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Conference Paper · June 2019

DOI: 10.1109/CCDC.2019.8833330

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A distributed and modularised coordination framework for mission oriented fixed-wing UAV swarms

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Abstract: In this paper, a distributed and modularised coordination framework for mission oriented fixed-wing UAV swarms is proposed. The framework is fully distributed such that no central point is needed for coordination. Each UAV makes decision based on the information from the neighbors autonomously so as to achieve better scalability. Besides, the proposed framework is modularised into many modules with interfaces of inputs and outputs. Thus, the complexity of developing a large system can be reduced and different missions can be feasibly extended to the swarm system. Through field experiments with 21 fixed-wing UAVs, we evaluate the proposed framework and successfully demonstrate coordination missions such as formation flight, target recognition and tracking.

Key Words: UAV swarms, framework, fixed-wing UAV, coordination

1 INTRODUCTION

Unmanned aerial vehicles (UAVs) have attracted much attention due to their large potential application value in recent years. Applications in both civilian and military such as plan protection, disaster rescue, reconnaissance and surveillance leverage UAV technology extensively. As the complexity of the mission increases, a swarm of UAVs, which is able to provide more effective operational capabilities to accomplish complex tasks which cannot be well accomplished by a single UAV, have gained much popularity.

In the last decade, many researchers have devoted tremendous efforts to studying UAV swarms from different prospectives [1, 2, 3, 4]. However, most of the aforementioned works focus on the specified missions such as formation control [1, 2], search-and-rescue[3], transportation [4], etc. Few is revealed in the perspective of the framework design that aims to integrate different missions and functionalities, especially for fixed-wing UAV swarms, up to the authors's knowledge.

There are three main challenges for designing a framework for UAV swarms. Firstly, how to support a large scale of UAVs. More importantly, how to integrate diversified missions. Last but not least, how to handle heterogeneous aerial platforms. Unfortunately, the existing frameworks cannot effectively tackle all these three challenges. Sanchez-Lopez et al. [5] propose an framework named by AeroStack for multi-UAV systems. This framework uses a five layers architecture, i.e., reactive, executive, deliberative, reflective and social layers. Grabe et al. [6] propose Telekyb, an end-to-end control framework for controlling heterogeneous UAVs. Kohlbrecher et al. proposes the "hector quadroto" framework that focuses on heterogeneous cooperation for search and rescue (SAR) tasks. However, all of these frameworks are evaluated by experiments of small scales of UAVs (i.e. two to five). It is known that with the scale increases, system designs are more challenging both theoretically and practically. Besides, these frameworks are proposed for quadrotors but not for the fixed-wing UAVs.

Admittedly, Hauert et al. [7] achieve flocking for a swarm of small fixed-wing flying robots (up to 10 robots) in outdoor experiments. Live-fly field experiments of 50 fixed-wing UAVs are recently documented in [8] and autonomous flight operations are successfully demonstrated. However, these proposals mainly focus on formation flight for UAV swarms, the collective behaviors and mission coordination are not included in this swarm system.

For the purpose of tackling these aforementioned challenges, we propose a distributed and modularised framework for mission oriented fixed-wing UAV swarms in this paper. Compared to existing work, there are three main contributions that are summarized as follow.

- The proposed framework is fully distributed such that no central point is needed for coordination. Each UAV makes decision based on the information of UAV neighbors autonomously. In this way, better scalability of the swarm system can be achieved.
- The proposed framework is modularised into many modules with interfaces of inputs and outputs. Each module can be considered as a blackbox that the detail of its implementation is abstracted away. Thus, this not only reduces the complexity of developing a large system, but also facilitates the system extension to support diversified missions and different platforms.

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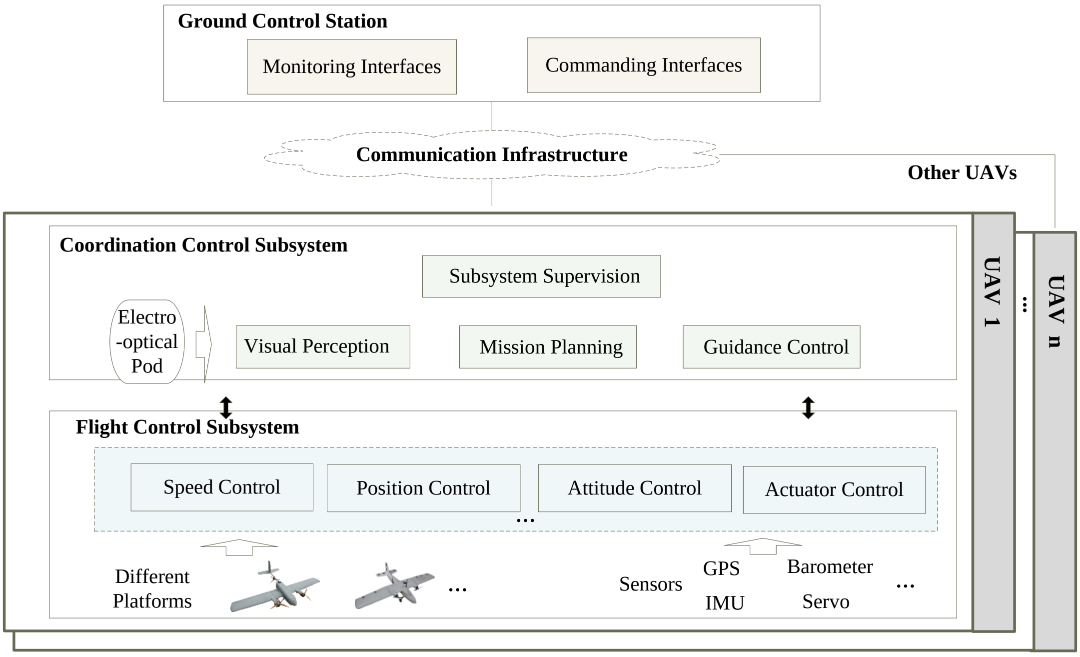


Figure 1: System architecture

- We build a prototype system based on the proposed framework and successfully conduct field experiments using 21 low-cost fixed-wing UAVs. Important missions such as formation flight, target recognition and tracking are demonstrated.

The remainder of this paper is organized as follows. The overall system architecture of UAV swarm is given in Section 2. The detail of the coordination control subsystem is elaborated in Section 3. The field experiment results are presented and analyzed in Section 4. Concluding remarks are finally given in Section 5.

2 SYSTEM ARCHITECTURE

The system architecture is outlined in Fig. 1. It mainly consists of the low-level control subsystem, the high-level control subsystem, the communication infrastructure and the ground control station. The low-level control subsystem is deployed on an embedded real-time operating system (e.g. Nuttx, QNX) which guarantees minimal system interrupt latency and thread switching latency. Hence, it is qualified for the work of low-level flight control (e.g. attitude control). Many open-source flight control software such as PX4 [9], APM [10] and Paparazzi [11] can be used here. The high-level control subsystem is the critical part of the proposed framework. This subsystem is deployed on a high performance on-board processing unit which makes it possible to run computation intensive tasks on-board, such as visual perception, mission management and guidance control. Through communication infrastructure, this subsystem interacts with the ground control station and other UAVs. It is responsible of executing commands from the ground control station, performing coordination control and instructing the low-level control subsystem for flight control (see details in Section 3).

The communication infrastructure facilitates the message transmission among all the components in the swarm system. And the ground control station provides interfaces for monitoring the UAV status, the sensed data and the geographical environment. It also offers interfaces for commanding the UAV swarm system.

This architecture breaks the controlling of the swarm system into two levels. The high level focuses on the coordination tasks and the outer control loops, which has less strict timing but higher computing requirements. In comparison, the low level concentrates on the inner control loops, where the timing requirements may reach the magnitude of microseconds. This design of the two level controlling not only compensates insufficient processing capacities for the embedded real-time platform, but also brings more flexibility on implementing the high-level algorithms. Besides, this architecture is built on the ground of modularity theories. It divides the system functionality to separated modules and abstracts away the implementation details of each module. In this way, each module can be viewed as a black box with interfaces of inputs and outputs, and developers of other parts can easily use the functions provided by the module without the need of knowing the details. As a result, this can significantly reduce the complexity of developing a large system.

Note that based on this system architecture, we have accomplished flight experimentations of a swarm with hybrid aerial platforms including fixed-wing and tilt-rotor aircrafts. Since the paper focuses on the coordination control for the UAV swarms, in the following section, we will provide the details of the high-level subsystem of the proposed framework, which is the critical part of the proposed framework.

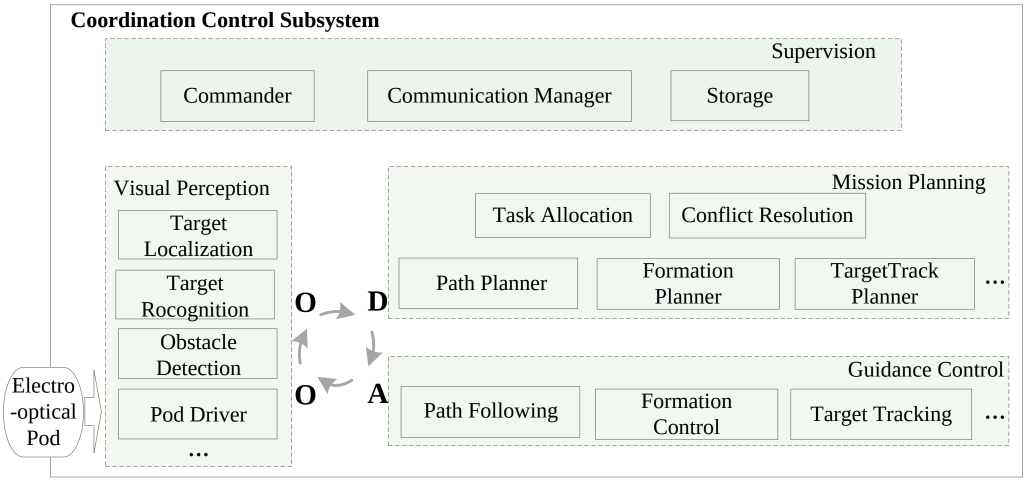


Figure 2: The design of the coordination control subsystem

3 THE COORDINATION CONTROL SUBSYSTEM

The coordination control subsystem concentrates on the tasks such as visual perception, mission planning, guidance control, etc. It leverage the high-performance processing unit to run high computationally demanding algorithms onboard. And it follows the Observe-Orient-Decide-Act loop for realizing swarm autonomous, as shown in Fig. 2. More specifically, a electro-optical pod is attached to this subsystem and the visual perceptional processing module, which provides the information related to the targets, is included in the subsystem. This represents the observe and orient procedures. In addition, the mission planning module is deployed for realizing mission coordination, which produces task plans that can accomplish the user demanding missions. This stands for the decide procedure. Besides, guidance control that intends to guide the UAVs to reach the desired point in coordination with other UAVs is included, which is implied for the act procedure.

3.1 Visual Perception

Perception for UAVs intends to become aware of the current state of itself and the environment through on-board sensors . Due to higher requirements of the update rate, the awareness of its current state (e.g. attitude, velocity and airspeed) is deployed on the low-level control subsystem. Here, we consider to use the vision and range devices. And the visual perception module is responsible of high-level perceptional processing including target recognition, target localization and situation understanding.

Target recognition has been studied for years and plenties of proven solutions have been proposed. Recently, this technique has been widely used in unmanned systems [12]. By attaching cameras or other imaging devices (e.g. infrared and hyper-spectrum), image or video stream can be obtained continuously. Identifying the interested objects from the incoming image or video data in real-time, and thereby providing detection results to other decision module timely becomes an essential procedure of accomplish the missions.

Target localization is trying to localize ground-based objects based on image data from UAVs. By using the target recognition results, the pixel location of the target in an image can be obtained. Hence, according to the pixel location, the UAV's attitude and position, and the camera angles, the target localization in world coordinates can be estimated. Besides, in order to improve the accuracy of estimating the status of targets (e.g. positions, velocities), cooperative target status estimation algorithm using multiple UAVs can be included here [13].

Note that the perception module is not restricted to the tasks introduced above. Other perception tasks such as situation understanding and simultaneous localization and mapping (SLAM) algorithms can also be easily included here.

3.2 Mission planning

Mission planning module produces task plans that satisfies with the requirements for accomplishing the commanding missions while also abiding by constrains such as UAV's payload, endurance and airspace regulations. This is critical for maximizing the capabilities of UAV swarms as well as the quality of the mission execution. Moreover, due to the uncertainty exists while carrying out a mission plan (e.g. UAV failure, obstacle encounter, communication interference, etc.), the ability of re-planning missions adaptively becomes a basic need for achieving autonomy of UAV swarms. The main components of the proposed mission planning module are as follow.

Mission Manager decomposes the received mission into tasks (e.g. Follow a path, Develop a formation, Track targets, Search, etc.). And then the Mission Manager negotiates with other UAVs and allocate the tasks for each UAV in a distributed way. The task allocation schemes such as market-based [14] and network flow approaches [15] can be included here. After that, the tasks assigned to the hosted UAV can be decided. Then the Mission Manager schedules the tasks one by one in a sequential order to different task planners. Note that once a conflict that the an allocated task cannot be completed by the assigned UAV, a task re-allocation might be triggered.

Task Planner is in charge of generating the detailed plan for executing the specific task. More specifically, it receives the information from neighbor UAVs and develops a plan that can be carried out cooperatively. Besides, the task planner monitors the event at runtime and re-plan dynamically once some predefined conditions are triggered. In our proposed architecture, we includes path planner, formation planner and target planner described below.

- Path Planner is responsible for generating collision-free routes that can be satisfied with the task requirements (e.g. destination, threat avoidance, path length) while taking into account the geometric and physical constraints.

- Formation Planner is in charge of configuring the formation patterns of a UAV swarm according to mission requirement and geographical conditions (e.g. crossing a narrow valley).

- Target Tracking Planner is tasked with coordinating UAVs to track one or multiple interested targets. This planner needs to generating routes for arriving at and covering the target area.

3.3 Guidance Control

The guidance control module intends to guide the hosted UAV to reach the desired points or follow the command references produced by the mission planning module. More specifically, it uses the information given by the low-level control subsystem and other UAVs as feedback, and produces the control command references such as desired yaw, speed and height for the hosted UAV. The guidance control algorithms included in our architecture are as follow.

Path following. After completing the path planning, each UAV will need to follow the path accordingly. No matter it is coordinated or singular path following, the core goal of each vehicle is to follow a desired path so that the tracking error remains within an acceptable range. The problem of path following is usually decoupled into two-dimensional path following and height control. Many path following control methods, such as the vector field method [16] and PLOS[17], can be used here.

Formation control. The formation control intends to control a group of UAVs flying in formation cooperatively. And the formation pattern should be preserved during maneuvers such as heading change and speed change. Many formation control approaches have been proposed such as consensus-based approach[18], leader-follower approach [19] and behavior based approach [20]. In our work, we adopt a hybrid formation control approaches. For the leader UAVs, we use coordinated path following control; with respect to the follower UAVs, we use leader-follower coordinated control.

Target tracking. The guidance control for target tracking is responsible for guiding the hosted UAV to fly around the targets so that the targets remain in the UAV's detection range. The guidance control for target tracking is mainly implemented by the vector field methods [21, 22]. When it comes to multiple-vehicle tracking, this kind of methods builds an additional Lyapunov vector field for controlling the desire speed of the UAV in order to ensure the inter-vehicle angular spacing, thereby preventing these UAVs from collision and achieving multiple angles for surveillance.

3.4 Supervision

Supervision module is in charge of maintaining the system healthy inspection, allowing or disallowing operations based on mission requirements, managingthe communication of the system, recording the flight logs, etc. This is an essential module for ensuring the stability and proper functioning of the system. In particular, it consists of Commander, Communication manager, and Logging and storage three sub-modules explained below.

Commander inspects the healthy status of all modules, maintains a state machine in terms of the system level (e.g. current mode), and allows or prohibits actions according to its current state or mission requirements. In addition, commander is in charge of dispatching all the commands given by the ground station. Different commands may need different operator. For example, commands of mission execution class such as target tracking and coverage searching need to be dispatched to the mission planner; commands of system management class such as the predefined trajectories loading and configuration changing need to be dispatched to the logging and storage.

Communication Manager transfers the messages between the high-level control subsystem and other components in the swarm system architecture (i.e. the low-level control subsystem, other UAVs, the ground station). More specifically, there are mainly two aspects of work for Communication Manager as follow. (1) One is to manage the communication over the serial cable that connects to the low-level control subsystem. It acts like a abstract layer that bridges these two levels of controlling. (2) Another is to manage the communication over the communication infrastructure that connects other UAVs and the ground station. And it transfers the control and data messages among the swarms effectively through communication channels.

Logging and storage logs the state of the system including the state transaction, trigged events, flight data and custom logs. Other than this, the perceived images or videos can be stored on the platform selectively. This is very helpful for developers to analyze the UAV's behavior and performance over the entire process. Besides, configuration file, parameter lists, predefined waypoint lists are also stored onboard in order to fast fetch for on-board modules.

4 EXPERIMENTS AND RESULTS

In order to evaluate the performance of the proposed framework, we have built a prototype swarm system based on the proposed architecture and conducted a set of field experiments in an outdoor environment with five square kilometers. In the following subsections, the experimental set-up as well as the experimental methodology will be presented.

4.1 Experimental Set-up

In this section, the experimental set-up utilized for real flights is described in detail. The UAV employed in the

Figure 3: Overview of the experiment set-up

swarm experiments are all with the same miniature Fixed-wing UAVs. The wing span and the body length of the vehicle is about 1800 millimeters and 1220 millimeters, respectively. The cruise airspeed is approximately 18 m/s. The maximum forward speed and the stall speed is approximately 25 m/s and 8 m/s, respectively. All the UAVs have identical on-board avionics and instrumentations. Each UAV carries a GPS receiver to locate itself, and wireless modems to build a communication network among the UAVs.

A number of the miniature fixed-wing UAV, together with the inter-UAV communication, are constructed as a networked swarm system in the air. A ground station is refitted from a ground vehicle and integrated into the overall system by the ground-to-air communication. The ground station is operated by only one operator, supporting mainly flight state monitoring, command transmission, path plotting, etc. Thus, the overall system is composed of the UAV swarm in the air, the ground station, and communications. The frame and the real snapshot of the overall system are shown in Fig. 3.

4.2 Formation Flight

To illustrate the effectiveness of the proposed framework, we have conducted a series of field experiments using different numbers of fixed-wing UAVs. Some of typical snapshots are shown in Fig. 4. As we can see in Fig. 4, a formation flight of 21 UAVs is depicted. The UAV swarm are split to three groups and each group of the UAVs forms the "two columns" formation pattern. As explained in Section 3.3, we use a hybird formation control strategy that the coordinated path following control is used for the leader UAVs; the leader-follower coordinated control is used with respect to the follower UAVs. There are two leaders and five followers in each group.

4.3 Target Recognition and Tracking

Other than formation control, we have conducted a series of field experiments of target recognition and tracking. Fig. 5 shows snapshots of the target recognition and tracking experiments with multiple UAVs. More specifically, each UAV captures videos through its electro-optical pod at runtime. UAVs detect the target through the target detection and recognition algorithm. Once a target is detected, by applying target localization and multi-UAV data fusion algorithm, UAVs can obtain the target information and update the trajectory estimation of the target according to the runtime state. In terms of tracking the target, we adopt cooperative standoff target tracking guidance approach in the experiment. Take the cooperative tracking with three UAVs as an example, three UAVs fly a circular orbit around the target with a radius of 100 meter, and each UAV keep an angular spacing of 120 degrees with others. This can achieve the surveillance of multiple angles, which is useful in the condition that the target is keep out by the shelter such as buildings and trees.

5 CONCLUSIONS

In this paper, we have investigated the framework design that serves as a blue-print for developing a UAV swarm system and have proposed a distributed and modularised coordination framework for mission oriented fixed-wing UAV swarms. The detailed elaboration of the proposed framework is presented. Field experiments with 21 fixed-wing UAVs have also been conducted to evaluate the effectiveness of the proposed framework. Different missions such as formation flight, target recognition and tracking have been demonstrated. In the future work, we would like to extend the functionalities of the framework to enable a large-scale swarm of UAVs for accomplishing more complex missions such as cooperative surveillance, search and rescue.

Acknowledgements

The authors would like to express their deepest gratitude to the SWARM TEAM of the NUDT. Without their hard work, the flight experiments cannot be done.

REFERENCES

[1] A. Abdessameud and A. Tayebi, "Formation control of vtol unmanned aerial vehicles with communication delays," *Automatica*, vol. 47, no. 11, pp. 2383–2394, 2011.

[2] A. Kushleyev, D. Mellinger, C. Powers, and V. Kumar, "Towards a swarm of agile micro quadrotors," *Autonomous Robots*, vol. 35, no. 4, pp. 287–300, 2013.

[3] Jürgen Scherer, Saeed Yahyanejad, Samira Hayat, Evsen Yanmaz, Torsten Andre, Asif Khan, Vladimir Vukadinovic, Christian Bettstetter, Hermann Hellwagner, and Bernhard Rinner. An autonomous multi-uav system for search and rescue. In *Proceedings of the First Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use*, DroNet '15, pages 33–38, New York, NY, USA, 2015. ACM.

[4] Nathan Michael, Jonathan Fink, and Vijay Kumar. Cooperative manipulation and transportation with aerial robots. *Autonomous Robots*, 30(1):73–86, 2011.

[5] Jose Luis Sanchez-Lopez, Jess Pestana, Paloma De La Puente, and Pascual Campoy. A reliable open-source system architecture for the fast designing and prototyping of autonomous multi-uav systems: Simulation and experimentation. *Journal of Intelligent & Robotic Systems*, 84:1–19, 2015.

[6] V Grabe, M Riedel, H. H Bulthoff, and P. R Giordano. The telekyb framework for a modular and extendible ros-based quadrotor control. In *European Conference on Mobile Robots*, pages 19–25, 2013.

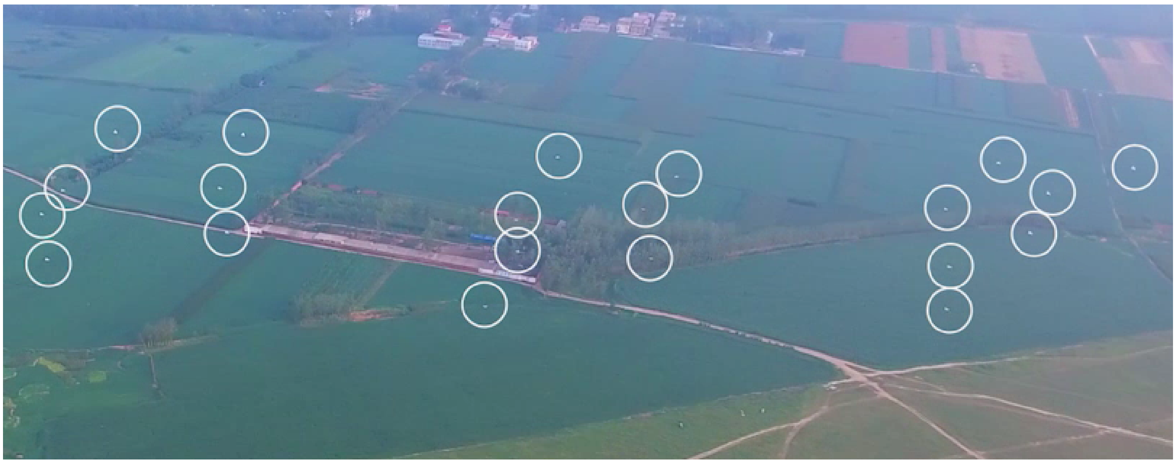
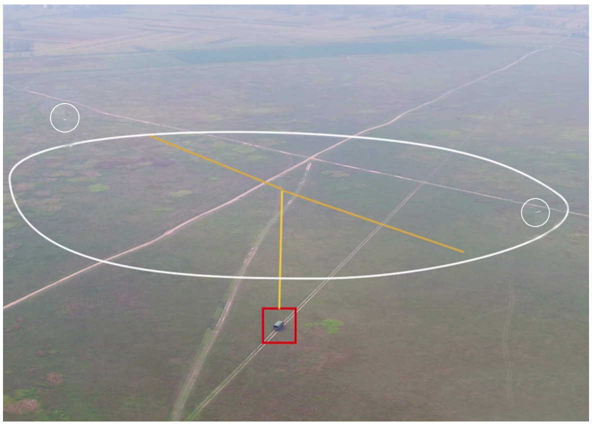


Figure 4: A snapshot of formation flight with 21 fixed-wing UAVs



(a) Cooperative tracking with Two UAVs

(b) Cooperative Tracking with Three UAVs

Figure 5: Target recognition and tracking

[7] S. Hauert, S. Leven, M. Varga, F. Ruini, A. Cangelosi, J.-C. Zufferey, and D. Floreano, "Reynolds flocking in reality with fixed-wing robots: communication range vs. maximum turning rate," in *The 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 5015–5020, IEEE, 2011.

[8] T. H. Chung, M. R. Clement, M. A. Day, K. D. Jones, D. Davis, and M. Jones, "Live-fly, large-scale field experimentation for large numbers of fixed-wing uavs," in *2016 IEEE International Conference on Robotics and Automation*, pp. 1255–1262, IEEE, 2016.

[9] L Meier, D Honegger, and M Pollefeys. Px4: A node-based multithreaded open source robotics framework for deeply embedded platforms. In *IEEE International Conference on Robotics and Automation*, 2015.

[10] G. Anup Venkatesh, P. Sumanth, and K. R. Jansi. Fully autonomous uav. In *International Conference on Technical Advancements in Computers and Communications*, pages 41–44, 2017.

[11] Balazs Gati. Open source autopilot for academic research-the paparazzi system. In *American Control Conference (ACC), 2013*, pages 1478–1481. IEEE, 2013.

[12] Prithviraj Dasgupta. A multiagent swarming system for distributed automatic target recognition using unmanned aerial vehicles. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, 38(3):549–563, 2008.

[13] Sara Minaeian, Jian Liu, and Young-Jun Son. Vision-based target detection and localization via a team of cooperative uav and ugvs. *IEEE Transactions on systems, man, and cybernetics: systems*, 46(7):1005–1016, 2016.

[14] Michael M Zavlanos, Leonid Spesivtsev, and George J Pappas. A distributed auction algorithm for the assignment problem. In *Decision and Control, 2008. CDC 2008. 47th IEEE Conference on*, pages 1212–1217. IEEE, 2008.

[15] K. E. Nygard, P. R. Chandler, and M. Pachter. Dynamic network flow optimization models for air vehicle resource allocation. In *American Control Conference, 2001. Proceedings of the*, pages 1853–1858 vol.3, 2001.

[16] Shulong Zhao, Xiangke Wang, Zhiyun Lin, Daibing Zhang, and Lincheng Shen. Integrating vector field approach and input-to-state stability curved path following for unmanned aerial vehicles. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, (99):1–8, 2018.

[17] Mangal Kothari, Ian Postlethwaite, and Da-Wei Gu. A suboptimal path planning algorithm using rapidly-exploring random trees. *International Journal of Aerospace Innovations*, 2, 2010.

[18] Yasuhiro Kuriki and Toru Namerikawa. Consensus-based cooperative formation control with collision avoidance for a multi-uav system. In *American Control Conference (ACC), 2014*, pages 2077–2082. IEEE, 2014.

[19] Mohammad A Dehghani and Mohammad B Menhaj. Com-

munication free leader–follower formation control of unmanned aircraft systems. *Robotics and Autonomous Systems*, 80:69–75, 2016.

[20] Huaxin Qiu, Haibin Duan, and Yanming Fan. Multiple unmanned aerial vehicle autonomous formation based on the behavior mechanism in pigeon flocks. *Control Theory & Applications*, 32(10):1298–1304, 2015.

[21] Seunghan Lim, Yeongju Kim, Dongjin Lee, and Hyochoong Bang. Standoff target tracking using a vector field for multiple unmanned aircrafts. *Journal of Intelligent & Robotic Systems*, 69(1-4):347–360, 2013.

[22] Hongda Chen, Kuochu Chang, and Craig S Agate. Uav path planning with tangent-plus-lyapunov vector field guidance and obstacle avoidance. *IEEE Transactions on Aerospace and Electronic Systems*, 49(2):840–856, 2013.