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where a right-handed coordinate system is adopted in each coordinate system. (x, y, z) denotes the coordinate of center of gravity of the aircraft in the inertial coordinate system, and ϕ, θ, and ψ are the rotational angles around the $\mathbf{X}$, $\mathbf{Y}$, and $\mathbf{Z}$-axis, respectively. Furthermore, the X4-Flyer mounts a circuit and a battery near the center of the airframe, and has a total of four rotors around these. While carrying out the flight by the thrust generated by each rotor, the attitude control of the airframe is also performed by adjusting the number of revolutions of each rotor.

III. Controller of the X4-Flyer

A. Controller of the Attitude Angle

In this article, the attitude of the X4-Flyer is controlled using a PD control method developed in Bouabdallah's [6]. When defining the P gains of the controller as k_1, k_3, and k_5, the D gains of the controller as k_2, k_4, and k_6, the target value of the attitude of the aircraft as ϕ_d, θ_d, and ψ_d, control inputs as U_1, U_2, U_3, and U_4, the PD controllers for postures are given by

$$\begin{aligned} U_2 &= -k_1(\phi - \phi_d) - k_2\dot{\phi} \\ U_3 &= -k_3(\theta - \theta_d) - k_4\dot{\theta} \\ U_4 &= -k_5(\psi - \psi_d) - k_6\dot{\psi} \end{aligned} \tag{1}$$

B. Controller of the Position

The position control of the X4-Flyer is performed by changing the attitude of the airframe. It is found from Fig.1 that the X4-Flyer can move $\mathbf{X}$-direction and $\mathbf{Y}$-direction by tilting the airframe to the direction $-\theta$ and ϕ, respectively. Therefore, the X4-Flyer in this paper is controlled to $\mathbf{X}$-axis and $\mathbf{Y}$-axis directions by changing the target value θ_d and ϕ_d in Eq. (4), respectively. That is, a feedback-roop is constructed to generate and change the target values of attitude angles of the airframe, by using the errors from the current position to the target position of the airframe. Here about the position control, a PD controller is assumed to be used as the control at the attitude angles. When defining the P gains of the controller as k_7 and k_9, the D gains of the controller as k_8 and k_{10}, and the target values of attitude of the airframe as x_d and y_d, the PD position controllers are given by

$$\begin{aligned} \theta_d &= -k_7(x - x_d) - k_8\dot{x}. \\ \phi_d &= -k_9(y - y_d) - k_{10}\dot{y}. \end{aligned} \tag{2}$$

The X4-Flyer is equipped with a tether, maintaining in the state where it is stretched. Then, the control input U_1 is set to be constant so as to generate a constant thrust to the height of $\mathbf{Z}$-axis direction.

IV. Position Measurement

In this study, the airframe position of the $\mathbf{X}$- and $\mathbf{Y}$-axis directions is determined by measuring the airframe height and the slope of the tether is attached to the X4-Flyer. In this section, a mechanism is described for measuring the slope of the tether, and it is applied to measuring the airframe position.

A. Mechanism for Position Measurement

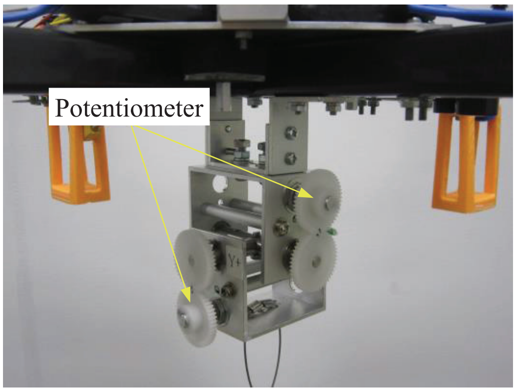

Fig. 2. A device for measuring the inclination of the tether attached to the airframe.

Fig.2 shows a situation where a device for measuring the inclination of the tether is attached to the airframe. This device consists of a gimbal mechanism equipped with potentiometers. This gimbal mechanism is composed of orthogonal two axes, which can incline in any direction respectively. The inclination of the X4-Flyer can be known by measuring the slope of each axis, because two axes move in any direction.

B. Position Measurement Using the Tether

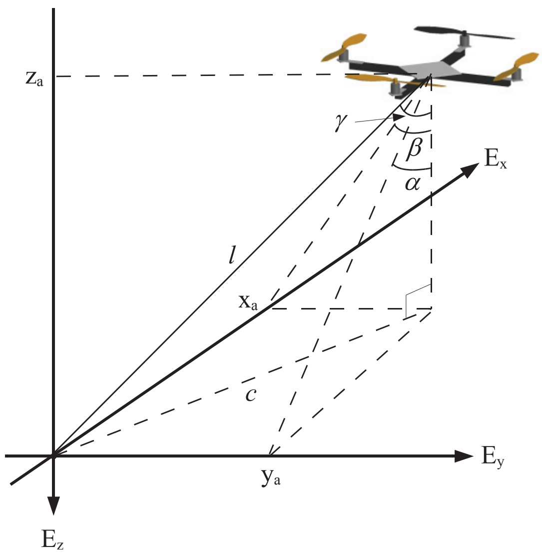

Fig. 3. The tether tilt and the airframe positions.

Fig.3 shows the relationship between the inclination of the tether and the airframe position. Let the $\mathbf{E_x}$-, $\mathbf{E_y}$-, and $\mathbf{E_z}$-axis positions of the airframe be x_a, y_a, and z_a. c denotes the distance from the origin of the coordinates to a point at which a perpendicular line given from the center of the

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airframe intersects the $\mathbf{E_x}$ - $\mathbf{E_y}$ plane, and l is the length of the tether. The slopes of the tether against the perpendicular line directed to $\mathbf{E_x}$ -axis and $\mathbf{E_y}$ -axis are defined by α and β, respectively, and the γ is a slope of the tether. Then, the airframe position in the $\mathbf{E_x}$ -axis is given by

$$x_a = z_a \tan\alpha \tag{3}$$

Furthermore, the airframe position in the $\mathbf{E_y}$ -axis is reduced to

$$y_a = z_a \tan\beta \tag{4}$$

The height za is required to measure the position of the X4-Flyer using Eq. (3) and Eq. (4). Now, the height z_a is fixed to the height at which the tether is extended up to the maximum length, satisfying the condition that the slope of the tether to the airframe becomes 0 [deg].

V. Experiments the Position Control Using the Tether

The position of the X4-Flyer is measured and controlled by using the position measurement method that applied the tether, shown in the previous section. In this paper, the proposed method is verified by mounting the position measuring device by the tether on the X4-Flyer, and measuring and controlling its position.

A. Experimental Conditions

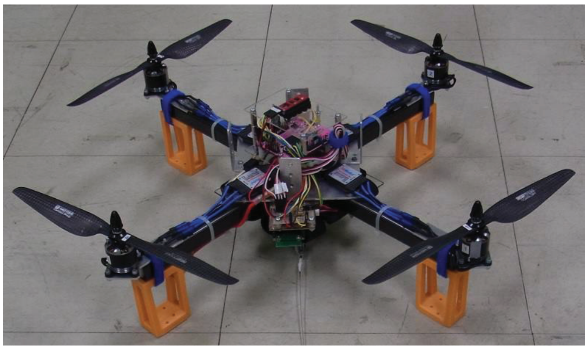

Fig. 4. Overview of the X4-Flyer used for experiment.

Fig.4 shows the X4-Flyer used in the experiment. The center of gravity of the airframe is approximately consistent with the center of the airframe, by collecting heavy loads, such as electronic circuits, batteries, etc., near the center of the airframe. Also, a brushless DC motor is used for rotating the rotor. The experimental setup is shown in Fig.5. A Wi-Fi module mounted on the X4-Flyer can realize wireless communication with a PC, so that it can be operated by a controller (i.e., a gamepad) via the PC and obtain the log data. Assume that the length of the tether is $l = 1$[m] and the experiments are conducted by fixing the other end of the tether on the ground. The target positions and attitudes in flight are set to $(\phi\ \ \theta\ \ \psi\ \ \dot{\phi}\ \ \dot{\theta}\ \ \dot{\psi}\ \ x\ \ y\ \ z)^{\mathrm{T}} = (0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ -1)^{\mathrm{T}}$. The values provided from the gamepad are used for the control input U_1 in the height direction to perform an operation such as takeoff etc. The constant gains in the PD controller for performing the attitude control are set to $k_1 = 4.5$, $k_2 = 1.5$, $k_3 = 4.5$, $k_4 = 1.5$, $k_5 = 1.2$, and $k_6 = 0.4$. The constant gains in the PD controller for performing the position control are set to $k_7 = 0.12$, $k_8 = 0.8$, $k_9 = 0.18$, and $k_{10} = 0.2$.

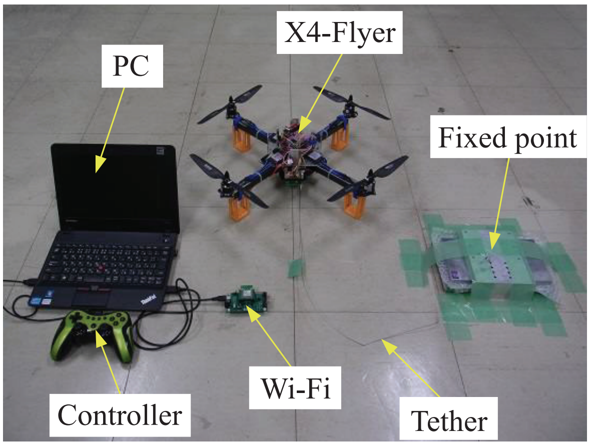

Fig. 5. Experimental setup.

B. Results and Consideration

The experimental results are shown in Fig. 6 to Fig.8. It is seen from Fig. 6 that the error in $\mathbf{X}$ -axis direction is in the range of ± 0.2[m]. It is seen from Fig. 7 that the error in $\mathbf{Y}$ -axis direction is in the range of at most ± 0.25[m]. However, it is found from Fig.8 that the airframe position in the $\mathbf{X}$ -axis direction deviates about -0.2[m]. Furthermore, this graph shows that the flight range of the airframe is in the range of at most 0.4[m] from -0.6[m].

From these results, it is considered that the airframe position can be measured and controlled by using the tether. However, it is considered that the constant gain in the position controller can be tuned more suitably to reduce the deviation in the $\mathbf{X}$ -axis direction as shown in Fig. 6. In addition, it is effective to consider that a PID controller is introduced to the position control so as to stabilize the flight range of the airframe in a narrower space, as shown in Fig. 8. However, it is considered that since the position of the airframe shown in these graphs are affected by the inclination of the aircraft when measuring the inclination of the tether, it is a larger or smaller value than the actual position in some cases.

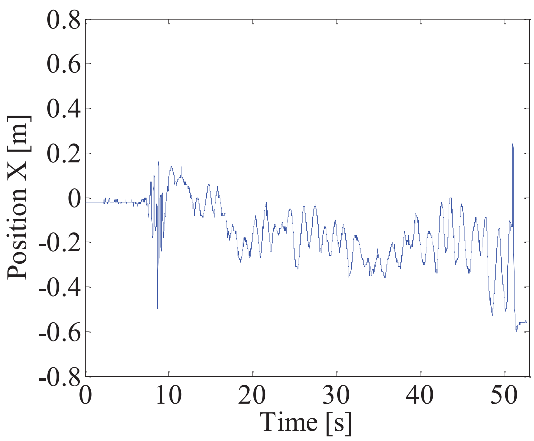

Fig. 6. Position in the X-axis direction of the airframe.

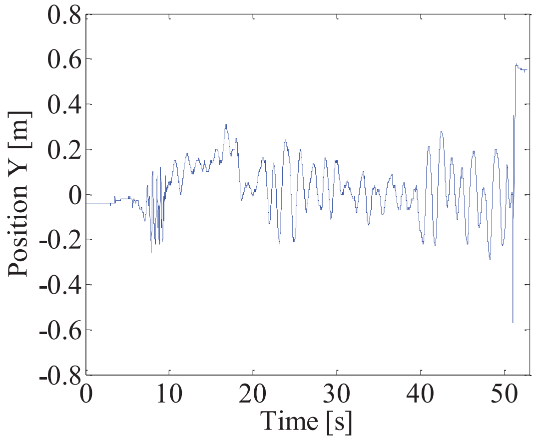

Fig. 7. Position in the Y-axis direction of the airframe.

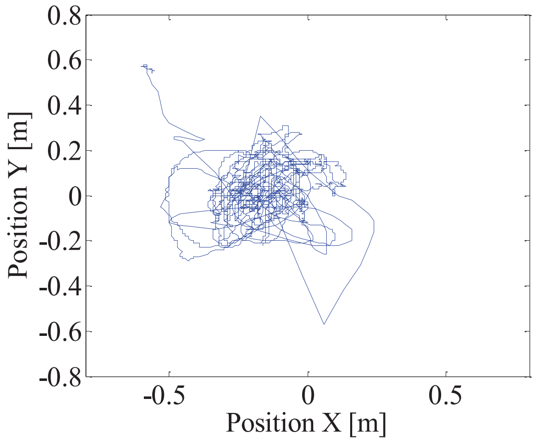

Fig. 8. Position in the Y-axis direction relative to the position of the X-axis direction of the airframe.

VI. Conclusion

In this paper, a method for measuring and controlling the position of an X4-Flyer has been described by using a tether. Furthermore, the proposed method was verified using a real system. It was concluded that although the airframe position was able to be measured, the accuracy of the position control was to be not too high because the airframe position in $\mathbf{X}$-axis direction deviated. For future work, the introduction of a PID controller as the position controller is considered to improve the accuracy of the position control. In addition, the flight experiment of the X4-Flyer is being fixed to the ground tether, so that, we are going to have a flight experiment that the tether will be handled by a human so that in the future.

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