Anti-UAVs Surveillance System based on Ground Random Fisheye Camera Array

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ABSTRACT

With the rapid development of various types of unmanned aerial vehicles, anti-UAVs surveillance is very urgent. This paper mainly focuses on monitoring various UAVs in unknown and GPS-denied wide areas. We innovatively construct a novel anti-UAVs surveillance system based on ground random fisheye camera array. The paper mainly includes three novel parts: (1) Construct a ground random fisheye camera array anti-UAVs surveillance platform; (2) Propose a fast self-calibration method for arbitrary layout of camera array; and (3) Design a set of multi-target detection, tracking and 3D localization algorithm based on fisheye camera array. Field experiments have been carried out using four UAVs with significant appearance difference, which performs robust in various complex scenes. The experimental results demonstrate that our system can track UAVs without artificial markers, which is sufficient to complement anti-UAVs surveillance task in unknown and GPS-denied wide areas.

CCS Concepts

• **Computing methodologies → Artificial intelligence→ Computer vision →Computer vision tasks →Visual inspection.**

Keywords

Random Fisheye Camera Array; UAVs Surveillance System; Self-calibration.

1. INTRODUCTION

Unmanned Air Vehicles(UAVs) have become more and more prevalent recently, and which have emerged in an increasing number of applications, mostly in military but also civilian. In this section, we discuss some previous works related to UAVs localization. The traditional measurement method mainly based high precision measuring sensors, different types of sensor such as the Global Navigation Satellite System(GNSS) and GPS/INS, laser range scanners(LRFs)[1, 2], monocular camera[3, 4], stereo cameras[5, 6] and the newly popular RGB-D sensors[7] have been explored. In the recent years, new measurement system which take visual sensors as cores have been applied widely and expanded to the UAVs localization[8]. Martinez et al.[9] designed a trinocular system, which is composed of three FireWire cameras fixed on the ground, to estimate the vehicle's position and orientation by tracking the land markers on the UAV. Researchers

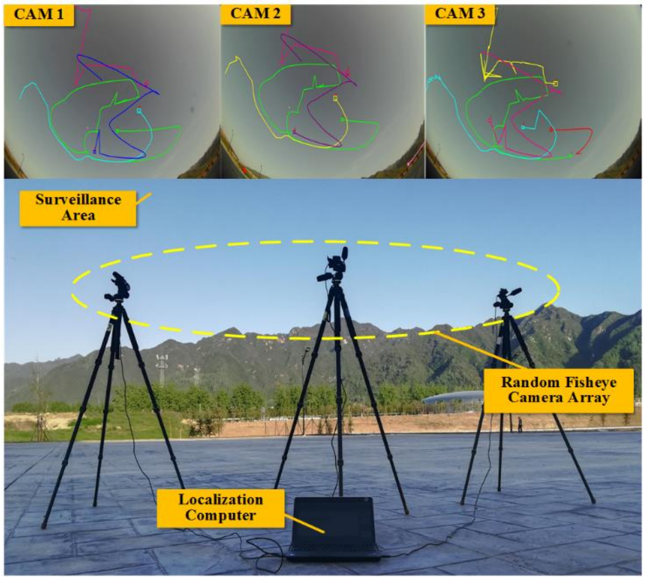

Figure 1. Architecture of the anti-UAVs surveillance system. The bottom of the figure is our ground random fisheye camera array surveillance system, and the top figure is tracking results of UAVs.

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in Chiba University[10] designed a ground-based stereo vision system to estimate the three dimensional position of a quadrotor. Most of the previous researches are applied indoors and with small measurement range.

To achieve wide range of outdoor UAVs localization, Kong et al.[11, 12] construct a system that mounted two separate sets of Pan-Tilt Unit integrated with visible light camera on both sides of the runway, which is able to detect the UAVs around 600m, while the system mainly focus on the fixed-wing aircraft. However, the process of the camera calibration is complicated. Tao et al.[13] proposed a high accuracy large scale outdoor camera array calibration method show in the work in 2015, the method mainly adopt the program combine the infrared cameras and laser lights, and which calculate the extrinsic parameters through the measured 3D points coordinates and the corresponding image coordinates. which is proved to be effective by field experiments. However, the most limitation is the small FOV.

For the anti-UAVs surveillance system, large monitoring range and high-precision 3D localization are two main issues. In general, the most of the cameras have limited field of view(FOV), though the visual range can be enlarged by the interaction of the multiple cameras, while it will bring many other issues in the meantime. In this paper, we select fisheye camera as our main sensors, which provide a large FOV, in addition, a number of wide-angle fisheye camera further expand the monitoring area when combines together. This paper presents three main contribution:

- Constructing a new type of wide-angle ground fisheye camera array for the first time, which applys to monitor and track multiple UAVs in large areas.
- Proposing a fast self-calibration method for arbitrary layout of ground camera array.
- Designing a real-time intelligent anti-UAVs surveillance system, plenty of filed experiments fully proved the effectiveness of the system.

2. SYSTEM ARCHITECTURE

To satisfy surveillance performance, this paper construct a novel ground fisheye camera array anti-UAVs surveillance system, which shown in Fig.1.

Random Fisheye Camera Array: To cover the larger airspace, we construct a novel anti-UAVs surveillance system based on ground fisheye camera array. The system is mainly consist of several fisheye cameras, which are fixed on a steel bar, the steel bar is mounted on a tripod with a pan. The device can be rotated with the pan, which helps to quickly adjust the camera's vision.

The focal length of the camera lens is 3.8 mm with a Wide Field of View (WFOV) up to 170 °. The camera link using USB3.0 ensure high-speed image synchronization acquisition process, which captures the images by 30 frames per scend with resolution 1920x1080. Our localization computer is equipped with Intel Core i7 processor and 8 GB DDR3. In the experiment, we totally design three different types of camera array structures, which shown in the Fig.2(a). The structures ensure the larger camera public view.

Multiple UAVs Platform: Four types of UAVs with different appearance and size, which shown in the Fig.2(b). An eight-rotor unmanned aerial vehicles and three DJI quad-rotor vehicles. In the experiment, all the flight experiment data collection via manual flight, remote control or autonomously with the aid of our GPS waypoint navigation system. In order to ensure the robustness of target detection, the four aircraft are placed in different height of the airspace, and all flying altitudes are less than 50 meters.

(a) Random camera array system architecture

(b) The experimental rotor UAVs

Figure 2. The experimental platform. (a)The setup of our ground random fisheye camera array surveillance system architecture. (b)The four experimental UAVs with different appearance and size.

3. GROUND FISHEYE CAMERA ARRAY UAVS SURVEILLANCE SYSTEM

This paper mainly focus on the content of the vision-based wide range of anti-UAVs surveillance. The system framework shows in Fig.3, which is mainly consist of four main modules: (1) ground fisheye camera array image synchronization acquisition and self-calibration process, (2) multiple targets detection, (3) multiple targets tracking and (4) 3D localization and motion trajectories.

3.1 Fisheye Lens and Self-calibration

We adopt the fisheye camera array, and how to accurately calibrate the wide angle camera array is our first task. The accuracy of the camera parameters directly determined the localization accuracy.

The fisheye cameras are wide angle lens, and the images obtained with such lens are highly distorted. The most popular are the equiangular fisheye lens: the angular resolution provided by the lens is constant. They are characterized by the equality $r = f\theta$, where f is the focal length of the lens, θ is the incoming ray angle and r is the projection of the ray on the image plane.

For calibrating intrinsic parameters of the lens, we use the OPENCV toolbox of the fisheye camera model, which derived a projection function that can cope with any type of wide angle lens. It is briefly described below.

$$\theta_d = \theta(1+k_1\theta^2+k_2\theta^4+k_3\theta^6+k_4\theta^8) \tag{1}$$

We can easily get the internal parameters K_i and distortion coefficient $D_i\,(i=1,2,3\ldots)$ of each camera.

As for the extrinsic parameters between cameras, the conventional calibration methods are mostly based on calibration plates or markers in the scene. While they are not valid for the case of upward field of camera view.

This paper proposes a novel and generic ground camera array self-calibration method. Firstly, we adopt the UAVs as our collaborative targets, there are associated detection point sets $\{X_i^{m_1}, X_i^{m_2}, ..., X_i^{m_k}\}(i=1,2,3...)$ of which subscrip i represent the i camera and subscript m_n is the total number of the matching detection results. Secondly, we can easily estimate the fundamental matrix based on the matching point sets and obtain the epipolar inliers matching sets $\{X_i^{e_1}, X_i^{e_2}, ..., X_i^{e_k}\}(i=1,2,3...)$ at the same time.

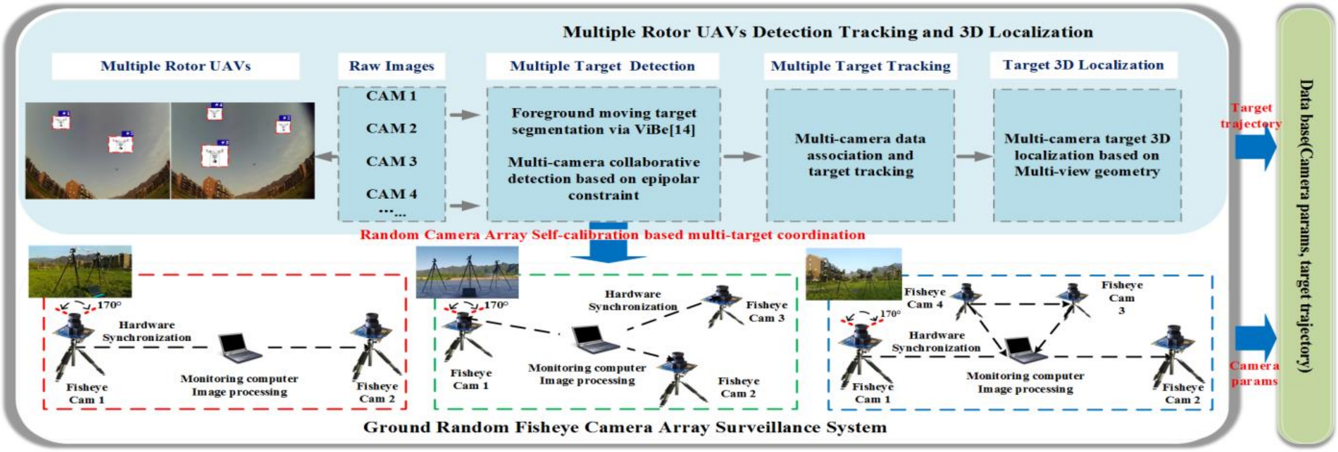


Figure 3. The framework of the ground fisheye camera array anti-UAVs surveillance system, showing four main modules: (1) ground fisheye camera array image synchronization acquisition and self-calibration, (2) multiple target detection, (3) multiple target tracking and (4) target 3D localization and motion trajectories.

On the basis of the above, the essential matrix can be calculated by fundamental matrix, matching epipolar inliers point pairs and the camera internal parameters, and rotation and relative translation matrix are obtained by singular value decomposition (SVD) of the essential matrix. Finally, recovering the real scale of translation from relative translation by measuring the real distance between cameras, and we get the external parameters R, T .

3.2 Multiple UAVs Detection and Tracking

As we can see in the Fig.2(a), our fisheye cameras are installed on the tripod with static and upward camera view. In order to get good foreground targets, in this paper we use the ViBe[14] method, which performs robust and produces complete segmentation.

We regard the image centroid coordinate of each cluster as the coordinate of the candidate target in the image. The pixel distance is defined as:

$$f_{pd}(p_i, p_i) = \sqrt{(p_i^x - p_j^x)^2 + (p_i^y - p_j^y)^2} \qquad (2)$$

Where p_i and p_j are image pixels, (p_i^x, p_i^y) and (p_j^x, p_j^y) are pixel coordinate of p_i and p_j respectively.

To determine the corresponding relationship of the candidate targets and remove the false targets, epipolar geometry constraints between the two cameras are used. Epipolar geometry between the two cameras refers to the inherent projective geometry between the views. It only depends on the camera intrinsic parameters and the relative pose of the cameras. Thus after the target is detected on the two cameras independently, epipolar geometry constraints between the cameras can be used to get data association results. In this way, the corresponding relationship of the candidate targets are confirmed and parts of false targets are removed.

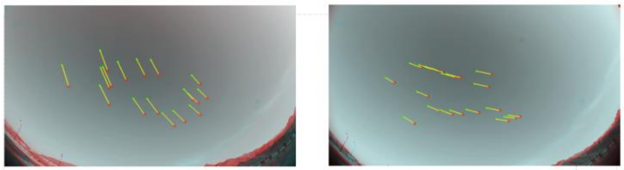
Define $I_1 = \{x_1^1, x_2^1, ..., x_m^1\}$ and $I_2 = \{x_1^2, x_2^2, ..., x_n^2\}$ as the detection results of the first and second camera. The duty of the data association is to find the corresponding relationship between x_i^1 and x_j^2 . Distance measurement is obtained by the symmetric transfer error between $x_i^1(i=1,2,...,m)$ and $x_j^2(j=1,2,...,n)$, and then calculate the matching matrix D . The global optimal matching result is obtained by solving the matching matrix D using Hungarian algorithm, which is taken as the final detection result.

The Euclidean distance is used as the distance measurement in the 3D space. Define the historical target tracking result $T_i^t(i=1,2,...,p)$ and current localization result $X_j^{t+1}(j=1,2,...,q)$, the distance is computed as $d(T_i^t, X_j^{t+1})$ .Thus we can easily calculate the matching matrix D_t^{t+1} , and the Hungarian algorithm is used to get the multiple targets tracking results from D_t^{t+1} .

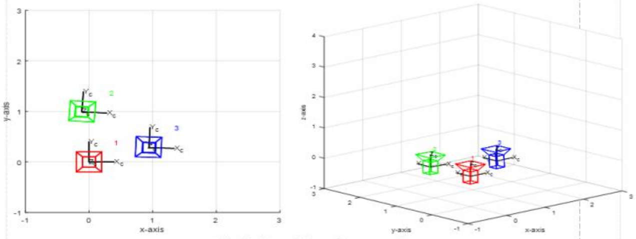
3.3 3D Localization and Motion Trajectories

In Section 3.1, we obtain the fisheye camera parameters including the intrinsic K_i , distortion coefficient D_i and external parameters (the relative rotation R and translation T between cameras). Supposing that the world coordinate coincides with the first camera coordinate system, and the world coordinates of the UAVs are $X = \{X_1, X_2, ..., X_n\}$, the camera projection matrix is P_i , which can easily calculate by the intrinsic and external parameters. For detection results, supposing the image coordinates of the UAVs are $x_i = \{x_i^1, x_i^2, ..., x_i^n\}$.

We explain the principle with two camera models. We obtain initial value of x_l and x_r by DLT algorithm firstly, and then we optimize the $\hat{x}_l$ and $\hat{x}_r$ using Levenberg-Marquardt's iterative non-linear optimization. Set $x_l \cong P_l X$ and $x_r \cong P_r X$, with the homogeneous relations $x_l P_l X = 0$ and $x_r P_r X = 0$. The above is linear equations with respect to X, which can be written as $AX = 0$, although each set of points corresponding to the three equations, of which only two are linearly independent, and therefore each point just gives two equations correspondingly with respect to X.



(a) Epipolar Inliers



(b) Self-calibration result

Figure 4. Ground camera array self-calibration results. (a)The matching results of epipolar inliers between cameras. (b)The camera array self-calibration result of relative poses between cameras.

Since X is homogeneous coordinates, which only three degrees of freedom are scale-independent, however, the linear equation set $AX = 0$ contains four equations, thus the above system is over-determined system. To find the approximate solution of the equation $AX = 0$, we make it as an optimization: $\min_X \|AX\|$ with $\|AX\| = 1$.

Primarily, we obtain the initial value of X by the above formula, and then optimize the value of X using the method of multiple view projective reconstruction by bundle adjustment, we get the final X by minimizing the follow function:

$$\min \sum_{i=1}^{n} v_i d(Q(X, I_i), x_i)^2 \tag{3}$$

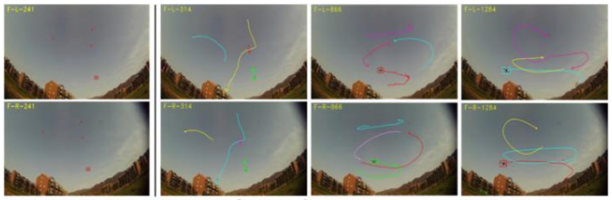
Where I_i is the i camera, if there have target point on the I_i, we set $v_i = 1$, else set $v_i = 0$. $Q(X, I_i)$ is the projection on the i camera and $d(Q(X, I_i), x_i)^2$ is the reprojection errors computed using the corresponding projection matrices.

4. EXPERIMENTAL RESULTS

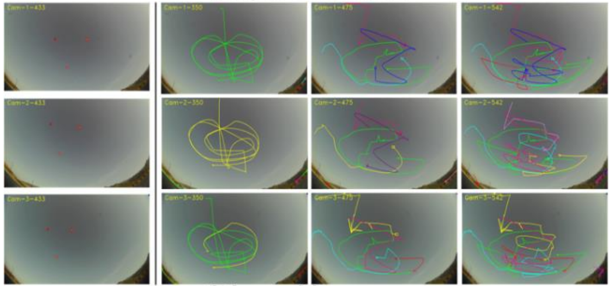
We have conducted a series of experiments to evaluate the ground random fisheye camera array anti-UAVs surveillance system. The experiments carry out in different environment and adopt various of aircrafts with significant difference in appearance and size.

4.1 Camera Array Self-calibration

We conducted a number of different scenarios experiments to verify our proposed self-calibration method based on target coordination. In our method, the most of the wrong matching and outlier points are removed by epipolar constraint. In the Fig.4(a), the matching results of epipolar lnliers between camera 1 and 2 and camera 1 and 3, respectively. The camera array self calibration result of relative poses between three independent cameras shown in Fig.4(b), which is a top view and a front view respectively.



(a) layout of two cameras



(b) layout of three cameras

Figure 5. A part frames of the detection and tracking results of UAVs based on our ground random fisheye camera array surveillance system.

4.2 Detection and Tracking Results

In order to verify and evaluate the stability of the surveillance system, we carry out the field experiments in a variety of camera array structures and different environments using four rotor unmanned aerial vehicles.

Multiple targets detection: As we all known, the motor propeller movement is greater than the fuselage when the vehicles in the hover or low speed flight. The original ViBe algorithm causes over-segmentation and produces too many small pieces. In order to solve the problem, we do morphological processing and carry out further regional mergers in space, which produces good detection performance.

A part of detection results of UAVs are shown in the first column of the Fig.5. As we can see in Fig.5, there are some false detection results in the bottom right of the frame, The removal of false targets is mainly reflected in three aspects. In the process of multi-camera collaborative detection based on the epipolar constrain, the false targets can be removed by the symmetric transfer error; In the process of the camera array vision localization, the false targets can be removed by the space motion track constraints of the UAVs; In the process of the target tracking, the false targets can be removed by analyzing the motion directions and velocities of the candidate targets. In this way, the target can be detected correctly. And the object of the intermittent detection could also be associated by the tracking algorithm.

Multiple targets tracking: The UAVs tracking experimental results are shown in the second column of the Fig.5. Some false targets are effectively excluded by tracking process and strategy.

4.3 Multiple UAVs 3D Localization

We use multi-camera for multiple target 3D localization. In the experiments, there are three UAVs flying in different altitude airspace. In order to let the UAVs appear in the public view of the camera array, we control the UAVs to fly over the camera. The Fig.6 shows the UAVs fight process and 3D trajectories.

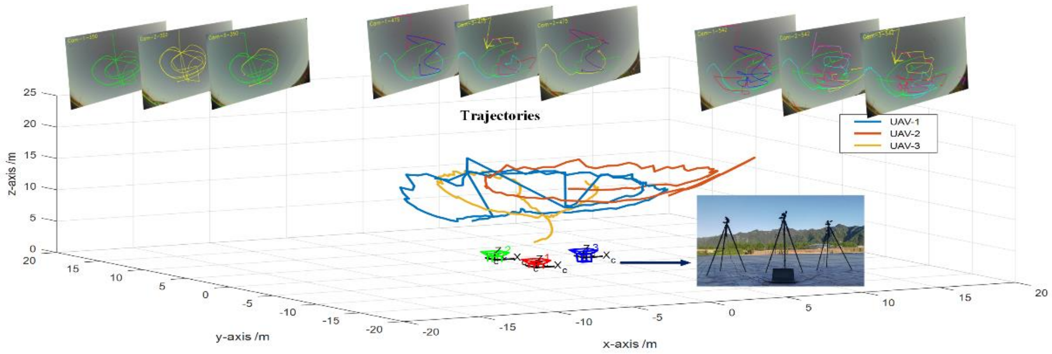


Figure 6. Multiple UAVs 3D localization and motion trajectories

5. CONCLUSIONS

In this research, we construct a novel anti-UAVs surveillance system based on ground random fisheye camera array, which solves the airspace monitoring tasks. The system with the capability of detection, tracking and 3D localization for multiple UAVs. Besides, we firstly propose a generic camera array self-calibration method without any available markers, which performs robust under many different circumstances. The system has been evaluated according to robustness and precision by several field experiments with four UAVs both qualitatively and quantitatively, and which also show that our surveillance system can effectively monitor the airspace within 50 meters. The future work is to improve the tracking algorithms and 3D position estimation methods. Beside, we plan to change our static ground random fisheye camera array surveillance system to a moving platform, which will has more flexible and powerful surveillance capabilities.

6. ACKNOWLEDGMENTS

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