Vision-based Autonomous Landing of UAV on Moving Platform using a New Marker

Huang Xiaoyun\(^1\)*, Xu Qing\(^1\) and Wang Jianqiang\(^1\)

\(^1\)School of Vehicle and Mobility, Tsinghua University, Hai Dian, Beijing, 100084

\(^*\)hxly0820@126.com

Abstract. The research of Unmanned Aerial Vehicle (UAV) flight autonomous landing on a moving platform based on computer vision has important significance, especially for the rescue and spray UAV in the future. A vision-based relative position and attitude estimation algorithm with a novel color marker and its recognition method was proposed for the UAV autonomous landing system. The new marker is designed with a pattern which make it is as visible as possible in the whole landing process. The proposed relative position and attitude estimation algorithm is based on the four corner points on the marker which are detected by the combined approach of vanishing point of parallel lines and Levenberg-Marquardt (L-M) optimization method. Indoor and outdoor experiments were carried out. The results indicate that the method of marker detection has real-time and robust performance and the position and attitude estimation accuracy attain cm-level, which shows the feasibility of landings on moving platform automatically.

1. Introduction

As an indispensable part of mini UAV, vision system has been paid great attention by colleges and research organizations in the world. UAV is increasingly replacing manned systems in situations that are dangerous, remote, or difficult for manned aircraft to access. UAV stabilization by pose estimation from visual sensors is an active research area. It can be used where Global positioning sensor (GPS) or Inertial Navigation Sensor (INS) system are not available or with other sensors to obtain better estimations. Vision-based techniques are proving their effectiveness and robustness in handling this problem [1, 2].

Vision-based methods were first introduced by Ettinger [3]. He proposed to install a perspective camera on a Micro AIR Vehicle (MAV) to have vision-guided flight stability. After that, Omnidirectional sensors (such as fisheye and catadioptric cameras) attitude estimation was also arisen [4, 5]. Omnidirectional sensors have the advantage of wide surrounding of the UAV, which make horizon is always present in the image. However, these images contain significant deformations due to the geometry of the mirror and to the sampling of the camera. So they are usually used in high altitude.

There are basically three group methods of position and attitude estimation with monocular camera. The first group tries to detect the skyline in the world to estimate the up direction and hence the attitude of the vehicle [6]. Nevertheless, the skyline might not be visible in urban environments. The second group tries to detect a horizontal reference from artificial structures to estimate the pose of UAV [7, 8], such as structures and runway. However, artificial structures are not existed everywhere. Most of them could not obtain the position estimation.

The third group tries to use an artificial marker which could be recognized on a platform by UAV...
vision system [9]. Then, the position and altitude information could be estimated from the functional relationship between the coordination of image and camera. Sharp, C.S. et al [10] designed a marker which consists of 6 rectangles. They used the corners’ information of those rectangles to estimate UAV pose. Lei et al [11] developed a color marker which consists of 6 solid circles. In [12], the marker consists of one hollow and solid circle and ten points on them were detected. The centres of them were extracted based on joint method of projection and wavelet transform. Na Meng et al [13] used four corners information to calculate UAV pose based on a rectangular marker made up of a red and blue square. All of those methods are based on point information on marker. Some researchers used lines information from markers, such as Liu Shiqing [14] and Guili X [15]. They estimated the UAV pose using the vanishing point of parallel lines on the marker. Comparing with point-based method, line-based method is more stable and reliable due to more ample information is used. Additionally, there are other markers which are designed to use the surface information under some assumptions, such as area [16] and image moment [17]. However, surface-based method is difficult to obtain all of the pose information with complex calculation. Furthermore, those markers hardly meet the requirement of landing on a moving platform.

Landing on a moving platform becomes to be a hot and difficult issue in recent years [18-21]. Borowczyk [22] at el used the marker of ApritiTag to estimate relative position and velocity with kalman filter. Borschova [23] at el achieved relative pose estimation using color-based object detection. Abdullah M. Almeshal [24] designed a vision-based neural network controller to track the target for autonomous Landing. Overall, most of them are under the stage of simulation. Usually, the marker or target will be out of the field of camera view when the UAV land at a lower altitude as a big size of it is needed for high altitude.

In this paper, in order to make the marker is as visible as possible in the whole landing process, a new color marker is designed as well as its detection method with the single perspective camera. A combining pose estimation algorithm based on vanishing point of parallel lines on the marker and L-M with lightweight computation and strong robustness is proposed.

This paper is organized as follows: in Section 2, a system and equipment description is developed; Section 3 describes how to obtain the relative position and attitude estimation based on vision system; Section 4 presents a designed landing marker and its detection approach; experimental results of the whole system are described in Section 5; finally, Section 6 concludes the paper.

2. System Description

![Figure 1. The marker designed in our application.](image)

In our study, the vision-based autonomous landing system is consisted of a UAV with monocular camera and a landing marker which could be put on the moving or un-moving platform. There also have some conventional on-board sensors on the UAV, such as inertial measure unit (IMU) and GPS.

As we assume that the each part size of the marker is known, the 3-D reconstruction could be calculated using the projecting model and the camera calibration parameters by the vision system. We also assume the UAV computer system can receive the real-time GPS location of the landing platform. Therefore, UAV could fly to the around area to prepare for landing. In the light of the following four factors, a RGB tri-phosphor based marker is designed as shown in figure 1. a) Compared to black-and-white marker, color marker helps to distinguish from the surrounding environment with rich color information; b) Red, green and blue are basic three primary colors, which helps to detect points or lines from the marker; c) Because of landing on a moving platform, the location of the marker may
changes at any time. The relative position and attitude should be calculated throughout the whole
landing processing; d) As the platform may be moving, the direction is also necessary.

So, the new marker consists of two blue parts as undertone, two red parts as directional reference
and a green part as an isolation belt. It is painted on the spot landing surface. And the centre point is
the landing spot. The bigger blue and red blocks on the outer circle of the marker constitute a pattern
that will be used when the UAV flies at high altitude. On the other hand, when UAV is close to the
landing spot at low altitude, this pattern will be out of the camera view. The smaller blue and red
blocks in the isolation belt will be detected as an inner pattern to support the autonomous landing of
UAVs on a moving platform. Flow diagram of landing program is shown in figure 2.

![Flow diagram of landing program](image)

**Figure 2.** Flow diagram of landing program.

### 3. Vision-based Position and Attitude Estimation for UAV

#### 3.1. Vision-based Position and Attitude Estimation Principle

Shown in figure 3 are the coordinate systems adopted in the UAV vision systems. There are four
following coordinate in the system:

- WCS \((X_W, Y_W, Z_W)\): World coordinate system, \(x_w-y_w\) plane is parallel to ground;
- CCS \((X_C, Y_C, Z_C)\): Camera coordinate system, which represents the camera mounted on the
UAV;
- IPCS \((x, y)\): Image plane coordinate system, which means the coordinate system of the sensor;
- ICS \((u, v)\): Image coordinate system, which is a two-dimensional coordinate system. The
origin is set at the lower left point.

The aim of this research is to estimate the relative position \((x_w, y_w, z_w)\) and attitude \((\phi, \theta, \psi)\) of
UAV in WCS from ICS. The relationship between ICS and WCS coordinate systems could be derived
from the relationship of ICS, IPCS and CCS [10].

![Relationship between different coordinate system](image)

**Figure 3.** Relationship between different coordinate system.
The relationship between CCS and WCS coordinate systems could be described as follow:

\[
\begin{bmatrix}
X_C \\
Y_C \\
Z_C
\end{bmatrix} = R \begin{bmatrix}
X_W \\
Y_W \\
Z_W
\end{bmatrix} + T
\]  

(1)

Where, \( R \) is the rotation matrix of the camera coordinate system relative to the world coordinate system. \( T \) is the three-dimensional translation vector from the world coordinate to the camera coordinate system.

The rotation matrix is defined as follow:

\[
R = \begin{bmatrix}
\frac{\cos \theta \cos \phi}{\sqrt{\cos^2 \phi + \sin^2 \theta \cos^2 \phi}} & -\sin \theta \cos \phi & \cos \theta \sin \phi \\
\frac{\cos \theta \sin \phi}{\sqrt{\cos^2 \phi + \sin^2 \theta \cos^2 \phi}} & \sin \theta \cos \phi & \cos \theta \sin \phi \\
-\sin \phi & \cos \phi & 0
\end{bmatrix}
\]  

(2)

The three-dimensional translation vector is as follow:

\[
T = \begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
\]  

(3)

Combining the relationship between ICS and CCS, the relationship between ICS and WCS coordinate systems is:

\[
\begin{bmatrix}
Z_C \\
W_C \\
1
\end{bmatrix} = \begin{bmatrix}
f_u & 0 & u_0 \\
f_v & 0 & v_0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
r_{11}x_w + r_{12}y_w + r_{13}z_w + t_x \\
r_{21}x_w + r_{22}y_w + r_{23}z_w + t_y \\
r_{31}x_w + r_{32}y_w + r_{33}z_w + t_z
\end{bmatrix}
\]  

(4)

equal to:

\[
\begin{cases}
u = f_u(r_{11}x_w + r_{12}y_w + r_{13}z_w + t_x) + u_0 \\
v = f_v(r_{21}x_w + r_{22}y_w + r_{23}z_w + t_y) + v_0
\end{cases}
\]  

(5)

Where, assume \( f \) is the focal length of camera, \( f_u = f/d_u, f_v = f/d_v \). \((d_u, d_v)\) is the pixel size of the camera sensor. \((u_0, v_0)\) are the pixel value of the IPCS origin in ICS. Assume that we have coordinates in ICS and WCS of \( n \) points, a set of equation by equation (5) will be shown as follow:

\[
\begin{cases}
(u_1 - u_0)(r_{31}x_w + r_{32}y_w + r_{33}z_w + t_x) - f_u(r_{11}x_w + r_{12}y_w + r_{13}z_w + t_x) = 0 \\
(v_1 - v_0)(r_{31}x_w + r_{32}y_w + r_{33}z_w + t_x) - f_v(r_{21}x_w + r_{22}y_w + r_{23}z_w + t_y) = 0 \\
\vdots
\end{cases}
\]  

(6)

In this set of equation, \( f_u, f_v, u_0, v_0 \) can be obtained from camera calibration. Theoretically, if we have the coordinates in ICS and WCS of 3 points at least, \( t_x, t_y, t_z, \theta, \phi \) and \( \rho \) could be calculated employing only the equations set by combining equation (2) and (6). However, due to the existing of error from calibration and point detection, the exact solution of the equations probably cannot be obtained. So, a optimization method of L-M is employed in this work.

3.2. Pose Estimation using L-M and Vanishing Point Method

Setting \( x = (\theta, \phi, t_x, t_y, t_z) \) and \( F(x) = (f_1(x), f_2(x), \ldots, f_{2n}(x))^{T} \) (means that \( F(x) \) represents the left side of equation (6)), the solution of equation (6) could be described as an optimization problem as equation (7).

\[
\min F(x) = \min \sum_{i=1}^{2n} || f_i(x) ||^2
\]  

(7)

Levenberg-Marquardt (L-M) is a widely used least square method to calculate the minimum value.
of multidimensional nonlinear equations. For this issue, the objective function is \( F(x) = 0 \). The steps of L-M method are shown as follows:

Step 1: Set termination control parameter \( \varepsilon \), damping variable \( \lambda_0 \) and \( s \). Initializing count of number \( k = 0, x = x_0, \) get \( \varepsilon_k = \| F(x_0) \| \);

Step 2: Calculate Jacobi matrix \( J_k \) and \( \overline{N}_k = J_k^T J_k + \lambda_k I \);

Step 3: Calculate adjustment coefficient \( \delta_k \) from incremental normal equation \( \overline{N}_k \delta_k = J_k^T \varepsilon_k \);

Step 4:

a) If \( \| F(x_k + \delta_k) \| < \varepsilon_k \) and \( \| \delta_k \| < \varepsilon \), stop the loop. Export the result \( x_{k+1} = x_k + \delta_k \);

b) If \( \| F(x_k + \delta_k) \| < \varepsilon_k \) and \( \| \delta_k \| \geq \varepsilon \), set \( x_{k+1} = x_k + \delta_k, \lambda_{k+1} = \lambda_k / s, k = k + 1 \), then go to step 2;

c) If \( \| F(x_k + \delta_k) \| \geq \varepsilon_k \), set \( \lambda_{k+1} = s \times \lambda_k \), then go to step 2.

Initial value \( x_0 \) is important for L-M method. Otherwise, the result will be diverging with an improper value. When UAV vision system has been under tracking processing, the estimation result of this moment could be used as \( x_0 \) for next moment. However, at the start of this system, we have to use another way to get \( x_0 \), which as explained as followed.

A vanishing point is a point on the image plane of a perspective drawing where the two-dimensional projections (or drawings) of mutually parallel lines in three-dimensional space appear to converge. Assume that there is a line on the two-dimensional plane \( (X_W, Y_W) \) and the equation is \( y = ax + b \) \( (z = 0, a \) is the slope of this line), combining equation (5) the vanishing point \( P(u_p, v_p) \) will be as follows:

\[
(u_p, v_p) = (\lim_{x \to \infty} f_u (r_{11} + r_{12}a)x + r_{12}b + r_{13}t_z + u_0, \lim_{x \to \infty} f_v (r_{21} + r_{22}a)x + r_{22}b + r_{23}t_z + v_0)
\]

\[
= (f_u r_{11} + r_{12}a + u_0, f_v r_{21} + r_{22}a + v_0)
\]

(8)

From equation (8), we can see that the coordinates of vanishing point in ICS is only related to the slope \( a \) except the internal parameters \( f_u, f_v, u_0 \) and \( v_0 \). These internal parameters could be calculated by camera calibration. Therefore, if we set \( a = 0 \), the vanishing point \( P_0(u_{p,0}, v_{p,0}) \) of the lines parallel to \( X_W \)-axis will be as follow:

\[
(u_{p,0}, v_{p,0}) = (f_u r_{11} + u_0, f_v r_{21} + v_0)
\]

(9)

In addition, the roll angle \( \varphi \) is usually very small in landing. In order to get the initial values which close to the true value, we also set \( \varphi_0 = 0 \), combining equation (2) the vanishing point \( P_0(u_{p,0}, v_{p,0}) \) will be converted to:

\[
(u_{p,0}, v_{p,0}) = (f_u \frac{1}{\tan \theta_0} + u_0, f_v \frac{\tan \varphi_0}{\sin \theta_0} + v_0)
\]

(10)

When \( (u_{p,0}, v_{p,0}) \) is obtained from image process, the \( \theta_0 \) and \( \varphi_0 \) could be calculated from Eqs.13. Then, combining equation (5) the initial value of translation vector \( T_0(t_{x,0}, t_{y,0}, t_{z,0}) \) could be obtained too. Lastly, using all of the initial values into the steps of L-M method, the final result of relative position and attitude will be calculated.

4. Marker Detection Algorithm
As mentioned in section 3.1, theoretically, only 3 points are enough to calculate \( t_x, t_y, t_z, \theta, \) and \( \varphi \). In this paper, we use the corners of outer or inner pattern. See figure 1, when the outer pattern is used, the four black corner points 1–4 are detected for calculating relative position and attitude. When the inner pattern is used, the four corner points 6–8 are detected. On the other hand, once the four corner points are detected, the sidelines of marker rectangle are also determined. Then vanishing point will be calculated by these sidelines which parallel to \( X_W \)-axis in WCS.

4.1. Detection of outer marker pattern
The flow chart of outer marker pattern detection method is illustrated in figure 4. This method
includes two main stages: marker region detection and target points detection. Marker region detection is to segment marker region from whole image. Target points detection is to detect corner points and location from segmented region. Then the needed vanishing point coordinate could be calculated.

![Flow chart of outer pattern detection algorithm](image)

**Figure 4.** The flow chart of outer pattern detection algorithm.

This new marker is designed based on color. So color information will be used in the detection method. For RGB model, the color image could be divided into R, G and B three gray images. In order to keep blue and red pixels and wipe off background, the calculation between three gray images will be employed. First, the R, G and B images are divided from color image; then, different-images of B-G and R-G are calculated; lastly, the different-images are merged into a binaryzation image by union. However, small noises and holes often remain in the binary images. So, open and close processes are employed to remove them (see figure 5).

Target edge points detection and location. In order to detect the four corner points which are shown in figure 6, we had tried to use common corner detection method such as Harris. However, because of the noise, the edges of marker region are generally jagged and irregular. Some ruleless points are detected, which lead to more difficult to identify the true corners. On the other hand, line features are more reliable than point features in real environment. So, line edge detection algorithm is employed to identify the four marker edges first. Then, the coordinate values of corner points will be calculated from these linear equations.

![Result of marker region detection](image)

**Figure 5.** Result of marker region detection

(1) Edge points classification

Given that the points on the same edge have same or similar gradient characteristic including gradient magnitude and direction. The point gradient characteristic could be the classification judgment to identify whether in the same edge. For this work, we designed 8 gradient operators to calculate the gradient magnitude of the 8 directions for every pixel (see figure 5, \( q = 0.1 \)). The pixel value means the gradient magnitude in this direction. So, the larger the gradient of the pixel, the value in result image is closer to white. So, the points on the same edges present max magnitude in the same direction. Because the outer marker has the maximum connected region, the inner pixels could be removed.

(2) Linear fitting

Although most of edge points have correct classification, error points will cause false linear fitting
if the fitting method is weak robustness such as least-squares estimation. So, we adopt Huber fitting method which is insensitivity to outliers. The fitting principle is to minimize the sum of distance function $\sum \rho (r)$ . The distance function $\rho (r)$ is defined in equation (11).

$$\rho (r) = \begin{cases} 
    \frac{r^2}{2}, & \text{if } r \leq \delta \\
    \delta \left(\frac{r - \frac{\delta}{2}}{2}\right), & \text{otherwise}
\end{cases}$$  \hspace{1cm} (11)

where, $r$ is the difference between the fitting value and true value: $|y - f(x)|$ ($f(x)$ is the equation of the line currently fitted). $\delta$ is a threshold. When $r$ is bigger than $\delta$, the distance function of this point will be decreased to cut down the impact of outliers.

(3) Corner and vanishing points calculation

When the edge lines are obtained after linear fitting process, corner points are the intersections of two lines. Corner points coordinate value could be calculated by the equations of edge lines. Similarly, the vanishing point coordinate value we needed in the L-M method will be calculated by the intersection of the two edge lines that parallel to $X_w$-axis.

4.2. Detection of inner marker pattern

Under whole landing process, the outer marker pattern will be out of the field of camera view when the UAV fly blow a certain height. At this moment, the aim of this algorithm is to detect the points 5~8 of inner marker pattern in figure 1.

Inner marker pattern is surrounded by a green isolation belt, which is a trait we will use to detect the image area of it. So, the basic flow chart of inner marker pattern detection method is the same as figure 3. The different are the processing details in the stages of ‘Image segmentation’ and ‘Extract maximum connected region’.

In the image segmentation stage, the R, G and B images are also divided from color image. Then, different-images of G-B and G-R are calculated. Lastly, the different-images are merged into a binaryzation image by and operation. In the extract maximum connected region stage, conversely, the inner edge points are preserved. After this stage, the detection method for inner marker pattern is the same as for outer marker pattern.

5. Experiments

In the marker design and its detection method research process, we did experiments for different verification goals. One is to test the marker detection algorithm. Another one is to test the accuracy of the whole method proposed in this paper. In those tests, moreover, algorithms are programmed by Visual Studio C++ platform with OpenCV. All of results are calculated by offline processing.

5.1. Marker detection algorithm test

Given the security and operability, we did indoor test for this algorithm. The equipment and tools are shown in figure 7. UAV-M100 from DJI company is used for this test. The camera calibration is also finished before test.

![Figure 7. The equipment and tools for marker detection algorithm test](image)

In order to test the robustness of this algorithm, a scene with complex background is selected. There are not only lots of objects with different colors, but also have interference from strong light. Figure 8 shows the mainly processing procedures and results for 5 images. 63 images were tested and
the average error is 10 pixels with $4000 \times 3000$ camera resolution.

Moreover, analysing the intermediate processing image which has large line fitting error, we found that most of them have hackly edge after marker region detection process. The hackly edge is formed from binaryzation for different-images of B-G which is introduced in Section 4.1.1. So, we changed the threshold of binaryzation and observe the accuracy of line fitting as shown in figure 9. Therefore, binaryzation is sensitive to the threshold value as well as the final detection results.

![Figure 8. Partial marker detection algorithm test results](image)

| Threshold | 50 | 40 | 30 |
|-----------|----|----|----|

**Figure 9.** Partial line fitting results with different binarization thresholds

### 5.2. Whole method test

An outdoor experiment is implemented for whole pose estimation method. A printed marker with the size of $600 \times 500$ mm is fixed on the ground. At the same time as the UAV test, two other cameras record the flight track from $X_W$-axis and $Y_W$-axis directions respectively. To obtain the reference ground truth, we draw the measure unit of distance on the ground for $X_W$-axis and $Y_W$-axis. For $Z_W$-axis direction, a rod is used as the measure unit. It is set on the centre of the marker and perpendicular to the ground. The cameras in the $X_W$-axis and $Y_W$-axis directions take the pictures which will be the standard to measure the height of UAV and its camera (see figure 10).

![Figure 10. $Z_W$-axis standard measure images](image)

a) From $X_W$-axis direction  

b) From $Y_W$-axis direction

**Figure 10.** $Z_W$-axis standard measure images

**Figure 11.** A set of line fitting result images captured from UAV camera
Figure 11 is a set of line fitting result images captured from UAV camera on this scene. From these images we can see that abundant shadows provided by the profusion of the woods. Even so, this algorithm still works. Using those fitting lines, the coordinate value of corner and vanishing points will be obtained. Then, import them into the position and attitude estimation program. The comparison from estimation results and reference ground truth is shown in figure 12. The numbers in figure 12 correspond to the numbers in figure 11. The average error of this test is 22 mm.

![Figure 12. Comparison from pose estimation results and reference ground truth](image)

6. Conclusion
After analysing the key and difficult points of autonomous landing technology of UAV on unmoving or moving platform, a new inner and outer combined color-based fixed point landing marker is presented, as well as its vision detection algorithm. Position and attitude could be estimated accurately and quickly using L-M and vanishing point combined method. On the other hand, irregular quadrilateral edge points are successfully classified using maximum gradient magnitude and direction feature, which is an important foundation to the edge lines fitting using Huber loss function and final corner point calculation. The indoor and outdoor experiments in various scenarios are implemented. From these results we can see that the proposed method fulfills the requirements of being accurate, whole covered and robust for vision-based landing system.

In future work, we plan to research the track algorithm to improve the real timing. Combining with the UAV control, real tests landing on a removing platform are required to update the marker and its detection algorithm.

Acknowledgments
The research is sponsored by the National Science Fund for Distinguished Young Scholars (51625503). The authors would like to thank all partners for their cooperation and valuable contribution.

References
[1] Shabayek, A E R, Cédrice Demonceaux, Morel, O and Fofi, D 2012 Vision based UAV attitude estimation: progress and insights Journal of Intelligent & Robotic Systems 65 pp 295–308
[2] Angelino C V, Baraniello V R and Cicala L 2013 High altitude UAV navigation using IMU, GPS and camera Int. Conf. on Information Fusion IEEE
[3] Ettinger S M, Nechyba M C, Ifju P G and Waszak M 2003 Vision-guided flight stability and control for micro air vehicles Advanced Robotics 17 pp 617–640
[4] Tarhan M and Altug, E 2011 EKF based attitude estimation and stabilization of a quadrotor UAV using vanishing points in catadioptric images Journal of Intelligent & Robotic Systems 62 pp 587–607
[5] Natraj A, Cédric Demonceaux, Vasseur P and Sturm P F 2011 A geometrical approach for
vision based attitude and altitude estimation for UAVs in dark environments 2011 Int. Conf. on Intelligent Robots and Systems IEEE/RSJ (San Francisco)

[6] Moore R J D, Thurrowgood S, Bland D, Soccol D and Srinivasan M V 2011 A fast and adaptive method for estimating UAV attitude from the visual horizon Int. Conf. on Intelligent Robots & Systems IEEE

[7] Hwangbo M and Kanade T 2011 Visual-inertial UAV attitude estimation using urban scene regularities IEEE Int. Conf. on Robotics and Automation (Shanghai) pp 2451–2458

[8] Laiacker M, Kondak K, Schwarzbach M and Muskardin T 2014 Vision aided automatic landing system for fixed wing UAV IEEE/RSJ Int. Conf. on Intelligent Robots and Systems

[9] Skoczylas M, Gadomer L and Walendziuk W 2017 Multirotor micro air vehicle autonomous landing system based on image markers recognition Society of Photo-optical Instrumentation Engineers Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series

[10] Sharp C S, Shakernia O and Sastry S S 2003 A vision system for landing an unmanned aerial vehicle IEEE Int. Conf. on Robotics & Automation vol 2 pp 1720–1727

[11] Li Xiaojie 2009 Study and Implementation of Position and Attitude Estimation for Four-rotor Mini Rotorcraft Based on Vision (Changchun:Jilin University)

[12] Wan Li 2014 Target Location and Landing Based on Unmanned Aerial Vehicle (Xi’an: Xidian University)

[13] Na Meng and Jia Peifa 2006 A vision system for autonomous flight of micro helicopter Computer Engineering and Applications 30 pp 220–22

[14] Liu Shiqing, Hu Chunhua and Zhu Jihong 2004 A method for estimating position and orientation of an unmanned helicopter based on vanishing line information Computer Engineering and Applications 40 pp 50–54

[15] Guili X, Xiaopeng Q, Qinghua Z, Yupeng T, Ruipeng G and Biao W 2013 Use of land's cooperative object to estimate UAV's pose for autonomous landing Chinese Journal of Aeronautics 26 pp 1498–1505

[16] Lange, Sunderhauf and Protzel 2009 A vision based onboard approach for landing and position control of an autonomous multirotor UAV in GPS-denied environments IEEE Int. Conf. on Advanced Robotics

[17] Yang S W, Sebastian AS and Zell A 2013 An onboard monocular vision system for autonomous takeoff, hovering and landing of a micro aerial vehicle J. Intell. Robot Syst. 69 pp 499–515

[18] Muskardin T, Balmer G, Wlach S, Kondak K, Laiacker M and Ollero A 2016 Landing of a fixedwing UAV on a mobile ground vehicle IEEE Int. Conf. on Robotics and Automation pp 1237–1242

[19] Chen X, Phang S K, Shan M and Chen M B 2016 System integration of a vision-guided UAV for autonomous landing on moving platform IEEE Int. Conf. on Control and Automation

[20] Polvara R, Sharma S, Wan J, Manning A and Sutton R 2017 Towards autonomous landing on a moving vehicle through fiducial markers European Conference on Mobile Robots pp 1-6

[21] Francisco A, Manuel G and Ivan M 2019 A precise and gnss-free landing system on moving platforms for rotary-wing UAVs Sensors 19 886

[22] Skoczylas M, Gadomer L and Walendziuk W 2017 Multirotor micro air vehicle autonomous landing system based on image markers recognition Society of Photo-optical Instrumentation Engineers Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series

[23] Borshchova I and O*Young S 2017 Marker-guided auto-landing on a moving platform International Journal of Intelligent Unmanned Systems 5

[24] Abdullah M. Almeshal and Mohammad R. Alenezi 2018 A vision-based neural network controller for the autonomous landing of a quadrotor on moving targets Robotics 7 71