Chapter 2
Unmanned Aerial and Ground Vehicle Teams: Recent Work and Open Problems

Steven L. Waslander

Abstract Unmanned aerial and ground vehicle teams present a majoropportunity for expanded operation over individual autonomous vehicles alone. The different perspectives available for sensors, the different operating ranges and payload capabilities, and the ability to observe a target environment from all angles at once all add up to significant improvements in ability to search for and track targets, to inspect infrastructure, to persistently perform surveillance, and to map 3D environments. This chapter surveys recent efforts in unmanned air vehicle (UAV)/unmanned ground vehicle (UGV) team coordination and presents a description of open problems that remain to enable the many applications for which aerial and ground vehicles are well suited.

Keywords Unmanned aerial vehicles • Unmanned ground vehicle • Multi-vehicle coordination • Robotics

2.1 Introduction

Both unmanned air vehicles (UAVs) and unmanned ground vehicles (UGVs) continue to find new applications through the relentless advances of sensing, computation, and algorithmic capabilities. Wherever tasks exist that are either dangerous, boring, or both, the development of robotic alternatives to human labor has been both swift and valuable. Both classes of vehicles provide different advantages and shortcomings when attempting to automate particular tasks, and the complementarities of their differing skill sets make UAV/UGV team a promising area for future development (Fig. 2.1).

S.L. Waslander (✉)
University of Waterloo, Waterloo, ON, Canada
e-mail: stevenw@uwaterloo.ca

K. Nonami et al. (eds.), *Autonomous Control Systems and Vehicles*,
Intelligent Systems, Control and Automation: Science and Engineering 65,
DOI 10.1007/978-4-431-54276-6_2,

Fig. 2.1 Quadrotor/UGV team performing coordinated landing [10]

It is important to highlight two different classes of UAV/UGV teams, based on two different classes of UAVs, in particular. Teams that rely on large-scale, long-range, fixed-wing UAVs can capture large overviews of a region of operation with high-quality sensors but must maintain a significant minimum speed during flight operations, making detailed inspection difficult (see Fig. 2.2). It is also difficult to envisage operations involving precision coordination, autonomous landing, or UAV/UGV interaction with large fixed-wing vehicles and moderately sized ground vehicles, and these systems therefore tend to focus on coverage and surveillance problems, where the aerial perspective can prove invaluable. In this configuration, the UAVs offer rapid response, long-range sensing options, and an overview of the operations area, while the UGVs can play the role of detailed target inspectors or sample collectors. The second class of UAV/UGV teams involves much smaller aerial vehicles and particularly rotorcraft with vertical takeoff and landing capabilities. In this case, the aerial vehicles can provide detailed inspection capabilities, can identify possible travel routes for the ground vehicles, and can place sensors in specific locations to maximally cover areas or maintain connectivity of communications networks. The small size that enables such advantages in

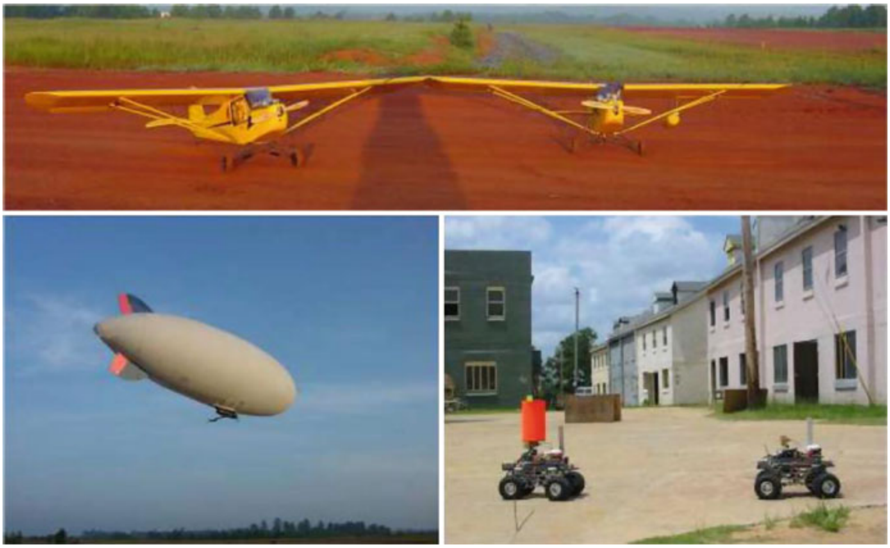

Fig. 2.2 Fixed-wing and blimp aerial vehicles coordinating with small ground vehicles [6]

agility and flexibility also lead in their largest drawbacks, which are the limited onboard payload and reduced flight times that result. This class of UAV/UGV team must therefore exploit the UGVs capabilities for carrying larger payloads to provide battery replacement, long-range transportation, and computational resources to the team. The combined system can perform detailed inspection tasks and can still operate over extended ranges and for extended periods of time, albeit limited to the average speed of ground vehicle motion.

Much work has been performed in developing control algorithms for team management in both the large fixed-wing class and the small rotorcraft class of heterogeneous vehicle teams. This chapter seeks to identify the leading applications and methods for both categories of UAV/UGV teams, as well as to identify the major challenges that remain in exploiting their capabilities. The specifics of UAV/UGV team coordination fall under the broader topic of multi-vehicle coordination and distributed task assignment, while collaborative sensing is part of the broad field of mobile sensor networks and distributed simultaneous localization and mapping (SLAM) with heterogeneous teams. The precision control of UAVs and UGVs for autonomous landings requires advanced techniques in nonlinear estimation and control, and finally there are strong connections to target tracking literature, as well. In short, this is a difficult field to summarize succinctly, and an arbitrary line has been drawn to include works explicitly incorporating UAVs and UGVs but excluding closely related works that consider slightly different team compositions that might also be heterogeneous.

2.2 Potential Applications

There are five main areas of application that have been investigated for possible deployment of UAV/UGV teams. The *search* problem requires the heterogeneous team to operate in an unknown environment in order to find a particular set of static targets. The combination of aerial and ground perspectives allows for rapid refinement of the target location estimates and broad coverage of a large search area in minimal time.

The second application is *target tracking*, inspired by the dangers of high-speed police chases and similar military scenarios. The task is to use a mixed team of pursuers to track and potentially capture moving targets. Target tracking with a UAV/UGV team is also useful for wildlife monitoring and sport videography.

The third application involves *inspection* of expensive or safety critical infrastructure, which can be defined with respect to a known environment, with a known list of inspection tasks to be assigned to a fixed set of UAVs and UGVs. Inspection can also be extended to perform specific tasks at the known locations, other than inspection, as is the case is forest fire fighting, where fire retardant can be deployed, for example.

The fourth application is the *persistent surveillance* problem, where multiple aerial vehicles are used to monitor an area for intruder detection. This application differs from the inspection task in that the monitoring requirements are continuous instead of discrete, changing the nature of the underlying task assignment problem. Here, aerial vehicles perform station-keeping operations and distribute themselves to best cover an area, while ground vehicles can both complement the coverage and provide recharge and computation tasks for the aerial fleet. This application also encompasses the networking problem, which relies on UAVs to augment ground-based vehicle networks for remote operations through extended range line-of-sight communications. In both applications, a continuous task assignment problem must be solved.

Finally, the *mapping* problem requires the heterogeneous team to operate in an unknown environment, localize each of the robots with respect to the environment and each other, and explore a bounded region of the unknown environment in order to either develop a comprehensive map. The difficulty in mapping lies in finding correspondences between the information collected from the very different perspectives of the aerial and ground vehicles, but once overcome, the resulting maps can be built extremely quickly, with both a good overview of the region and detailed information near the ground.

2.3 Current Results

The UAV/UGV team landscape can be subdivided into six technical challenges: relative tracking, coordinated landing, formation control, target detection and tracking, task assignment, and SLAM. All six challenges and their related work are described below.

2.3.1 Relative Tracking

Given the importance of full-state estimation for autonomous vehicle operation and the inherent limitations of many of the sensors used to provide accurate state information, it is not surprising that significant work has been performed to augment the state estimation capabilities of UAVs or UGVs by tracking the vehicles from the ground or the air. Rao et al. [1] define an image-based visual servoing controller which relies on a small UAV to track a UGV using monocular vision in order to enable the UGV to track a desired trajectory without reliance on GPS or magnetometer. Simulation results are presented that demonstrate reliable ground vehicle control along prescribed trajectories, based on the identification of differential flatness for the ground vehicle in the image plane.

Zhang et al. [2] propose a more direct approach, decorating their ground vehicle with active markers and enabling a quadrotor vehicle to estimate its position and yaw relative to the ground vehicle and to maintain a relative pose as the ground vehicle moves. The state estimate is arrived at using an extended Kalman filter (EKF), which fuses the visual feature estimates with IMU data from the vehicle. Position and orientation control are achieved with PID control, as the quadrotor plant behaves quite linearly about its hover operating point. Flight demonstrations reveal that the vision based position estimation is sufficiently reliable and timely enough to implement control on board the vehicle.

Inverting the helpful UAV paradigm, Rudol et al. [3] exploit the stability and payload capabilities of a ground vehicle to aid a micro-air vehicle to attain autonomous flight operation. In this case, active markers are attached to the aerial vehicle in a box configuration, and a single facet is detected with a pan-tilt camera mounted on the ground vehicle. Planar pose estimation is performed without the benefit of filter-based estimation, using a robust solver that identifies both solutions and selects the most likely based on the previous solution [4]. Test results demonstrate that the solution is viable and enables a small coaxial helicopter to operate fully autonomously without GPS, in coordination with a ground vehicle that can track its motion.

If aerial vehicles can be assumed to have reliable state measurements, due to the use of larger UAVs operating at higher altitudes with unobstructed views to GPS satellites and to the ground below, the UAVs can act as mobile localization systems for teams of deployed UAVs. This approach has been extensively studied [5, 6] and has produced numerous convincing field trials. Chaimowicz et al. have developed and tested a decentralized information filter localization problem, where UAVs can use vision to detect and localize both themselves and ground vehicles operating in obstacle terrain below, by relying on a few fixed targets of known location in a global reference frame. Both field [5] and urban deployments [6] have been studied, with blimp and/or aircraft tracking of the ground operations.

In all, these relative localization methods present numerous limitations and possibilities for improvement. Each of the methods presented assumes that one of the two vehicles has inertial pose estimates available or that motions are sufficiently modest to require only planar position and heading estimation to be sufficient for all vehicles. For small aerial vehicles in particular, this is limiting, as they are capable of far more aggressive maneuvers. Additionally, the methods should be extensible to multiple aerial and ground vehicles tracking each others' motion, as similar sensors on aerial and ground vehicles will be plagued by similar difficulties in reliable state estimation in challenging conditions. Nonetheless, the advantage of augmenting onboard state measurement with the separate perspective of a cooperative UAV/UGV teammate is clear and has been successfully demonstrated.

2.3.2 Coordinated Landing

Given that reliable tracking of aerial and ground vehicles has been established, attention can be turned to the task of coordinating a landing of a small aerial vehicle onto a larger ground vehicle. The coordinated landing capability enables UAV range extension through recharging, sensor swapping, or even sample collection and storage. The main issues involve reliable tracking as the distance between the vehicles diminishes, coordinated control in the presence of time delay, and aerodynamic ground effects that disrupt vehicle control.

Esmailifar and Saghafi [7] have presented a controller design and simulation results for landing on a moving platform where the aerial vehicle pose relative to the base is assumed known. The focus of the work is on evaluating and modeling the effects of wind disturbances on tracking performance and relies on solution of a state-dependent Riccati equation for control. In [8], Voos and Bou-Ammar define a method for landing an aerial vehicle on a moving base through tracking of the relative motion between the two. The assumption is that the base moves at constant velocity, and EKF estimation can be used to track the motion through target features on the base platform. Feedback-linearized control is used but has not yet been implemented, which may be due to the difficulty of correctly identifying the actual parameters in the decoupling matrix for a given UAV.

More recently, both Li et al. [9] and Daly et al. [10] have successfully demonstrated coordinated landings of UAVs on moving ground platforms. Both systems rely on visual tracking of targets to provide a relative pose estimate that is available throughout the landing procedure. Li et al. perform a smooth takeoff by following a prescribed spline in the altitude command, and tracking and landing are achieved by relying on the commercially available PID control for the inner (attitude) and a sliding mode outer (position) loop on the Ascending Technologies Hummingbird platform, which is needed to combat difficulties that arise from the ground effect. A sequence of position commands are generated, and the landing sequence is constrained to have an exponential speed decay, and the results are demonstrated indoors with indoor positioning system (IPS) state measurement and were repeated outdoors as well.

Daly et al. [10] developed a distributed controller that enables both the ground and aerial vehicles to coordinate their motion when executing a landing procedure and rely on feedback linearization of both the quadrotor and ground vehicle models to produce a linear relative position control problem. The UGV tracks the UAV relative position using vision data and a standard EKF, and the issue of time delay in the communication of position information arises as both vehicles need the relative position information to achieve coordination. The linear system is evaluated in the context of retarded functional differential equations (RFDEs), which provide a maximum time delay for which stability can be maintained. The resulting system has been demonstrated both indoors and outdoors [11], with similar issues relating to ground effect disturbances requiring a fixed z trajectory to be used for the final descent.

It is clear that UAV/UGV team operations requiring landing of the UAV on the UGV are possible, but refinement of the ground effects modeling remains an important challenge. The variability and unpredictability of the effect as the aerial vehicle is partially over top of the ground platform makes ground effect prediction a challenging problem, for which either adaptive or robust control methods may prove beneficial. As always, the availability of high-quality pose measurement data from an IPS greatly simplifies the problem, and it is only with the latest outdoor experiments that true functionality has been verified.

2.3.3 Formation Control

Many studies have been directed at defining provably stable control algorithms for operating multiple air and ground vehicles together in an environment. Application of formation control capabilities to the maintenance of communication networks and to safe traversal of convoys through environments with obstacles are often cited as motivation, and indeed demonstrations of both scenarios have been successfully achieved. The use of controllers for multi-vehicle team motion planning provides a method with significantly lower computational complexity than the task assignment and motion planning methods described below, but at the cost of reduced flexibility of the solution and unpredictability of the specific motions that the vehicles will execute in advance. Nonetheless, formation control algorithms relying on nearest neighbor rules exhibit very strong scalability properties, enabling simulation results with many tens of vehicles to be performed in real time. A brief survey of flocking and formation control results for UAV/UGV teams can be found in [12].

The benefit of a single aerial vehicle in coordinating a team of ground vehicles over terrain with occlusion or failure of ground-based line-of-sight communications is well established [13, 14]. Using existing UAV and UGV platforms, Shulteis and Price evaluated aerial deployment of the UGVs using parachutes and expanded the range of remote operation of the UGVs from 1–2 to 30 km by having the UAV act as a communication link in the sky. Although no autonomy was incorporated, the benefit of the UAV/UGV cooperation for network expansion was apparent. Michael et al. [14] have proposed a formation control strategy that allows a single aerial vehicle to manage a ground vehicle formation in a decentralized manner. By abstracting the models of the individual ground vehicles into a formation model, the aerial vehicle guides the formation, while collision avoidance and formation maintenance are performed by the ground vehicles with local information only. This idea is expanded to multiple UAVs and multiple teams of ground vehicles in [15]. Ground teams are able to merge and split while navigating through obstacles, and each ground vehicle team is monitored by a single UAV. The ground vehicles are organized into groups by expectation maximization, where they are group based on a distribution over their positions that is simultaneously identified. This allows the teams to form and the UAVs to manage the formation's motion.

Tanner and Christodoulakis [16] propose decentralized control of both ground and aerial formations, in which ground vehicles estimate their formation centroid and follow local control rules to stabilize their formations at a constant velocity. The aerial vehicles have access to the same centroid information and track this centroid in formation, and both decentralized controllers are guaranteed to remain stable through stability analysis. The result is a reliable two-layered formation that would implicitly satisfy networking or surveillance application requirements, all without the need for explicit planning of either the network topology or the vehicle trajectories. However, no guarantee on performance for either connectivity or surveillance can be generated.

The network problem specifically has garnered its own interest, and Chadrashekar et al. [17] provides a method for guaranteeing full connectivity of air-ground networks by placing UAVs at strategic locations. This is a minimum covering circle problem, with clustering of the ground node locations into subnets that are connected by aerial links. Each of the subnets must be connected to the others by an aerial link of fixed communication range, and the number of UAVs required to maintain the network can be determined from the subnet clusters locations. The fixed communication model is expanded in [18] where signal quality is optimized over an ad hoc wireless network with a fixed number of UAVs and UGVs held at static locations. The aerial vehicles are again positioned to improve network performance, and experimental demonstrations reveal that the models are reasonably accurate.

The use of formation control and flocking strategies for exploration, surveillance, and networking tasks remains a challenging area and will most likely continue to be used to relieve computation burden on small aerial vehicles, instead of more involved trajectory planning algorithms used on individual vehicles. Decentralized collision avoidance and formation management is simple to execute when in control form, once stability can be guaranteed with the appropriate selection of controller for the particular team configuration. However, it is unlikely that vehicles need only move through environments without particular tasks to execute or targets to identify and track or environments to map. As a result, it may not always be possible to rely solely on formation control for motion planning, and more specific routing procedures may be needed.

2.3.4 Target Detection and Tracking

The localization of ground vehicles by aerial vehicles can be directly extended to detection and tracking of noncooperating targets as well. In fact, the work of Grocholsky et al. [19, 20] for finding and localizing targets with a combined team feeds directly into localization efforts by Chaimowicz et al. [5, 6] which track ground vehicle movements from their aerial counterparts, and the same estimation methods are simply adapted for the purpose. In addition, search algorithms are introduced which either a fixed pattern over a known region or a greedy ascent of the information value to be collected in the sensor footprint based on the current global uncertainty map allows all vehicles to move in the direction that will most improve the target detection probability without requiring central coordination of their actions. Field tests are performed which demonstrate multiple aircraft and ground vehicles detecting and localizing numerous static targets in a fraction of the time it would take either aerial or ground vehicle teams.

If the targets are able to move, the problem becomes one in the pursuit-evasion class of games, and once again, the benefits of air and ground coordination to pursue an evading target have been well studied [21–23]. The targets can either evade randomly or optimally, although formal proof of the optimality of the pursuit of the evasion control strategy is quite challenging beyond simple scenarios of two vehicles with planar kinematic motion models.

In [21], Tanner presents a method for coordinating the motions of aerial and ground teams to track a single target vehicle. The ground team forms a perimeter formation using navigation functions that surrounds the targets, while the aerial vehicles use velocity synchronizing formation control to scan a prescribed route in the enclosed area to locate the targets. Results are presented in simulation and rely on state-based task synchronization, so that the ground vehicles are in position before the aerial vehicles cover the area.

Building on previous studies in optimal pursuit-evasion strategies, Vidal et al. [22, 23] develop coordination strategies for aerial and ground team tracking of moving targets that are assumed to evade with random control inputs, as depicted in Fig. 2.3. While moving through the environment, a 2D occupancy grid is populated and shared amongst the pursuers, tracking the probability of detecting an evader in each cell at the next timestep. The pursuers use a greedy policy that moves them to the adjacent cell with the highest probability of containing an evader, or move in a direction that will lead to the highest probability of catching an evader in the future. A team of one aerial helicopter and two ground pursuers were tested chasing a ground evader, and proof of a nonzero probability of capture was demonstrated.

The methods proposed for aerial and ground team detection and tracking have focused on ground targets and are operating at speeds and in conditions that do not come close to the complexity of the real-world applications of police chases or combat missions. Nonetheless, the results do exploit the varied capabilities of aerial and ground vehicle perception and motion and achieve greater tracking performance than either ground or air alone. The limitations lie mostly in individual

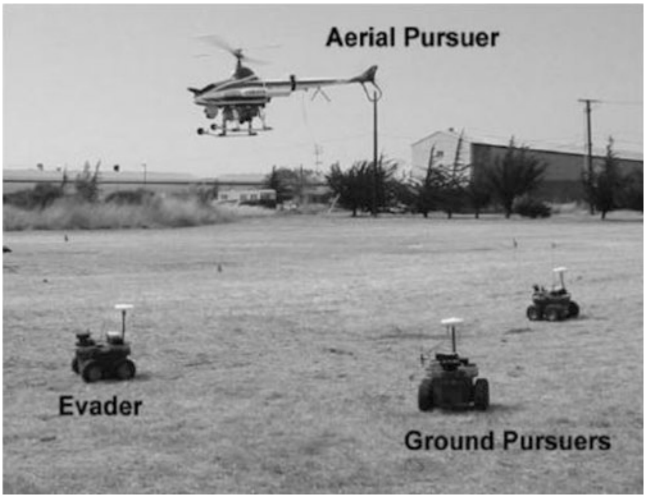

Fig. 2.3 Pursuit-evasion games with two ground and one aerial pursuer of a ground target [23]

vehicle capabilities, that is, in high-speed operation of unmanned vehicles in uncontrolled environments. It remains unclear whether the reactive formation control approaches can work reliably when chasing fast-moving targets or whether a more involved team planning approach will be needed.

2.3.5 Task Assignment

The task assignment problem for multiple vehicles can be resolved in a variety of ways with varying levels of fidelity in the optimization problem models that are included. The discrete nature of allocating a fixed list of tasks to a fixed number of vehicles lends itself to mixed integer linear programming formulations, complicated slightly by typically nonholonomic vehicle models and collision avoidance constraints. The wide literature on multi-vehicle task assignment is surprisingly poorly represented when it comes to UAV/UGV coordination; however, there are some notable exceptions, discussed below.

One example of a task assignment and execution method was recently demonstrated by Luo et al. [24]. In searching for a particular target in an indoor location, a UAV is first tasked with the search mission and then relays information about the target upon detection, at which point a ground vehicle is deployed to recover the target. Using AR.Drone quadrotors and NXT Lego Mindstorm robots, the method was successfully demonstrated indoors, using only vision and sonar for localization and detection. This simple hierarchical approach to task allocation, although not computationally complex, may frequently provide a useful solution to practical problems.

A task assignment algorithm for a fleet of aerial and ground vehicles was presented by Phan and Liu [25], who built a forest fire fighting mission solution in which aerial and ground vehicles drop water and retardant and centrally defined locations in order to combat the progress of a forest fire over time. The assignment problem is a constrained mixed integer linear program, which is solved centrally once task locations are identified through fire front modeling. The central planners solves a small multiple traveling salesperson problem for both UAVs and UGVs to execute, and simulation results demonstrate the feasibility of the approach on a small team of vehicles. Natural extensions to heuristic and approximation algorithms should be possible, allowing the problem formulation to be solved on a larger scale for more realistic forest fire scenarios.

Finally, the decentralized task assignment methods developed by How et al. [26] present a method that is able to scale to larger numbers of vehicles and to operate in a distributed manner, in real time as new information becomes available in the environment. Applied to the detection and tracking problem [27] described in the previous section of this survey, the underlying algorithm is fundamentally a decentralized mixed integer linear program task assignment solver, and it is by converting detection and tracking to a sequence of discrete tasks for teams of unmanned vehicles to perform that the detection and tracking problem is approached. The method was demonstrated using an indoor multi-vehicle testbed [28], although with only a limited number of vehicles on a relatively small test area.

Task assignment methods offer general solutions to a broad range of the applications envisioned for UAV/UGV teams, as it is often possible to decompose problems into a sequence of discrete tasks (surveillance points, water drop locations, targets to track, search locations to visit, etc.), and use existing frameworks in either centralized or decentralized assignment to find solutions rapidly. The drawbacks arise in the approximations that are needed to define a sequence of discrete tasks in what are often continuous objectives (search an area, maintain a persistent surveillance coverage), but it remains unclear what the relative strengths of each of the algorithms presented is, due to a distinct lack of comparisons drawn in the existing literature.

2.3.6 Simultaneous Localization and/or Mapping

The final topic for discussion in this review is that of generating maps with or without the benefit of global state measurements. If GPS and IMU can be relied on to accurately sense vehicle pose for both air and ground vehicles, the problem becomes one of mapping alone, while if the robot motion must also be estimated, SLAM algorithms are needed. Most commonly, the aerial overview of an environment can be extremely beneficial for the operation of ground vehicles in unknown terrain, as the limited sensor footprint for equipment attached to the ground vehicle does not allow for long lookahead times. As a result, ground vehicles are frequently

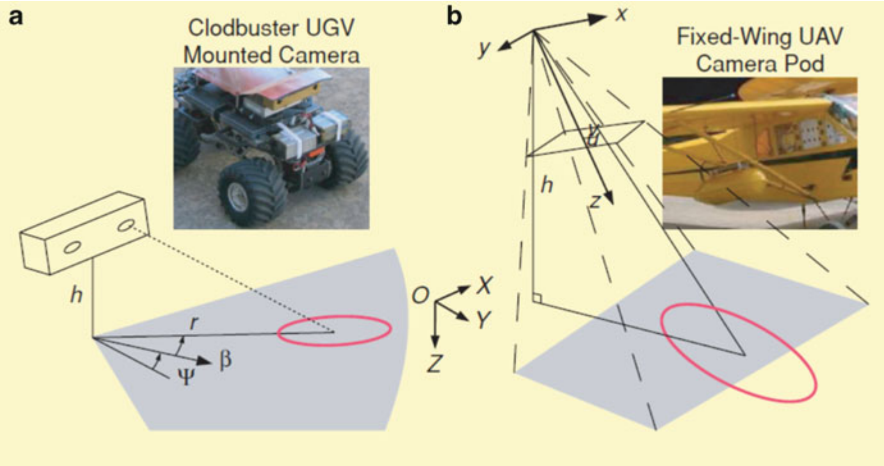

Fig. 2.4 Different perspectives on ground features for aerial and ground-sensing platforms [19]

speed limited due to sensor perspective, and this limitation can be drastically reduced by providing drivability information sensed from above.

This is the approach presented by Stentz et al. [27] and Vandapel et al. [28]. In [27], the benefit to path planning is investigated if an aerial scout is able to provide a 2D occupancy grid map of the environment in advance of the planning phase for ground vehicle motion. The system relied on stereo vision and ladar to generate the map with RTK-GPS, capable of 2 cm position accuracy worldwide, and provided the complete map in advance of the ground vehicle motion. The results demonstrated significantly more direct routes than if satellite imagery or topographical maps were used, but did not explore the issue of the different perspectives for aerial and ground vehicles.

The fact that aerial vehicle senses a very different ground surface from ground vehicles led to the work in Vandapel et al. [28] to expand on the previous work. Trees, in particular, present much larger obstacles in the aerial map than obstruct ground vehicles, and it is therefore important to assess the differences in perspective and understand what information is to be trusted. Further, the authors do not assume that ground vehicles will always have reliable localization and therefore seek to match the current laser scans collected by ground vehicles with the existing information collected by the aerial scout. This is, in fact, the core challenge of mixed perspective mapping and is well discussed in a survey article on the subject of UAV/UGV SLAM [29]. Since common visual features, point clouds, and stereo depth maps may all look quite different from the aerial and ground perspectives, the matching of these sensor measurements to a common map remains an open problem (see Fig. 2.4).

Thompson and Sukkarieh [30] present a visual feature angular characterization system, which is working toward describing features as they are observed from a wide range of angles, allowing for better correspondence calculations between ground and aerial sightings. The ultimate goal is to develop feature descriptors that are measurement angle dependent, allowing for more reliable estimation through better correspondence. In this same vein, Vandapel et al. [28] attempted to remove foliage, a particularly troublesome artifact of natural environments, from aerial data to improve matching of the aerial 2D drivability map with the ground vehicle measurements. Finally, Vidal et al. [31] rely on edge detection and projection to identify common structural elements that are observable from both the air and the ground. In this case, features are composed of geometric patterns of detected edges, describing, for example, a road between two buildings.

The difficulty of reliably fusing aerial and ground information remains, however, the primary challenge in deploying UAV/UGV teams in unknown environments, particularly where localization for either aerial or ground vehicles cannot be independently measured. Both Vandapel et al. [28] and Vidal et al. [31] must be commended for providing the first SLAM solutions for UAV/UGV teams, but much remains to be done to fully capitalize on the rich information available in the dual perspectives of aerial and ground vehicles.

2.4 Conclusions and Future Directions

The field of UAV/UGV coordination has seen an extensive amount of attention over the last decade and continues to be an active area of research. The clear complementarity of the perception and motion capabilities of aerial and ground vehicles ensures that limitations that occur with one platform can often be addressed by coordinating with the other. From low-level improvements in vehicle localization and range extension through rendezvous to high-level applications such as mobile target tracking, persistent surveillance and mapping, many compelling examples of well-developed algorithms and successful field demonstrations in UAV/UGV coordination exist.

There remain, however, numerous difficulties and open problems that need to be resolved for widespread deployment of UAV/UGV teams to begin. The following list touches briefly on the main challenges:

1. *Vehicle autonomy*: Many of the limitations of the team results hinge on the individual capabilities of the vehicles, either in terms of robust state and environment measurement, or dynamic motion planning and vehicle control. Aerodynamic effects that are difficult to model when controlling individual aerial vehicles are only made more complex when multiple vehicles operate in the same area. To fully exploit the benefits of small aerial vehicles, reliable tracking and landing in a wide range of flight conditions remains to be demonstrated, as do fully functioning multi-vehicle teams wherein repeated charge/discharge cycles occur.
2. *Integrated formation control*: Current methods in flocking and formation control of UAV/UGV teams treat the UAVs and UGVs as two distinct classes of vehicles and do not consider operations where both UAVs and UGVs are executing particular

tasks in coordination with each other. The added complexity of heterogeneous formation control may not always lend itself to stability analysis or control law definition, but more opportunities surely remain in defining strategies for coordination that do not rely on large-scale optimization techniques. The manner in which surveillance, coverage, search, and tracking tasks can be efficiently achieved with formation control algorithms is not yet well understood, and a more systematic framework is needed to evaluate these methods against common optimization techniques and receding horizon methods.

3. *Task assignment efficiency*: The methods applied to heterogeneous task assignment with aerial and ground vehicles do not yet touch on the large body of work in approximation algorithms for routing problems. Many of the characteristics of the problem formulation are the same, and there is a clear gap between the small scale real-time solvable mixed integer linear programming approaches presented to date and the full-blown applications that have been proposed for UAV/UGV teams.
4. *Multi-vehicle localization*: Much of the relative localization work for UAV/UGV teams has assumed that the aerial vehicle motion is well understood and that GPS is at least sometimes available to ground vehicles. In dense forest, with small aerial vehicles, these types of assumptions may not be valid, and the value of multiple vehicles may become even greater, as mutual localization should be possible. Reliable intra-team localization would also be a boon to the 3D mapping problem, as it should make feature matching from widely differing perspectives more tractable by providing good initial estimates for subsequent refinement.
5. *Aerial/ground perspective correspondence*: Finally, it has not yet been demonstrated that aerial and ground data from lasers, cameras or both, can be reliably combined into dense 3D representations of the environment, without reliance on global positioning and expensive high-accuracy inertial measurements. The work in this area is promising but highlights a problem somewhat unique to the aerial and ground vehicle team coordination domain. Feature or structure correspondence from wildly different perspectives is not straightforward and involves matching point clouds with large amounts of occlusion, or of identifying the same visual elements from wildly different points of view. Most SLAM algorithms rely heavily on the ability to find correspondence between measurements from different viewpoints, and without this critical capability for UAV/UGV teams, it is not possible to fully exploit the information available to the team in reconstructing 3D representations of the environment.

In summary, the field of UAV/UGV coordination is both well established, in terms of the quantity of useful algorithms and convincing results developed to date, and wide open, in terms of the number of challenging problems that remain to be solved prior to full-fledged deployment in realistic applications. As such, the area is ripe for major contributions in the coming years, as more and more teams around the globe become proficient in UAV and UGV design and development and as the limitations of existing methods are brought more clearly into focus through experimentation.

References

1. Rao R, Kumar V, Taylor C (2003) Visual servoing of a UGV from a UAV using differential flatness. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems, Las Vegas, NV, USA, pp 743–748
2. Zhang T, Li W, Achtelik M, Kuhnlenz K, Buss M (2009) Multi-sensory motion estimation and control of a mini-quadrotor in an air-ground multi-robot system. In: Proceedings of 2009 I.E. international conference on robotics and biomimetics (ROBIO), 19–23 December 2009, Guilin, China, pp 45–50
3. Rudol P, Wzorek M, Conte G (2008) Micro unmanned aerial vehicle visual serving for cooperative indoor exploration. In: Proceedings of IEEE aerospace conference, Montana
4. Schweighofer G (2006) Robust pose estimation from a planar target. IEEE Trans Pattern Anal Mach Intell 28(12):2024–2030
5. Chaimowics L, Grocholsky B, Keller J, Kumar V, Taylor C (2004) Experiments in multirobot air-ground coordination. In: Proceedings of the IEEE international conference on robotics & automation, New Orleans, April 2004, pp 4053–4058
6. Chaimowicz L, Cowley A, Gomez-Ibanez D, Grocholsky B, Hsieh M, Hsu H, Keller J, Kumar V, Swaminathan R, Taylor C (2005) Deploying air-ground multi-robot teams in urban environments. Multi-robot systems. From swarms to intelligent automata, Vol III. Springer, pp 223–234
7. Esmailifar SM, Saghafi F (2009) Autonomous unmanned helicopter landing system design for safe touchdown on 6DOF moving platform. In: Fifth international conference on autonomic and autonomous systems, 20–25 April 2009, Valencia, Spain, pp 245–250
8. Voos H, Bou-Ammar H (2010) Nonlinear tracking and landing controller for quadrotor aerial robots. In: 2010 I.E. international conference on control applications (CCA), Yokohama, pp 2136–2141
9. Li W, Zhang T, Klihnlenz K (2011) A vision-guided autonomous quadrotor in an air-ground multi-robot system. In: Proceedings of 2011 I.E. international conference on robotics and automation (ICRA), 9–13 May 2011, Shanghai, China, pp 2980–2985
10. Daly JM, Ma Y, Waslander SL (2011) Coordinated landing of a quadrotor on a skid-steered ground vehicle in the presence of time delays. In: Proceedings of 2011 IEEE/RSJ international conference on intelligent robots and systems (IROS), San Francisco, 25–30 September 2011, pp 4961–4966
11. Ma Y (2012) Coordinated landing and mapping with aerial and ground vehicle teams. Master's Thesis. University of Waterloo, Waterloo (August 2012)
12. Duan HB, Liu SQ (2010) Unmanned air/ground vehicles heterogeneous cooperative techniques: current status and prospects. Sci China Technol Sci (Springer) 53(5):1349–1355
13. Schulteis T, Price J (2004) Project stork UAV/UGV collaborative initiative. In: Proceedings of unmanned ground vehicle technology IV, SPIE, vol 5422, Bellingham
14. Michael N, Fink J, Kumar V (2007) Controlling a team of ground robots via an aerial robot. In: Proceedings of IEEE/RSJ international conference on intelligent robots and systems, San Diego, pp 965–970
15. Chaimowicz L, Kumar V (2007) Aerial shepherds: coordination among UAVs and swarms of robots. In: Distributed autonomous robotic systems, vol 6. Springer, Springer Heidelberg New York Dordrecht London, pp 243–252
16. Tanner HG, Christodoulakis D (2007) Decentralized cooperative control of heterogeneous vehicle groups. Robots Auton Syst 55(11):811–823
17. Chandrashekar K, Dekhordi MR, Baras JS (2004) Providing full connectivity in large ad-hoc networks by dynamic placement of aerial platforms. In: Proceedings of IEEE military communications conference, Monterey, pp 1429–1436
18. Gil S, Schwager M, Julian BJ, Rus D (2010) Optimizing communication in air-ground robot networks using decentralized control. In: Proceedings of 2010 I.E. international conference on robotics and automation (ICRA), 3–7 May 2010, Anchorage, Alaska, USA, pp 1964–1971

19. Grocholsky B, Keller J, Kumar V, Pappas G (2006) Cooperative air and ground surveillance. IEEE Rob Autom Mag 13(3):16–25
20. Grocholsky B, Bayraktar S, Kumar V, Taylor C, Pappas G (2006) Synergies in feature localization by air-ground robot teams. In: Ang M, Khatib O (eds) Experimental robotics IX, Springer tracts in advanced robotics, vol 21. Springer, Berlin, pp 352–361
21. Tanner HG (2007) Switched UAV-UGV cooperation scheme for target detection. In: Proceedings of IEEE international conference on robotics and automation, Roma, pp 3457–3462
22. Vidal R, Rashid S, Sharp C, Shakernia O, Kim J, Sastry S (2001) Pursuit evasion games with unmanned ground and air vehicles. In: Proceedings of IEEE/RSJ international conference on robotics and automation, Seoul, May 2001
23. Vidal R, Shakernia O, Kim HJ, Shim DH, Sastry S (2002) Probabilistic pursuit-evasion games: theory, implementation, and experimental evaluation. IEEE Trans Rob Autom 18(5):662–669
24. Phan C, Liu HHT (2008) A cooperative UAV/UGV platform for wildfire detection and fighting. In: 7th international conference on system simulation and scientific computing, Chengdu, China, pp 494–498
25. How JP, Fraser C, Kulling KC, Bertuccelli LF, Toupet O, Brunet L, Bachrach A, Roy N (2009) Increasing autonomy of UAVs. IEEE Rob Autom Mag 16(2):43–51
26. How JP, Bethke B, Frank A, Dale D, Vian J (2008) Real-time indoor autonomous vehicle test environment. IEEE Control Syst Mag 28(2):51–64
27. Stentz T, Kelly A, Herman H, Rander P, Amidi O, Mandelbaum R (2002) Integrated air/ground vehicle system for semi-autonomous off-road navigation. Robotics Institute Technical Report Paper 18
28. Vandapel N, Donamukkala RR, Hebert M (2006) Unmanned ground vehicle navigation using aerial ladar data. Int J Rob Res 25(1):31–51
29. Lacroix S, Le Besnerais G (2011) Issues in cooperative air/ground robotic systems. In: Kaneko M, Nakamura Y (eds) Robotics research, vol 66, Springer tracts in advanced robotics. Springer, Berlin, pp 421–432
30. Thompson P, Sukkarieh S (2006) Development of an angular characterisation system for cooperative UAV/UGV applications. In: Corke P, Sukkariah S (eds) Field and service robotics, Springer tracts in advanced robotics. Springer, Berlin, pp 105–116. ISBN 978-3-540-33452-1
31. Vidal T, Berger C, Sola J, Lacroix S (2011) Environment modeling for cooperative aerial/ground robotic systems. In: Pradalier C, Siegwart R, Hirzinger G (eds) Robotics research, vol 70, Springer tracts in advanced robotics. Springer, Berlin, pp 681–696