

## Development of Autonomous Flight Control System for a Small UAV - Measurement of Moment of Inertia using two-point suspension method -

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In our laboratory, we develop Unmanned Aerial Vehicle to fly to return to the point. In this paper, we show the results of measuring the moment of inertia for two point suspension method. In addition, Aerodynamic derivatives calculated using the estimation equation, and we show vertical position control of the simulation results.

### 1. Introduction

Recent years, an Unmanned Aerial Vehicle (UAV) has been actively researched and developed.

In our laboratory, we have started to develop a UAV of approximately 2m in length and 3m in width, and 10kg in mass in cooperation with a company. In this study, we aim to design an automatic control system so that the UAV autonomously flies to the target point and return to an initial takeoff point through some way points specified a priori.

To achieve this mission, an advanced collision avoidance and autonomous flight capability is essential. However, before performing an actual flight experiment, we need to verify the validity of the designed flight control system by performing flight simulations. It is also necessary to estimate the stability and control derivatives of the target UAV to determine the equations of motion of the UAV. Therefore, we carried out a flight simulation under a horizontal steady flight using the parameters estimated by conventional estimation equations. In addition, as a part of the estimation of the UAV dynamics, we clarified the moments of inertia around X, Y, and Z axes using two-point suspension method.

### 2. Specification of the UAV

Table 1 shows the specifications of the UAV under consideration.

Table 1. Specifications of the UAV

Parameters	Numerical
mass[kg]	6.645
length[m]	1.727
width[m]	2.693
material	Balsa wood

### 3. Control System of UAV

The overview of the attitude control system of UAV is shown in Fig. 1. Here,  $G_{F1}, G_{F2}, \dots, G_{Fn}$  are gains, and/or any other transfer functions. In addition, the blocks in the framework of the dotted line indicate a PC + interface board.

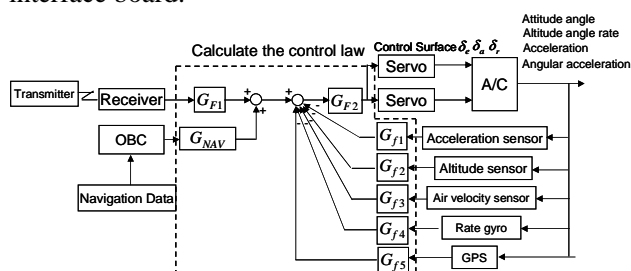


Fig.1 Control System of UAV

Input signals to the actuators for the attitude stabilization of the UAV are consists of the command signals for the steering angles received from the transmitter, generated by manual operation, command signals guided to the target point received from the navigation equipment (On-Board Computer developed for satellite control), and the state feedback signals of the UAV received from the sensors.

### 4. Aircraft equations of motion

In this study, as an initial dynamical model, we employ a conventional linear model under a steady level flight according to a small-perturbation theory.

$$\begin{bmatrix} \dot{u}(t) \\ \dot{w}(t) \\ \dot{q}(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} X_u & X_w & -g & 0 \\ Z_u & Z_w & 0 & U_0 \\ M_u + M_{\dot{w}}Z_w & M_w + M_{\dot{u}}Z_w & M_q + U_0M_{\dot{w}} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u(t) \\ w(t) \\ q(t) \\ \theta(t) \end{bmatrix} + \begin{bmatrix} Z_{\delta_u} \\ Z_{\delta_w} \\ M_{\delta} + M_{\dot{w}}Z_{\delta} \\ 0 \end{bmatrix} \delta \quad (1)$$

### 5. Measurement of moment of inertia.

In this study, for the measurement of the moments of inertia, we employed a two-point suspension method, where an object is suspended from the ceiling by two threads (Fig.2). In this state, we gave a small perturbation to the object to excite a slight vibration to determine the moment of inertia of the UAV around an axis from the period. Here  $l$  is the length of string,  $w$  the length between a suspended point by the string and the center of gravity of the object.

The equation of rotational motion is given by

$$\frac{d^2\theta}{dt^2} = \frac{mgw^2}{I\ell} \theta. \quad (2)$$

Where,  $I, \theta, m, g$  are moment if inertia of the object, rotational angle, the mass of the object, and gravitational acceleration, respectively. From the eq. (2), the period of harmonic oscillation can be given as follow:

$$T = 2\pi\sqrt{I\ell/mgw^2} \quad (3)$$

Rewriting the above equation, we obtain the moment of inertia

$$I = mgT^2w^2 / (4\pi^2\ell). \quad (4)$$

Thus, the moment of inertia around each three axis of the UAV can be calculated by measuring the period.

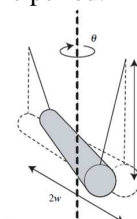


Fig.2 two point suspension method

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The obtained moments of inertia are shown in Table2.

Table.2 Calculated measurement of moment of inertia

Parameters	Numerical
moment of inertia around of X-axis $I_{xx} [kg \cdot m^2]$	0.197
length of string $\ell [m]$	0.5
mounting position of the string $w [m]$	0.200
period $T [s]$	0.645
moment of inertia around of Y-axis $I_{yy} [kg \cdot m^2]$	2.02
length of string $\ell [m]$	1.22
mounting position of the string $w [m]$	0.34
period(Winged) $T [s]$	0.406
period(No wings) $T [s]$	0.415
moment of inertia around of Z-axis $I_{zz} [kg \cdot m^2]$	0.974
length of string $\ell [m]$	1.7
mounting position of the string $w [m]$	0.200
period $T [s]$	0.283

If moment of inertia of the aircraft wing attached is  $I_{y0}$ , moment of inertia of the aircraft wings attached is  $I_{y1}$ ,  $I_{yy}$  is (5)

$$I_{yy} = I_{y0} + (I_{y1} - I_{y0}) \quad (5)$$

### 6. Attitude control system

Fig.3 shows an example of the attitude control system in the present paper.

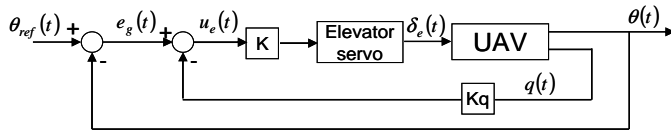


Fig.3 Block diagram of a longitudinal Attitude control system

Here,  $K$  and  $K_q$  indicate feedforward and feedback gains,  $\theta_{ref}(t)$  is pitch angle command, and is set as  $\theta_{ref}(t) = 0$ . In this study, we assumed that the dynamic of the elevator servo actuator is modeled as a first-order delay element, and its time constant is 0.1[s] as shown in eq. (6)

$$G_e(s) = \frac{\delta_e(s)}{e_g(s)} = \frac{1}{T_A s + 1} = \frac{1}{0.1s + 1} \quad (6)$$

### 7. Simulation results

Figs. 5~7 show the simulation results. In the simulation,

as an initial condition, we applied a small perturbation to the UAV during the level flight. The conditions in the simulation are shown in Table 3.

### 8. Future work

In the near future, we will attempt to design a lateral control system to achieve a level flight.

### 9. Reference

- [1]D.Kato, A.Otuka, K.Tsukazawa : “Introduction to aircraft dynamics” 1982.
- [2]Y.Shimada : “An Introduction to Control Systems” 2004.
- [3]Y.Naruoka : 2010 The University of Tokyo Doctor thesis “Obtain of a small unmanned aircraft flying through System Identification,

Table 3. Simulation conditions

Parameters	Numerical
altitude $f [m]$	50
mach number $M [-]$	0.0294
weight $W [kg]$	6.645
X-axis velocity $U_0 [m/s]$	4.167
Y-axis velocity $V_0 [m/s]$	0
Z-axis velocity $W_0 [m/s]$	0
angle of attack trim $\alpha [deg]$	2

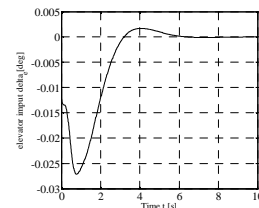


Fig.4 Time history of elevator deflection angle

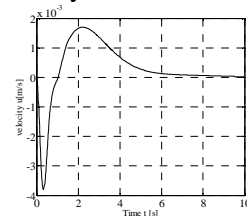


Fig.5 Time history of velocity u

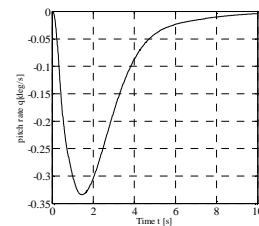


Fig.6 Time history of pitch rate angle

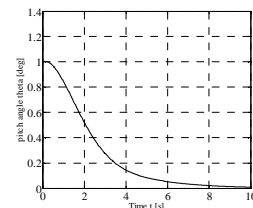


Fig.7 Time history of pitch angle

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