

Folding Angle Measurement and Control Technology of Deformable UAV

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Abstract

The deformable UAV has the advantage over the traditional fixed-wing aircraft in expanding the flight envelope. In this paper, a folding wing mechanism is designed to meet the accurate angle control requirement. Accordingly, an angle measurement method based on MEMS (micro-electromechanical systems) accelerometers is studied. The accurate folding angle in any condition can be derived from analysis of the folding wing's acceleration in different positions, upon which the fuzzy control law of the wing's folding angle is proposed. Finally, the validity and accuracy of the algorithm is verified with experiment.

Keywords: folding wing, MEMS accelerometers, angle measurement, fuzzy control

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1. Introduction

Fixed-wing UAV is taking more and more different tasks in exploration and detection in military and civil use by its own advantages in speed, range and stability. However, the wing aspect ratio has a non-ignorable influence on a fixed-wing aircraft's aerodynamic characteristics and flight quality. Applying the controllable folding wing to change wing aspect ratio is an efficient way to obtain the best overall performance of the aircraft in different flight mission phases [1].

In the wing folding, on the one hand, the folding wing's strength and stability need to be ensured, on the other hand, accurate measurement and efficient control of the folding angle is necessary when the aircraft is under any attitude.

Most existing folding wing can only realize two states control at the maximum and minimum folding angle, which neglects the transition states of the process; therefore the flight performances in different transition angle states are not developed. In this paper, a folding wing control mechanism is designed for small-sized UAV, realizing the self-locking function in any folding angle within its variation range.

Accurate measurement is the premise of folding angle control. Conventional platform high accuracy gyro usually has a large volume, bad anti-overload capacity, and rather high price, not suitable for small-sized UAV wing box. Therefore, when taking angle measurement, strapdown inertial gyro and miniature potentiometer have severe integration accumulated error and are strongly influenced by state variations of the aircraft [2].

UAV navigation system usually adopts inertial sensors such as high accuracy gyro and accelerometer, obtaining the flight attitude by integration of collected signals. Based on the inertial navigation system of the aircraft, this paper brings forth an accelerometer-information-based folding angle measurement method [3, 4, 5].

This paper gives a folding angle measurement method by measuring the folding wing's acceleration in different positions and by comparative analysis with the acceleration information from the UAV navigation system. This measurement method has small occupying space, high accuracy, and good real-time capability, which is suitable for micro deformable UAV.

Based on the accurate measurement of folding angle, this paper describes a fuzzy method to precisely control the folding angle, to gain the best flight performance for the aircraft in any flight condition.

2. Research Method

2.1. Wing Folding Deformation Mechanism

During the flight of the deformable UAV, according to flight condition requirement, continuous adjustment of the folding angle is needed in order to obtain the best flight performance, as shown in Figure 1. This paper gives a design of folding wing mechanism composed of converted servo motor, worm and worm wheel mechanism, and parallelogram mechanism, as shown in Figure 2.

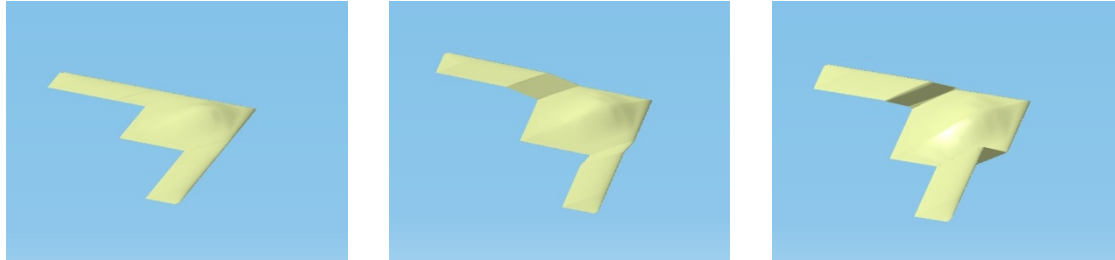


Figure 1. Folding Wing Angle Variation under Different Flight Condition

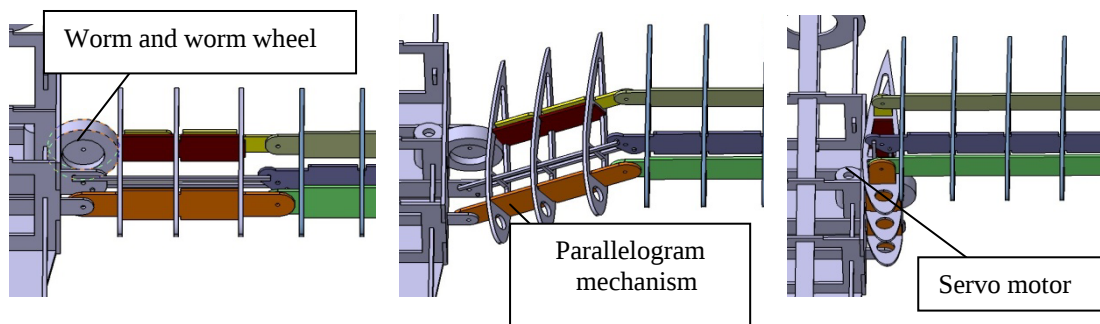


Figure 2. Folding Wing Deformation Mechanism

In the deformation mechanism, servo motor drives the worm, the worm drives the worm wheel which fixed on the inner wing spar, driving the inner wing to rotate. The servo motor's rotate range is converted from $0^\circ \sim 110^\circ$ to unlimited angle range. Worm and worm wheel has self-locking function in order to lock the wing floding at any angle. The parallelogram mechanism ensures the outer wing and the fuselage planar are always parallel, in order to obtain a stable aerodynamic efficiency.

2.2. Measurement of the Folding Angle

The aircraft's attitude data mainly contain roll angel, pitch angle and the yaw angle. The motion of the folding wing determines that there is only one angle velocity component during the folding process. With the component of gravitational acceleration shown in the accelerometer, it can work out the folding angle with inverse trigonometric. The analysis can be classified according to different attitudes.

While the aircraft has no angle deflection, the body's coordinate system (x_b, y_b, z_b) is coincide with the geodetic coordinate system (x_g, y_g, z_g) [6]. The data in the body accelerometer which lies in the center of the gravity can be read as (a_{bx}, a_{by}, a_{bz}) , and the data in the two accelerometers which lies in the folding wing is (a_{w1}, a_{w2}) . The roll angel, pitch angle and the yaw angle is zero, then the folding angle of the wing is:

$$\phi_w = \arccos \frac{a_w}{a_{bz}} \quad (1)$$

ϕ_w is the wing folding angle, a_w is the acceleration in the folding wing, a_{bz} is the acceleration in the fuselage.

To reduce the installation error, a method with two accelerometers is used. An instantaneous acceleration will generate in the original folding state, it will strongly impact the acceleration, and lead a measurement error. Two accelerometers which lie in different location in the spanwise can get the component of the gravity and the instantaneous acceleration, Figure 3 illustrates the location of arrangement position.

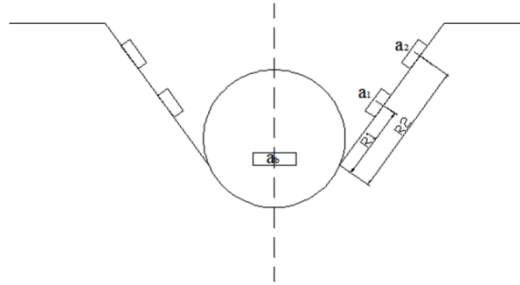


Figure 3. The Install Location of the Accelerometers

The ratio of the tangential accelerations lies in the plot A and B is:

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{r_1}{r_2} \quad (2)$$

r_1, r_2 are the distances between the wing bracing and the acceleration in plot A and B, respectively.

After considering the gravity acceleration, the linear acceleration is:

$$a_w = g_b \cos \phi - a^r \quad (3)$$

Then,

$$\frac{a_{w1} - g_b \cos \phi}{a_{w1} - g_b \cos \phi} = \frac{a^{r1}}{a^{r2}} = \frac{r_1}{r_2} \quad (4)$$

$$\phi_w = \arccos \left(\frac{r_1 a_{w2} - r_2 a_{w1}}{g(r_1 - r_2)} \right) \quad (5)$$

ϕ_w is the wing's folding angle.

While the aircraft is in the angle deflection, the body's coordinate system (x_b, y_b, z_b) is not coincide with the geodetic coordinate system (x_g, y_g, z_g).

When the aircraft has a roll angle ϕ , a pitch angle θ and a yaw angle ψ , the acceleration in the z axis is $a_z \cos \phi \cos \theta$, the acceleration in the folding wing is $a_w \cos \phi \cos \theta$, and then the wing's folding angle is:

$$\phi_w = \arccos \frac{a_w \cos \varphi \cos \theta}{a_{bz} \cos \varphi \cos \theta} = \arccos \frac{a_w}{a_{bz}} \quad (6)$$

The wing's folding angle is:

$$\phi_w = \arccos \left(\frac{r_1 a_{w2} - r_2 a_{w2}}{g(r_1 - r_2)} \right) \quad (7)$$

2.3. Fuzzy Control on the Folding Angle

The wing folding angle need to be precisely controlled to adapt to the states of the different flight speed, the aircraft attitude at each moment during the fixed-wing UAV flight. At the same time, in order to ensure that the aircraft is in flight stability, wing folding needs to be as gentle as possible, to avoid the wing of intense vibration occurs. The Wing folding variation corresponds to of the aircraft state belongs to the context of aircraft flight dynamics analysis, this article does not expand the introduction. This paper describes the fuzzy method to precisely control the folding angle, in the case of known expectations folding angle [7].

Based on actual experience in aircraft flight, wing folding impacts on flight stability seriously at high flight speed or large roll angle, therefore the folding change should be as gentle as possible in these cases [8]. After the above analysis, we designed a fuzzy control method of wing folding angel. The deviation between actual value and expected value of the wing folding angle $\Delta\phi_w$, UAV flight air speed V_a and the roll angle of aircraft ψ are used as fuzzy controller input, servo motor interaction coefficients η is fuzzy controller output.

We develop a series of fuzzy rules in accordance with the wing folding control characteristics analysis results, as follows:

R_1 : If V_a is Very small and ψ is very small and $\Delta\phi_w$ is very large, then η is very large;

R_2 : If V_a is Very small and ψ is very small and $\Delta\phi_w$ is large, then η is very large;

...

R_n : If V_a is very large and ψ is very large and $\Delta\phi_w$ is very small, then η is very small.

Generalized affirmative reasoning method is used in our fuzzy controller, and we use Minimum algorithm in Fuzzy implication relations calculation, Maximum - minimum synthesis in Composition operation.

Figure 4 illustrates the Hypersurface section diagram of Fuzzy Control Rules that η corresponding to $\Delta\phi_w$, V_a and ψ .

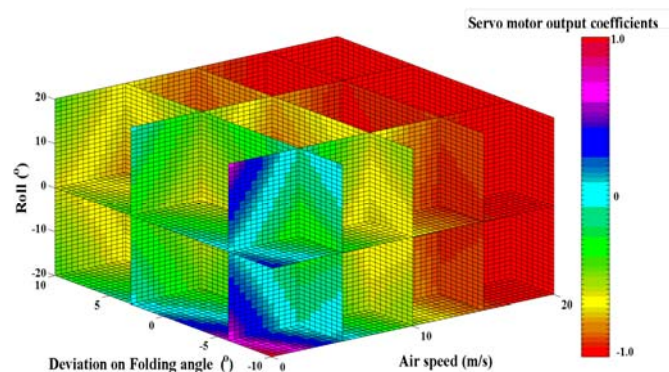


Figure 4. Hypersurface Section Diagram of Wing Folding Fuzzy Control Rules

2.4. Test System

We build a test system that consists of signal projector, signal receiver, UAV flight control system, two acceleration transducer ADXL345 and the folding wing steering engine.

The signal projector sends a expected folding angle A as input, and the onboard DSP estimates the actual folding angle B , based on the wing's acceleration given by the accelerometers on the wing and the body's acceleration information given by the flight control system. Then, combined with the UAV flight states given by the aircraft flight control system, onboard processor performs a fuzzy control process and to issue a control instruction to the servo motor in deformation mechanism. As result, actual folding angle B will constantly approaching the expected folding angle A .

Since measurement error may be present in actual value estimating, we also use mechanical measuring means to obtain the true value of the folding angle, which can verify the accuracy of the wing folding angle control.

Figure 5 shows a triple axial accelerometer LIS344ALH in the flight control board. MEMS accelerometers sample them into digital signals. Acceleration values can be calculated according to the relationship between voltage and the acceleration. Then the DSP processor could get the value of angle with a high degree of accuracy.

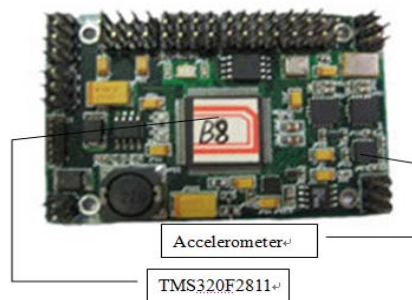


Figure 5. Triple Axial Accelerometer in the DSP Processor

Both of the two accelerometers in the folding wing are the ADXL345 module. ADXL345 is a ultra-low power accelerometer with little size, high resolution and wide range of measure ($\pm 16g$). It is ideally suited for mobile devices, which can test the static acceleration of gravity and the dynamic acceleration under the state of movement or impact.

3. Results and Analysis

We made a group of 17 tests to verify our system. Input expected value, output actual value and true value of the folding angle were collected, and Table1 illustrates the results of these tests.

Table 1. Data Collection of Different Test Points

Test point	Input value/ $^{\circ}$	Output value/ $^{\circ}$	True value/ $^{\circ}$
1	0.11	-0.94	-1.26
2	4.71	6.59	6.43
3	10.97	11.65	10.79
4	16.43	17.63	16.38
5	20.05	20.62	20.43
6	24.62	25.35	25.68
7	31.52	30.53	33.31
8	34.79	36.42	35.81
9	40.26	41.51	41.96
10	44.42	41.97	45.63
11	48.91	49.41	51.73
12	54.93	56.85	57.89
13	59.17	58.15	62.93
14	64.01	64.12	68.14
15	69.41	70.31	73.66
16	75.48	75.49	78.12

In order to judge the accuracy of this method, compared the ratios between the output value and the true value:

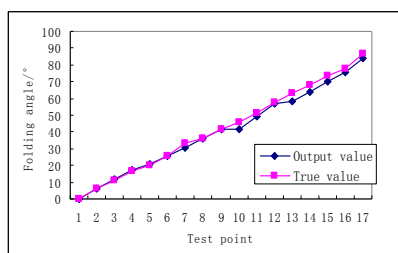


Figure 6. Output Value and True Value

As can be seen from Figure 6, less than 3 degree difference is shown in 30°, 40° and 60°. The output value is shown to well correspond to the true value, which demonstrate the accuracy of wing folding measurement method.

To test the efficiency of the control system, compared the input value with the true value of the angle:

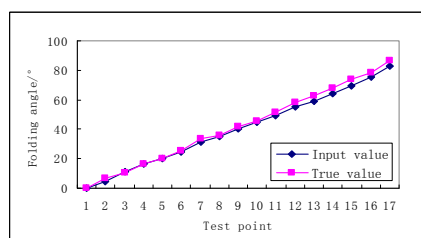


Figure 7. The Input Value and the True Value

It is manifest from Figure 7 that the input value accords well with the true value, there is less than 2 degree difference is shown from 50° to 90°. The true value is shown to well correspond to the input expected value. The results indicate that the platform built for the test is effective, accurate, and useful.

4. Conclusion

The angle measurement algorithm and the control system illustrated in the article can measure and control the wing's folding angle accurately, and make it at any angle between the minimum and the maximum state. What's more, with its high reliability and low cost, it could be widely used in deformable UAVs.

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