Pitch Angle Control using Flapping Frequency for a Flapping-Wing Robot

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Abstract: This paper presents methods of estimating and controlling the pitch angle for a flapping-wing robot. Measured values by the rate gyro sensor and the acceleration sensor mounted on a flapping-wing robot include high frequency noises and the drift caused by accumulating the error. For controlling a flapping-wing robot using values of internal sensors, we estimate the pitch angle of a flapping-wing robot based on the value combined the low-pass filtered output of the rate gyro sensor with the high-pass filtered output of the acceleration sensor. And a flapping-wing robot is controlled using the estimated pitch angle and the robot's characteristics which the pitch angular velocity changes in response to the flapping frequency.

Keywords: flapping-wing robot, attitude estimation, control

1. INTRODUCTION

Recently, a lot of researchers have been studying on several types of MAVs (Micro Aerial Vehicles)[1]. Flapping-wing robots, one of the MAVs, shaped like dragonflies[2] and birds are considered to have superior flying ability as well as such animals. However the autonomous control of a flapping-wing robot with the on-board computer has never realized, because of the limit of the payload and the noise in sensors caused by flapping the wing for flying. In this paper, we present the estimation method of the pitch angle of the flapping-wing robot using internal sensors include such noises, and validate its method through the experiment. Moreover, the flapping-wing robot is controlled using the estimated pitch angle and the robot's characteristic, flies autonomously with the on-board computer.

2. FLAPPING-WING ROBOT

Fig.1 shows our flapping-wing robot and mounted devices. This robot has the 2D rate gyro sensor, the 3D acceleration sensor for measuring the robot's attitude angles and the controller unit composed of the microcomputer and the 2D motor driver. A 2-cell lithium polymer battery supplies the power to the motor for flapping the wing, sensors and the controller unit. Parameters of the flapping-wing robot are shown in Table1.

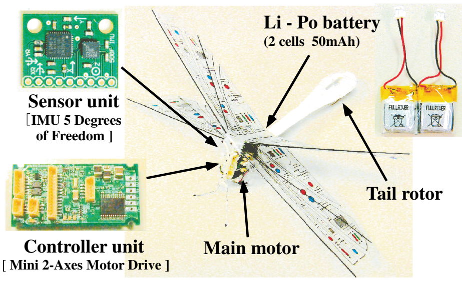

Fig. 1 The sensor unit (the 2D rate gyro and the 3D acceleration sensor), the controller unit (the microcomputer and the 2D motor driver), our flapping-wing robot, and Li-Po battery.

Table 1 Physical parameters of the flapping-wing robot.

Parameter	Value
Mass	28.5g
Length	280mm
Wing Span	410mm
Chord (Average)	80mm
Flapping Frequency	15.0Hz(Max)

3. PITCH ANGLE ESTIMATION

3.1 Estimation Method

In theory, the pitch angle is able to be calculated by integrating outputs of the rate gyro sensor and the relation between outputs of the acceleration sensor and the gravitational acceleration. However the pitch angle calculated from outputs of the rate gyro sensor drifts because of accumulating the error in flight. The acceleration sensor measures the robot's acceleration include inertia noises caused by flapping the wing. Thus the pitch angle calculated from the acceleration is also incorrect for controlling the robot.

For getting more accurate pitch angle using these sensors, we estimate the pitch angle from eq.(1) using high-frequency component of measured values by the rate gyro sensor $\mathrm{HPF}(\theta_{\mathrm{n}}^{\mathrm{gyr}})$ and low-frequensy component of measured values by the acceleration sensor $\mathrm{LPF}(\theta_{\mathrm{n}}^{\mathrm{acc}})$[3].

$$\theta_n^{\mathrm{est}} = \mathrm{HPF}(\theta_{\mathrm{n}}^{\mathrm{gyr}}) + \mathrm{LPF}(\theta_{\mathrm{n}}^{\mathrm{acc}}) \qquad (1)$$

In eq.(1), the drift of the rate gyro sensor's values is removed by passing the high-pass filter (HPF), inertia noises caused by flapping are removed by passing the low-pass filter (LPF). Where HPF and LPF in eq.(1) are first-order IIR (Infinite Impulse Response) filters. However, because a power unit composed 2-cell lithium polymer battery supplies the power to the motor, the conrtoller unit and all sensors by reason of the robot's payload, the pitch angle calcurated by the rate gyro sensor $\mathrm{HPF}(\theta_{\mathrm{n}}^{\mathrm{gyr}})$ has the offset caused by change of the input voltage to the rate gyro sensor response to the duty ratio of the motor, viz. the wing's flapping frequency. This problem solving, we use the correct method which changes the zero point of the rate gyro sensor response to the duty ratio. And the estimated pitch angle is represented by eq.(2) using the corrected output of the rate gyro sensor $\mathrm{HPF}(\theta_{\mathrm{n}}^{\mathrm{gyr}*})$. The detail of the estiomation and the correction is shown in [4].

$$\theta_n^{\mathrm{est}*} = \mathrm{HPF}(\theta_{\mathrm{n}}^{\mathrm{gyr}*}) + \mathrm{LPF}(\theta_{\mathrm{n}}^{\mathrm{acc}}) \tag{2}$$

3.2 Validation of Estimation Method

Fig.2 shows experimental results with the flapping wing robot (Fig.1) for validating above estimation method. In the upper figure, the estimated pitch angle θ^{est} calculated from eq.(1) has the error to the given reference θ^{msr} along with the change of the flapping frequency f^{flap}. On the other hand, the pitch angle $\theta_n^{\mathrm{est}*}$ estimated using the corrected value $\mathrm{HPF}(\theta_{\mathrm{n}}^{\mathrm{gyr}*})$ approximately corresponds to the reference θ^{msr} though the flapping frequency f^{flap} changes.

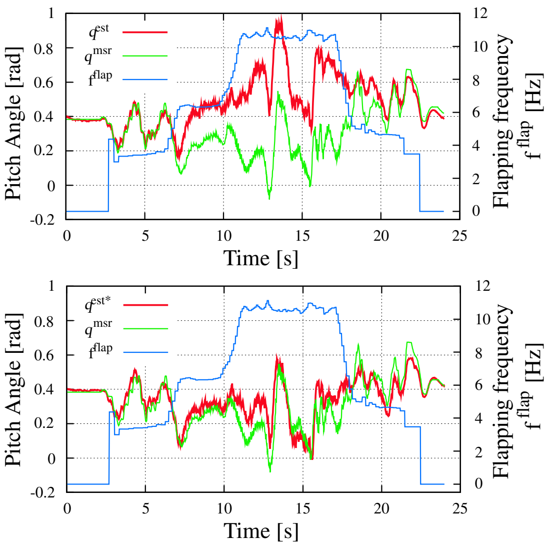

Fig. 2 Experimental results of the estimation. The θ^{msr} is a reference angle of the pitch. The f^{flap} is the flapping frequency. **Upper:** The pitch angle θ^{est} calculated from eq.(1). **Lower:** The pitch angle $\theta^{\mathrm{est}*}$ calculated from eq.(2).

4. PITCH ANGLE CONTROL

The flapping-wing robot has the characteristic that its pitching moment depends on both the flapping frequency and the airspeed. Causing this characteristic the fluctuation in flight without the pitch angle control, the robot gradually descends and cannot fly for a long time.

For stabilizing the pitch angle, the flapping frequency is controlled by PD controller considering the robot's characteristic and using the estimated angle $\theta_n^{\mathrm{est}*}$.

Fig.3 shows experimental results of the pitch angle control in autonomous flight. Where the flapping frequency is constant for the level flight in the experiment without the pitch angle control. In another experiment, the flapping frequency is controlled based on this constant value. In the controlled flight, the desired pitch

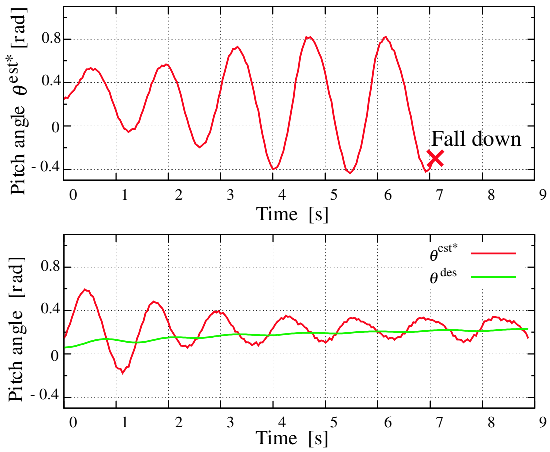

Fig. 3 Experimental results of self-contained flight. **Upper:** The estimated pitch angle $\theta^{\mathrm{est}*}$ in flight without the control. **Lower:** The estimated pitch angle $\theta^{\mathrm{est}*}$ and the desired pitch angle θ^{des} in controlled flight.

angle θ^{des} is the estimated angle passed low-pass filter $\mathrm{LPF}(\theta^{\mathrm{est}*})$.

The upper figure shows the result that the amplitude of the pitch angle increases as time passes, as a result, the robot falls down at 7th second. When the robot flies with the pitch angle control, the experimental results, bottom figure, shows tendency to converge on the desired pitch angle θ^{des}.

5. CONCLUSIONS

This paper has presented the estimation method the pitch angle for the flapping-wing robot using the rate gyro sensor and the acceleration sensor. The validation experiment has shown the pitch angle was able to be calculated from the measured value by internal sensors include the several noises. In addition, we have controlled the flapping frequency using the estimated pitch angle based on the robot's characteristic, have succeeded in autonomous flight of the flapping-wing robot by the on-board computer.

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