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Development of an Anemometer to Assist a Quadrotor with Auxiliary Thrusters

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Abstract— **In recent years, rapid deterioration of infrastructure equipment is regarded as a problem and the maintenance management of it is important for preventing serious accidents. Particularly, in a bridge like the Seto-Ohashi, it takes a long time to inspect the whole and it is also dangerous because of high-place work. Then, use of unmanned aerial vehicles (UAVs) can be considered as one of the alternative ways to the human visual-check. Among them, Quadrotors are attracting attention and they have excellent maneuverability and operability because they control the position and attitude of the airframe by changing the revolution velocity of four rotors. However, since a thrust cannot be generated except for upward direction, there is a weak point in which it is out of control, if it is affected by the influence of an ascending current etc. when hovering. In particular, vortices are generated around huge structures represented by bridges, so that it is difficult to inspect without considering this effect. In this research, it is aimed at developing a Quadrotor that can check infrastructures in harsh environments by attaching auxiliary thrusters and an anemometer. This paper first outlines a proposed Quadrotor. In addition, it verifies the accuracy of our own built-in anemometer. Finally, the effect of the airframe on the anemometer is verified through some experiments. The experimental results showed that the manufactured anemometer needs to be redesigned.**

***Index Terms*— Infrastructure Inspection, UAV, Quadrotor, Aux-iliary Thrusters**

I. Introduction

In recent years, rapid aging of infrastructure facilities such as tunnels and bridges that were developed intensively during the period of high economic growth is regarded as a problem [1], and the maintenance and management of existing infrastructure facilities is an important issue from the viewpoint of accident prevention [2]. These infrastructure inspections are conducted by proximity inspection by human [3]. In the case of a long infrastructure bridge located at a high place on the sea such as Seto Bridge, which is a large-scale infrastructure facility, a girder surface work vehicle is used as a foothold to carry out work. Therefore, the whole inspection takes about 20 years, so that it needs a more efficient inspection method [4]. Furthermore, efficient and safe inspection methods are needed, because there exist the dangers in work at a high place. Therefore, unmanned aerial vehicles (UAVs) are attracting attention as an alternative to visual inspection by human. In particular, vertical take-off and landing (VTOL) type UAVs do not need a large space such as a runway for operation and can realize a special operation such as hovering. Among VTOL-type vehicles, those that fly using four rotors are called quadrotors. The quadrotor can control the position and attitude of the airframe by changing the revolution velocities of the four rotors. Thus, the quadrotor has excellent maneuverability and operability [7]. However, since the thrust cannot be generated except upward direction, it cannot cope with the occurrence of strong updraft, gusts or vortices in a severe environment such as a long bridge on the sea, and thus there is a risk of crash [9].

In this research, we aim to develop a quadrotor that can inspect the infrastructure in severe environment by mounting an auxiliary thrust mechanism and an anemometer on a conventional Quadrotor. The auxiliary thrust mechanism uses a brushless DC motor that can rotate forwardly or reversely, and it is possible to change the thrust direction up and down by changing the rotational direction. It is thought that this enables high-speed attitude and position control to the conventional quadrotor. A mechanism that can change the thrust direction up and down is known as a variable pitch mechanism, whereas although the method of using forward and reverse rotations in the motor is inferior in response to that mechanism, it can be constructed with a small number of parts so that it is expected to improve the reliability. The anemometer adopts a ultrasonic anemometer that can measure even under a low-speed environment. A feedforward control system is constructed by acquiring the relationship between the wind velocity and the attitude change preliminarily. It is thought that the influence due to a wind disturbance can be suppressed by this. This paper first outlines the proposed quadrotor. In addition, our own built-in anemometer is verified in the point of accuracy. Finally, it is examined how the airframe affects the anemometer.

II. Overview of a Quadrotor With Auxiliary Thrusters

Fig. 1 shows the structure of a Quadrotor with auxiliary thrusters. In addition to four main rotors for flight, this airframe has auxiliary thrusters consisting of four sub-rotors that can be used in forward-reversal rotation. The definition of the airframe coordinate system **C** is also shown in Fig. 1, where the body coordinate system **C** takes the center of the body as the origin O, and the positive directions in X-, Y-, and Z-axes are set to the front of the body, the right-hand direction of

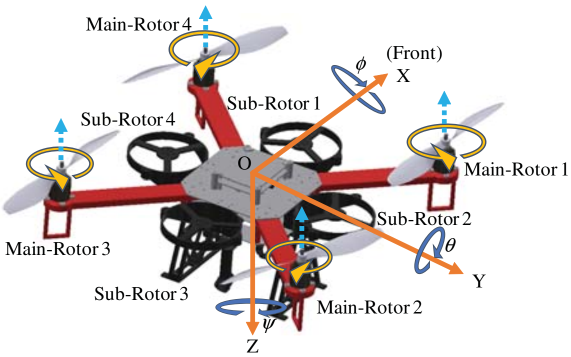

Fig. 1: Structure of a Quadrotor equipped with auxiliary thrusters

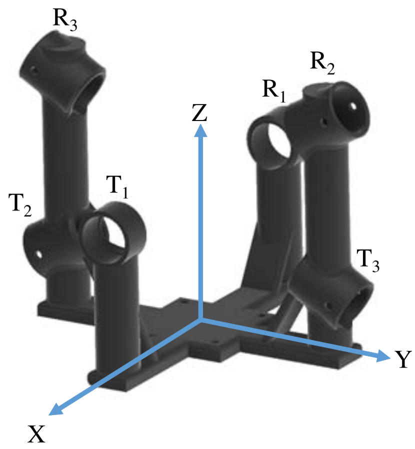

Fig. 2: Anemometer

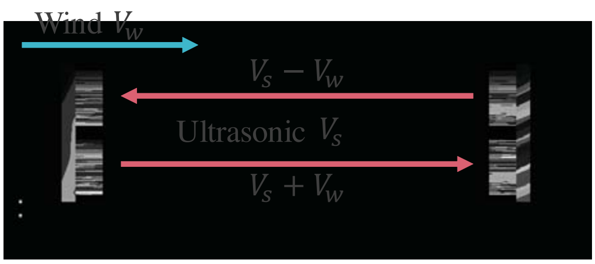

Fig. 3: Principle of wind speed measurement

the body, and the lower side of the body, respectively. The attitude of the airframe is represented by roll angle (ϕ), pitch angle (θ) and yaw angle (ψ) respectively. The main rotor 1, main rotor 2, main rotor 3 and main rotor 4 are defined clockwise, based on the rotor in the X-axis direction. To cancel the counter torques from the main rotors, the main rotors 1 and 3 are rotated clockwise, whereas the main rotors 2 and 4 are rotated counterclockwise. The rotational direction of the sub-rotor in the auxiliary thrusters is determined clockwise or counterclockwise, depending on the data obtained from the anemometer and on the attitude of the aircraft. In addition, a control circuit, a battery, and a motor driver are installed at the center of the airframe. Furthermore, it is possible to attach an anemometer to the bottom surface.

III. Development of Anemometer for Quadrotor

A. Outline of Anemometer

The airspeed of helicopters and fixed wing aircrafts is generally measured by a pitot tube and a static hole. Note however that, with this measurement method, an accurate atmospheric velocity cannot be measured at the low velocity region of about 20 m/s [10]. The anemometer using an ultrasonic can measure the atmospheric velocity in three axes, compared to the Pitot static tube, and it has several properties such as having an excellent responsiveness, being able to catch a rapid change of air flow, and being able to be used from zero airspeed, etc. In addition, ultrasonic anemometers do not affect attitude control and position control because they do not have moving parts, which exist in wind-wave well-type anemometers and windmill-type anemometers. Therefore, it is considered appropriate to use an ultrasonic anemometer for the airspeed measurement of a quadrotor.

B. Anemometer Design

Inoguchi [11] developed an ultrasonic air velocity sensor for aircraft, in which each axis-center of the support rod for multiple ultrasonic transmitter-receivers is located at each vertex of a triangle. Multiple sets of ultrasonic transmission and reception paths are formed by setting multiple ultrasonic transmitter-receivers to a different position, so that the three-dimensional information on air velocity is obtained from the propagated time information. Since the support rod is not symmetrical with respect to each axis of the orthogonal coordinate system on a plane, it needs to compensate the control input when controlling the attitude and position of the airframe. Therefore, an ultrasonic anemometer was developed using four support rods symmetrical to each axis of the orthogonal coordinate system on the plane. Fig. 2 shows the structure of such an anemometer. This mechanism consists of three sets of ultrasonic sensors. The wind velocity is measured based on using the measurements and temperature of three sets of ultrasonic sensors. The distance between the transmitter and the receiver of the ultrasonic sensor is l=0.1 m. In the ultrasonic sensor i (i=1$\sim$3), the transmitter is defined as T_i, and the receiver is represented as R_i. The ultrasonic sensors 2 and 3 are inclined 30 degrees with respect to the Y axis to obtain the Y- and Z-components of the wind velocity.

C. Principle of Wind Speed Measurement

Fig. 3 shows the principle of wind velocity measurement in one dimension. Define the velocity of sound as V_s [m/s], the distance between the transmitters and receivers of one ultrasonic sensor as l [m], and the time it takes for the ultrasonic waves generated from the transmitter to reach the

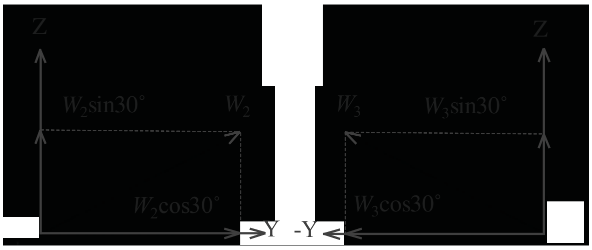

Fig. 4: Decomposition of wind vectors

receiver as t [s]. Then, assuming that the wind velocity from upwind to downwind is W_{d} [m/s] and the wind velocity from downwind to upwind is W_{u} [m/s], the wind velocity can be expressed by

$$W_{\mathrm{d}} = l/t - V_{\mathrm{s}} \tag{1}$$

$$W_{\mathrm{u}} = l/t + V_{\mathrm{s}} \tag{2}$$

D. Derivation of Wind Velocity

A method of measuring the wind velocity is described in three dimensions. First obtain the temperature to estimate the velocity of sound. Letting the velocity of sound be V_{s} [m/s] and the temperature be T [°C], the velocity of sound can be expressed by

$$V_{\mathrm{s}} = 331.5 + 0.6T \tag{3}$$

If the measured time t satisfiest $t \leq l/V_{\mathrm{s}}$, then Eq. (1) is used to obtain the wind velocity W in each element direction, whereas if the time t does not satisfy $t \leq l/V_{\mathrm{s}}$, then Eq. (2) is used to obtain it. Thus,

$$W = \begin{cases} W_d & \text{if} \quad t \leq l/V_{\mathrm{s}} \\ W_u & \text{otherwise} \end{cases}$$

Let the velocity of each element direction obtained by ultrasonic sensors 1 to 3 be W_1, W_2 and W_3, respectively. The X-component of the wind velocity is obtained by the ultrasonic sensor 1 Also, from the decomposed view of the wind vector on the YZ plane shown in Fig. 4, the Y component of the wind speed is obtained by the difference between the respective Y components of W_2 and W_3, whereas the Z component of the wind speed is obtained by the sum of the respective Z components W_2 and W_3. Let the X component, the Y component, and the Z component of the wind velocity be described as W_{X}, W_{Y}, and W_{Z}. Each component of the wind velocity can be expressed, using W_1, W_2, and W_3, as follows:

$$W_{\mathrm{X}} = W_1 \tag{4}$$

$$W_{\mathrm{Y}} = W_2 \cos 30^\circ - W_3 \cos 30^\circ \tag{5}$$

$$W_{\mathrm{Z}} = W_2 \sin 30^\circ + W_3 \sin 30^\circ \tag{6}$$

Assuming that the wind velocity to be solved be V [m/s], the wind velocity can be expressed as by

$$V = \sqrt{W_{\mathrm{X}}^2 + W_{\mathrm{Y}}^2 + W_{\mathrm{Z}}^2} \tag{7}$$

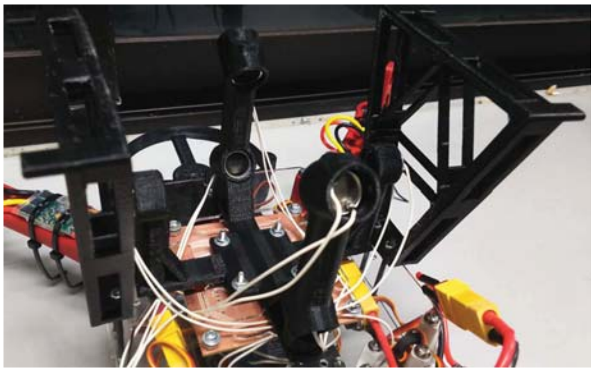

Fig. 5: Quadrotor equipped with anemometer

IV. Accuracy Verification of Anemometer

A. Experimental Method

The wind velocity is measured, at a place where the influence of wind is small, by using a self-made anemometer. Fig. 5 shows an anemometer mounted on the Quadrotor with an auxiliary thrust mechanism. An electric fan is used to generate a wind, and 500 measurements are conducted with an anemometer attached to this machine, where the wind velocity is calculated by the moving average method, which is based on using the data of the latest 5 sets, with 10 times as one set. There are three targets to be measured: i.e., an average wind velocity of 0.0 m/s, an average wind velocity of 2.1 m/s, and an average wind velocity of 3.3 m/s. The average measurements provided by Monotaro's simple digital anemometer are taken as the average wind velocity, and it is verified by comparing their measurements with the measurements by the developed anemometer. The error of Monotaro's simple digital anemometer is $\pm 5\%$ from the displayed value. However, the wind velocity of 20 m/s or more is regarded as an abnormal value, and it is set to 20 m/s.

B. Experimental Results

Fig. 6 shows the measurement results, whose environment has an average wind velocity of 0.0 m/s. It is found, in an environment with an average wind velocity of 0.0 m/s, that the wind velocity is measured in the range of approximately 0.0 m/s to 0.4 m/s. The difference between the maximum and minimum of the measurements is 0.4 m/s, and the average value of the measurements is 0.2 m/s.

Fig. 7 shows the measurement results, whose environment has an average wind velocity of 2.1 m/s. It is found, in this environment, that the wind velocity is measured in the range of approximately 1.5 m/s to 2.7 m/s. Note however that the wind velocity of the electric fan changed from 1.8 m/s to 2.4 m/s.

The difference between the maximum and minimum of the measurements is 1.2 m/s, and the average value of the measurements is 2.0 m/s. Fig. 8 shows the measurement results, whose environment has an average wind velocity of 3.3 m/s. In this measurement, the wind velocity is shown to

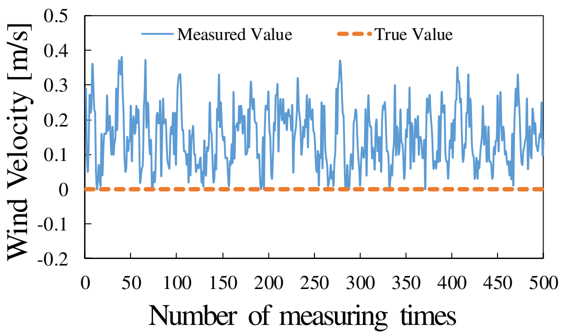

Fig. 6: Measurement experiment 1

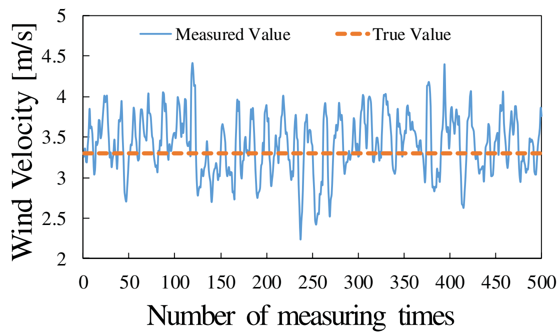

Fig. 8: Measurement experiment 3

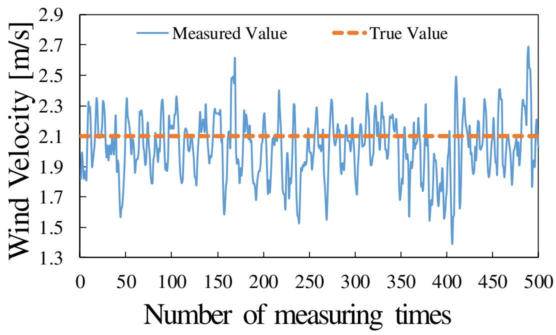

Fig. 7: Measurement experiment 2

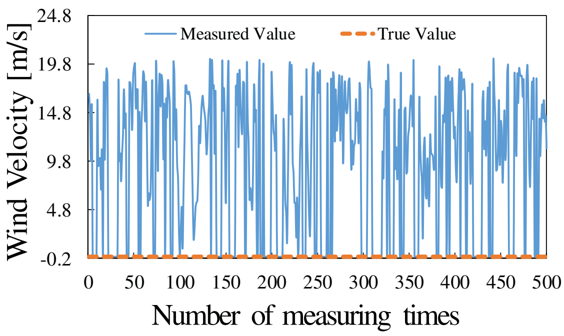

Fig. 9: Measurement experiment 4

be measured in the range of about 2.3 m/s to 4.5 m/s. Note, however, that the wind velocity of the electric fan changed from 3.0 m/s to 3.6 m/s. The difference between the maximum and minimum of the measurements is 2.2 m/s, and the average value of the measurements is 3.4 m/s.

C. Consideration

It can be said that the measurement can be performed with high accuracy, because the difference between the true value and the measurements is 0.13 m/s on average. Note however that the fluctuation of the measurements increases as the average wind velocity increases. This is attributed to the fact that a large force, which causes the occurrence of distortion and vibration, is applied to the whole of airframe and the anemometer as the average wind velocity becomes faster. To improve it, it needs to redesign the airframe and the anemometer, and to make them with more rigid materials. In addition, it is thought possible to be measured in high accuracy by using high frequency and high-resolution ultrasonic sensors and optimizing the control.

V. Influence of the Rotation of Rotors on the Anemometer

A. Experimental Method

The effects of the rotor vibration and of the generated wind on the anemometer are confirmed. In an environment in which the average wind velocity is 0.0m/s, the wind velocity is measured under rotating the rotors of the airframe equipped with propellers.

B. Experimental Result

Fig. 9 shows the measurement results of the wind velocity when rotating the rotor equipped with propellers in an environment having the average wind velocity of 0.0 m/s. It is found that, for the environment having the average wind velocity of 0.0 m/s, the wind velocity is measured in the range of 0.0 m/s to 20 m/s approximately, and the average value is 10.8 m/s.

C. Consideration

As a reason why the measurements are largely different from those obtained in the above-mentioned experiment, it is considered that the vibration of the rotor may yield a change in the distance between the ultrasonic transmitter-receivers of the anemometer and the wind generated by propellers may be an obstacle to accurate measurement.

VI. Conclusion

This paper has proposed a Quadrotor with auxiliary thrusts for inspecting infrastructures under a severe environment. In particular, the principle of anemometer and its development were described, and then an experiment was conducted to verify the accuracy of the anemometer and it was shown to be possible to measure the wind velocity. Furthermore, it was confirmed that the rotor motion affected the measurements by the anemometer. As a result, it was found that the manufactured anemometer needs to be redesigned. In the future, we will improve the accuracy of the anemometer, take a way against disturbances and develop a measurement system for airspeed. Moreover, we will develop a control system using an anemometer and verify its usefulness.

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