global information about the surrounding environment from a certain height, and lose much local knowledge. Through both collaborations, the global path planning of UGVs can be realized. As described in [21], utilizing air-ground collaboration in a subterranean environment allowed UAVs for path planning, and UGVs executed search and rescue missions rapidly.
2. In complex environments, UGVs carry sensors with limited perception range to detect negative height obstacles (potholes, lowlands) [22, 23], which could be affected their ability for path planning and trajectory prediction after making wrong decisions. In contrast, the UAVs can detect unique terrain such as negative obstacles with the advantage of height and hovering or pre-notifying the suspected area to the UGVs to detect with its sensing system [24].
3. When performing complex missions like dynamic target detection, pursuing escapees, and post-disaster rescue, the UGVs have limited access to environmental information due to obstacle occlusion. However, the UAVs can provide an area of interest for the UGVs with the help of onboard sensors so that the latter can perform the mission efficiently [25]. Also, in [26], UAVs displayed a widespread and efficient target detection ability at low altitude datasets, so the collaboration between both is

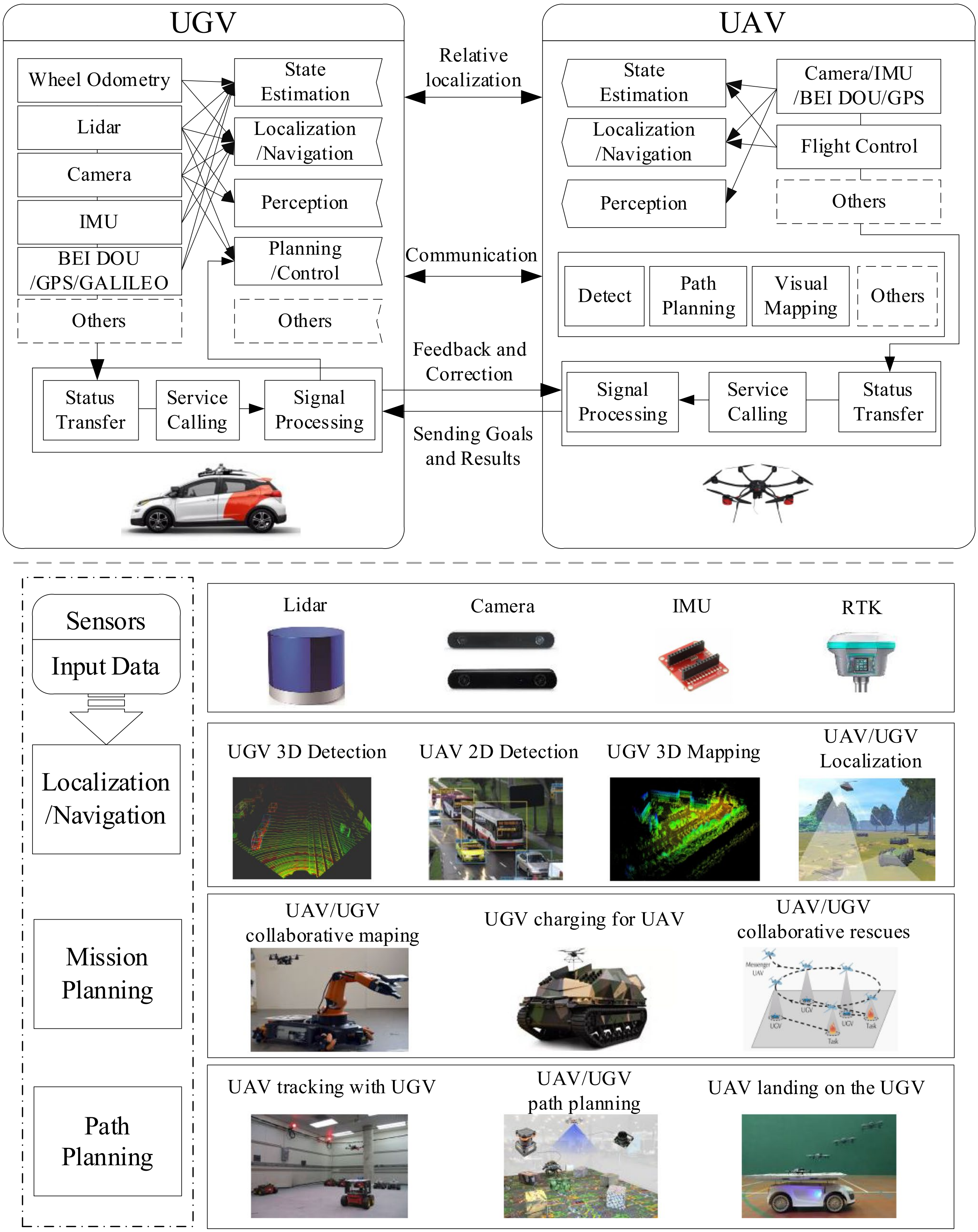


Fig. 1 Air-Ground collaboration flow diagram

more often used for patrols, exploration, and other missions.

4. UAVs/UGVs collaboration is a distributed system with three layers: mission management, communication, and control. The strength of the former over the centralized system is that each agent still has some edge computing power, which significantly alleviates the challenges with communication and information processing [27]. But usually, both are somewhat opposing requirements. When processing information on edge devices, it is required to send a large quantity of data over the network, which the result is affecting collaboration efficiency.
5. There are some limitations to air-ground collaboration as well. For example, an increase in the number of devices implies a piece of additional information. Inappropriate operations might also reduce the efficiency of cooperation. At the same time, the heavy load of data exchange and processing operations can decrease service life. Poor communication and flight deviation make collaboration challenging when performing long-duration and distance missions. For instance, [28] proposed using air-ground collaboration for emergency communication networks after natural disasters, which improved rescue efficiency by transmitting critical rescue information.

In summary, compared with a unique device, the advantages of air-ground collaboration are highlighted in large scenarios and multi-task composition. However, the same attention should be paid to the redundancy and complexity of air-ground collaboration. As described in [29], multi-robot collaboration is developed chiefly for planning and control systems, and high-dimensional tasks are also required with robust decision-making relationships.

1.4 Comparison with Other Surveys and Our Goals

Several survey papers have extensively discussed air-ground collaboration. For example, a related review was published by Chen et al. [30], which reviewed some fully implemented air-ground collaboration systems and proposed classification. Similarly, Duan et al. [31] analyzed some critical issues in air-ground collaborative systems, including heterogeneous docking, formation control and stability, network control, and practical applications. Waslander et al. [32] described in detail six challenging techniques for air-ground collaboration: relative tracking, collaborative landing, formation control, target detection and tracking, mission assignment, localization, and mapping. Çaska and Gayrette et al. [33] summarized various frameworks and methods based on the application of air-ground collaboration. Meanwhile, Cajoet et al. [34] discussed the control issues of UAV/UGV over the last decade. Although the paper contains a section that briefly discusses the roles performed by UAVs and UGVs, it does not overview this field comprehensively, primarily due to the explosion of role switching between agents, as the majority of them are modeled with UAVs as sensors "Flying Eye," and UGVs as actuators.

Therefore, in this work, we focused our description on: (I) A more comprehensive overview of UAVs/UGVs collaboration and discussed the architecture of air-ground collaboration, which involved the operational environment, communications, level of autonomy, and human–robot interaction. (II) Categorized the essential elements, tasks types, metrics criteria, and scenarios for air-ground collaboration. (III) Described several vital roles in the air-ground collaborative system and their relationship. (IV) Explored the development of heterogeneous robot collaboration from internationally funded projects and competitions.

Our overview of air-ground collaboration aims to keep researchers informed about the progress and dilemmas in this field. Then, whether more significant results can be identified for future research. Finally, this review is expected to serve as a user guide for new researchers.

The organization of this paper can be summarized as follows: Section II gives an overview of the four essential elements of UAVs/UGVs; Section III outlines the roles of UAVs/UGVs and identifies their categories based on the functions; Section IV summarizes the collaboration modes of UAVs/UGVs; Section V highlights the application of air-ground collaboration in SAR and provides further inspiration regarding funded projects and competitions. Section VI presents an overview of the insights and challenges for future cross-domain robot collaboration, as shown in Fig. 2.

2 The Basic Elements of UAVs/UGVs

The section will analyze the essential elements in the air-ground collaboration system, including the task type, sensors, metrics, and scenarios. In addition, the differences in structure, functions, and advantages are also necessary to achieve air-ground collaboration.

2.1 The Types of UAVs/UGVs

UGVs are usually available in two configurations: crawler-type and wheel-type. The crawler-type increases the contact area of the vehicle with the ground [35]. Siegwart et al. [36] described the wheel-type as respective advantages and disadvantages in terms of stability, maneuverability, and controllability, as shown in Fig. 3a, b. UAV types may also differ from missions, as shown in Fig. 3c, d, e, categorized as single-rotor, fixed wing, and multi-rotor.

Single-rotor: Which vertically takeoff, lands, hovers, and travels back and forth. Single-rotor is more stabilized than

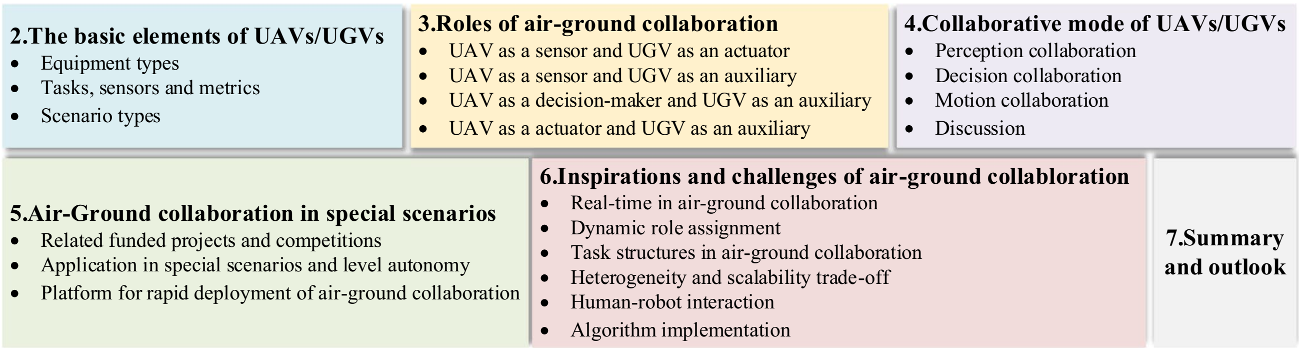


Fig. 2 The article structure diagram

Fig. 3 The types of UAVs and UGVs

Table 1 The comparison of various UAV/UGV

Types	Adaptability	Mobility	Loads	Perception range	Durability	Level of difficulty
Single-rotor	Enables landing in confined areas or on rough surfaces	Low speed, hovering, vertical takeoff	small	Precision Search	Short	Easy
Multi-rotor	Enables landing in confined areas or on rough surfaces	Fast, hovering vertical takeoff and landing	Medium	Precision Search	Long	Difficult
Fixed wing	Requires a large landing space	Fast, hovering, not support vertical takeoff	Large	Large coverage	Long	Medium
Crawler-type	Ability to travel over multiple terrains	Low speed, flexible rotation and climb	Large	Narrow views	Short	Difficult
Wheel-type	Easy to slide and sink into soil or wetlands	Fast, high operability	Large	Narrow views	Long	Easy

multi-rotor [37]. However, a single-rotor has higher price and relatively complex mechanical structure; Fixed wing: Which has lower energy requirements and longer endurance than a multi-rotor. However, they cannot hover, which limits the deployment of UAVs for some special missions; Multi-rotor: This category has at least one or more rotors that can achieve hovering and flight by adjusting the speed, which is more widely used in civilian applications [38, 39], as shown in Table 1.

Table 1 lists part of the characteristics of UAVs and UGVs. It can be seen that both have their limitations that reduce efficiency [40]. On the other hand, the significant heterogeneity and complementarity of dynamics, speed, sensor configurations, and communication capabilities allow many tasks.

2.2 The Task Types, Sensors and Metrics of UAVs/UGVs

Task Type Air-ground collaborative systems generally involve different tasks. At the same time, the tasks' complexity maybe determined by the operating environments, the objects, the periods, the characteristic of the missions, and the costs, which may directly affect the devices' numbers, types, and accuracy. For example, a single UGV can perform small-scale mapping, detection, and navigation. Similarly, multiple UGVs with the same objectives as a single UGV aim to perform missions efficiently and precisely. The difference is that the former requires more consideration of the environment, communication, main quests decoupling, multi-intelligence collaboration strategy, and resource allocation of software/hardware. At the same time, multiple UGVs could be classified into decentralized and centralized collaboration. The decentralized system emphasizes task distribution mechanisms and collaboration between UGVs [41]. The centralized system describes more about the interaction between UGVs and command center, which has the advantage of unified management and centralized issuance of commands. On the contrary, the disadvantage is the more significant network transmission between UGVs and command center.

Sensors UAVs are called flying sensors based on their stability, accuracy, and low power consumption. They typically include flight controls (IMU/CPS), ultrasonic sensors, GPS, cameras, and environment-specific sensors: humidity sensors, MEMS microphones, and network processors. It also includes a sensor redundancy mode for enhanced fault tolerance. Because of their flexibility and lightness, UAVs are unsuitable for carrying large equipment. UAVs are ideal for visual localization, detection, etc. UGVs, owing to their large size and high payload, incorporate most of UAVs' sensors and carry heavy devices depending on the type of tasks, compared with the former, which have higher safety performance. On the contrary, they are less flexible and difficult to deploy rapidly. Therefore, which are more suitable for LiDAR localization, path planning, and long-distance transportation.

Metrics Metrics are essential to evaluate performance, feasibility, efficiency, quality, and robustness. Nevertheless, some evaluation metrics for air-ground collaborative systems are domain-specific; for exploration, mapping, localization, and navigation, the error in localization accuracy is one of the metrics [42]. In addition to some domain-specific criteria, there are several standard metrics for air-ground collaboration: optimality of solutions, scalability, robustness, resource utilization, time consumption, generalization, and load balance.

2.3 Types of Scenarios for UAVs and UGVs

The environment provides a "shell" for UGVs/UAVs to perceive and interact. The environment faced by UGVs and UAVs differs significantly, with UGVs facing a complex and diverse ground environment, such as steep slopes and ditches, which may limit the actions of UGVs and force them to change running trajectory.

In addition, there are also defined standard ranges for structured and unstructured roads nowadays. Structured roads have a known, constant geometry (lane width, pavement markings, and the radius of curvature). Unstructured roads may have variable geometry, be prone to interruptions, and are hardly distinguishable from the surrounding scene (e.g., paved or unpaved roads). Dynamic objects in the environment (humans, animals, high-speed vehicles) may suddenly change in arbitrary situations, bringing challenges to the UGVs [43]. Likewise, complex environments (e.g., occlusions, cluttered backgrounds, changes in lighting) can also render detection troublesome.

There are also some limitations for UAVs.[1] Most of them we described belonging to low-altitude UAVs (low-altitude refers to flight in an area below 1000 m. Civil aviation flight altitude is generally above 6000 m, while airspace below 3000 m is also divided into controlled airspace, surveillance airspace, and reporting airspace). The flight of UAVs is not arbitrary, and the airframe, weight, load, and system framework[2] must comply with the standard. At the same time, the relevant no-fly zones[3] and control measures are also stipulated. However, the main advantages of UAVs in the air compared to UGVs on the ground are:

1. The airspace has a broader range and is clear of apparent obstacles, which is suitable for maneuverable UAVs to perform missions;
2. Compared to complex ground traffic, the environment of UAVs is relatively fixed and "clean." At the same time, under the premise of ensuring low altitude and reliable performance, the safety factor of UAVs will be higher than UGVs through automatic planning of flight paths.

However, the airspace also has sophisticated conditions (e.g., foliage, haze, birds, and variable weather) that could increase the difficulty of UAV exploration [44].

3 Roles of the Agents in the Air-ground Collaborative System

The characteristics of UAVs and UGVs make both strongly complementary, and the combination of different roles makes them more prospering. When capturing ground features (e.g., moving pedestrians, obstacles), UGVs as actuators are usually limited by speed, environmental occlusion, and traffic, while UAVs as sensors can be rapidly deployed.

[1] https://www.easa.europa.eu/en/the-agency/faqs/drones-uas

[2] http://www.caac.gov.cn/XXGK/XXGK/GFXWJ/201610/P020161008345668760913.pdf

[3] https://www.faa.gov/uas/getting_started/where_can_i_fly

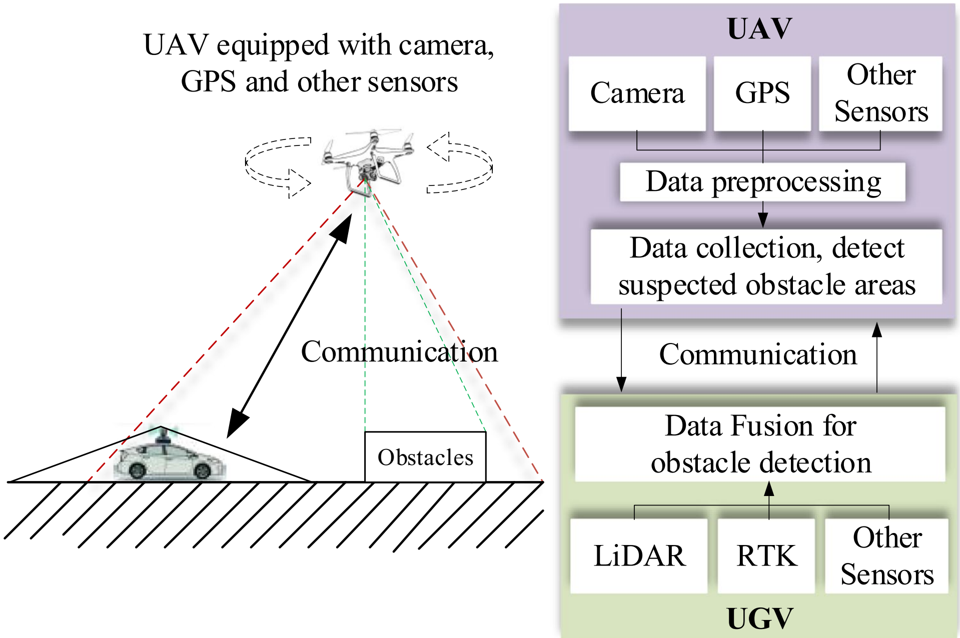


Fig. 4 UAV used the field of view and high altitude to inform UGV of obstacle and localization information

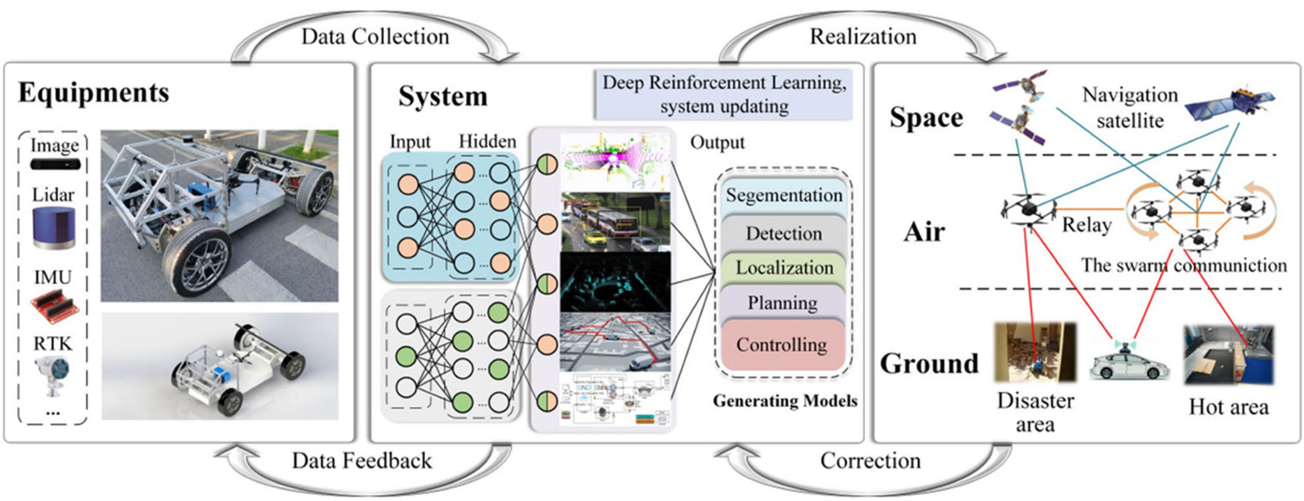


Fig. 5 Relevant technologies and research in air-ground collaborative system

Secondly, because the UAVs have the advantage of multiple degrees of freedom (DoF) at high altitudes, their communication capabilities (e.g., BeiDou/GPS, low latency, or data transmission) are more challenging to interrupt by obstacles than UGVs. Therefore, UAVs located at different positions can be used as a communication bridge to indirectly link both [45, 46] and determine the status of UGVs in the natural environment. At the same time, compared to UGVs, UAVs in the air also have some limitations while enjoying their advantages, which often bring some sensors under certain loads and need to fly back after collecting data or charging. On the contrary, the UGV as a carrier has a more significant load, as shown in Fig. 4.

3.1 UAV as a Sensor and UGV as an Actuator

In this collaborative air-ground system, the UAV can act as a sensor to collect, transmit, detect, and track. At the same time, the UGV plans the path based on the information shared by the UAV and provides feedback on the real-time status of the roadway for further corrections. Usually, UAVs have high mobility and a wide field of view to obtain information quickly. Finally, the data transmitted to the UGV can significantly accelerate the efficiency of the task [47, 48]. As shown in Fig. 5, the task types, the number of devices and sensors, the data flow, and the closed-loop patterns are usually determined before performing missions.

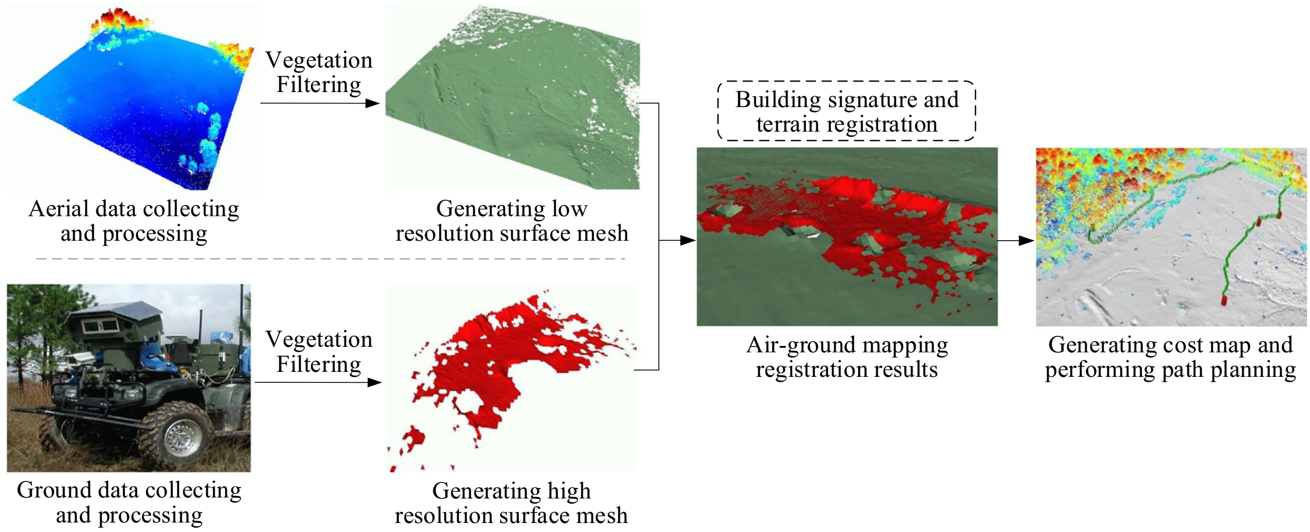


Fig. 6 UAV/UGV collaborative mapping, registration and path planning [48]

Table 2 The properties of UAV as a sensor and UGV as an actuator

Years	Citation	Scenarios	Types
2017	[42]	Outdoor	Six-rotor UAV (GPS/INS/Camera) and UGV (LiDAR/Camera/GPS/INS)
2016	[49]	Indoor	Quad-rotor UAV (Camera) and walking robot (Camera/Laser range sensor)
2018	[50]	Outdoor	Quad-rotor UAV (Camera) and UGV (LiDAR/Camera/Landing Carpet)
2018	[51]	Outdoor	Six-rotor UAV (RTK/Camera), UGV (RTK/Camera) and Ground station
2014	[52]	Indoor	Multi Quad-rotor UAVs (Camera) and UGV (Camera/Laser/QR code)

With the advance in autonomous exploration, the UAVs collect ground information and use image processing technologies while constructing a map so that the UGV can avoid obstacles. Kaslin et al. [49] proposed an elevation map-based localization for UGV, which allows the UGV to find its reference provided by the UAV without relying on sensors such as GPS. Zhang et al. [50] developed an autonomous air-ground collaborative system in which the UAV provides UGV with a set of bird's-eye views for obstacle avoidance and path planning. Finally, the UAV will land on the UGV. Peterson et al. [51] proposed a collaborative system that uses the overhead view of the UAV to determine the path of the UGV and correct it in real-time. Lanza et al. [42] used the UAV to generate a 2D map and created a 3D map of the target area using photogrammetry, which assisted the UGV in planning, as shown in Fig. 6. On the other hand, Kim et al. [52] used both UAVs to offer stereo vision and parallax to generate a depth map for UGV decision-making.

In summary, it can be seen that UAVs are not highly automated and compensate for the field of view limitations of UGVs. The properties of this category are summarized in Table 2.

The characteristics are as follows: 1) Tiny scenes and short or mid-cycle missions; 2) UAVs with small computing power, battery capacity, and load; 3) UGVs with path planning capability or capable of carrying a camera or LiDAR; 4) No high degree of automation, can also be remotely controlled.

3.2 UAV as a Sensor and UGV as an Auxiliary

UAVs can hover or fly at any altitude. Highly maneuverable UAVs (e.g., quadrotor UAVs) can provide more precise detection. However, the limited flight time of small UAVs implies that it is difficult to accomplish tasks in large-scale environments. UGV, as a medium mobile device, will compensate for the disadvantage of UAVs in terms of flight time, allowing to collect of data in large scenarios and only return to the UGV platform for charging in case of power warning.

The U.S. Army's Combat Capabilities Development Command's Army Research Laboratory pointed out that air-ground collaboration can enable SAR missions in remote and dangerous environments but requires localization and communications. In SAR missions, where the onboard GPS of a UAV is low accuracy and susceptible, an essential capability to perform missions without soldier intervention was to land on a stationary or moving UGV for recharging or overhauling autonomously. A

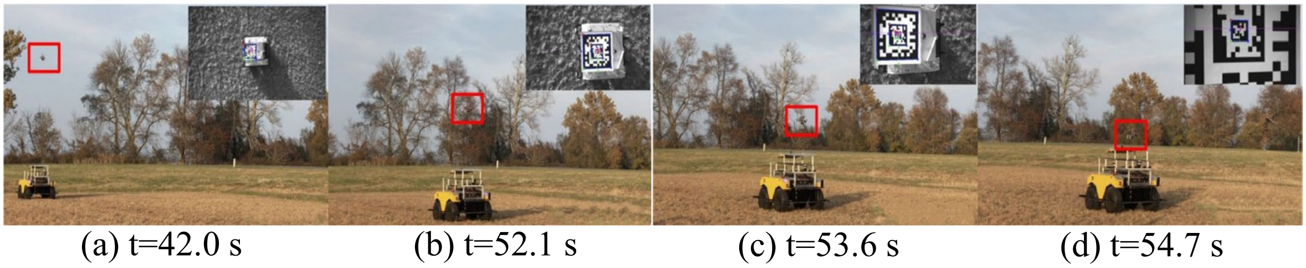


Fig. 7 UAV landing on UGV by using visual localization (https://www.thedefensepost.com/2021/04/07/us-army-self-reliant-drones/)

Table 3 The properties of UAV as a sensor and UGV as an auxiliary

Years	Citation	Scenarios	Types
2016	[40]	Agriculture	A single UAV and UGV (Theoretical analysis and simulation)
2018	[53]	Simulation	UAV and UGV (Simulation for path planning)
2019/2019/2018	[54–56]	Outdoor	Multi-UAVs and a single UGV
2018	[57]	Outdoor	Multi-UAVs and multi-UGVs

unique marker is placed on the roof of a UGV, which is composed of a significant marker nested within a small marker, mainly used to assist the UAV in landing steadily on the UGV, as shown in Fig. 7.

Similarly, air-ground collaborative systems in civil applications are commonly deployed in critical infrastructure inspections such as precision agriculture irrigation and power inspections. Tokekar et al. [40] proposed an air-ground data acquisition system for precision agriculture in UAVs to monitor and move UGV for charging due to limited energy. Ropero et al. [53] introduced a hybrid air-ground system to inspect a group of targets distributed in the exploration area. The above research only considered that UGV was supporting a single UAV, which cannot work simultaneously for different targets in several regions. References [54–56] used multi-UAVs to multi-targets, significantly improving efficiency and enlarging the service range. Hu et al. [57] proposed using a single UGV to multi-UAVs to perform sensing missions in designated areas.

Among them, the [40, 53] mainly address the collaboration between a single UAV and UGV, which focuses on the task. Whereas [54–57] are concerned more about the communication between multiple agents, and they focus on cooperation. The properties of this category are summarized in Table 3.

The characteristics are as follows: 1) This type is more suitable for large outdoor scenarios, such as cluster control and formation; 2) Relatively challenging to deploy, requiring network communications with low latency; 3) High redundancy, robustness, and efficiency.

3.3 UAV as a Decision Maker and UGV as an Actuator

In this collaborative air-ground system, the UAV provides environmental information and planning, acting as the "Flying Eye" and decision-maker, providing a priori information to the UGV.

Michael et al. [58, 59] proposed an abstract UAV teams' model that allows controlling UGV teams without knowing their number. They only know a general model of the position and orientation. Chaimowicz and Kumar et al. [60] proposed the deployment of multiple UGVs in the urban, where a group of UAVs can be used to assist in UGVs scheduling. Aranda et al. [61] proposed a vision-based control approach that uses UAVs equipped with multiple cameras as control units to drive a group of ground mobile robots to the desired formation, considered an active-control and passive-execution distributed solution. Another vision-based control approach is proposed in [62], which requires only simple path planning and does not require a sophisticated coordination strategy for UAVs, as shown in Fig. 8.

Compared to the first two parts, UAVs have more sophisticated functionality and a higher level of automation, allowing testing in larger environments. UGVs only act as devices that receive information and are implemented. The properties of this category are summarized in Table 4.

The characteristics are as follows: 1) UAVs as active command publishers and UGVs as passive command receivers; 2) The former requires more enormous computing resources to handle the information, while the latter requires faster

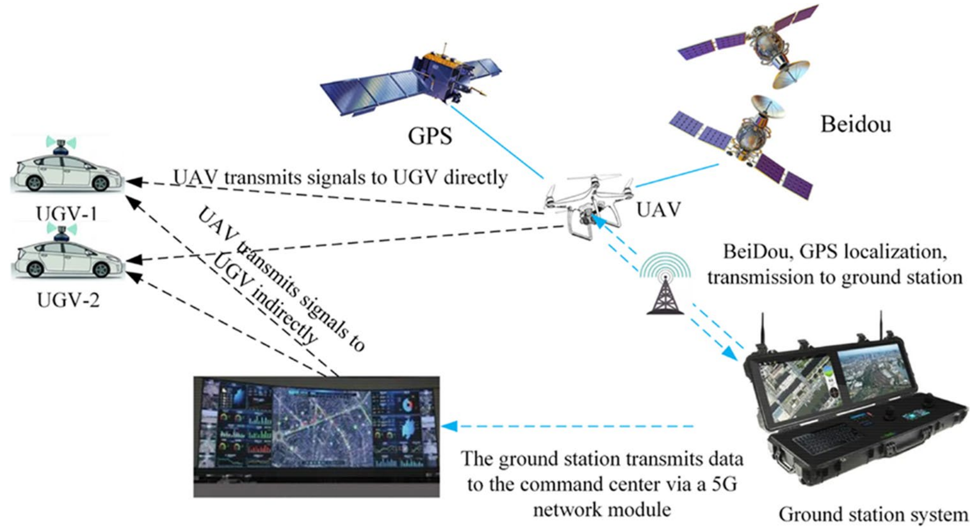


Fig. 8 UAV act as sensors and decision makers and send signals to UGVs

Table 4 The properties of UAV as a sensor and UGV as an auxiliary

Years	Citation	Scenarios	Types
2007/2008	[58, 59]	Indoor	A single UAV and multi-UGVs
2004	[60]	Outdoor	Multi-UAVs (A single blimp or UGVs) and multi-UGVs
2015	[61]	Outdoor	Multi-UAVs and multi-UGVs (Multi-UAVs control UGVs formation)
2018	[62]	Simulation	Multi-UAVs and multi-UGVs (Including overlapping sections)

responsiveness; 3) Simpler to deploy than Sec. 3.3, but requires a reasonable control strategy.

3.4 UAV as Actuator and UGV as an Auxiliary

The significance of this type is that UGVs as auxiliary can assist UAVs. In other words, the former can be used as mobile carriers to transport the latter to the vicinity of reconnaissance targets and maintenance. On the other hand, UGVs can also be used as reference stations for the Global Navigation Satellite System (GNSS) to mitigate the uncertainty in UAVs' navigation.

UAVs Landing on UGVs UAVs can fly overcrowded roads and provide rapid and economical delivery services or SAR missions [63]. Due to the limited battery capacity, the hovering time is relatively short, restricting the further movement of UAVs. In this case, UGVs can be used to assist UAVs. The vertical takeoff and landing capabilities of multi-rotor are well suited for docking with UGV, as the takeoff, landing, and boost spaces for them are typically small, so many studies have focused on the precision landing of UAVs. This ability which enables autonomous docking of UAVs to mobile charging stations, is critical in missions that require repeated flights. Table 5 lists some literature and methods for landing.

Table 5 Methods related to the landing of UAVs on UGVs

Scenarios	Types of UAV	Citation	Methods
Outdoor	Single-rotor	[64]	Timing control
	Fixed wing	[65]	Slip-form control
	Multi-rotor	[66–69]	Vision-based control / Nonlinear optimization / Vision-based UAV landing/ Adaptive control
Indoor	Multi-rotor	[70, 71]	Deep Reinforcement Learning / Distributed Collaboration

UGVs Aids UAVs in Material Transportation Amazon's Prime Air has provided express delivery in some areas for civilian applications. In recent years, Walmart has also committed to creating super storage centers and UAVs/UGVs collaborative logistics delivery, of which automatic UAV and automatic delivery robots speed up delivery efficiency. According to the weight of the products, the UAV with suitable load-bearing capacity will be picked for distribution, and the automatic delivery robot will be set off together as a supply station. At the same time, the UAV will also automatically take off into the predetermined transportation to

(a) HorseFly' s drone and truck combo (b) DHL' s Packetkopter (c) Google X' s Project Wing (d) Amazon' s Prime Air

Fig. 9 UAV/UGV (**a**) collaborative logistics transportation and UAV (**b**, **c**, **d**) parcel delivery [72]

carry out logistics distribution for users in the area. UAV package delivery must be followed the relevant laws.[4,5,6] The logistics UAV needs to comply with: 1) Small and light; 2) Nominal track; 3) Route protection area; 4) Takeoff, landing, waiting point, etc., and it also requires supervised delivery of package. At the same time, companies worldwide have been gradually entering the UAV logistics industry, including German courier companies and DHL's Packetkopter, Google, and its X-Labs' "Project Wing," FedEx, Amazon, and others, as shown in Fig. 9.

Many studies on UAVs-assisted parcel delivery have also been mentioned in the literature [72–75]. UGV carried UAVs, and parcels traveled near the targets. UAV took off from the UGV, carried individual packages, and returned to the UGV after finishing the delivery, while the UGV had moved to the new target. In this case, the effective flight distance can be enhanced by transporting the UAV from the target to achieve more distribution tasks.

4 Collaboration Mode of UAVs/UGVs

In cross-domain robot collaboration, UGVs and UAVs have significantly differenced in observation patterns, accuracy, angles, and mechanical structures. Therefore, effective collaboration can improve the efficiency of tasks, while designing corresponding collaboration modes for different scenarios helps expand other studies, so we classify the modes as perception, decision, and motion collaboration [76].

[4] https://www.faa.gov/uas/advancedoperations/nepaanddrones/amazon-prime-air-drone-package-delivery-operations-lockeford

[5] https://www.faa.gov/uas/advanced_operations/package_delivery_drone

[6] http://www.caac.gov.cn/XXGK/XXGK/BZGF/HYBZ/202208/P020220811600885528858.pdf

4.1 Perception Collaboration

Perception collaboration allowed them to exchange information to simulate the environment accurately. At the same time, (Sensors-information-fusion) can be classified as complementary-type or collaborative-type between information streams [77, 78]. Multiple sources provide information about the same characteristics [79, 80]. While the latter uses data from numerous independent sensors to compensate for the limitations of a single sensor [81–83]. Part of the SLAM (Simultaneous Localization and Mapping) methods can be used in collaborative systems to generate a map of the environment and localize itself, which uses the collaboration of heterogeneous robots to deal with sophisticated environments. At the same time, researchers have also proposed distributed SLAM with sparse robot networks and hierarchical active SLAM [84, 85], which enable robots to construct maps and perform localization rapidly.

4.2 Mission Collaboration

Planning and decision are critical components of the air-ground collaboration system, which are responsible for the decision, including mission and path planning [86]. So far, most studies on planning and decision have focused on path planning. Meanwhile, task distribution is considered an optimal problem, and the literature proposes a comprehensive taxonomy of task distribution for heterogeneous robotics systems [87]. Air-ground systems may face constraints not encountered by other heterogeneous robotic systems, including space, time, sensor type, and communication. As a result, heuristic algorithms [73, 88], policy function approximation based on geographic region division [89], K-means [90], and hybrid genetic algorithms [91] have also been developed.

4.3 Motion Collaboration

The goal of motion collaboration is to allow air-ground systems to perform motion planning [92] based on the

Table 6 Application of centralized and distributed systems in real scenarios

Strategies	Scenarios	Citation	Methods
Centralized	Outdoor	[96]	A collaborative approach was applied to construct a visual map in a known environment. Ultimate goal: navigation and avoidance
	Outdoor	[97]	A monocular SLAM-based multi-UAVs system was developed using multi-robot data interaction
	Indoor	[98]	Collaborative air-ground mapping system with the advantage of maintaining consistency of visual maps in large scale scenes
	Outdoor	[99]	Robots collaborate within the same map, using IMU to augment the robustness of the air-ground collaborative system
	Outdoor	[100]	Collaborative multi-robot stereo vision localization using the Extended Kalman Filter (EKF) framework. Advantage: Real-time performance in large scale scenes
	Outdoor	[101]	Centralized collaborative monocular SLAM. the main contribution was to analyze the communication and bandwidth burden of centralized and given the corresponding optimization methods
Distributed	Outdoor	[102]	How to better deliver data in unknown environments with multi-robot collaboration. Contribution: Distributed back-end factor graph optimization-based method
	Indoor	[103]	Apply the Distributed architecture to optimize the communication latency between multi devices
	Outdoor	[104]	Robustness verification of distributed collaborative SLAM
	Outdoor	[105]	Developed a distributed system that used the EKF framework for correlation between multiple robots to improve real-time and robustness

constraints of the overall, such as formation [93], maneuvering [94], and target search/tracking [95]. In these problems, the motions of individual robots are no longer independent. On the contrary, the collaborative system must adopt synchronized actions for the whole system based on prespecified motion constraints.

Generally, two strategies can be used for motion collaboration in UAVs/UGVs: centralized and distributed. In the former, all computations and controls are performed in a central CPU, while more necessary functions are run on the agent. Therefore, this strategy leads to a high burden on the main CPU. However, distribution does not require a central CPU, and all measurements are performed by each other, with less coupling, communication, and collaboration. Although both strategies are feasible, the latter is more widely used in reality due to many physical constraints, such as lower communication bandwidth and limited computational/memory resources. Some of the centralized and distributed applications are listed in Table 6.

4.4 Collaboration Mode and Roles Distribution: Discussion

With numerous roles in UAVs/UGVs and collaboration models, choosing wisely could accomplish missions efficiently. Generally, the decision is based on the devices and the tasks to be performed.

Based on the missions If the experimental scenario is more extensive, the devices of multi-UAVs/multi-UGVs are preferred regardless of the number of devices and communication limitations. It should be noticed that multiple agents will bring about an amount of redundant information and area overlap, so the distribution strategy should be preferred—for example, the mapping in significant scenarios. Typically, we choose vehicle-mounted LiDAR to construct a map in large-scale environments. At that moment, the information provided by multi-UAVs is the marker of passable area, the numbers of whether that mapping in overlapping area many times. Therefore, the multi-agents are required to have the ability of edge computing, which can appropriately reduce the resource consumption of the central CPU.

Based on the Running Time The operating time of the devices is also significant. Without considering UGV, single-rotor and fixed wing could perform the missions in this scenario rather than multi-rotor. However, the latter's disadvantage is that hovering operation is impossible (Inspection and small target searching). Large scenarios can also be divided into areas so that the advantages of multi-rotor and single-rotor can be exploited, considering edge information processing.

Based on the Scenarios Large scenarios have been discussed, and for small scenarios (Indoor), a single UAV/UGV can be considered. In the meantime, a centralized strategy should be preferred. For example, utilizing the visual information of UAVs for target tracking and potential obstacle detection, then passing to UGV. Planning/controlling single-UAV/multi-UAVs (formation/clustering) can also be performed. These applications can also choose a centralized strategy, which is more real-time.

Others Based on the computing power of the devices; Based on the number and types of sensors.

5 Air-Ground Collaboration in Special Scenarios

The first half of the paper focuses on the essential elements, task types, collaboration modes, and roles of air-ground collaboration. Most of the experimental scenarios are designed manually. However, another significant advantage of air-ground collaboration is its implementation in unique scenarios, which refers to post-disaster, wilderness, rural, and forest areas—enabling searches for victims, real-time monitoring, or establishing emergency communication networks. Compared with others, UAVs and UGVs are often deployed in dangerous conditions or areas with limited communication. Therefore, this part will overview relevant funded projects, competitions, and SAR examples.

5.1 Funded Projects and Competitions Related to Air-Ground Collaboration

Over the past two decades, multiple funded projects have been focused on UAV/UGV air-ground collaboration, often developing multi-robotic solutions and multi-modality fusion algorithms. This section reviews some relevant funded projects and competitions in multi-robotic technology, as shown in Appendices Tables 10 and 11. Also, some funded projects focus on developing sophisticated multi-robot systems that can be operated remotely [106].

COMETS (Real-Time Collaboration and Control of Multi-Machine Heterogeneous UAVs) was first proposed, designed, and developed for multi-machine collaboration as an early project [107]. For this purpose, the researchers created a small airship and an autonomous helicopter, which realized the cooperative perception [108]. Recently, in NIFTi (Human–Robot Interaction in Dynamic Environments) [109], a project on autonomous multi-robot systems was designed explicitly for SAR operations. Then autonomous navigation in harsh environments using UGVs and UAVs focused on human–robot interaction and data distribution for human operators at multiple levels. In ICARUS (Unmanned Search and Rescue), researchers developed a large-scale UGV, a set of rapidly deployed UAVs with mapping tools, including a multi-area robotic command and control center for communication [110, 111], which focused on algorithms and the design of multi-robot systems. Similarly, TRADR (Long-Term Human–Robot Collaborative Disaster Rescue) focuses on collaborative human–robot interaction and multi-robot path planning in response to disaster rescue. Meanwhile, the results of TRADR include a group of frameworks for integrating UAV collaborative approaches in SAR missions [112–115]. Furthermore, Smokebot (a mobile robot with novel sensors) emphasizes developing multi-sensors fusion methods for harsh environments [116–118].

Many researchers have developed related topics in UAV/UGV air-ground collaborative systems in recent years. Dong et al. [119] studied vision-based air-ground robot collaboration, in which the avoidance method is that the flight attitude will be adjusted after the UAV detects the obstacle. UGV receives the information and performs path planning, achieving static obstacle detection and avoidance. Zhuang et al. [120] researched collaborative air-ground environment perception in indoor scenes. They proposed a method in which a UGV carries a 3D range laser to model the environment, and then a UAV uses a vision sensor to estimate the relative location of the UGV. Feng Gu et al. [121] explored a color space-based dynamic target recognition and tracking method for collaborative air-ground robots. Li et al. [122] exploited the vision of UAVs to obtain ground maps to reinforce the recognition of environmental information by UGVs and proposed a hybrid path optimization method combined with local optimization. Zhao et al. [123–125] performed the works of recognition, tracking, and path planning of ground targets and using a vision of UAVs under air-ground collaboration, including established accessible maps, global path planning, and motion control of UGVs. Wang et al. [126] proposed a collaborative mapping based on UAV visual SLAM, which utilized the wide-range perception capability brought by the UAV to assist UGVs. At the same time, the UGVs planned the global path to the target, ensuring that UGVs could achieve autonomous movement in unknown environments without any human participation. Liu et al. [127] proposed a method for collaborative UAV/UGV mapping with orthogonal viewpoints, which is favorable for UGV to construct higher-resolution maps, summarized in Table 7.

In terms of competitions, a pioneer of cross-domain robotic collaboration in performing SAR operations is the European Robotics Federation Championship. The [128] describe the details of the first multi-domain (air, land, and sea) multi-robot competition, in which sixteen teams participated, with tasks such as environmental surveillance and mapping (merging data of ground and air); Searching for missing workers in an abandoned building; Pipeline inspection. There are similar multi-robot collaborative competitions in China. In the China Robotics Competition (RoboCom Robotics Developer Competition), teams, including many well-known universities, set up several competitions in line with the hot spots and difficulties of robotics development, such as aerial and rescue robots. Appendix Table 11 lists some of the competitions in this field, with the same organization as Appendix Table 10.

Table 7 Exploration of air-ground collaboration

Years	Citation	Methods
2013	[119]	Obstacle avoidance and path planning with vision sensors from UAV/UGV
2016	[120]	UAV assisted UGV to construct a map in indoor
2012	[121]	Target recognition and tracking with air-ground collaboration
2016	[122]	Enhancing UGV localization accuracy in local environments with UAV
2019/2018/2018	[123–125]	UAV/UGV collaboration for tracking, path planning and mapping, etc
2020	[126]	After UAV performs mapping, UGV performs path planning
2018	[127]	Using different viewpoints for mapping to guarantee consistency

5.2 Application in Special Scenarios and Level of Autonomy

At present, the literature on collaboration is still poorly involved in ideal. UAVs can fly outdoors at heights exceeding 20 m and use GPS for precise localization [129–131]. On the contrary, the autonomy, accuracy, efficiency, and generalization are reduced because of various constraints, which depend not only on the intelligence level but also on the proficiency of the operators. The level of autonomy includes: remote control by the operator only: non-autonomous; Some of the functions require the operator (e.g., grasping in complex environments): semi-autonomous; Only setting goals for the collaborative system: full-autonomous. Some of the research and classifications are as follows:

After the 2012 Miranda earthquake in Italy, aerial and ground robots were gradually deployed inside damaged buildings to construct 3D environmental maps, and these heterogeneous robots performed missions by remote control [132]. However, the operators were reported to have a high level of mental pressure, as shown in Fig. 10a. The work in [133] demonstrated how UAVs assist UGVs in mapping and autonomously collaborating on damaged indoor buildings after an earthquake in Japan. The UGV was equipped with a LiDAR, a UAV with a 3D laser, and an RGB-D depth camera. However, the mapping method assumed without the UGV moving during the UAV flight and mentioned whether the global map was processed online or offline, as shown in Fig. 10b. A UAV/UGV formation for surveillance and tracking missions was proposed in [134]. The UAV search for escapee targets in the air is then verified and tracked by the UGV, which achieves limited human–machine interaction, mainly since a wireless network within a specific range was required during the mission. In [135], UAVs assisted ground workers in searching for victims. At the same time, several search strategies, including sensor configuration and selection, were discussed between outdoor and rescue workers, as shown in Fig. 10c.

The UAV was described in [136] using vision monitoring to assist UGVs in arriving at the targets but only performing local planning, as shown in Fig. 10d. Grayson et al.'s studies [137] focused on the multi-robot systems for SAR operations, including task assignment algorithms, communication, human–robot interaction for homogeneous (UAV formation or UGV formation), and heterogeneous (UAV/UGV collaboration) multi-robot systems, as shown in Fig. 10e. In 2016, Sara Minaeian et al. proposed a vision-based target detection [141]. They developed a probability-based pursuit-escape solution to achieve the pursuit of moving targets using a group of UAVs/UGVs. Finally, the local and global maximum strategy was analyzed, which showed that the latter has better results. In 2016 Asif Khan et al. [142] reviewed the problem of dynamic target tracking with multi-robot collaboration and proposed five elements: environments, targets, robots, sensors, and collaborative methods, then discussed the development of related technologies such as joint tracking, multi-target detection, and pursuit and escape, while pointed out that most of the research work based on simulations and laboratory studies, which challenging to apply to practical scenarios. In 2007, Tanner HG et al. [143] in the United States investigated using a group of UAVs/UGVs for switching collaboration to detect a single moving target on the ground. They verified the effectiveness of the way using numerical simulation. Grocholsky [138] and Chaimowicz [144, 145] carried out a series of studies, which used fixed wing and UGVs to achieve target retrieval and localization in a given area, then established a framework for a collaborative UAV/UGV system and a vision-based target retrieval and localization algorithm, as shown in Fig. 10f.

Similarly, in [136, 139, 140, 146], UAVs and UGVs performed navigation and exploration, where UAVs provided wide ranges for UGVs to navigate in unknown environments, as shown in Fig. 10g, h. In addition, tether-linked UAV/UGV collaborative systems have been developed in [147, 148]. However, these collaborative systems only utilized the UAV as a "Flying Eye" and mainly provided a wide range of global information. In [149], the motion planning among agriculture fields was investigated using air-ground collaboration, the UGV navigated to the target with minimum energy consumption, and the environment map constructed by UAV, which was used as a benchmark to achieve the optimal planning, some summarized in Table 8.

5.3 Platform for Rapid Deployment of Air-Ground Collaboration

Usually, in experiments, we would like to test some features in an air-ground system. However, we are limited by the completeness of the code, the coupling between devices, and the security, which cannot immediately deploy the software to the hardware. So a priori experiments are required in the datasets and simulation platform. Similarly, we presented several simulation platforms that may quickly deploy air-ground systems.

(1) Robot Operating System (ROS): ROS, an excellent robot operating system, allows rapid deployment of relevant functions and operations. It incorporates the Gazebo simulation platform and the Rviz visualization interface. The descriptions are shown in Table 9.

Hector Quadrotor Technical University Darmstadt develops a simulated quadrotor UAV for deployment in ROS Gazebo. It allows the user to record data from sensors such as LiDAR, depth cameras, etc., and test flight and control algorithms in simulation. Also, both indoor and outdoor simulation scenarios are covered.

RotorS RotorS contains multiple indoor and outdoor scenarios and multiple UAVs models. It includes monocular, binocular, depth camera, IMU, and GPS sensors, which can be deployed simultaneously with multiple UAVs, enabling easy autonomous localization and navigation.

PX4 PX4 includes software-in-the-loop simulation (SITL) and hardware-in-the-loop simulation (HITL). Compared to the first two simulators, px4 can interact with the natural environment. It contains many flight controllers, which can precisely control the flight of the UAV and have higher accuracy in estimating its position.

AR-drone AR-drone is a quadrotor UAV that also includes a variety of sensors compared to other simulators, including some SLAM localization, autonomous flight, and self-positioning correction capabilities.

CAT-vehicle This type of simulator contains some basic scenarios and sensors. Custom sensors and functions, such as LiDAR and obstacle avoidance algorithms can be added externally. However, autonomous driving under traffic rules is not incorporated.

Husky Husky is a medium-sized mobile wheeled unmanned vehicle, which is equipped with LiDAR/Camera/GPS/IMU and other sensors, fully compatible with ROS, and has a relatively simple implementation.

Autoware.ai/Apollo Both include a simulator under Gazebo for completely autonomous driving, including LiDAR mapping, HD map, and simulation in scenarios with traffic rules.

Although the above presentation is the simulation platform for a single device, however, under Gazebo, they can be combined to co-build a platform for air-ground systems.

(2) Simulation platform with real scenarios and physical meaning: AirSim[7] is a simulator for UAVs, UGVs, and more. It is open-source, cross-platform, and supports software-in-the-loop simulation for physically and visually realistic simulations. It can also construct more complex tasks such as cooperative air-ground localization, mapping, and path planning.

6 Inspirations and Challenges of Air-Ground Collaboration

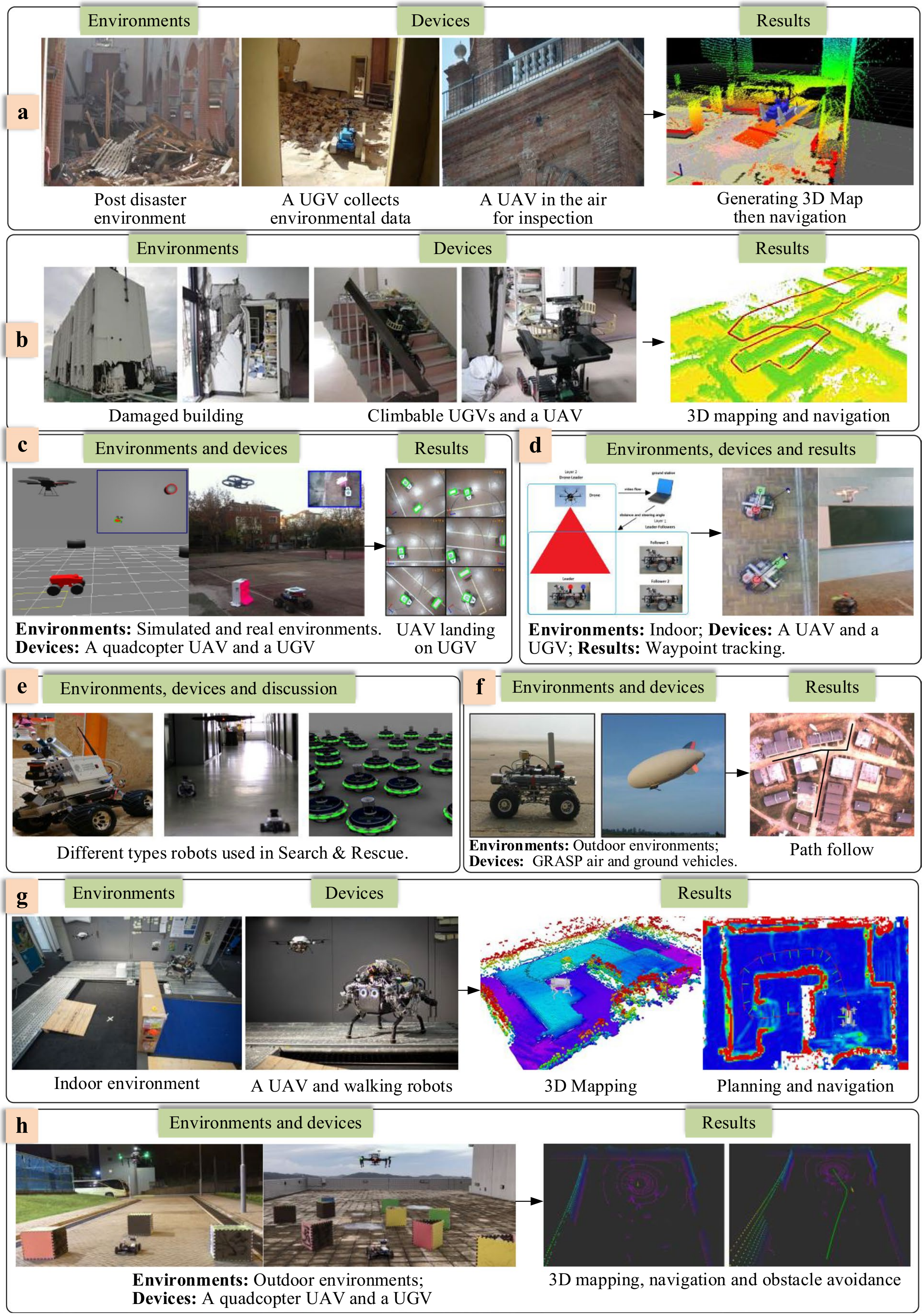
The significant heterogeneity and complementarity between UAVs and UGVs in terms of dynamics, speed, and communication enable them to perform missions efficiently. These advantages are better than possessing a powerful homogeneous robot for the same functions. A key advance of multi-robot systems is embedding more intelligence for collaborative systems [150]. This section will discuss the limitations of air-ground systems and the scenarios that need to be faced in the future.

6.1 Real-Time in Air-Ground Collaboration

Real-time is divided into hardware responses and network latency.

The Hardware Response Due to the requirement of real-time response for some applications, the air-ground collaboration should be reasonably distributed in terms of computational power. Because of the size and weight limitations, the

[7] https://github.com/microsoft/AirSim


a
Environments
Devices
Results
Post disaster environment
A UGV collects environmental data
A UAV in the air for inspection
Generating 3D Map then navigation
b
Environments
Devices
Results
Damaged building
Climbable UGVs and a UAV
3D mapping and navigation
c
Environments and devices
Results
Environments: Simulated and real environments.
Devices: A quadcopter UAV and a UGV
UAV landing on UGV
d
Environments, devices and results
Environments: Indoor; **Devices:** A UAV and a UGV; **Results:** Waypoint tracking.
e
Environments, devices and discussion
Different types robots used in Search & Rescue.
f
Environments and devices
Results
Environments: Outdoor environments;
Devices: GRASP air and ground vehicles.
Path follow
g
Environments
Devices
Results
Indoor environment
A UAV and walking robots
3D Mapping
Planning and navigation
h
Environments and devices
Results
Environments: Outdoor environments;
Devices: A quadcopter UAV and a UGV
3D mapping, navigation and obstacle avoidance

◂**Fig. 10** Scenarios and applications of air-ground collaboration. (Sub-figure **a** is derived from [132]; Sub-figure **b** is derived from [133]; Sub-figure **c** is derived from [135]; Sub-figure **d** is derived from [136]; Sub-figure **e** is derived from [137]; Sub-figure **f** is derived from [138]; Sub-figure **g**, **h** are derived from [139, 140].)

computational capacity, the effect of communication instability, and the minimum latency requirement are usually limited and may not be possible in real-time UAVs/UGVs [151]. Many interactions and the tightly coupled collaboration of robots add to the computational burden. This brings a further challenge for developing efficient embedded hardware.

The Network Latency The collaboration of UAVs and UGVs is not entirely unsupervised. A kind of humans/UAVs/UGVs in the loop are more stable. Generally, a person can only be monitored via video or remote signals. Therefore, the delay in signal transmission is significant. 4G/5G [152] and networking are equally critical to carrying out the mission. This contains video keyframe selection and efficient audio/video decompression techniques implementation.

6.2 Dynamic Role Assignment

As the collaborative systems developed, the number of degree of freedom (DoF) available for control increased dramatically (e.g., UGV formations, UAV displays). The concept of dynamic role switching needs to be further explored to provide adequate assistance and reduce staff supervision.

As described in Section III, roles between auxiliary and execution devices are necessary for UAVs and UGVs. For example, a collaborative system in different formation configurations could provide real-time sensor information over a large area. After merging data from all units, specifying the formation configuration could control the entire system, similar to managing a single robot. While many robots with fixed roles, systems with dynamic role switching appear to be rare [153], which is valuable for inspecting the level of adaptability of a robotic system, and role assignment can be dynamic, and time-varying to better cope with mission flexibility.

Table 8 Air-ground collaboration at varying times and scenarios

Years	Citation	Methods
2003	[135]	UAVs interact with humans during SAR, including design strategies
2004	[141, 144]	UAV/UGV collaborative detection; UAV/UGV collaborative detection and localization
2005	[145]	As above (same team), UAV/UGV collaborative detection and localization
2006	[138]	As above (two teams cooperating with each other), to achieve UAV/UGV collaboration
2007	[130, 143]	Air-Ground Collaboration for formation; UAV/UGV for single-target detection
2008	[134]	Air-ground collaboration achieves UAV detection and UGV tracking
2011	[131]	Multi-robot visual mapping in large scale scenes
2012	[132, 133]	Air-ground collaboration under post-disaster. (Including perception, mapping)
2014	[127, 147]	Human–machine collaboration; UAV/UGV for navigation in unknown environments
2015	[136, 148]	Semi-automation, where the UAV uses remote control; Limited regional collaboration
2016	[129, 139]	Real-time collaborative air-ground navigation at limited areas; Remote sensing-based technology for multi-robot localization and navigation
2017	[140, 142, 146]	Multi-robot for dynamic target tracking; Target tracking in complex environments; Air-ground collaboration from different perspectives
2019	[149]	Path planning for air-ground collaboration in agriculture

Table 9 ROS Gazebo based simulation platform

Types	Simulations	Control methods	Links
UAVs	Hector Quadrotor	Keyboard/Joystick	https://github.com/tu-darmstadt-ros-pkg/hector_quadrotor
	RotorS		https://github.com/ethz-asl/rotors_simulator
	PX4		https://github.com/PX4
	AR-drone		https://github.com/tum-vision/tum_ardrone
UGVs	CAT-vehicle	Keyboard/Joystick	https://github.com/sprinkjm/catvehicle
	Husky		https://github.com/husky
	Autoware.ai		https://github.com/autowarefoundation/autoware.ai
	Apollo		https://github.com/ApolloAuto/apollo

6.3 Task Structures in Air-Ground Collaboration

Modeling mission scenarios are fundamental to the air-ground collaborative system. Analysis of the current model allows for further research and task relevance.

Optimizing Well-Known Scenarios Most current research mainly requires manual classification and manual model tasks [154, 155]. This method requires collecting scenario data in time and then using non-linear optimization, filtering, and other technologies to generate maps offline. Due to assisting air-ground collaborative systems in accomplishing complex tasks under uncertain conditions, the charges should be automatically adjusted as the conditions change. These will also involve areas such as optimal theory and information theory.

Exploring Unknown Scenarios Air-ground collaboration involves higher hardware, software, and human resources, so these systems are often associated with performing massive missions [156]. At the same time, most scenarios are not immutable and frozen. Hence, tasks such as rapid collaborative mapping need to be scheduled and deployed in advance. The connection, such as UAVs/UGVs/Clouds, can be discussed in the future.

6.4 Heterogeneity and Scalability Trade-Off

In air-ground collaborative systems, heterogeneity generally refers to the differences between physical objects and the types of information. Scalability refers to the availability of generalization capabilities.

Heterogeneity Air-ground systems are mainly affiliated with unmanned devices, which are designed without human considerations (e.g., cockpits, etc.). The design philosophies of these devices are mission-centric. At the same time, technologies are not subject to human factors of physical and mental [157].

Scalability The modular design of hardware structure and functional expansion needs to be considered similarly.

Air-ground systems must adapt to dynamic environments and perform effectively in generalized scenarios. Some works [158, 159] have proposed decentralized planning and control for air-ground collaboration. The key novelty above is presenting a unified framework and the coordination strategy at a high level, then goal-oriented navigation at a low level, and providing a flexible probabilistic map under the assumption of a static environment. On the contrary, these challenges remain in dealing with scalability and heterogeneity in highly dynamic environments. Therefore, the development of algorithms can achieve some balance between both [160]. Local centralized and global decentralized can improve the generalizability.

6.5 Human–robot interaction

Collaborative systems are essential for air-ground interaction with humans, delivering the necessary intervention to individual robots or formations. The benefits of this type include improved adaptability and robustness to the environment.

Single Remote Control to Multi Remote Driving Remote control is the traditional control mode of UAVs and UGVs, limiting the signal transmission distance. In contrast, remote driving can be controlled in real-time over ultra-long distances via wireless networks such as 4G/5G [161]. However, there are currently only a few efforts focused on remote driving of a single device. This kind of technology is primarily applied in construction machinery, such as excavators in dangerous mines [162], to ensure the safety of the operators' lives. Therefore, when carrying out tasks, it not only needs air-ground collaboration for autonomous driving but also taking over manually in an emergency to achieve remote driving.

Human–Robot Interaction Strategy Development Human–robot interaction is not only sending and receiving commands between both but also evaluating the interaction towards the optimal solution [163]. However, most of the time, the human, as the highest priority, cuts off the "intelligence" once someone intervenes in executing the mission. Air-ground collaboration as a multi-intelligence ensemble also requires adaptive interaction with the human, including conventional filtering update strategies and training large-scale event libraries offline.

6.6 Algorithm Implementation

Currently, deep learning methods are used in various fields. However, high performance comes at the cost of sufficient training data. Especially Deep Reinforcement Learning (DRL) relies heavily on a simulation environment, mainly used to obtain effective strategies or inference. Yu et al. [164] cope with the resilience of heterogeneous robots against dynamic environments, which found optimal planning between device ontology and task assignment. Finally, they used continuous trial and error to search for the best combinations. In [165] proposed, an imitation augmented deep reinforcement learning (IADRL) model to bridge the gap between UAVs and UGVs in loading and climbing in unstructured environments, improving the efficiency of carrying out the missions. However, it remains simulation-based.

The above shows that the implementation of air-ground collaboration requires a large amount of data and simulation, which may be more challenging than in a utopian environment. Therefore, it is far-reaching to regard techniques such as semi/self-supervised learning and reinforcement learning for collaborative systems.

7 Summary and Outlook

Collaboration between UAVs and UGVs has attracted growing attention. This paper systematically reviews air-ground collaboration systems' achievements. It comprehensively surveys recent studies, funded projects, and competitions. It is summarized as follows:

1. We described the characteristics of single-agent and multi-agents and their advantages and shortcomings. Finally, a summary of why multi-intelligence agents' collaboration is desired, i.e., UAVs/UGVs collaboration systems.
2. A classification of the air-ground collaboration systems includes equipment types, tasks, sensors, scenarios, and metrics.
3. A review that allows for classifying the four roles (sensors, decision-makers, actuators, and auxiliary) of UAV/UGV collaboration and the tight between them can improve the collaborative capability. Finally, we described the strengths and weaknesses of UAVs/UGVs in several roles.
4. It categorized the collaboration modes of perception collaboration, decision collaboration, and motion collaboration. Finally, we discuss how to deploy the devices and tasks in real scenarios, which include missions, running time, and scenarios.
5. We analyzed the application of multi-robot collaboration from funded projects, competitions, and unique scenarios. Finally, we summarized and recommended the simulation platforms, which could be constructed as air-ground systems.
6. The potential challenges from air-ground collaborative system architecture, hardware types, and collaborative algorithms and insights are discussed.

Although air-ground collaboration has received substantial interest, there are still many limitations to deployments in migration from simulation to real life. Challenges remain at the system level, multi-agent control, human–robot interaction, and algorithmic perspectives.

Appendix 1

Table 10 Some funded projects for multi-robot collaboration. The utilization of different robots; whether a heterogeneous multi-robot system was used; and how the data were processed. The application refers to the experimental testing scenarios, but not necessarily to the characterization of all systems

About Multi-Robot Collaboration Funded Projects

Funded Projects	Description	Multi-Robots	Multi-UAVs	UGV	UAV	Robot Type	Data Process	Scenarios
COMETS	Real-time collaboration and control of multiple UAVs	√	√	√	√	UAVs; airships	Offline	Forest fires
Guardians	Application of robotic swarms for navigation and search in cities	√	-	√	-	-	Offline	Fire fighting
ICARUS	Development and assistance of multi-robot systems for SAR	√	√	√	√	UGV/UAV	Offline	SAR
NIFTi	Human–machine collaboration in dynamic environments	√	√	-	√	-	-	Urban disasters
SEAGULL	Multi-UAV marine environmental awareness	√	√	-	√	-	Offline	Seas
TRADR	Long-term human–machine collaboration in industrial accidents	√	√	√	√	UGVs/UAVs	Offline/Online	Industrial/Human defense
SmokeBot	Multi-robot collaboration in low-visibility scenarios	-	-	√	√	-	Offline	Fire
Cetauro	Remote operation of multiple robots in disaster scenarios	√	-	-	-	-	-	Harsh environment
MEXTDDT	Multi-robot collaboration for urban earthquakes	√	√	√	√	UGVs/UAVs	Offline	Earthquake
AutoSOS	Artificial intelligence based marine multi-UAVs	√	√	-	√	UGV/UAVs	Offline	Seas
SHERPA	Human and air-ground multi-robot collaboration in alpine rescue missions	√	√	√	√	UGVs/UAVs	Offline/Online	Alpine rescue
Darius	Integrated unmanned systems for urban, forest fire and marine search and rescue	√	√	√	√	UGVs/UAVs	Offline	Forests, cities and oceans
①	Multi-robot collaboration in cross-domain	√	√	-	√	UAVs	Offline	Urban environment

Table 10 (continued)

About Multi-Robot Collaboration Funded Projects								
Funded Projects	Description	Multi-Robots	Multi-UAVs	UGV	UAV	Robot Type	Data Process	Scenarios
②	For unstructured scenarios, UAV and UGV collaborative works. Including dynamic target tracking, negative obstacle detection, air-ground cooperative platform building	√	-	√	√	UAV/UGV	Offline/Online	Urban, wilderness
③	Research on the key technology of cooperative control between UAV and UGV	√	-	√	√	UGV/UAV	Online	Urban disaster rescue
④	UAV and UGV collaboration for disasters	√	√	√	√	UAVs; UGVs	Online	Disaster rescue
⑤	Multi-robot collaboration for location navigation	√	-	√	√	UGV/UAV	Offline	Unknown environment
⑥	Multi-robot collaborative mapping and path planning	√	-	√	√	UGVs; UGV/UAV	Online	Indoor, airport and factory

① Research on key issues of multi-robot cross-domain collaboration

② Negative obstacle detection and dynamic target tracking by UAV and UGV collaboration under unstructured road conditions

③ Research on key technology of cooperative control between UAV and UGV

④ Research on the theory and system of air-ground cross-domain multi-robot collaboration

⑤ Research on autonomous environmental mapping and collaborative localization of mobile robots

⑥ Intelligent mobile robots

Appendix 2

Table 11 Some competitions for multi-robot collaboration. We describe: the utilization of different types of robots whether a heterogeneous multi-robot system is used; how the data is processed and the form of robot control. The application scenarios are restricted to the competition test scenarios

About Multi-Robot Collaboration Competitions

Competition Name	Description	Multi-Robots	UAV	UGV	Control mode	Robot Types	Data Process	Scenarios
Robocup Rescue	Task challenges primarily in SAR applications and cross-domain multi-robot collaboration	√	√	√	Distributed	Heterogeneous robots; UAVs, UGVs	Offline/Online	Multi-application environments, including SAR
ImPACT-TRC	Complex technical challenges with multi-robot collaboration aimed at disaster response and logistics preparation	√	√	√	Centralized	UGVs/UAVs	Offline	Earthquakes, nuclear disasters and tsunamis
ERL-ESR	The European Robotics League (ERL), which focuses on emergency service multi-robot collaboration	√	√	√	Distributed	UGV/UAV; Multi-UAVs	Offline	Intra-city multi-disciplinary
RESCON	Large-scale rescue multi-robot collaborative competition on urban disasters	√	√	-	Centralized	Multi-UAVs	Offline/Online	Post-earthquake urban recovery
DARPA	The challenge of multi-robot collaboration under human supervision	√	-	√	Distributed	Multi-UGVs	Offline/Online	Urban disaster rescue
OnShape	On-campus rescue challenge with multi-robot collaboration, remotely operated for SAR	√	√	-	Centralized	UGVs/UAVs	Offline/Online	Simulation scenes
China Robotics Competition	Collaborative challenges such as aerial robots and rescue robots for hot spots	√	√	√	Centralized/ Distributed	UGVs/UAVs	Online	Limiting the area which include post-disaster
Artificial Intelligence Application Technology Competition	Service robot artificial intelligence applications, including inspection, measurement, mapping and automatic disinfection	√	-	√	Centralized	UGVs	Offline/Online	Manually designed scenes, including areas such as factories
World Robotics Competition (WRC)	Around the three major competition directions of scientific research, skills and science popularization, involving robot collaboration challenge	√	-	√	Centralized/Distributed	UGVs	Offline/Online	Sports competitions, collaborative robotic confrontations, etc

Table 11 (continued)

About Multi-Robot Collaboration Competitions

Competition Name	Description	Multi-Robots	UAV	UGV	Control mode	Robot Types	Data Process	Scenarios
China Engineering Robotics Competition	Multi-robot collaboration in handling, competition and racing challenges	√	-	√	Distributed	UGVs	Offline/Online	Robots collaborate on a specific mission
National Students Robotics Competition	Multi-robot collaborative competition, bionic battle, etc	√	-	√	Centralized/Distributed	UGVs	Online	Limiting areas, including collaborative robot offensive

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