Vision Positioning method for Autonomous Precise Landing of UAV Based on Square Landing Mark

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Abstract. Rotor-craft is a kind of VTOL UAV and is widely used in multiple fields. Among relative researches, vision guided autonomous landing of rotor-craft has been a hot spot, where vision positioning is the most crucial. The core of the algorithm is to calculate the position and attitude information according to the change of the visual image of the same object at different time or frame. Based on the real-time self calibration technology of airborne monocular vision, this paper puts forward a method that takes the designed landing mark composed of black and white squares as the cooperative target, solving the relative pose of camera and cooperative target to carry out the landing positioning of UAV, and realizes the full-automatic sub-pixel precision linear edge detection to ensure the accuracy of visual positioning. A series of simulation experiments show that for 768 * 576 pixel image, when the camera is about 12m away from the target and the noise deviation reaches 3 pixels, the total time of edge extraction and calibration is 0.511s, and the position and attitude estimation are still satisfactory, which shows that the proposed algorithm can effectively realize the autonomous landing of UAV.

1. Introduction
Due to its simple structure, flexible take-off and landing mode and small space required, rotor UAV is widely used for military and civilian purpose [1,2]. Among various researches and improvements of UAV, a very important part is to realize the automatic landing of the rotor UAV completely without controller’s intervention, so as to improve the working efficiency. It is necessary to accurately determine the real-time position and attitude of UAV below 10m height during landing.

There are many methods for UAV navigation and landing now. GPS navigation is most commonly used, but its position error is about 7m-13m [3], too large for terminal guidance. There are also methods for autonomous landing by acquiring distance information from airborne ultrasonic sensor array [4], but such sensors are vulnerable to serious environmental interference, which can not meet the requirements of accurate landing.

Besides the methods mentioned above, the machine vision guidance proposed in recent years has also been used for UAV autonomous landing. The image of landing site is shot to extract feature to acquire data for guidance. At present, the main differences among the methods are whether there are landing signs, the shape of landing signs and the algorithm of extraction.

Since landing without a landing mark is mainly used to obtain a suitable landing position [5], this paper chooses the method with a landing target for further research. There are two kinds of landing marks, symmetric [6] and asymmetric [7]. Although symmetric signs can provide landing position information, it fails to provide the relative orientation of UAV. Asymmetric signs can provide position information, so they are more commonly used.
In addition, SIFT, SURF, Hough, BRISK and other operators are mainly adopted [8] to extract image features whose major difference is speed. BRISK operator is novel and it only takes about 20ms to extract a small number of feature points[8]. However, the speed of these operators is greatly affected by the number of feature points, which is insufficient to make full use of image information since higher speed requires fewer points.

In this paper, a square landing marker which can be identified by UAV in the range of 3-10m is designed. The method of Carsten Steger[9] is applied to extract the edge parameters of the target image at the sub-pixel level. The high speed and full use of the target information can effectively improve the precision of the edge extraction parameters. At the same time, a calibration method of obtaining real-time internal and external parameters by using a single picture is proposed, which reduces computation and effectively improves the real-time landing performance. It can guide the UAV to land efficiently and accurately at a height below 10m.

In the second part of this paper, we will introduce and summarize the process and principle of extracting image edge information. In the third part, we will introduce the method of camera internal and external parameters calibration. In the fourth part, we will show the results of simulation experiments. In the fifth part, we will show the results of real image experiment.

2. The process of extracting image information
As mentioned above, the cooperation target with a completely symmetric figure cannot provide azimuth information, so the following asymmetric cooperation target is adopted in this paper to extract edge line for subsequent calculation, as shown in figure 1.

![Figure 1. Our target](image)

Since the line can be uniquely determined by two points, this paper firstly determines the line by extracting corner points. The specific extraction process of corner points is as follows:

(a) Image binarization, in order to improve the calculation speed, fixed threshold is adopted.
(b) Delete all points with black characteristics of the point and its eight field points, and the remaining points are used as outlines.
(c) Adopt eight-connected search strategy for contour tracking.
(d) Connected sequential algorithm is adopted to extract the connected domain.
(e) Harris method[10] is used to extract corner points.
(f) After corner extraction is successful, "and" operation is performed with contour tracking results and connected domain extraction results respectively to determine four external corner points and four internal corner points.
(g) To determine the position of the edge, it’s necessary to sort the outer corner points: the coordinates of the four outer corner points are converted to polar coordinates whose center and direction of axis is the same as the image. The distance between the coordinates and the center of the inner big square is calculated respectively. Then, the target can be achieved by numbering them from large to small.

In order to obtain high-precision edge line parameters, linear point is needed. In this paper, Steger’s method [9] is used for calculation. First, gaussian smoothing operator is used to convolve the original image. Then the eigenvalues and eigenvectors of the Hessian matrix are calculated to determine the
normal direction of the edge line, \((n_x, n_y)\). The normal direction along the edge line is the X-axis, and the Y-axis represents the gray scale. A two-parameter parabola model can be established, and the extreme value point of the parabola is the center point of the edge line. The second Taylor expansion of the quadratic function is used as the estimation of the parabolic model, the point with partial derivative of 0 in this direction is obtained, and whether it is within the pixel is obtained to judge the line points. The threshold value of the second partial derivative is set to obtain the line point set. The quadratic polynomial can be written as:

\[
22 21(, ) 2
x
y
x
x
x
x
y
y
y
y
y
y
x
y
x
y
z(t_x, t_y) = r + m_x r_x + m_y r_y + \frac{1}{2} t^2 n_x^2 r_x + t^2 n_y^2 r_y
(1)
\]

If we set its partial derivative to 0, namely \(\frac{\partial}{\partial t} z(t_x, t_y) = 0\), we can get

\[
t = -\frac{n_x r_x + n_y r_y}{n_x^2 r_x + 2n_y n_x r_y + n_y^2 r_y}
(2)
\]

As the image is discrete, the threshold is set as \(\pm 0.5\), and the points within this range can be judged as line points. Since the corner point is usually not an ideal step edge, the starting position of \(n\) pixels from the corner point is selected to obtain line points, and then the parameter equations of four edge lines can be calculated by fitting the line parameters.

The corner extraction process and results are shown in figure 2.

**Figure 2. Flow chart of the process of extracting image information**

### 3. Camera calibration

#### 3.1. Camera model

Each Camera calibration means acquiring the internal and external parameters of the camera. The camera model used in this paper is the classic pinhole model:

\[
\begin{pmatrix}
x_c \\
y_c \\
z_c \\
\end{pmatrix} = R \begin{pmatrix}
x_w \\
y_w \\
z_w \\
\end{pmatrix} + t = \begin{pmatrix}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33} \\
\end{pmatrix} \begin{pmatrix}
x_w \\
y_w \\
z_w \\
\end{pmatrix} + \begin{pmatrix}
t_1 \\
t_2 \\
t_3 \\
\end{pmatrix}
(3)
\]

In the formula mentioned above, \(R\) is the rotation matrix, and \(t\) is the translation matrix.
3.2. Calibration method
Under the condition that the target plane is unaligned with any coordinate axis of the camera image plane, the square on the target plane is no longer parallel to the opposite side after the camera's projection transformation. The intersection points \( p_1 \) and \( p_2 \) of its opposite sides are the image formed by the infinite points in the real space, which determine the line that is the image formed by the infinite line in the real space. Furthermore, \( q_1 \) and \( q_2 \) can be identified as the image of intersection points between two orthogonal diagonals in the square and line at infinity.

The infinity point is harmonic conjugate with the circular point. As described in literature [11], the image of a pair of circular points \( m_i \) and \( m_j \) can be obtained. This image point is also on the image of the absolute conic, which satisfies:

\[
m_i^T C m_i = 0, m_j^T C m_j = 0
\]  (4)

In the equation, \( C = K^{-T} K^{-1} \), \( m_i \) and \( m_j \) are conjugate points. Therefore, equation (5) can only provide the following two linear constraints on camera internal parameters:

\[
\text{Re}(m_i^T C m_j) = 0, \text{Im}(m_i^T C m_j) = 0
\]  (5)

Since this paper is a calibration zoom camera, the main change object is the focal length. In order to improve the real-time performance, only \( f_u \) and \( f_v \) are calibrated in the real-time calibration process. The main point is demarcated off-line. Therefore, only one image is needed to calibrate the camera parameters. As for the rotation matrix \( R \) and the translation matrix \( t' \), after obtaining the world coordinates \((X_w,Y_w,Z_w)\) and image coordinates \((u,v)\), all the elements of these matrices can be solved by homography matrix [11]. Specifically speaking, the scale coefficient \( k \) between \( t' \) and the actual translation matrix is shown in following equation:

\[
\begin{align*}
(u-u_0)(r_{21}X_w+r_{22}Y_w) & - (v-v_0)(r_{11}X_w+r_{12}Y_w) = k \\
(v-v_0)f_u t_1 & - (u-u_0)f_v t_2
\end{align*}
\]  (6)

\( r_{ij} \) is the element in row \( i \) and column \( j \) of the matrix \( R \), and \( t_i \) is the element in row \( i \) of the matrix \( t' \).

Above all, all the internal and external parameters can be obtained in this way.

4. Simulation experiment results

4.1. Set parameters
Camera's internal parameters are set as follows: \( u_0 = 384 \text{ pixel} \), \( v_0 = 288 \text{ pixel} \), \( s = 0 \), pixel pitch is \( dx = dy = 0.006 \text{mm} \). The image used is a simulation image with a size of 768*576. The size of the target (the largest black square in figure 1 is set to 910*910 mm). Three images are used in the experiment, and the focal length \( f \) is set as 6mm, 16mm and 26mm respectively. In the corresponding external parameters, the rotation angle is respectively \( \alpha_1 = 5^\circ \), \( \beta_1 = 20^\circ \), \( \gamma_1 = 30^\circ \); \( \alpha_2 = 8^\circ \), \( \beta_2 = 23^\circ \), \( \gamma_2 = 35^\circ \); \( \alpha_3 = 10^\circ \), \( \beta_3 = 31^\circ \), \( \gamma_3 = 29^\circ \). The translation vector are \( t_1 = [200,100,2500]^T \), \( t_2 = [300,200,7000]^T \), \( t_3 = [300,200,7000]^T \) (The unit is mm).

The camera calibration experiment uses the largest black square in the target. 100 points are selected evenly on each side of the square, and the image noise is added to the corresponding projection point. The equation of the line corresponding to each side of the square is fitted by the least square method. The noise amplitude is 0pixel-3pixel, and the pitch is 0.1pixel.
4.2. Result
The algorithm in this paper (Vw and n were taken 5 pixels in this experiment) and Hough transform method were used to detect the image and fit the parameters of the line.

In this paper, the relative error of slope extraction method is less than 0.1, and the relative error of intercept is less than 0.04. Among them, 80% of the extraction results of this method are better than that of Hough transform.

Next, the linear parameters obtained by this method are used to calibrate the internal and external parameters. The details are as follows. (Considering the paper length, there are only results)

Figure 3(a) - (c) respectively show the changes of absolute errors (AE) of internal and external parameters of the camera with noise in the camera calibration simulation experiment. (d) - (f) are the changing curves of mean square error (MSE) of internal and external parameters at different noise levels, and the results at each noise level are the mean value of 200 independent experiments. In these figures, the horizontal axis stands for the amplitude of the noise.

![Graphs](image1)

Figure 3. The changes with noise. (a) is AE for $u_f$ and $v_f$; (b) is AE for degree 1,2,3 of matrix $R$; (c) is AE for component 1,2,3 of matrix $T$; (d) is MSE for $u_f$ and $v_f$; (e) is MSE for degree 1,2,3 of matrix $R$; (f) is MSE for component 1,2,3 of matrix $T$.

It can be seen from the experiment results that the proposed method is accurate and robust, and the calibration results are still satisfactory in the case of large noise.

5. Real image experiment result
In the real image experiment, the camera adopts relong-160h, the CCD size was 1/3", the image acquisition card model is OK C30A, and the resolution is 768*576. In addition, due to the limitations of the site, the target size in the real image experiment is set as 130mm*130mm. We shoot two target images at two focal lengths respectively. After that, linear parameters of the four sides of the square are extracted by image segmentation and edge extraction. The main points are calibrated in advance with the method of Zhang [12]. In order to verify the rationality of the calibration results, $u_f$ and $v_f$ values of the calibration results are compared with the calibration results of the zhang method. The target is attached to a two-dimensional turntable, and the calibration results of R matrix are compared with the
angle set by the turntable. The length measurement tool and other auxiliary tools are used to measure the position relationship between the target and the camera lens, and the calibrated t-matrix results are compared with this (as shown in table 1, where the real conditions refer to the method \( f_u, f_v \) results, the Angle of the turntable and the length measurement results respectively, and considering the paper length, there are result of only one group at).

| Table 1. The calibration result of one group |
|---------------------------------------------|
| \( f_u (\text{pixel}) \) | \( f_v (\text{pixel}) \) | \( \alpha (^{\circ}) \) | \( \beta (^{\circ}) \) | \( \gamma (^{\circ}) \) | \( t[1](\text{mm}) \) | \( t[2](\text{mm}) \) | \( t[3](\text{mm}) \) |
| Calibration result | 3211.436092 | 3190.307815 | 13.931873 | -8.428606 | -30.898038 | -11.510091 | -34.794786 | 1212.304248 |
| real | 3135.19 | 3099.8 | 15 | None | -30 | -15 | -45 | 1100 |

Experimental results show that the calibration results of this method are close to the real conditions.

6. Conclusion

In this paper, a subpixel edge line extraction method based on corner ordering and image segmentation is proposed and applied to camera parameter calibration. The experimental results show that the edge line extraction method adopted in this paper has high precision and high speed. The calibration method adopted in this paper has strong anti-noise ability, and the internal parameters are divided into offline and online calibration under the condition of certain accuracy, which improves the real-time performance. In the next step, we plan to further analyze the experimental errors, improve the efficiency of the algorithm, and make targeted improvements to the problem of low real-time performance.

Acknowledgments

This work was supported in part by a grant from National Natural Science Foundation of China (61673039).

References

[1] R.~Freeland, B.~Allred, N.~Eash, L.~Martinez, and D.~Wishart, Agricultural drainage tile surveying using an unmanned aircraft vehicle paired with Real-Time Kinematic positioning-A case study[J]. Computers and Electronics in Agriculture,2019,165.

[2] L.~Sun, H.~Jiang, T.~Wu, and K. ~Jiang, “Research on intelligent target recognition technology for integrated reconnaissance/strike uav,” in Proceedings of SPIE - The International Society for Optical Engineering, vol. 10835, 2018.

[3] Merry Krista,Bettinger Pete. Smartphone GPS accuracy study in an urban environment.[J]. PloS one,2019,14(7).

[4] Minjun Xu.Uav 3D-SLAM technology based on ultrasonic sensor array [A]. Chinese association of automation. Proceedings of the 2018 China automation conference (CAC2018) [C]. Chinese association of automation: Chinese association of automation, 2018:7.

[5] Y. Lin, W. Lu, K. Chen and J. Guo, "Vision-based landing system design for a small UAV," 2015 IEEE International Conference on Consumer Electronics - Taiwan, Taipei, 2015, pp. 496-497.

[6] Jeon D, Cho K, Kim D H. Vision-Based Autonomous Landing for Small-Scale Unmanned Rotorcraft[C]. ISORCW, 2011 14th IEEE International Symposium on. IEEE, 2011: 274-280.

[7] Nguyen Phong Ha,Kim Ki Wan,Lee Young Won,Park Kang Ryoung. Remote Marker-Based Tracking for UAV Landing Using Visible-Light Camera Sensor.[J]. Sensors (Basel, Switzerland),2017,17(9).

[8] Marcin Skoczylas. Vision Analysis System for Autonomous Landing of Micro Drone[J]. Acta Mechanica et Automatica,2015,8(4).

[9] Steger. C. An Unbiased Detector of Curvilinear Structures[J]. IEEE Transactions on Pattern Analysis and Machine Intelligence, 1998, 20(2):113–125.
[10] Harris C. G., Stephens M. J. A combined corner and edge detector [A]. Proceedings Fourth Alvey Vision Conference [C]. 1988:147151.

[11] Rui Wang, Xin Li, Guangjun Zhang. Linear method for camera internal parameter calibration in guidance of monocular active vision uav [J]. Acta aeronautica sinica, 2006(04):676-681.

[12] Rui Wang, Guangjun Zhang. Automatic extraction method of edge line of square target [A]. In: Chinese society of image graphics. Proceedings of the 12th national conference on image graphics [C]. Beijing: tsinghua university press, 2005, 233 ~ 237.