Simulated Terrain Flight Control of Plant Protection UAV Based on Binocular Vision

Dong Wang1,2, Yeman Fan1,2, Haihui Zhang1,2, Yang Zhang1*

1 College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, China
2 Key Laboratory of Agricultural Internet of Things, Ministry of Agriculture, Yangling 712100, China

Abstract

The simulated terrain flight control method of plant protection UAV was presented based on binocular vision, aiming to overcome the poor operation effect and inconsistent flight height during the manual operation of the plant protection UAV. First, the depth image was obtained by stereo matching in binocular vision; then, the image was statistically analyzed to acquire the depth frequency distribution information of crop canopy area; thereafter, the depth value at the maximum frequency was taken as the effective distance between crop canopy and the UAV. Moreover, the PID controller was used to control the UAV flight height in real time. Capable of keeping the effective distance despite the varying terrain or crop canopy, the controller helps to improve the quality of plant protection operation and automation level of the UAV. The results show that the binocular vision has effectively obtained the crop canopy depth information, as the mean relative error of extracted effective distance was 0.11%, and the max relative error was 2.04%; the PID controller has a good effect on flight height control: when the control height was set at 300cm, the max relative error of height control was 8.15%, and the mean relative error was 0.26%. Thus, this research provides a strong guarantee for the simulated terrain flight control of the plant protection UAV.

Keywords: Aviation Plant Protection, Binocular Vision, Simulated Terrain Flight Control, PID Controller.

1. INTRODUCTION

Featuring fast speed, high efficiency and strong disaster resistance, agricultural aircraft spraying can reach remote fields inaccessible to agricultural machinery or farmers. Thus, it has become one of the research hotspots in the fields of agricultural plant protection (Xu et al., 2017; Huang et al., 2013). Over the years, the technology has been widely applied in Xinjiang Autonomous Region, Northeast China, and other major grain producing areas (Zhou et al., 2013). Thanks to the high efficiency and low cost of plant protection UAV, and the trend of intensive and large-scale cultivation encouraged by national policy, recent years has witnessed an increasing demand for agricultural aviation plant protection (Zhang et al., 2014).

In most cases, the UAV sprays pesticide in low and ultra-low volumes, attaching great importance to the utilization efficiency of pesticide. In addition to the crop yield and quality, the pesticide spraying effect hinges on the nozzle-target distance due to the drift of pesticide in agricultural aviation plant protection under the influence of wind and other factors (Xiong et al., 2016; Lan et al., 2016). Many Chinese scholars have explored the relationship between the spray height and distribution of pesticide droplets. For example, Wang C L examined the droplet distribution of pesticide sprayed by plant protection UAV at the height of 3.0±0.1m (Wang et al., 2016). Lan Y B analyzed the effects of UAV spray parameters on droplet deposition on rice canopy, suggesting that the flight height and velocity seriously affect the average deposition of droplets at the collection point in the target area (Chen et al., 2016; Wang et al., 2016). Xue X Y investigated the pesticide deposition model of aviation spraying at different heights, and concluded that the spraying effect is greatly affected by the height of the spraying (Xue et al., 2016). Qin W C studied the UAV pesticide spraying on fruit trees, pointing out that the spraying effect is achieved at the spray height of 1.5m (Qin et al., 2016). The above research findings have been applied to the plant protection operations of rice, wheat and other field crops, and received good results. Nevertheless, the findings cannot be directly used in crop protection operations in mountainous regions, as the crop canopy is irregularized by the fluctuating terrain. What is worse, the existing UAV operations are mostly controlled manually, resulting in inconsistent operation heights (Dint et al., 2011; Peng et al., 2014).
The irregular, flexible crop canopy makes it difficult to perform plant protection operation with common distance measurement method. Whereas the binocular stereo vision system, grounded on image technology, ensures the accuracy of crop canopy distance measurement (Ji et al., 2015), this paper presents a simulated terrain flight control method of plant protection UAV based on binocular stereo vision system, aiming to maintain the consistent flight height over crop canopy. The proposed method guarantees the effective distance between crop canopy and the UAV, improves the effect of UAV pesticide spraying, and assures the accuracy and efficiency of plant protection operation results in mountainous regions.

2. BINOCULAR STEREO VISION SYSTEM

2.1. Binocular stereo vision model

The basic principle of binocular stereo vision lies in the acquisition of the 3D information of the scene. First, the same object is observed from two perspectives to obtain the projection image from different view angles; then, the parallax between image pixels is calculated by triangulation to acquire the 3D information. In the 3D space, the position of each point on the image plane corresponds to its spatial position, and the relationship between the image coordinates and the real-world coordinates is determined by the camera mathematical model. The standard binocular stereo vision model is shown in Figure 1.

![Figure 1. Binocular stereo vision model](image)

For the mathematically calibrated model in Figure 1, the two forward-facing cameras are assumed to be parallel to each other, and point \( p \) corresponds to two imaginary points \( p_l \) and \( p_r \) at the x-axis coordinate of \( x_l \) and \( x_r \), respectively. Thus, the corresponding parallax of \( p \) can be obtained by formula (1).

\[
d = x_l - x_r
\]  

where \( x_l \) and \( x_r \) are the number of rows; \( B \) is the baseline, i.e. the distance between the two cameras; \( d \) is the corresponding parallax of \( p \). Since the depth and parallax inversely proportional, the depth value \( Z \) can be obtained by triangular similarity with the formula below.

\[
\frac{B}{Z} = \frac{(B+x_l) \cdot x_l}{Z-f}
\]

Formula (2) can be simplified as formula (3).

\[
Z = \frac{Bf}{x_l-x_r} = \frac{bf}{d}
\]

where \( f \) is the focal length of camera.

Because of the nonlinear inverse relationship between depth and optical parallax, the binocular system only works well in the depth estimation for close objects (Figure 2).
Figure 2 reflects the correlation between the shooting distance and the parallax: the parallax decreases non-linearly with the increase of the shooting distance, and approximates zero when the shooting distance is infinitely long.

2.2. Extraction of depth information

Being the first step of depth information extraction, 3D matching finds the projection points (image points) of a 3D physical space in an image plane, and, at the same time, locates the corresponding projection points in another image plane. The parallax of the target object is available through the multi-point search. After determining the baseline between the two cameras, the relationship between the depth and the parallax is computed by triangular similarity. In this way, the depth information is obtained for the target object in the 3D scene.

Obtained by the stereo matching algorithm, the parallax between the pair of stereo images fails to provide enough information for spatial location. To realize the function of spatial location, the 3D coordinate point of the physical space is also needed. Therefore, the 2D coordinate point of each image plane is mapped into 3D coordinate point following a certain mathematical relationship.

According to the basic theory of binocular stereo, the mapping relationship can be described by a 4×4 reprojection matrix $Q$. Given the parallax and the 2D coordinate point $(x, y)$, the depth information can be calculated from $Q$ by formula (4).

$$
\begin{bmatrix}
    x \\
    y \\
    d \\
    1
\end{bmatrix}
= 
\begin{bmatrix}
    X \\
    Y \\
    Z \\
    W
\end{bmatrix}
$$

The 3D coordinates are $(X/W, Y/W, Z/W)$. The re-projection matrix $Q$ can convert the coordinates of each pixel and the inputted parallax value into 3D coordinate points of the physical space.

2.3. Obtainment of crop canopy depth information

2.3.1. Binocular stereo camera

Considering the depth measurement accuracy of binocular stereo camera and the actual needs of plant protection UAV, the author adopted the DM461 type binocular stereo camera (Tuyang Technology Co., Ltd.). With the aid of the active binocular technology, the camera (resolution: 560×460; field angle: 56°/46°; depth range: 50~600cm) can obtain more detailed information than the traditional binocular stereo camera. Specifically, the camera receives two infrared image data with a low voltage differential interface, and realizes high speed computation on an embedded FPGA chip. The depth data of each point in the view field are acquired.
and transmitted to the host computer via USB3.0 interface. Furthermore, this camera can accept external trigger signals to the satisfaction of real-time image capture requirements on depth calculation.

![Image of binocular stereo camera]

**Figure 3. Binocular stereo camera**

2.3.2. Depth information processing

Since the crop canopy is generally not flat, the depth information on the current image must be processed to obtain more accurate depth value distribution information, thus ensuring measurement accuracy of the canopy area. After obtaining the crops canopy depth image, the statistical frequency method was utilized to find the maximum frequency. Then, the depth value at the maximum frequency was taken as the effective distance between crop canopy and the UAV.

Prior to frequency calculation, formula (5) was introduced to calculate the depth range, i.e. the max-min difference in the whole data. The difference depicts the rangeability of the variable. Next, the Sturges’ formula was selected to determine the number of classes, which ensures that the data are properly distributed in each class. The Sturges’ formula is shown in formula (6).

\[
R = \max(X) - \min(X) \tag{5}
\]

\[
H = 1 + \frac{\log N}{\log 2} \tag{6}
\]

where \(X\) is all depth values; \(R\) is the depth range; \(N\) is the number of data; \(H\) is the number of classes. In this research, \(R=550\) and \(N=257,600\) because the depth range is 50~600cm, and the resolution is 560×460 for the DM461 camera.

![Image of maize field]

**Figure 4. Maize field**

![Image of depth image]

**Figure 5. Depth image**
The test object was the maize field on the north of the College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi Province. The binocular stereo camera was placed at about 350cm above the ground to capture the depth image. The depth information was saved for frequency calculation, and then the distribution histogram was made based on the frequency information. The maize field, the depth image and the frequency histogram are presented in Figures 4, 5 and 6, respectively.

As shown in Figure 6, most of maize canopy was 224~253cm deep. These parts of the field should be the focus of pesticide spraying. Then, the depth value at the maximum frequency was taken as the effective distance between crop canopy and the UAV.

The simulated terrain flight control system consists of outer loop control and inner loop control (Figure 7).

The outer loop control is a self-designed flight control system, which acquires the depth information of crop canopy and controls the path and flight height of the UAV. The inner loop control system adopts the A2 type commercial flight controller (DJI Innovations Science and Technology Co., Ltd.) to control the flight height and
stability of the UAV based on the integrated inertial measurement unit. The double loop control structure provides a strong guarantee for the simulated terrain flight control of the plant protection UAV.

### 3.2. Outer loop control system

With the LattePanda module as core processor, the 2.76”x3.46” outer loop control system integrates the Intel Atom Cherry Trail 1.8GHz quad-core processor, contains 4GB running memory and 64GB hard disk, and supports Wi-Fi, Bluetooth 4.0 and USB3.0. The system runs on the Windows 10 operating system.

![Figure 8. LattePanda](image)

The Windows 10 OS runs on LattePanda and the binocular depth information acquisition program is developed in the Visual Studio 2013 environment. The depth information of crop canopy area is obtained by obtaining the depth frequency distribution information. The software flow is displayed in Figure 9.

![Figure 9. Flow chart of effective distance acquisition](image)

### 3.3. UAV platform

The UAV platform was assembled for the flight control test. The platform adopts the conventional X-shape four-motor arrangement. The body structure is made of light-weight and high-strength carbon fiber material. The components are listed in Table 1.
Table 1 The components of the UAV

<table>
<thead>
<tr>
<th>Items</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Quadcopter</td>
</tr>
<tr>
<td>Diagonal motor distance</td>
<td>650mm</td>
</tr>
<tr>
<td>Motor type</td>
<td>SUNNYSKY-X4108s-kv380</td>
</tr>
<tr>
<td>Speed controller type</td>
<td>HOBBYWING-Platinum-30A-Pro OPTO</td>
</tr>
<tr>
<td>Propeller model</td>
<td>15*55</td>
</tr>
<tr>
<td>Body frame type</td>
<td>Tarot 650</td>
</tr>
<tr>
<td>Flight controller type</td>
<td>DJI A2</td>
</tr>
</tbody>
</table>

3.4. Simulated terrain flight control method

The proportional–integral–derivative (PID) controller was used to guarantee the simulated terrain flight control and ensure the consistency of effective distance. Based on the effective distance obtained by the outer loop control system, the PID controller is a linear control system that achieves the simulated terrain flight control of plant protection according to the deviation of the actual effective distance from the preset working distance and the actual effective distance. The controller mainly functions through the proportional, integral and differential modules. The proportional module is prone to cause overshoot, despite the quick reduction in response time and deviation. The integral module may slow down the system response, albeit the elimination of static deviation and improvement of control accuracy. By contrast, the differential module corrects the deviation early before it is too big to amend, and thus shortens the time for response and adjustment. The calculation process is shown in formula (7).

\[ U(t) = K_P \left( e(t) + \int_0^t \frac{e(t)}{T_I} dt + T_D \frac{de(t)}{dt} \right) \]  

(7)

where \( U(t) \) is the output of the controller; \( e(t) \) is the deviation signal, i.e., the difference between the given quantity and the output quantity; \( K_P \) is the scale factor; \( T_I \) is the integral time constant; \( T_D \) is the differential time constant.

Nevertheless, formula (7) is applicable to continuous system only. To adapt to the needs of discrete system, the formula must be discretized by the backward difference method. Hence, the integral transfer function in formula (7) was transformed into a continuous s domain model, and the domain mapping relationship from s to z was obtained by the backward difference method. The transformation process is described in formulas (8)–(10).

\[ G_C(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_P}{T_I} + K_P T_D s = \frac{K_P T_D s^2 + K_P T_I + K_P}{T_I s} \]  

(8)

\[ s = \frac{z - 1}{z^T} = \frac{1 - z^{-1}}{z^T} \]  

(9)

\[ G_C(z^{-1}) = \frac{U(z^{-1})}{E(z^{-1})} = \frac{p_0 + p_1 z^{-1} + p_2 z^{-2}}{1 - z^{-1}} \]  

(10)

where \( p_0 = K_P + K_I + p_2; p_1 = -K_P - p_2; p_2 = K_D; K_I = \frac{K_P T_I}{T_I}; K_D = \frac{K_P T_D}{T_D} \).

Figure 10. Depth measurement test
4. SYSTEM TEST

4.1. Depth measurement test

The purpose of depth measurement test is to measure the difference between measured values and actual values. The test was carried out on the northside road of the College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi Province. A gray carton was moved step by step from the nearest distance of 50cm to the maximum distance of 600cm. Each step length was 50cm. In each step, the distance was measured three times and averaged, and the average distance was compared with the actual distance measured by the meter. Figures 10 and 11 show the test process and the results, respectively.

As shown in Figure 10, the depth measurement is highly accurate in the depth range of the binocular stereo camera. There is a good linear relationship between the measured values and the actual values, as the coefficient of determination $R^2$ is 0.999, the intercept is 2.113, and the proportionality coefficient $k$ is 0.991. With the max relative error of 2.04% and the mean relative error of 0.11%, the results meet the requirements of this research.

4.2. Verification of simulated terrain flight control

For the purpose of measuring the difference between actual height and preset height, the simulated terrain flight control test was carried out on the concrete road with slope about 20°, 400m outside the north gate of Northwest A&F University. The abovementioned terrain flight control system was used to control the UAV platform. For the sake of safety, the take-off and landing were controlled manually. When the UAV climbed to the vicinity of the preset height, the control mode was switched from manual operation to the terrain flight control model. The test process is displayed in Figure 12.
The height was measured at the sampling interval of 1s and stored in LattePanda. The result equals the average depth of the road area measured by the binocular stereo camera. The UAV flew along the straight road for about 60m. In order to estimate the error, the author considered only the values that remain stable after the system is put under control. The results are illustrated in Figure 13.

![Figure 13. Results of simulated terrain flight control test](image)

According to Figure 13, the PID controller controls the UAV flight height from the road perfectly in the simulated terrain flight process. When the control height was set at 300cm, the max relative error of height control was 8.15%, and the mean relative error was 0.26%, indicating that the controller achieves a good effect on simulated terrain flight in the current environment.

5. CONCLUSIONS

Based on binocular vision, the simulated terrain flight control method of plant protection UAV was presented to overcome the defects in existing operation control methods for plant protection UAV and to ameliorate the poor pesticide spraying effect resulted from manual operation. First, the crop canopy depth information was obtained by binocular stereo vision; then, the depth frequency distribution information of the canopy area was extracted by the statistical frequency method; later, the depth value at the maximum frequency was used as the effective distance between crop canopy and the UAV, and the PID controller was adopted to achieve automatic flight control. To sum up, this paper makes the following innovations.

(1) The binocular stereo vision was introduced to measure the depth information of the irregular, flexible crop canopy, the statistical frequency method was used to obtain the depth value distribution information, and the depth value at the maximum frequency was taken as the effective distance between crop canopy and the UAV. These strategies ensure the good effect of pesticide spraying in the largest possible area.

(2) The depth measurement is highly accurate in the depth range of the binocular stereo camera. There is a good linear relationship between the measured values and the actual values, as the coefficient of determination $R^2$ is 0.999, the max relative error is 2.04% and the mean relative error is 0.11%. The results meet the requirements of this research.

(3) The PID controller was employed to control the flight height stability for simulating terrain flight, and controlled the UAV flight height perfectly in the simulated terrain flight process. When the control height was set at 300cm, the max relative error of height control was 8.15%, and the mean relative error was 0.26%. The results shed new light on simulating the terrain flight of plant protection UAV.

ACKNOWLEDGMENTS

The authors would like to express their acknowledgment for the support from the Key Projects in the National Science & Technology Pillar Program during the Twelfth Five-year Plan Period (2012BAH29B04).

REFERENCES


