Method of pose estimation for UAV landing

Likui Zhuang (庄丽葵)[1], **Yadong Han (韩亚东)**[2], **Yanming Fan (范彦铭)**[3],
Yunfeng Cao (曹云峰)[1,2*], **Biao Wang (王 彪)**[2], **and Qin Zhang (张 琴)**[2]

[1] *Academy of Frontier Science, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[2] *College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[3] *Shenyang Aircraft Design and Research Institute, AVIC, Shenyang 110035, China*
* *Corresponding author: cyfac@nuaa.edu.cn*

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In order to achieve the goal of the autonomous landing of fixed-wing unmanned aerial vehicles (UAVs), a new method is put forward for using the monocular camera on board to provide the information, which is need for landing. It is not necessary to install additional equipment in the airport. The vision-based method only makes use of the two edge lines on both sides of the main runway and the front edge line of the airport without using the horizon. While the runway width is known, the method can produce the attitude and position parameters of landing. The results of the hardware-in-the-loop simulation show the proposed method has better accuracy and faster computation speed.

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In recent years, the study on autonomous landing of unmanned aerial vehicle (UAV) has being a research focus, especially based on vision. This approach has two attractive features. Firstly, video cameras/sensors are passive sensors; hence, they cannot be detected and artificially interfered with easily. Secondly, most UAVs are already equipped with video cameras (e.g., for ground reconnaissance); hence, vision-based navigation does not require much additional hardware or payload. Research on the key technology of vision-based navigation is the measurement of landing attitude and position of UAV using the runway images taken by the camera on UAV.

There is some work done on the use of machine vision for landing of UAVs at present. Sara *et al.*[1] used a single camera to shoot the runway edge lines and the horizon for pose estimation. If the horizon cannot be shot, the attitude parameters can be got from the inertial navigation system (INS). Liu *et al.*[2] used three points on the runway and the horizon to estimate the attitude and position parameters. But two cameras were installed in both the wings, which caused the vibration of the UAV having a deep influence on the precision. It was not stable to extract the feature points and the image processing system must have a high computing power. It is shown that there are many methods to calculate the position of the UAV to the runway.

In order to estimate the attitude and position of UAV, the features of the runway image must be extracted firstly. These features are including points and lines. The feature points can be used to get high-precision attitude and position parameters, but it is very sensitive to noise in the process of the feature points extraction. The image definition must be high, or it will greatly increase the probability of feature point mis-match and lead to an estimation failure of attitude and position parameters. However, these disadvantages can be overcome by the use of the feature lines. In generally, military airport has two parallel runways: one is main, the other is auxiliary. The aprons connect the main runway ends and the auxiliary runway ends, which makes the military airport rectangular structure. So, the runway image has obvious edge line features. Due to the above reasons, many researchers use the estimation method based on the feature lines.

In this letter, a new method is designed to solve the problems in the research of UAV autonomous landing, for example, the processing results must have high precision and the processing time must be in real-time. The two edge lines on both sides of the main runway and the front edge line of the airport are used to estimate the attitude and position parameters.

In this letter, the pin-hole model is chosen as the camera imaging model. It is assumed that there is no relative motion between the camera and the UAV. Before taking-off, the intrinsic parameters and lens aberration coefficient of the camera are offline calibrated.

As shown in Fig. 1, it is assumed that the two edge lines on both sides of the main runway L_1 and L_2 and the front edge line of the airport L_3 are detected. The three lines have two intersections P_1 and P_2. The width of the main runway is W.

World coordinate system ($O_\mathrm{W}X_\mathrm{W}Y_\mathrm{W}Z_\mathrm{W}$): the middle

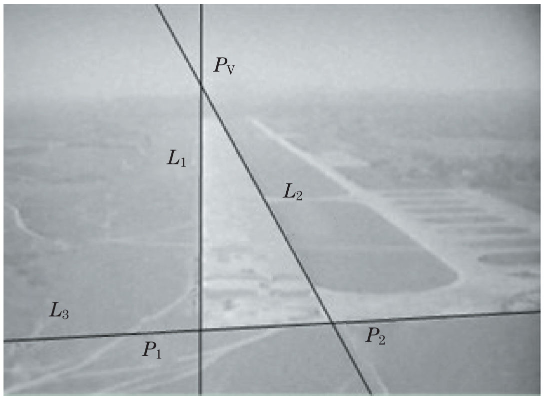

Fig. 1. Runway.

point of the line segment P_1 and P_2 is taken as the origin; the $O_\mathrm{W}X_\mathrm{W}$ axis points to infinity along the centre line of the main runway; the $O_\mathrm{W}Y_\mathrm{W}$ axis perpendicular to the $O_\mathrm{W}X_\mathrm{W}$ axis points to the left; the $O_\mathrm{W}Z_\mathrm{W}$ axis is determined by the right-hand rule (Fig. 2).

Camera coordinate system ($O_\mathrm{C}X_\mathrm{C}Y_\mathrm{C}Z_\mathrm{C}$): the optical centre of the camera is taken as the origin; the $O_\mathrm{C}Z_\mathrm{C}$ axis points to the runway along the optical axis of the camera. In this letter, the camera coordinate system takes place of the UAV coordinate system.

Physics image coordinate system and pixel coordinate system are described in Fig. 3, according to the conventional definition.

Suppose the position of one point P_i on the runway projected to the image is $p_i(X_i, Y_i)$ and the distance between the point P_i and the optical centre of the camera O_C is K_i. Therefore, the position of P_i in the camera coordinate system is

$$P_i^\mathrm{C} = \left(\frac{K_iX_i}{M_i}, \frac{K_iY_i}{M_i}, \frac{K_if}{M_i}\right), \tag{1}$$

where $M_i = \left(f^2 + X_i^2 + Y_i^2\right)^{\frac{1}{2}}$ and f is the focal length of the camera.

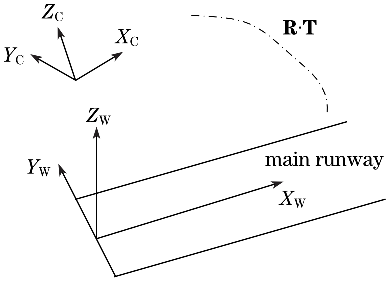

Fig. 2. World coordinate system and camera coordinate system.

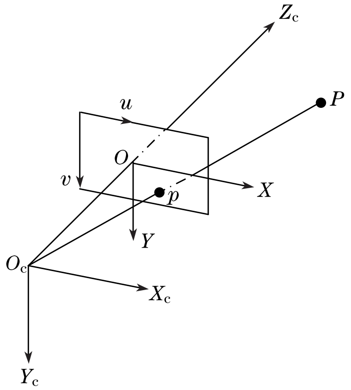

Fig. 3. Image coordinate system and camera coordinate system.

The linear model[3] of optical visual imaging system is

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_x & 0 & u_0 \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \mathbf{R} \begin{bmatrix} 0 & -1 & 0 & t_x \\ 0 & 0 & -1 & t_y \\ 1 & 0 & 0 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_\mathrm{w} \\ y_\mathrm{w} \\ z_\mathrm{w} \\ 1 \end{bmatrix}, \tag{2}$$

where

$$\mathbf{R} = \begin{bmatrix} \cos\psi\cos\phi - \sin\psi\sin\theta\sin\phi & \cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi & -\sin\psi\cos\theta & 0 \\ -\cos\theta\sin\phi & \cos\theta\cos\phi & \sin\theta & 0 \\ \sin\psi\cos\phi + \sin\phi\cos\psi\sin\theta & \sin\psi\sin\phi - \cos\psi\sin\theta\cos\phi & \cos\psi\cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3}$$

and α_x, α_y, u_0, and v_0 are all the internal parameters of the camera, which depend on the structure of the camera. $\alpha_x = f/\mathrm{d}x$, $\alpha_y = f/\mathrm{d}y$, in which $\mathrm{d}x$, $\mathrm{d}y$ are the physical size of pixels in the X and Y axes. θ, ϕ, and ψ represent pitch angle, roll angle, and yaw angle, respectively.

According to imaging principle[4], the two parallel lines L_1 and L_2 of the main runway intersect one point $P_\mathrm{V}(X_\mathrm{V}, Y_\mathrm{V})$, which is called vanishing point. And $O_\mathrm{C}P_\mathrm{V} /\!/ L_1 /\!/ L_2$.

In view of the characteristics of the imaged runway, the internal geometric constraint relations of the runway imaging principle graph is analyzed. Obviously, there are the following constraint relations:

① $L_1 \perp L_2$, ② $|P_1P_2| = W$, ③ $L_1 /\!/ L_2$.

In this letter, the camera is firmly installed on the UAV. The cross section of the UAV and the image plane of the camera are parallel and the optical centre of the camera is in the body axis of the UAV. Therefore, the UAV coordinate system could be replaced by the camera coordinate system.

The distance between the point P_1 and the optical centre of the camera O_C should be calculated, so did P_2. Then we can produce the positions P_1^C, P_2^C of P_1 and P_2 in the camera coordinate system.

According to Eq. (1), we can get the direction vector l_3 of the line L_3:

$$l_3 = \overline{P_1^\mathrm{C}P_2^\mathrm{C}} = \Big(\frac{K_1X_1}{M_1} - \frac{K_2X_2}{M_2}, \frac{K_1Y_1}{M_1} - \frac{K_2Y_2}{M_2}, \frac{K_1f}{M_1} - \frac{K_2f}{M_2}\Big).$$

And $\overline{O_\mathrm{c}P_\mathrm{v}} = (X_\mathrm{v}, Y_\mathrm{v}, f)$. For $\overline{O_\mathrm{c}P_\mathrm{v}} /\!/ l_1$ and $l_1 \perp l_3$, we can get $\overline{O_\mathrm{c}P_\mathrm{v}} \cdot l_3 = 0$. It can be described as

$$\left(\frac{K_1X_1}{M_1} - \frac{K_2X_2}{M_2}\right) \cdot X_\mathrm{v} + \left(\frac{K_1Y_1}{M_1} - \frac{K_2Y_2}{M_2}\right) \cdot Y_\mathrm{v} + \left(\frac{K_1f}{M_1} - \frac{K_2f}{M_2}\right) \cdot f = 0, \tag{4}$$

then

$$K_2 = nK_1, \tag{5}$$

where

$$n = \frac{M_2}{M_1} \cdot \frac{f^2 + X_1X_\text{v} + Y_1Y_\text{v}}{f^2 + X_2X_\text{v} + Y_2Y_\text{v}}. \tag{6}$$

According to $|P_1P_2| = W$, then

$$\left(\frac{K_1X_1}{M_1} - \frac{K_2X_2}{M_2}\right)^2 + \left(\frac{K_1Y_1}{M_1} - \frac{K_2Y_2}{M_2}\right)^2 + \left(\frac{K_1f}{M_1} - \frac{K_2f}{M_2}\right)^2 = W^2. \tag{7}$$

According to Eqs. (5) and (7), a quadratic equation on K_1 is got. For the runway is always in front of the camera, $K_1 > 0$. Then

$$K_1 = \left(\frac{W^2}{\left(\frac{1}{M_1} - \frac{n}{M_2}\right)^2 f^2 + \left(\frac{X_1}{M_1} - \frac{nX_2}{M_2}\right)^2 + \left(\frac{Y_1}{M_1} - \frac{nY_2}{M_2}\right)^2}\right)^{\frac{1}{2}}. \tag{8}$$

For K_1 and K_2 have been calculated, we can know P_1^C, $\underline{P_2^\text{C}.}$ Then l_3 can also be known. l_1 is represented by $\overline{O_\text{c}P_\text{v}}$. According to these two direction vector, the unit orthogonal matrix in the camera coordinate system can be described as $\mathbf{A} = \left(\frac{l_1}{|l_1|}, \frac{l_3}{|l_3|}\right)$. And the corresponding unit orthogonal matrix in the world coordinate system can be described as $\mathbf{B} = \left(\frac{L_1}{|L_1|}, \frac{L_3}{|L_3|}\right)$. The rotation matrix $\mathbf{R}$ is decided by $\mathbf{RB} = \mathbf{A}$. Obviously, $\mathbf{A}$ and $\mathbf{B}$ are both 3 by 2 matrix, and the number of $\mathbf{R}$ is countless. But due to the orthogonality of the rotation matrix, the problem to solve this linear equations can be transformed into

$$\begin{cases} \min ||\mathbf{A} - \mathbf{RB}||^2 \\ \mathbf{R}^\text{T}\mathbf{R} = \mathbf{I}_3 \end{cases}. \tag{9}$$

To solve this problem, the method of Umeyama[5] can be used. A simple introduction about this method is presented.

Assuming $\mathbf{A}$ and $\mathbf{B}$ are 3 by n matrix and $\mathbf{R}$ is 3 by 3 rotation matrix. The singular value decomposition of $\mathbf{AB}^\text{T}$ is $\mathbf{U}D\mathbf{V}^\text{T}(\mathbf{UU}^\text{T} = \mathbf{VV}^\text{T} = \mathbf{I}$, $D = \text{diag}(d_i), d_1 \geqslant d_2 \geqslant d_3 \geqslant 0)$. So when $\text{rank}(\mathbf{AB}^\text{T}) \geqslant 2$, $\mathbf{R} = \mathbf{U}S\mathbf{V}^\text{T}$ makes $||\mathbf{A} - \mathbf{RB}||^2$ have minimum, where

$$\mathbf{S} = \begin{cases} \mathbf{I}_3 & \det(\mathbf{AB}^\text{T}) \geqslant 0 \\ \text{diag}(1, 1, -1) & \det(\mathbf{AB}^\text{T}) < 0 \end{cases}.$$

When $\text{rank}(\mathbf{AB}^\text{T}) = 2$,

$$\mathbf{S} = \begin{cases} \mathbf{I}_3 & \det(\mathbf{U})\det(\mathbf{V}) = 1 \\ \text{diag}(1, 1, -1) & \det(\mathbf{U})\det(\mathbf{V}) = -1 \end{cases}.$$

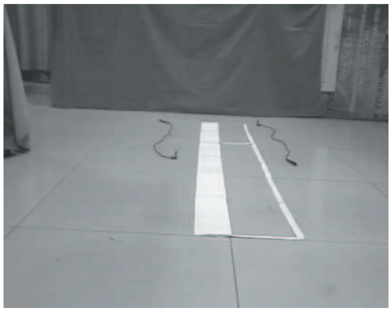

Fig. 4. Simulate runway.

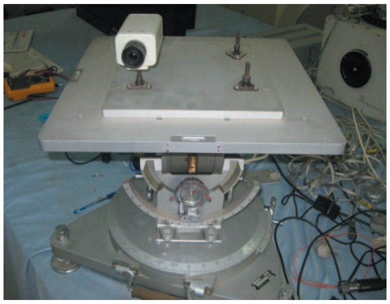

Fig. 5. Camera and 3-axis flight simulator.

According this theory, we can produce the attitude parameters of the UAV.

In the world coordinate system, the positions of P_1, P_2 and the middle point of them could have been known before taking-off. If the corresponding positions in the image coordinate system also have been extracted, we could produce the translation vector $\mathbf{T} = [t_x \; t_y \; t_z]^\text{T}$ according to Eq. (2).

Our approach was tested through the hardware-in-the-loop simulation in our laboratory. We built a simulate runway, as shown in Fig. 4. And in Fig. 5, the camera (MS-923D, MITSUGI) was installed in the 3-axis turntable, which simulated the movement of the UAV. The major component of the vision navigation system was the SSD-DM642 Ver2.0 type image processing hardware platform. The platform used TMS320DM642 DSP with 600 MHz and 4 800 MIPS as the core.

We simulated the whole process of the landing of UAV from far to nearly. It was assumed that the start point was 10 km far from the airport with 500-m height. Then the real landing scene was reduced 500 times to be the experiment landing scene in the laboratory. And our vision navigation system could extract three lines of the runway. The lines extracted by the vision navigation system are very good by intuition. The results of four positions chosen from the whole process are shown in Tables 1 and 2. According to the results, this new method is valid. Even though the precision is not very high, it is a big step in the UAV autonomous landing based on vision.

In conclusion, a vision-based method to assist landing of UAV is presented. This approach does not require the addition marks. Only three lines of the main runway are required to pose estimation. From the experimental results, the method is feasible for pose estimation.

Table 1. Results of the Estimation of Attitude (deg.)

Number		*a*	*b*	*c*	*d*
Roll Angle	Estimate Angle	–6.27	4.43	–1.62	–0.49
	Real Angle	–5.50	5.00	–1.00	0
	Difference	–0.77	–0.57	–0.62	–0.49
Pitch Angle	Estimate Angle	3.97	3.62	3.79	3.89
	Real Angle	5.00	4.50	4.50	4.58
	Difference	–1.03	–0.88	–0.71	–0.69
Yaw Angle	Estimate Angle	–5.89	3.59	1.05	–0.55
	Real Angle	–5.00	3.00	0.50	0
	Difference	–0.89	0.59	0.55	–0.55

Table 2. Results of the Estimation of Position (m)

Number		*a*	*b*	*c*	*d*
T_x	Estimate Distance	8.136	4.502	2.892	0.881
	Real Distance	8.000	4.400	2.800	0.800
	Difference	0.136	0.102	0.092	0.081
T_y	Estimate Distance	0.103	0.087	0.075	–0.009
	Real Distance	0.141	0.116	0.090	–0.010
	Difference	–0.038	–0.029	–0.015	0.001
T_z	Estimate Distance	0.452	0.257	0.122	0.056
	Real Distance	0.504	0.226	0.106	0.052
	Difference	–0.052	–0.031	–0.016	–0.004

So the approach can be used to assist fixed-wing UAV autonomous landing. But on the other hand, this method has a flaw. If the UAV flies over the front edge line of the airport, the vision navigation cannot extract the line. In this case, this approach is becoming invalid. The INS on board can solve this problem. In fact, when the UAV flies over the front edge line during the process of landing, the altitude of the UAV is very low. Even without the INS, the UAV could land safely.

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References

1. S. Sara, H. Gomi, T. Ninomiya, T. Inagki, and Y. Hamada, in *Proceedings of AIAA 38th Aerospace Sciences Meeting and Exhibit* 1 (2000).
2. T. Liu and G. Fleming, in *Proceedings of AIAA 44th Aerospace Sciences Meeting and Exhibit* 35 (2006).
3. X. Liu, "Research on methods of vision-based pose estimation for UAV autonomous landing" Master Thesis (Nanjing University of Aeronautics and Austronautics, 2005).
4. H. Richard and Z. Andrew, *Multiple View Geometry in Computer Vision* (Cambridge University Press, London, 2003) p.56.
5. S. Umeyama, IEEE Trans. Pattern Anal. Mach. Intell. **13,** 376 (1991).