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Decentralized Control of Multi-UAVs for Target Search, Tasking and Tracking

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Abstract: This paper considers integrated target search, tasking and tracking using multiple fixed-wing UAVs in urban environments. The problem is to design autonomy for each individual UAV autonomous and distributed tasking. Control logic design based on finite state automaton (FSA) model, integrating the four modes of operations, i.e., takeoff mode, fly-to-AO (area of operation) mode, search mode and tracking mode, is developed. An efficient distributed multi-UAV target search algorithm is also presented. UAV guidance and control is built based on combined urban road map and target detection probability map information. For target tracking, by using geometric relations (relative position, orientations, speed ratio, and minimal turning radius), a systematic algorithm is developed to generate an optimal path online for a fixed-wing UAV to track a moving target. In addition, control method for a group of UAVs to keep track a target convoy is also addressed. Finally, the proposed decentralized algorithms are evaluated by simulations adopting a real UAV model.

1. INTRODUCTION

Large group of mobile vehicles equipped with sensors (such as camera, Lidar, sonar) are currently being developed to facilitate area surveillance, coverage, search and rescue Hu et al. [2013], Bethke [2007]. Decentralized control of UAVs makes it possible to autonomous tasking which can reduce the burden of operators Cortes et al. [2004]. In this paper, we are interested in multi-UAV target search and tracking problems in urban environments. As we known, UAV's camera view is often blocked or interfered by tall buildings, trees, et.al. The monitoring tasks become quite challenging which require UAVs autonomously and cooperatively search and tracking targets of interest. Efficient decentralized deployment strategies need to be designed for UAVs to finish the tasks cooperatively and time efficiently.

Deployment of UAVs for coverage search and tracking has been studied extensively Cortes et al. [2004], Hu et al. [2013], Meng et al. [2013], Rathinam et al. [2007], Bethke [2007], Skoglar et al. [2012]. In Cortes et al. [2004], control and coordination algorithms for groups of vehicles is presented. Distributed coverage control algorithm is developed base on locational optimization method. In Rathinam et al. [2007], a fixed-wing UAV is used for searching and mapping boundaries of a river. In Bethke [2007], a vision based persistent search and track using multiple UAVs is addressed. The main contribution therein is target detection (based on video data) and task assignment methods. In Skoglar et al. [2012], the authors consider the problem of keeping track of all discovered targets and simultaneously search for new targets by controlling the pointing direction of the vision sensor and the motion of the UAV. In this research work, only one UAV is used. Furukawa et al. [2006] presents a coordinated control technique that allows heterogeneous vehicles to autonomously search and track multiple targets using recursive Bayesian filtering. UAVs can switch their operational mode from search to track. However, the proposed algorithm is centralized. In Hu et al. [2013], a distributed target search algorithm using multiple UAVs is developed. However, the developed gradient control laws only can be applied to omni-directional vehicles. In addition, the search region is assumed to be a free space.

Our case study in this work consists of a team of fixed-wing UAVs performing search and tracking tasks over urban environments. The extracted road map is assumed known to all UAVs. We present the overall high-level control logic design, integrating the four modes of operations, i.e., takeoff mode, fly-to-AO mode, search mode and tracking mode. Each mode is implemented using several module processes running concurrently, supporting communication, coordination. Our aim is to provide decisional architectures for multi-UAV systems which act autonomously with minimal supervision from human beings. In addition, efficient algorithms are developed to enable UAVs autonomously and cooperatively search and keep tracking target convoys moving along the roads.

2. SEARCH AND TRACK PROBLEM DESCRIPTION

UAVs are deployed to perform search and track related tasks. An operator first marks out the boundary of an area for search. The targets may be mobile. In this case these locations will change over time and will be tracked based on the onboard logic.

The operator uploads mission commands to all UAVs while they are waiting for launch. The UAVs acknowledge receipt of commands. The operator launches the UAVs in sequence due to the assumption that we use fixed-wing UAVs in the case study. They fly into two predefined race courses at separate altitudes, where UAVs wait for others to join the

4. Inform operator when a target is located. If operator decides to track target, the UAV team will assign a UAV to track the target. The other UAVs will take up the search task left off by the UAV.

3. Self assignment to the search areas, starting from the most likely locations

2. Climb as a flock

1. One command launch

5. One command recovery

Fig. 1. Scenario description: Operations in Search and Track Mission

flock. When all UAVs are in the race courses, they fly towards the search area as a flock.

Upon reaching the area, the UAVs collaboratively search for the target convoys based on road map information and *a priori* information about the targets. The UAVs will head for the high probability locations, exchange search results, update the target location probability map to be maintained on each UAV. As time progresses and if the targets are mobile, the previously searched areas need to be searched again. The UAVs ensure that they do not overlap in their respective search areas to ensure the best search effectiveness. When a target is detected, one UAV will be assigned autonomously to track the target. The path to track the target and continue search will be computed and adopted by the UAV assigned to the task. additional tracking task. The operator issues the recovery command. The UAVs acknowledge receipt and returns to the recovery area as a flock. Upon reaching, they go into the two race courses awaiting the operator's command to land singly. Fig. 1 depicts the whole scenario.

3. DECENTRALIZED ALGORITHMS FOR TARGET SEARCH, TASKING AND TRACKING

3.1 Control Logic Design

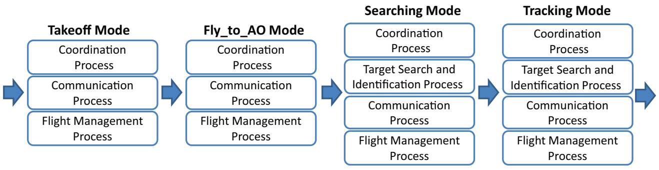


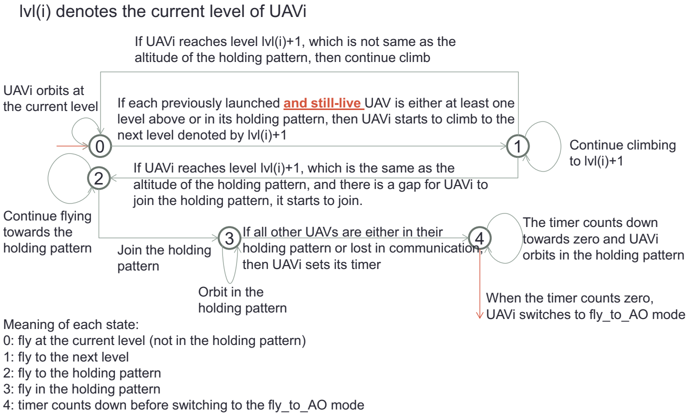
Fig. 2. Operational modes

In this paper, we first briefly present the high level control logic design which will serve as the 'brain' of the whole surveillance system. The UAVs work in one of the four operational modes as shown in Fig. 2, i.e., take-off mode, fly-to-AO mode, searching mode, and tracking mode. A finite-state automata (FSA) template model of UAV operations has been developed. Upon the FSA template model coordination protocols are synthesized, whose instantiations to each individual UAV serve as local supervisors that can guide each individual UAV to act properly based on other UAVs' status to ensure conformation with prespecified global requirements.

3.2 Take-off Mode

The take-off operation is the phase of operation starting from when the UAVs are on the ground and ending just after they are all released to fly to the AO. This includes the launch, the climb and the flight in the holding pattern.

We assume that the takeoff sequence is determined by the operator and reflected in the UAV IDs. The coordination process describes that at state 0 UAVi either orbits at its current location (i.e., Orbit(lvl(i)) when it is in the air or stays still when it is on the ground (i.e., onGrd when lvl(i)=0). Based on the received heartbeat information, if all predecessor UAVs are either above UAVi's target intermediate orbit or have moved to their designated race course, then UAVi will start to fly to the target intermediate orbit, whose altitude is specified by lvl(i)+1, and progress to state 1. UAVi stays at state 1 while continuing its flight to the orbit at lvl(i)+1. When the target orbit is reached, UAVi will check whether this orbit is at the same altitude as that of its assigned race course. If it is not, then UAVi will return back to state 0 and continue climbing to the next orbit; otherwise, UAVi will wait for a sufficiently large gap appearing in the race course before it starts to join the race course and moves to state 2. UAVi will stay at state 2 until it successfully joins the race course, then its state is updated to state 3. UAVi will stay in the race course until all other "live" UAVs are all in their respective race course. When this happens, UAVi moves to state 4, while it starts count down of its timer from value D. This process will allow other UAVs to have time to receive the latest status of UAVi via its heartbeat message. After the countdown is over, UAVi will fly to the AO area. Here, UAVs may leave the race course at different times due to imperfect communication. An FSA with text explanations is depicted in Fig. 3.



lvl(i) denotes the current level of UAVi

If UAVi reaches level lvl(i)+1, which is not same as the altitude of the holding pattern, then continue climb

UAVi orbits at the current level

If each previously launched **and still-live** UAV is either at least one level above or in its holding pattern, then UAVi starts to climb to the next level denoted by lvl(i)+1

Continue climbing to lvl(i)+1

If UAVi reaches level lvl(i)+1, which is the same as the altitude of the holding pattern, and there is a gap for UAVi to join the holding pattern, it starts to join.

Continue flying towards the holding pattern

Join the holding pattern

If all other UAVs are either in their holding pattern or lost in communication, then UAVi sets its timer

The timer counts down towards zero and UAVi orbits in the holding pattern

Orbit in the holding pattern

When the timer counts zero, UAVi switches to fly_to_AO mode

Meaning of each state:
0: fly at the current level (not in the holding pattern)
1: fly to the next level
2: fly to the holding pattern
3: fly in the holding pattern
4: timer counts down before switching to the fly_to_AO mode

Fig. 3. Textual explanation of coordination protocol of take-off operation

Proposition 1. The proposed coordination protocol described in Fig. 3 will ensure (1) mutual exclusion at intermediate climbing zones; (2) all UAVs reach their designated holding patterns eventually; (3) the maximum delay between the first UAV flying to AO and the last UAV flying to AO is bounded.

3.3 Target Search and Task Assignment

Assume Q is a convex search region and area of operation (AO) for UAVs. Each UAV is equipped with a downward camera.

Classical target search methods, such as spiral or lawnmower are of centralized which need offline planning and not robust to online UAV failures. Another concern is that these methods do not perform well in dynamic environments. Recently developed coverage search which relies on locational optimization techniques can be implemented in a distributed fashion in the sense of the Delaunay graph Cortes et al. [2004]. The locational optimization function to serve as a measure of coverage can be written as follows

$$\mathcal{H} = \sum_{i=1}^{N} \int\limits_{V_i} \|q - p_i\|^2 \phi(q) dq, \tag{1}$$

where N denotes the number of UAVs; V_i is Voronoi partition of i-th UAV. $q \in Q$ denotes a point or cell in the search region. $\phi(q)$ represents an *a priori* measure of information on Q. Each Voronoi region has mass M_i and centroid C_i, where $M_i = \int_{V_i} \phi(q)dq$ and $C_i = 1/M_i \int_{V_i} q\phi(q)dq$.

The problem formulation in (1) can be used for static target search in a free space. However, our objective is to develop target search and tracking techniques using multiple fixed-wing UAVs in a urban environment with a known road-map. Targets are moving on the roads. For the formulation (1), at each step, the UAV should move to the centroid $C_i, \forall i$. However, in a urban area, UAVs are supposed to follow the road to have a better view of targets due to the obstruction of tall buildings and trees. On the other hand, general used Lloyd-like gradient descent control law for the problem formulation in (1) is applied to omni-directional vehicles. However, fixed-wing UAVs have its own dynamic constrains, such as turning rate and speed constraints. Hence a novel and efficient search algorithm needs to be developed.

Basic Idea: In our problem setting, UAVs sequentially enter the AO and are required to find moving targets within a certain time constraint. We divide each road into a small number of cells. The size of each cell can be determined base on field of view (FOV) of UAVs. Each cell is associated with a probability of target existence, i.e., $Prob_i(t), i = 1, \ldots, K$, where K denotes the number of cells. The initial values of $Prob_i(0)$ are all set to be 0.5. Since targets are moving and hence we need to model probability changes adaptive to dynamic environments. Here we propose to use the following simple decay function to represent the probability transitions with time,

$$Prob_i(t+1) = \exp(-\alpha)t + Prob_i(t) \tag{2}$$

where α is a small positive scalar.

In this paper, we propose a novel search algorithm in which UAVs decide their waypoints according to both road map and probability map information. The driving force is to constrain the UAVs to follow the road while they are in the search mode. The logic will disperse a bunch of UAVs approaching the road junction such that the UAVs are on different roads. If the roads are not available (may be the road is already being searched or there is another UAV on the same road) then the UAV will chose the road which has the maximal probability of finding the targets. Using this logic you will see that the within minutes all the UAVs are well separated and searching different roads which guarantees the solution.

Algorithm 1. Cooperative Road-map Based Target Search Automata for Individual UAV

1) Initialization: Initialize waypoint (entry area of AO), detection probability, false alarm;
   Divide each road into several cells and set initial probability of each cell to 0.5 (the largest uncertainty of target existence).
2) Sampling step: UAV takes measurement and update its probability map. Then sharing the probability map with its neighbors.
   If target found, then UAV first check whether the target is tracked by other UAVs. If not, then UAVs will assign itself as the leader, switch to task assignment and tracking mode.
   UAV (leader) calls its nearest two neighbors to join so that they can track the whole found convoy.
3) Waypoint planning: If no target found, then UAV keeps itself in search mode.
   If UAV is approaching road junction, then it will check the next available roads. Two important factors will be considered in the decision making: The roads not currently occupied by other UAVs have higher priority; The roads which have higher uncertainty (in terms of probability map) also have higher priority.
   The next waypoint of UAV will be ending point of the chosen available road.
4) Waypoint based path planning and then go to Step 2.

The detailed search algorithm is presented in Algorithm 1.

For the task assignment, for our scenario we use a simple strategy. If one UAV finds a target convoy, then it will check whether this convoy is tracked by other groups of UAVs. If not, then it will assign itself as a leader and call other one or more UAVs to help to keep tracking all targets in the convoy.

Remark 2. At each time step, UAVs need to share its position and probability map with its neighbors. The map fusion can use a general consensus protocol Hu et al. [2013]. In addition, UAVs need to store the road map of AO. Due to the limited memory, each UAV only needs to know junction points of roads.

3.4 Tracking Mode

After UAVs finding the targets, they are required to keep tracking the target convoys. Each convoy has several targets. For simplicity, we assume that UAV FOV is larger than separation distance between the targets. We also assume that UAV's speed is larger than the targets. To achieve the tracking task, the UAV needs to fulfill two objectives, i.e., keep synchronous motion with the target, and minimize the relative distance between itself and the target. Thus, to ensure the successful path planning, the UAV dynamics and sensor coverage range must be taken into consideration. By adoption of a geometric approach, systematic path planning algorithms are developed based on the ratios between the speeds of UAV and moving target.

Assume that the speed of the target can be estimated by UAVs and the target moves along a direct line (approximate) during a small time interval. We discretize the path planning in each time interval t_i and design the control input u_i. The target locates at Q_0 and the UAV locates at A_0 with orientation α_0 at time $t = t_0$, see Fig. 4. Assume the speed of the target is $v = v_0$ for $t \geq t_0$. Due to the symmetry with respect to x-axis, without loss of generality, we only consider the ordinate value of A_0 to be nonnegative at time $t = t_0$.

Denote R as the minimum turning radius of fixed-wing UAVs. To do the path planning, compute right and left externally tangent circles $\mathcal{C}_1$ and $\mathcal{C}_2$ of point A_0 with the common tangent direction α_0. Denote H_1 and H_2 be highest points of $\mathcal{C}_1$ and $\mathcal{C}_2$ respectively. Let point A_1 be the intersection of circle $\mathcal{C}_1$ and the trajectory line of the target, i.e., x-axis. Denote θ_1 the angle at point A_1 between circle $\mathcal{C}_1$ and x-axis. To make the computation easier, we build the Cartesian coordinate system as follows: the target moves along x-axis, and center O_1 of $\mathcal{C}_1$ locates on y-axis. Assume $Q_0 : (x_0^q, 0)$ in the defined coordinate system.

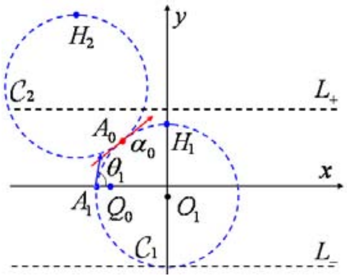


Fig. 4. The image of $\mathcal{C}_1$, $\mathcal{C}_2$, L_+ and L_-.

The point A_0 is uniquely defined by the values α_0 and θ_1. Thus we use α_0 and θ_1 to describe the initial state of the UAV.

Denote $k_0 = \frac{V}{v_0}$. d_0 is obtained by,

$$d_0 = \begin{cases} R - R\cos\theta_0, & k_0 \leq k^*, \\ R, & k_0 > k^*, \end{cases}$$

where $k^* = 3.005327402$ (The detailed derivative of k^* can be found in He et al. [2013], $\frac{\theta_0}{\sin\theta_0} = k_0$, $\theta_0 \in (0, \pi)$. . Therefore, the standard lines L_+ and L_- are defined respectively as

$$L_+ : y = d_0, \; L_- : y = -d_0.$$

The path planning algorithms are designed based on the values of α_0, H_1, and d_0. Four different scenarios are discussed as follows.

C2.1 $\alpha_0 \in [0, \pi)$ and H_1 is under line L_+,

C2.2 $\alpha_0 \in [0, \pi)$ and H_1 is above or on line L_+,

C2.3 $\alpha_0 \in [\pi, 2\pi)$ and H_1 is above or on line L_+,

C2.4 $\alpha_0 \in [\pi, 2\pi)$ and H_1 is under line L_+.

C2.1. In this case, the standard line L_+ is higher than point H_1 whose y-position is d^*, thus the aim of the UAV is to track the higher standard line L_+ above x-axis, see Fig. 5.

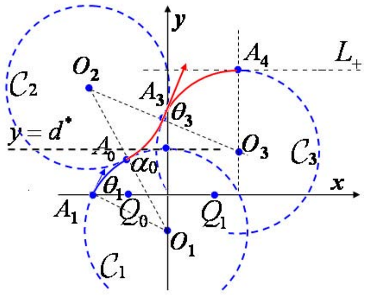


Fig. 5. The image of case **C2.1**. Red path $A_0\widehat{A_3}A_4$ is the track path.

The center of circle $\mathcal{C}_2$ locates at

$$O_2 : (2R\cos(\alpha_0 + \frac{\pi}{2}), -R\cos\theta_1 + 2R\sin(\alpha_0 + \frac{\pi}{2})).$$

We continue to find circle $\mathcal{C}_3$ which is externally tangent with circle $\mathcal{C}_2$ and is tangent with line L_+, where

the center of circle $\mathcal{C}_3$ locates at $O_3 : (x_{O_3}, -R\cos\theta_0)$, and x_{O_3} satisfies $||O_2O_3|| = 2R$, i.e.,

$$\begin{aligned} x_{O_3} = &2R\cos(\frac{\pi}{2} + \alpha_0) \\ &+R\sqrt{4 - [2\sin(\frac{\pi}{2} + \alpha_0) - \cos\theta_1 + \cos\theta_0]^2} \end{aligned} \tag{3}$$

The tangent point between circles $\mathcal{C}_2$ and $\mathcal{C}_3$ locates at A_3. Compute the angle $\theta_{O_2O_3}$ between the line O_2O_3 and positive x-axis,

$$\begin{aligned} \theta_{O_3O_2} = &\arctan\frac{y_{O_3} - y_{O_2}}{x_{O_3} - x_{O_2}} \\ =&\arctan\frac{-\cos\theta_0 + \cos\theta_1 - 2\cos\alpha_0}{\sqrt{4 - (\cos\theta_0 - \cos\theta_1 + 2\cos\alpha_0)^2}}, \end{aligned} \tag{4}$$

and

$$\theta_3 = \frac{\pi}{2} + \theta_{O_2O_3}. \tag{5}$$

The length of curve $\widehat{A_0A_4}$ is $L_{A_0A_4} = R(2\theta_3 - \alpha_0)$. In the same time duration $T = L_{A_0A_4}/V$, the target moves with the distance

$$L_Q = \frac{(2\theta_3 - \alpha_0)R}{k_0}$$

from point Q_0 to $Q_1 : (x_0^q + L_Q, 0)$ straightly.

Let W_1 be the new translocation difference along x-axis between the UAV and the target as the UAV flies from A_0 to A_4,

$$\begin{aligned} W_1(k_0, R, \theta_1, \alpha_0) = &(x_{Q_1} - x_{Q_0}) - (x_{O_3} - x_{A_0}) \\ = &-\frac{R(2\theta_3 - \alpha_0)}{k_0} + R\cos(\frac{\pi}{2} + \alpha_0) \\ &R\sqrt{4 - [2\sin(\frac{\pi}{2} + \alpha_0) - \cos\theta_1 + \cos\theta_0]^2}. \end{aligned} \tag{6}$$

(7)

After approaching point A_3 on circle $\mathcal{C}_3$ with the center O_3, the UAV is in new synchronous state. The tracking path $\mathbf{s}(t)$ is curve $A_0\widehat{A_3}A_4$.

Similarly, we can derive the optimal path planing for UAVs for **C2.2.**, **C2.3.** and **C2.4.**

C2.2. In this case, the aimed standard line L_+ is lower than point H_1, see Fig. 6.

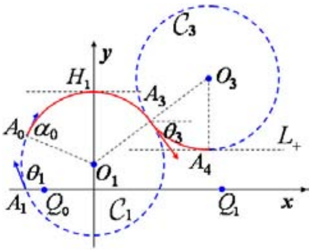


Fig. 6. The image of case **C2.2**. Red path $A_0\widehat{A_3}A_4$ is the track path.

C2.3. $\alpha_0 \in [\pi, 2\pi)$ and H_1 is above or on line L_+. Using similar notations of A_1, θ_1 and circles $\mathcal{C}_1$ and $\mathcal{C}_2$.

We need further more two auxiliary circles, $\mathcal{C}_3$ and $\mathcal{C}_4$, and their corresponding centers O_3 and O_4 respectively. Both circles $\mathcal{C}_3$ and $\mathcal{C}_4$ locate on the right hand side of $\mathcal{C}_1$. $\mathcal{C}_3$ is above line L_+. It is externally tangent with $\mathcal{C}_1$ at point A_3, and tangent with line L_+ at point A_5. $\mathcal{C}_4$ is above line L_-. It is externally tangent with $\mathcal{C}_1$ at point A_4, and tangent with line L_-, see sub-figure (a) on the top left in Fig. 7.

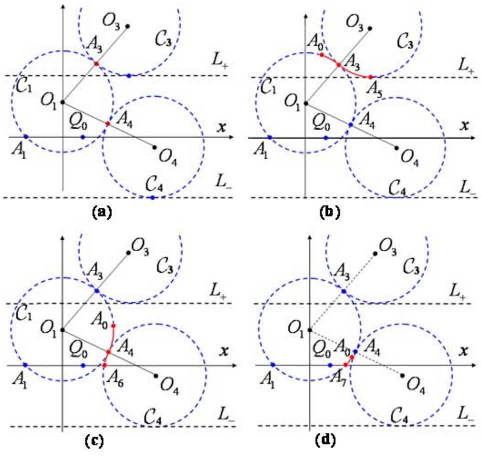


Fig. 7. The images of case **C2.3**. The red path in each sub-figure is the track path.

Compare three ordinate values of A_0, A_3 and A_4, we have different tracking paths above x-axis:

C2.3.1. $y_{A_3} \leq y_{A_0}$. The tracking path $\mathbf{s}(t)$ for the UAV is $A_0\widehat{A_3}A_5$, see sub-figure (b) on the top right in Fig. 7,

C2.3.2. $y_{A_4} \leq y_{A_0} < y_{A_3}$. The tracking path $\mathbf{s}(t)$ for the UAV is $A_0\widehat{A_4}A_6$, see sub-figure (c) on the bottom left in Fig. 7,

C2.3.3. $y_{A_0} < y_{A_4}$. The tracking path $\mathbf{s}(t)$ for the UAV is $\widehat{A_0A_7}$, see sub-figure (d) on the bottom right in Fig. 7.

C2.4. $\alpha_0 \in [\pi, 2\pi)$, H_1 is under standard line L_+. Different from **C2.3**, special circles $\mathcal{C}_3$ and $\mathcal{C}_4$, which exist in Fig. 7, cannot be constructed in the current case. With the help of similar notations A_1, θ_1 and circle $\mathcal{C}_1$, see Fig. 8, let A_2 be the intersection of circle $\mathcal{C}_1$ and x-axis. In this case, the tracking path $\mathbf{s}(t)$ for the UAV is the curve $\widehat{A_0A_2}$ along the circle $\mathcal{C}_1$. Once the UAV arrives at A_2, the ordinate of A_2 equals 0 and the orientation is $\alpha_2 \in [\pi, 2\pi)$. It is another case due to the symmetry respect to x-axis. Denote $\widetilde{A}_2$ and $\widetilde{\alpha}_2$ the mirror images of A_2 and α_2 respect to x-axis. We have $y_{\widetilde{A}_2} = 0$ and $\widetilde{\alpha}_2 \in [0, \pi)$. Thus we treat $(\widetilde{A}_2, \widetilde{\alpha}_2)$ as a new initial state of the UAV in case **C2.1**.

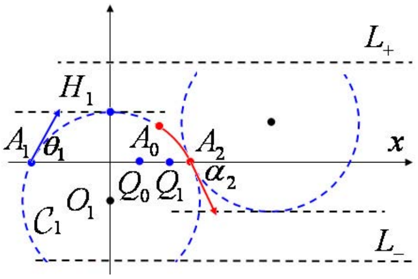


Fig. 8. The image of case **C2.4**. Red path $\widehat{A_0A_2}$ is the track path.

4. SIMULATION RESULTS

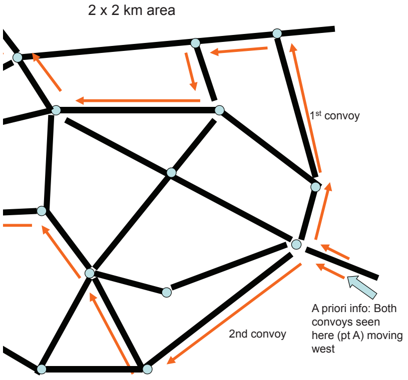


Fig. 9. Road map

In the studied urban environment, road map is as presented in Fig. 9. The size of the map is around 2 km × 2 km. There are total 23 roads distributed through the map. Two target convoys are assumed to appear from the bottom of the map sequentially. There are total 10 moving targets and each convoy contains 5 targets. Targets moving along the roads and two convoys move towards different directions after they enter the AO. The speed of the targets is around 8.3 m/s.

A real fixed-wing UAV model is used for our simulation as shown in Table 1. UAVs are expected to know that targets have moved into the search region before they approach to this region in 2 minutes. The speed of the UAVs is around 14 m/s. The field of view of camera mounted on the UAVs is around 80 m^2 square region.

Table 1. Fix-wing UAV Model

Parameter	Max/Min values
Flight path angle	13 deg/ 0 deg
Bank angle	12 degrees / -12 degrees
Air speed	16.4 m/s / 12.4 m/s
Acceleration (forward direction)	3.0 m/s^2 / 0 m/s^2
Turn rate	7.1 deg/s / 0 deg/s

At first, 6 UAVs are all in take-off mode and then hover in 2 circular areas autonomously. After all UAVs hover above the ground, they fly sequentially to AO. When UAVs enter the AO, they change to search mode. In the search mode, UAVs cooperatively and autonomously search the moving targets. Once a target found which is not tracked by other UAVs, the founder UAV will switch to tracking mode. All the control logic will follow the method we have addressed in Sections 3 and 4.

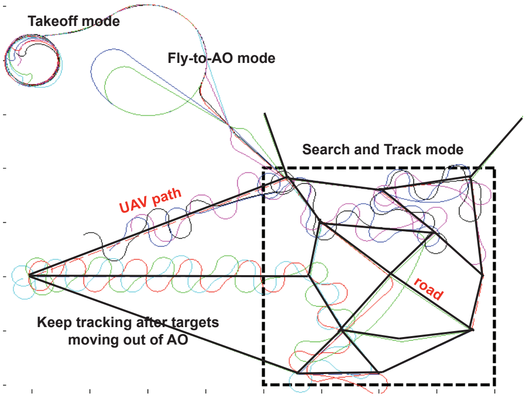


Fig. 10. Mode explanation

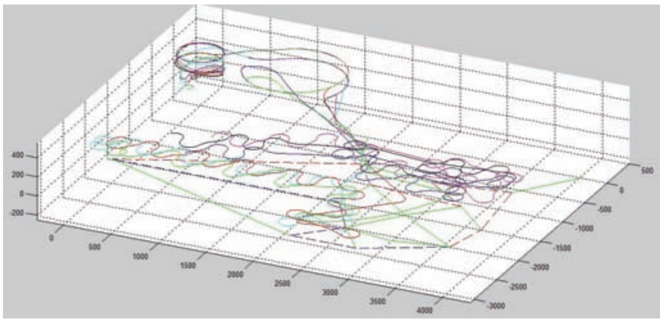


Fig. 11. 3D snapshot

Simulation results are shown in Figs. 10 and 11. From Fig. 10, we can clearly see the mode transmissions, i.e., take-off, fly to AO, search, tracking modes. Fig. 11 is a 3D view of UAV path.

Specially, in Fig. 12, we show how groups of UAVs cooperatively keep track target convoys. In this simulation, we assign UAVs to track head, middle and tail of each convoy separatively.

5. CONCLUSIONS

In this paper, we have considered decentralized control of multi-UAV for autonomous take-off, search and tracking. An autonomous take-off strategy was presented. Based on the given road map information of urban environments, an efficient search algorithm, which combine road map and probability map information, was designed. To keep tracking target convoys, the optimal UAV path was determined based on a geometric approach. Through the simulation tests, we can see that the proposed decentralized UAV control algorithm was efficient which can handle autonomous UAV take-off, search, tasking and tracking.

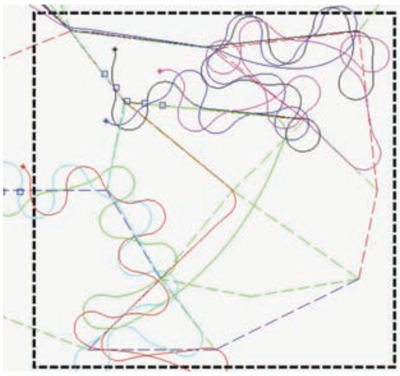


Fig. 12. Tracking mode

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