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Unmanned air/ground vehicles heterogeneous cooperative techniques: Current status and prospects

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Multiple unmanned air/ground vehicles heterogeneous cooperation is a novel and challenging filed. Heterogeneous cooperative techniques can widen the application fields of unmanned air or ground vehicles, and enhance the effectiveness of implementing detection, search and rescue tasks. This paper mainly focused on the key issues in multiple unmanned air/ground vehicles heterogeneous cooperation, including heterogeneous flocking, formation control, formation stability, network control, and actual applications. The main problems and future directions in this field were also analyzed in detail. These innovative technologies can significantly enhance the effectiveness of implementing complicated tasks, which definitely provide a series of novel breakthroughs for the intelligence, integration and advancement of future robot systems.

unmanned air vehicle (UAV), unmanned ground vehicle (UGV), heterogeneous cooperation

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1 Introduction

With the advances in science and technology and the escalation of air combat, the air defense weapons become more and more sophisticated. The survival conditions of the combat aircraft and pilots are worsening, and many new technologies are adopted to improve the combating performance. In this case, unmanned air vehicle (UAV) is born. Compared with manned aircrafts, UAV has the advantages of zero casualties, high-speed overload, good stealth performance, short operational preparation time, and relatively low life-cycle cost. These advantages increase the capability of high-risk targets penetration, suppressing enemy air defense, deep target attacking and dominating the battle space. In this way, UAV can play a variety of unique roles in strategic, operational and tactical level operations, and will also be in a prominent place in the future complicated wars. For the increasingly complicated battlefield environments, the tactical missions are generally with high multiplicity and complexity, and a single UAV can hardly complete the assigned task, thus multiple UAVs cooperation has become an inevitable choice. Cooperation is one of the key technologies for multiple UAVs, which mainly includes trajectory planning and re-planning, task allocation, formation flying and reconfiguration, situation assessment, communication, and information fusion. Western countries have achieved a leading position in multiple UAVs technology and exact implementation, while there are still a lot of research gaps in multiple UAVs cooperative control technology.

Unmanned ground vehicle (UGV) is a type of robotic platform that is used as an extension of human capability. This type of robot is generally capable of operating outdoors and over a wide variety of terrain, functioning in place of humans. A fully autonomous UGV in the real world has the ability to gain information about the envi-

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*Corresponding author (email: hbduan@buaa.edu.cn) ronments, work for extended durations without human intervention, travel from one place to another place without human navigation assistance, avoid dangerous situations, repair itself without outside assistances, and detect objects of interests.

Multiple UAVs can be used to cover large areas to search for targets [1]. However, sensors on UAVs are typically limited in operating airspeed and altitude. This, combined with attitude uncertainty, places a lower limit on their ability to resolve and localize ground features. UGVs on the other hand can be deployed to accurately locate ground targets, but they have the disadvantage of not being able to move rapidly or see through such obstacles as buildings or fences. Therefore, multiple UAVs/UGVs heterogeneous cooperation provides a new breakthrough for the effective application of UAV and UGV (see Figure 1).

This paper mainly focuses on the key issues in multiple unmanned air/ground vehicles heterogeneous cooperation, which include: 1) heterogeneous flocking, 2) formation control, 3) formation stability, 4) network control, 5) actual applications. Finally, the main problems and future directions in this field are also analyzed in detail.

2 Heterogeneous flocking

Refs. [2–13] presented a detailed study on the main problems (such as distributed and combination) in heterogeneous agents flocking. The work in ref. [2] gave a hierarchical architecture in which a few number of UAVs were used to command, control and monitor swarms of UGVs. Refs. [6, 11] proposed the concept of maintaining cohesion and separation behavior by means of inter-agent potential forces. Refs. [7, 13] mainly focused on a group of nonholonomic mobile agents that can synchronize their headings and speeds using local control laws.

Ref. [2] developed a hierarchical architecture to allow a group of UAVs to coordinate and control swarms of UGVs. The third level of the hierarchy is composed of medium altitude UAVs that hover over the groups. Every group must have a shepherd UAV but one UAV can escort one or more groups simultaneously (see Figure 2).

The initial assignment of UAVs to groups is done in a distributed manner using the EM algorithm and the UAVs are responsible for controlling the groups' shape, pose and motion. An important feature of this architecture is that the communication requirements grow linearly with the number of vehicles, making it scalable to tens and hundreds of robots. But this work failed to execute simulations to obtain more detailed performance measurements of this architecture, especially in regard to communication and control.

Ref. [3] developed an abstraction for the team of UGVs that allows the UAV platform to control the team without any knowledge of the specificity of individual vehicles. This happens in much the same way as a human operator can control a single UGV by simply commanding the forward and turning velocities without a detailed knowledge of the specifics of the vehicle. The abstraction includes a gross model of the shape of the formation of the team and information about the position and orientation of the team in the plane. They derived controllers that allow the team of vehicles to move in formation while avoiding collisions and respecting the abstraction commanded by the aerial platform. Ref. [3] overcomed the key limitation of ref. [4] in that the need for a global observer to provide estimates of the abstract state.

Figure 1 Multiple UAVs and UGVs heterogeneous cooperation scenario.

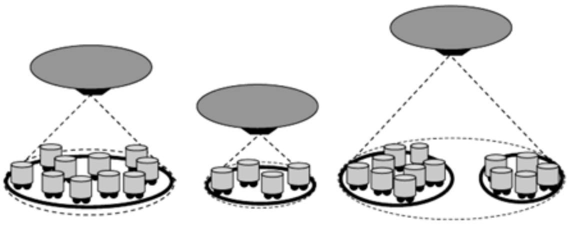

Figure 2 Hierarchical architecture in which three UAVs shepherd a number of groups of UGVs.

Ref. [6] coordinated in discrete time the interaction of two heterogeneous groups of UGVs and UAVs. The UGVs interacted with each other through time-invariant, nearest-neighbour rules. The UGVs estimated their formation's centroid using only locally available delayed information. That same information was transmitted to the UAV group, which orbited above the ground formation's centroid, while avoiding midair collisions. A Lyapunov analysis was also used to ensure that UAVs tracked the UGV group's centroid. Ref. [7] focused on the motion of a group of synchronized nonholonomic mobile agents by using local control laws, and the synchronization strategy was inspired by the early flocking model proposed in refs. [8–10], which could ensure that all agent headings and speeds converged asymptotically to the same value and collisions between the agents were avoided.

In ref. [11], the flocking behavior of UGVs and UAVs emerged from aggregating the control actions of all group members; it was not imposed by some centralized control scheme. Each vehicle was locally controlled by a combination of a potential field force and an alignment force. The former control component ensured collision avoidance and attraction towards the group, while the latter steered each vehicle to the average heading of its 'neighbors'. Ref. [12] used the force sensors for robot navigation in an unknown environment, offering guarantees of convergence to a desired configuration and recovery from collisions. Ref. [13] proposed a set of nonsmooth control laws that enabled a group of vehicles to synchronize their velocity vectors and move as a flock while avoiding collisions with each other and with static obstacles in their environment. The proposed control law could steer each vehicle based on local information that was obtained from a spherical neighborhood around it. Only the nearest neighbors and obstacles might affect a vehicle's motion, as the vehicles moved the neighborhoods change discontinuously.

3 Formation control

Refs. [14–24] discussed the formation control problem, among which ref. [14] proposed a vision-based formation controller; refs. [17, 23, 24] mainly focused on decentralized navigation functions for formation control; refs. [19, 20] analyzed the leader-to-formation stability.

Ref. [14] described a framework for coordinating multiple robots in cooperative manipulation tasks in which vision was used for establishing relative position and orientation and maintaining formation. Ref. [17] designed a switched cooperative control scheme that could scale nicely with the size of the UAVs and UGVs for the purpose of locating a moving target in a given area, in which the distributed synchronization algorithms and navigation functions presented in ref. [18] were used for formation control.

Ref. [20] introduced a leader-to-formation stability (LFS) gains in an effort to characterize analysis of how leader inputs and disturbances affected the stability of the group (see Figure 3).

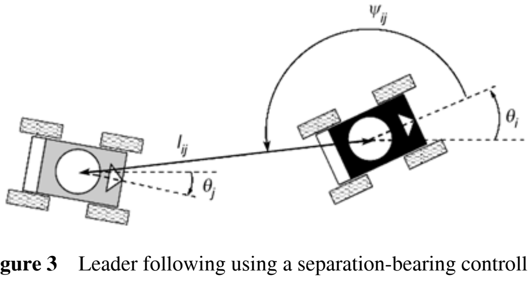

Figure 3 Leader following using a separation-bearing controller.

A formation control graph $F_c=(V, E, D)$ is a directed acyclic graph consisting of

1) a finite set $V=\{v_1,\ldots, v_p\}$ of p vertices and a map assigning to each vertex v_i a control system $\dot{x}_i = f_i(t,x_i,u_i)$, where $x_i \in R^n$ and $u_i \in R^m$;

2) an edge set $E \subset V \times V$ encoding leader-follower relationships between agents;

3) a collection $D=\{d_{ij}\}$ of edge specifications, defining control objectives (setpoints) for each j:$(v_j,v_i) \in E$ for some $v_i \in V$.

The above notion is based on input-to-state stability and its invariance properties under cascading in refs. [21, 22], and LFS quantifies error amplification during signal propagation in leader-following formations. Ref. [23] presented a navigation function through which a group of mobile agents could be coordinated to achieve a particular formation, both in terms of shape and orientation, while avoiding collisions between themselves and with obstacles in the environment. Ref. [24] developed a motion planner and nonholonomic controller for a mobile UGV, with global collision avoidance and convergence properties, but that work needs extension to multiple UAVs or UGVs systems with articulated mechanisms and considering the full dynamics.

4 Formation stability analysis

Refs. [18, 19, 20, 25] analyzed the stability of flocking and formation control. Among them, ref. [18] verified that the direction of local potential function was a direction along which some common Lyapunov function decreased monotonically; ref. [19] presented a methodology for analyzing the stability properties of formations of vehicles based on the notion of input-to-state stability (ISS). The approach exploits the property of ISS to be preserved in certain types of cascade and feedback interconnections in order to propagate stability bounds from a leader-follower pair to the whole group. The methodology allows the characterization of different formation structures in terms of stability and provides formal justification for experimental data concerning the effect of network topology on stability.

Ref. [20] investigated the stability properties of mobile agent formations based on leader-following, and the nonlinear gain estimates were derived to capture how leader behavior affected the interconnection errors observed in the formation; ref. [25] developed a discontinuous backstepping approach for stabilization of nonholonomic UGVs. The methodology is not restricted, but can be applied to a broad class of strictly feedback discontinuous nonlinear systems. It was also indicated that backstepping discontinuous reference control signals can help alleviate the effect of chattering.

5 Network control

Since Wiener N published the book: "Cybernetics: Or the Control and Communication in the Animal and the Machine" in 1948 [26], how to improve communication between man and machine has become a key issue. With the development and mutual penetration among the control, networking and communication technologies, the control system structure becomes more and more complex, and the requirements for complex system control performance are increasingly stringent. Refs. [27–32] applied the network control technologies to heterogeneous cooperation.

Ref. [27] presented a robust decentralized algorithm for mapping the nodes in a sparsely connected sensor network using range-only measurements and odometry from a UGV. This approach utilizes an extended Kalman filter (EKF) in polar space to model the nonlinearities within the range-only measurements using Gaussian distributions.

Communication is essential for coordination in most cooperative control and sensing paradigms. Ref. [28] proposed an experimental study of strategies for maintaining end-to-end communication links for tasks such as surveillance and search and rescue where team connectivity is essential for providing situational awareness to a base station. This approach considered the differences of monitoring point-to-point signal strength versus data throughput.

Ref. [29] showed that if an interconnected system of agents with time-invariant, nearest neighbor interaction laws is stable (in the sense that all agents states asymptotically synchronize), the introduction of communication delays in the dissemination of state information between neighboring agents does not disrupt the stability of the system. This was shown formally in discrete time, by exploiting properties of special classes of non-negative matrices and by observing that the system trajectories are not affected by parts of the full-blown delayed dynamics.

Ref. [30] discussed the interplay between networks and control systems. Ref. [32] addressed the problem of providing full connectivity to disconnected ground MANET nodes by dynamically placing UAVs to act as relay nodes, and a heuristic algorithm was provided to find the minimal number of such UAVs required to provide full connectivity and find the corresponding locations for these UAVs. The movement of the UGVs was also tracked, and the location of the UAVs was updated from time to time. The communication architecture was designed to work with the existing MANET routing protocols (see Figure 4).

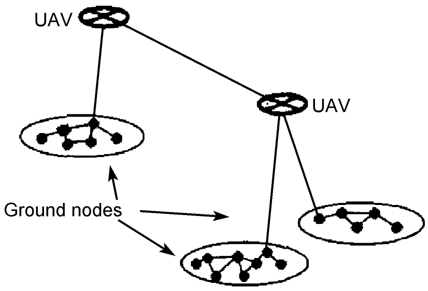

Figure 4 MANET with three partitions and two connecting UAVs.

6 Actual applications

6.1 Searching and localization

Automatic target recognition is one of the key tasks for the reconnaissance UAVs or UGVs. There are some key problems to tackle with, such as the number of reconnaissance UAVs or UGVs used in a number of interactions, the network delay for central positioning, and the perceiving ability of attack systems for positioning centers. Ref. [33] mainly focused on the coordination aspects between UAVs to efficiently decide how they are to act by using a swarming mechanism, and described algorithms for the different operations performed by the UAVs in the system and for different swarming strategies, which are embedded within software agents located on the UAVs. Ref. [34] described the implementation of a decentralized architecture for autonomous teams of UAVs and UGVs engaged in active perception, and also proposed a theoretical framework based on an established approach to the underlying sensor fusion problem. This provided transparent integration of information from heterogeneous sources, and the approach was applied to missions involving searching for and tracking multiple ground targets.

Ref. [35] presented some of the efforts that had been done by the GRASP Laboratory of University of Pennsylvania for deploying teams of UAVs and UGVs in urban environments as part of the MARS2020 project. Sponsored by Defence Advanced Research Projects Agency (DARPA), this project focused on the development of critical technologies required to realize network-centric control of heterogeneous platforms that is strategically responsive, survivable and sustainable for reconnaissance, surveillance or search and rescue type missions. In this endeavor, the University of Pennsylvania was teamed with the Georgia Institute of Technology and the University of Southern California. The multi-robot team consisted of 5 UGVs, 2 fixed wing UAVs and a blimp (see Figure 5).

Ref. [36] presented a complete system which incorporates a vision-based pose estimation method to allow an MAV to navigate in indoor environments in cooperation with a ground robot (see Figure 6).

The pose estimation technique uses a lightweight light

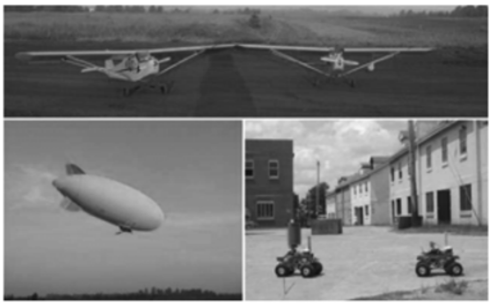

Figure 5 Multi-robot team composed of air and ground vehicles.

Figure 6 Main elements of the experimental system: The LinkMAV and the ground robot.

emitting diode (LED) cube structure as a pattern attached to an MAV. The pattern is observed by a ground robot's camera which provides the flying robot with the estimate of its pose. The system is not confined to a single location and allows for cooperative exploration of unknown environments. It is suitable for performing missions of a search and rescue nature where the MAV extends the range of sensors of the ground robot. All functional subcomponents and interconnections between them are presented in Figure 7.

6.2 Tracking and pursuit-evasion

As safety and security has become a critical problem worldwide, aerial video surveillance (AVS) systems based on UAV or UGV have now been playing more and more important roles in not only civil but also military applications. Active vision is a kind of intelligent visual information acquisition mechanism. It is based on actively changing the sensor orientation and location to acquire visual information. Ref. [37] presented an active vision based video surveillance system that is schematically shown in Figure 8.

Ref. [38] developed a system- and control-oriented intelligent agent framework called the hybrid intelligent control agent (HICA), as well as its composition into specific kinds of multi-agent systems. HICA is essentially developed around a hybrid control system core so that knowledge-based planning and coordination can be integrated with verified hybrid control primitives to achieve the coordinated control of multiple multimode dynamical systems. The scheme was successfully applied to the control of teams of UAVs and UGVs engaged in a pursuit-evasion war game. Figure 9 describes a conceptual view of multivehicle-pursuit-evasion involving UAVs and UGVs.

Ref. [39] proposed a generally applicable method for the tracking of UGVs by UAVs. The beauty of this approach is that the only information provided to the UAV guidance system was waypoints required to establish and maintain track of the target. Therefore, no modification of any sort was required on the UAV's guidance and control systems. As long as the vehicle could follow simple waypoint commands in a closed loop, it would work with the proposed method. Another advantage is that it works very well for UAVs that have sensors of fixed attitude and geometry. Ref. [40] presented a leader-follower control law

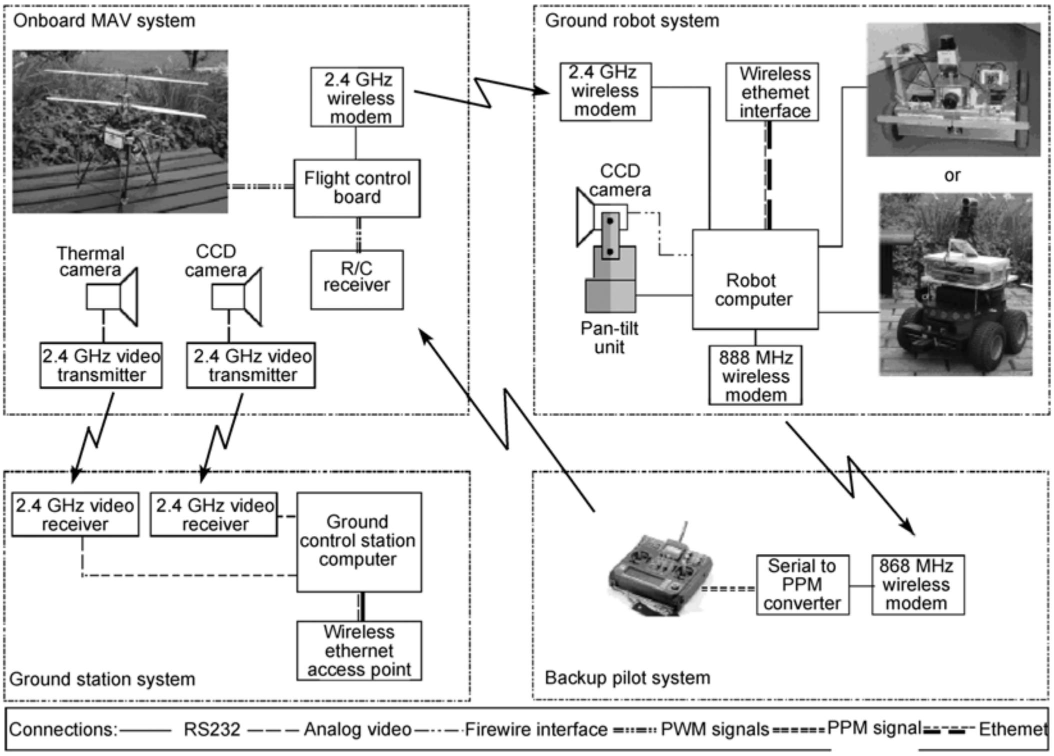

Figure 7 The experimental system subcomponents and interconnections between UAV and UGV.

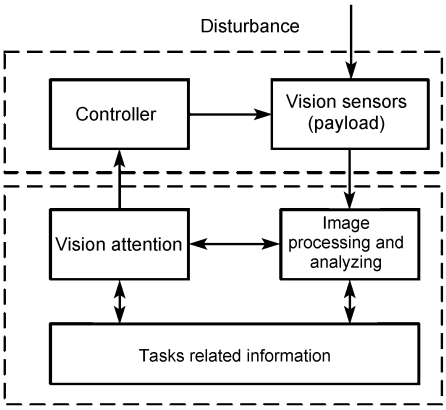

Figure 8 Active vision based video surveillance system.

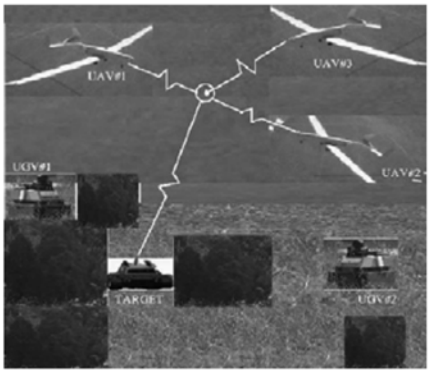

Figure 9 Conceptual view of multivehicle-pursuit-evasion involving UAVs and UGVs.

that made a mobile robot track a desired trajectory at a specific position in the plane with respect to its leader, and it highlighted its potential use in formation control. This control law has been designed using backstepping, based on a unicycle model that includes a dynamic extension.

7 Future orientations

Although multiple UAVs and UGVs heterogeneous cooperation has made great progresses in the past years, there are still some fundamental and interesting issues in this specific field that are worth probing further.

(1) The current progresses in this field is rather superficial, the dynamic and time-varying topology of the multiple UAVs and UGVs flocking system is a promising direction. Furthermore, how to construct a more complex environment with multi-functional vehicle systems is also an interesting research direction.

(2) For the flocking movement and formation control of multiple UAVs and UGVs, there are various methods, and the stability and robustness of these approaches need further analysis. A more in-depth theoretical foundation of heterogeneous cooperative control should be established before rushing into large-scale multiple UAVs and UGVs heterogeneous system implementation.

(3) In heterogeneous UAVs and UGVs systems, it is rather difficult to design the communication structure which meets the requirements of real-time communication among UAVs and UGVs. There are strong connections with cooperative control, but usually it is less concerned with the data rate through a communication channel than with the patterns of information flow among the networked agents. Implementation issues in both hardware and software are at the center of successful deployment of networked control systems. Data integrity and security are also very important and may lead to special considerations in control system design even at an early stage.

(4) Future framework to analyze and design algorithms for the pursuit evasion games with sensor networks should include a more extensive comparison in order to evaluate possible trade-offs between the two. Also, the algorithms can be extended more rigorously when there are more pursuers than evaders and coordinated maneuvering of pursuers allows the capture of ”fast and smart” evaders similarly as observed in mobs of lions hunting an agile pray.

8 Conclusion

This paper reviewed the recent advances in multiple UAVs and UGVs heterogeneous cooperation, and we attempted to provide an insightful source for the researchers and scholars interested in this new field. We believe that the exact realization of multiple UAVs and UGVs heterogeneous cooperation can significantly enhance the effectiveness of implementing complicated tasks, which can definitely provide a series of novel breakthroughs for the intelligence, integration and advancement of future robot systems.

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1 Grocholsky B, Keller J, Kumar V, et al. Cooperative air and ground surveillance: A scalable approach to the detection and localization of targets by a network of UAVs and UGVs. IEEE Robot Autom Mag, 2006, 13: 16–26
2 Chaimowicz L, Kumar V. Distributed Autonomous Robotic Systems. Japan: Springer, 2007. 243–252
3 Nathan M, Jonathan F, Vijay K. Controlling a team of ground robots via an aerial robot. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. San Diego: IEEE, 2007. 965–970
4 Michael N, Belta C, Kumar V. Controlling three dimensional swarms of robots. In: Proceedings of IEEE International Conference on Robotics and Automation. Orlando: IEEE, 2006. 964–969
5 Reynolds C. Flocks, birds, and schools: a distributed behavioral model. Comput Graph, 1987, 21: 25–34
6 Tanner H G, Christodoulakis D. Decentralized cooperative control of heterogeneous vehicle groups. Robot Auton Syst, 2007, 55: 811–823

7 Tanner H G, Jadbabaie A, George J. Flocking in teams of nonholonomic agents. Lecture Notes in Control and Information Sciences, 2009. 229–239

8 Reynolds C. Flocks, birds, and schools: a distributed behavioral model. Comput Graph, 1987, 21: 25–34

9 Vicsek T, Czirok A, Ben J E. Novel type of phase transitions in a system of self-driven particles. Phys Rev Lett, 1995, 75: 1226–1229

10 Jadbabaie A, Lin J, Morse A S. Coordination of groups of mobile autonomous agents using nearest neighbor rules. IEEE T Automat Contr, 2002, 48: 988–1001

11 Tanner H G, Jadbabaie A, Pappas G J. Coordination of multiple autonomous agents. In: Proceedings of the 11th Mediterranean Conference on Control and Automation. Washington D C, 2003. 3448–3453

12 Dushyant P, Herbert T. Hybrid velocity/force control for robot navigation in compliant unknown environments. Robotica, 2006, 24: 745–758

13 Tanner H G. Flocking with obstacle avoidance in switching networks of interconnected vehicles. In: Proceedings of IEEE International Conference on Robotics and Automation. Barcelona: IEEE, 2004. 3006–3011

14 Spletzer J, Das A K, Fierro R. Cooperative localization and control for multi-robot manipulation. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. Maui: IEEE, 2001. 567–573

15 Alur R. A framework and architecture for multirobot coordination. In: Proceedings of the 7th International Symposium on Experimental Robotics. Honolulu: IEEE, 2000. 977–995

16 Desai J, Ostrowski J P, Kumar V. Controlling formations of multiple mobile robots. In: Proceedings of IEEE International Conference on Robotics and Automation. Leuven: IEEE, 1998. 2864–2869

17 Tanner H G. Switched UAV-UGV cooperation scheme for target detection. In: Proceedings of IEEE International Conference on Robotics and Automation. Roma: IEEE, 2007. 3457–3462

18 Herbert G T, Amit K. Formation Stabilization of Multiple Agents Using Decentralized Navigation Functions. Robotics: Science and Systems I, MIT Press, 2005. 49–56

19 Herbert G T, Vijay K, George J P. Stability properties of interconnected vehicles. In: Proceedings of the 15th International Symposium on Mathematical Theory of Networks and Systems. Notre Dame: IEEE, 2002. 1–12

20 Herbert G, George J P, Vijay K. Leader-to-formation stability. IEEE T Robotic Autom, 2004, 20: 433–455

21 Krstic M, Kanellakopoulos I, Kokotovic P. Nonlinear and Adaptive Control Design. New York: John Willey and Sons, 1995

22 Isidori A. Nonlinear Control Systems II. Berlin: Springer, 1999

23 Herbert G T, Amit K. Towards decentralization of mutli-robot navigation functions. In: Proceedings of IEEE International Conference on Robotics and Automation. Barcelona: IEEE, 2005. 4143–4148

24 Tanner H G, Loizou S, Kyriakopoulos K J. Nonholonomic stabilization with collision avoidance for mobile robots. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. Hawaii: IEEE, 2001. 1220–1225

25 Tanner H G, Kyriakopoulos K J. Discontinuous backstepping for stabilization of nonholonomic mobile robots. In: Proceedings of the IEEE International Conference on Robotics and Automation. Washington D C: IEEE, 2002. 3948–3953

26 Wiener N. Cybernetics: Or the Control and Communication in the Animal and the Machine. New York: John Wiley & Sons, Inc., 1948

27 Joseph D, Sanjiv S, Benjamin G. Decentralized mapping of robot-aided sensor networks. In: Proceedings of IEEE International Conference on Robotics and Automation. California: IEEE, 2008. 583–589

28 Mong-ying A H, Anthony C, Vijay K. Towards the deployment of a mobile robot network with end-to-end performance guarantees. In: Proceedings of IEEE International Conference on Robotics and Automation. Florida: IEEE, 2006. 2085–2090

29 Tanner H G, Christodoulakis D K. State synchronization in local-interaction networks is robust with respect to time delays. In: Proceedings of 44th IEEE Conference on Decision and Control. Spain: IEEE, 2005. 4945–4950

30 Clauset A, Tanner H G, Abdallah C T, et al. Controlling across complex networks; emerging links between networks and control. Annu Rev Control, 2008, 32: 183–192

31 Tanner H G, Christodoulakis D K. Cooperation between aerial and ground vehicle groups for reconnaissance missions. In: Proceedings of the 45th IEEE Conference on Decision and Control. San Diego: IEEE, 2006. 5918–5923

32 Chandrashekar K, Dekhordi M R, Baras J S. Providing full connectivity in large ad-hoc networks by dynamic placement of aerial platforms. In: Proceedings of IEEE Military Communications Conference. Monterey: IEEE, 2004. 1429–1436

33 Prithviraj D. A multiagent swarming system for distributed automatic target recognition using unmanned aerial vehicles. IEEE T Syst Man Cy A, 2008, 38: 549–563

34 Ben G, Selcuk B, Vijay K. Synergies in feature localization by air-ground robot teams. In: Proceedings of International Symposium on Experimental Robotics. Singapore: IEEE, 2004. 353–362

35 Chaimowicz L, Cowley A, Gomez-Ibanez D. Deploying air-ground multi-robot teams in urban environments. In: Proceedings of the 2005 International Workshop on Multi-Robot Systems. Washington D C: IEEE, 2005. 1–12

36 Rudol P, Wzorek M, Conte G. Micro unmanned aerial vehicle visual serving for cooperative indoor exploration. In: Proceedings of IEEE Aerospace Conference. Montana: IEEE, 2008. 1–10

37 Li Z J, Ding J R. Ground moving target tracking control system design for UAV surveillance. In: Proceedings of IEEE International Conference on Automation and Logistics. Jinan: IEEE, 2007. 1458–1463

38 Fregene K, Kennedy D C, Wang D W L. Toward a systems- and control-oriented agent framework. IEEE T Syst Man Cy B, 2005, 35: 999–1012

39 Ariyur K B, Fregene K O. Autonomous tracking of a ground vehicle by a UAV. In: Proceedings of American Control Conference. Seattle: IEEE, 2008. 669–671

40 Jorge L P, Chaouki T A, Herbert G T. Leader-follower control with odometry error analysis. In: Proceedings of European Control Conference, Kos, Greece, 2007. 3783–3789