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Fuzzy Control for Kite-based Tethered Flying Robot

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Abstract— **Information from the sky is important for rescue activity in large-scale disaster or dangerous areas. Observation system using a balloon or an airplane has been studied as an information gathering system from the sky. A balloon observation system needs helium gas and relatively long time to be ready. An airplane observation system can be prepared in a short time and its mobility is good. However, a long time flight is difficult because of limited amount of fuel.**

We have proposed and developed a kite-based observation system that complements activities of balloon and airplane observation systems by short preparation time and long time flight[1]. This research aims at construction of the autonomous flight information gathering system using a tethered flying unit that consists of the kite and the ground tether line control unit with a winding machine. This paper proposes fuzzy controllers for the kite type tethered flying robot inspired by how to fly a kite by a human.

I. Introduction

Research and development of an information gathering system from the sky have done mainly for weather observation[2], [3], [4], [5]. Information gathering in large-scale disasters by manned aircraft has been becoming important because observation from the sky enables us to collect comprehensive information in one glance and it is usually hard to move around on the disaster affected ground. In case that people have to keep away from the area, remote-controlled airplanes are often used to gather wide-range comprehensive information from the sky. However, skilled remote operation is necessary to control the unmanned airplane safely. Lack of remote operation skill often causes undesired accidents, therefore, fostering of skilled remote operators has been a vital problem nowadays.

Autonomous observation systems using a balloon[6], [7] or an airplane[8], [9], [10] have been studied as a solution of information gathering systems from the sky. The balloon system is noiseless and able to stay in the sky for a long time. However, the helium gas reservation is necessary and it needs relatively long time and specialists of gas maintenance for the flight preparations. On the other hand, an airplane system needs less time for flight preparations, but a long-term activity is difficult due to limitation of the fuel.

Although it is not an information gathering system, power generation systems using a kite, a balloon, and an airplane have been studied so far[11], [12]. Yashwanth et al.[13] proposed to use a dynamo in a balloon, rotate a balloon by the power of a wind, and generate power. A balloon based power generation system tends to be a large scale to lift an electric dynamo in the sky. Power generation systems using a kite or an airplane[14], [15], [16], [17] control the kite or the airplane to have a certain trajectory so that they generate electric power by pulling the line connected to a power generator on the ground. An airplane based power generation system needs to fly at high speed in order to pull the line connected to the electric dynamo efficiently and stay in the air. It is useful to generate electric power during flying for a long-time self-contained observation, however, those systems are not suitable for small-scale stationary observation and information gathering system because flying at high speed and high attitude is not so good for stationary observation and information gathering.

We have proposed a tethered flying robot based on a kite that flies with wind power as one of the natural power sources[1]. It is supposed to be an information gathering system that compliments other ones based on a balloon or an airplane and has advantages of short setup time and long-term observation. This paper shows a prototype of the tethered flying robot we designed and built and its flight systems based on fuzzy controllers inspired by how a human flies a kite. The kite-based flying robot is controlled with one tether line connected to a rotor on the ground by releasing or winding the line. The robot has sensors that measure wind speeds around the robot, body posture and location in the air. Real robot experiments are conducted to confirm that the our controller takes the kite off from the ground autonomously and keeps it in the air stationary.

II. System Outline

Our tethered flying robot consists of a flight unit and a ground control unit. The concept of the flying robot and its schematic view are shown in Figs. 1 and 2, respectively. The flight unit carries sensors and transmits the surrounding wind state and position and orientation of the flight unit itself to the ground wirelessly. The flight unit is lifted from the ground by a kite. The ground control unit controls the line attached to the flying unit according to the data sent by the flight unit. A ZigBee module is used for wireless communication between the flight unit and the ground control unit.

A. Flight Unit

The flight unit is shown in Fig. 3. The wingspan and the chord length of the kite are 3.2m and 1.5m, respectively. The weight of the kite is about 700g. The kite is able to carry about 1.5kg equipment in total. The flight unit is equipped

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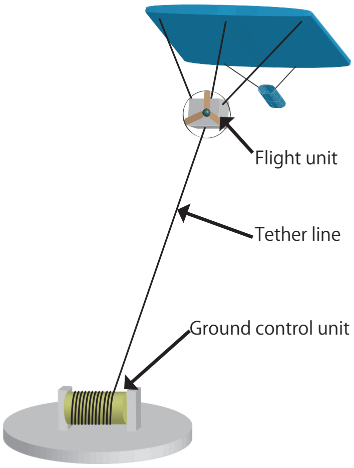


Fig. 1. Concept of Tethered Flying Robot

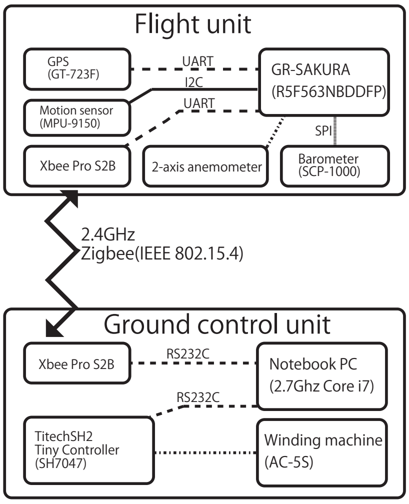


Fig. 2. Schematic Representation of Tethered Flying Robot

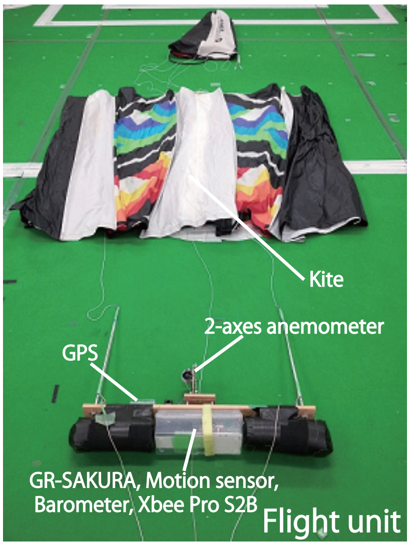


Fig. 3. Flight Unit of Tethered Flying Robot

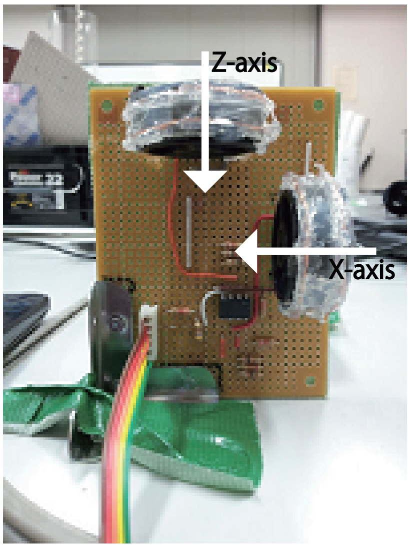


Fig. 4. 2-Axis Anemometer

with anemometers to measure the wind speeds around the unit. It is also equipped with a GPS for its own position estimation in the air, a accelerometer and a rate gyroscope for posture detection of the flight unit, and a ZigBee module (Xbee Pro S2B) for wireless data transmission to the ground unit. It has an barometer so that the flight unit's altitude is calculated based on the atmospheric pressure difference from the ground. The weight of the flight unit is about 850g.

Fig.4 shows the two-axes anemometer that we designed and developed. This anemometer uses impellers of commercially available portable anemometers and magnetic encoders. It can measure even weak wind because of very little resistance load. Since the kite has only one line to be controlled, the flight unit is not able to control its posture by itself. The anemometer is fixed on the flight unit and measures wind speed around the flight unit in orthogonal two directions. Even when the flying unit inclines, the wind speed against the flight unit is calculated from wind speeds in orthogonal two directions and it is used for control.

B. *Ground Control Unit*

The ground control unit consists of a notebook computer and a line-winding machine. The weight of the tether line is about 37.1g/100m. Fig. 5 shows the ground control unit which we developed. The notebook computer receives the data from the flight unit and controls a line-winding machine through a microcomputer and a motor driver. We adopt AC-5S manufactured by MIYAMAE Co.,Ltd which is originally an electric reel for sea fishing and modified it to the line-winding machine. The line-winding machine has an electric clutch to adjust the brake strength of release of a line. Moreover, it is possible to acquire information, including line length, number of rotations, etc., with the encoder in a line-winding machine. The length of the line set to the line-winding machine is about 300m. The maximum winding-up power is 64kg and maximum take-up speed is 2.5m/s.

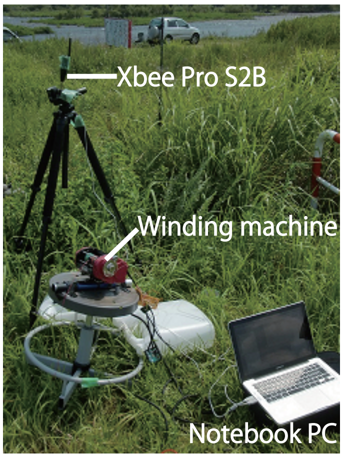


Fig. 5. Ground Control Unit

III. FUZZY CONTROLLER FOR FLYING

Our fuzzy controller is inspired by how a human flies a kite. Fuzzy set can reasonably represent unwritten policy how to fly a kite by human. A human control the line of the kite based on the wind speed, the drag force of the line, the altitude and the motion of the kite, and so on. Here, we design two fuzzy controllers for the flight. One of them controls the drag and release force based on a fuzzy set of altitude of the kite and wind speed measured by the flight unit. Another one takes altitude change of the kite into the consideration, too. The fuzzy controllers are represented based on a simplified reasoning method by Eqs. (1), (2) and (3). Eq. (1) shows calculation of degree in case of two inputs and Eq. (2) shows the one in case of three inputs.

$$\text{Rule } i : \text{if } w \text{ is } WS_i \text{ and } a \text{ is } ALT_i \text{ then } \varphi \text{ is } b_i \ (i = 1, 2, ..., \text{n})$$
$$h_i = \mu_{WS_i}(w) \times \mu_{ALT_i}(a) \quad (1)$$

$$\text{Rule } i : \text{if } w \text{ is } WS_i \text{ and } a \text{ is } ALT_i \text{ and } da \text{ is } DALT_i \text{ then } \varphi \text{ is } b_i \ (i = 1, 2, ..., \text{n})$$
$$h_i = \mu_{WS_i}(w) \times \mu_{ALT_i}(a) \times \mu_{DALT_i}(v_a) \quad (2)$$

where $\times$ indicates the minimum operator.

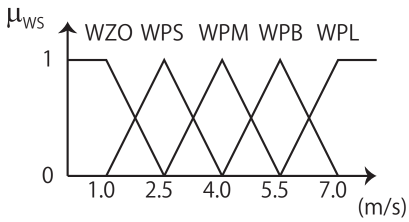
$$\varphi = \frac{\sum_{i=1}^{n} h_i b_i}{\sum_{i=1}^{n} h_i} \quad (3)$$

h_i in Eqs.(1) and (2) indicates the degree of rule i if the wind speed w, the altitude a, and the altitude change v_a are given. $\mu_{WS_i}(w)$, $\mu_{ALT_i}(a)$, and $\mu_{DALT_i}(v_a)$ are membership functions corresponding to wind speed, altitude, and altitude change for the rule i, respectively. The membership functions are shown in Fig.6.

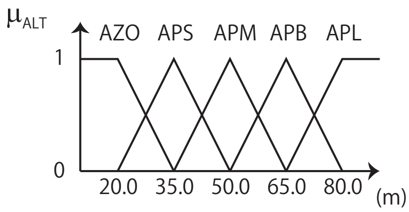
φ in Eq.(3) indicates control input to the winding machine. It is calculated as the weighted sum of the consequent singleton of the rule i with the weight of h_i. The singleton is represented in Fig. 7.

TABLE I shows the rule table of the fuzzy controller based on wind speed and altitude. The controller tries to drag the kite line when the altitude of the kite is low or the wind speed is small. It releases the line if the wind speed is big and the altitude is medium. If the altitude is high enough and the wind speed is relatively big, then, it tries to keep the line.

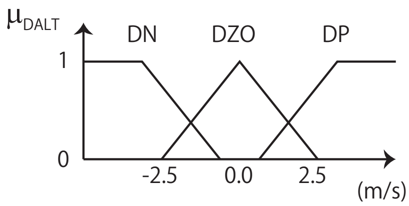
TABLE II shows the rule table of the fuzzy controller based on wind speed, altitude, and change of altitude. The idea of the controller is same with the one of 2 inputs controller shown in TABLE I and add another information, change of altitude. If the kite falls down, the controller tends to drag the line to keep the altitude of the kite as higher as possible. If the kite goes higher, the controller reduces to drag and releases the line if possible.



(a) Wind speed



(b) Altitude



(c) Altitude change

Fig. 6. Antecedent membership function

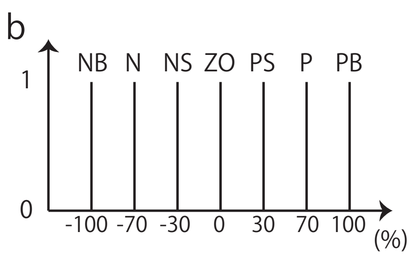


Fig. 7. Consequent singleton

A. Experiments

Experiments are conducted for evaluating how the fuzzy controllers work in real envorinment. First of all, the length

		Altitude				
		AZO	APS	APM	APB	APL
Wind speed	WZO	PB	PB	PB	P	NS
	WPS	PB	PB	PB	PS	NS
	WPM	PB	PB	P	ZO	ZO
	WPB	PB	P	PS	ZO	ZO
	WPL	P	NS	NS	ZO	ZO

TABLE I
FUZZY RULE (2 INPUTS 1 OUTPUT)

				Altitude				
				AZO	APS	APM	APB	APL
Wind speed	WZO	Altitude change	DN	PB	PB	PB	PB	PB
			DZO	PB	PB	P	PS	ZO
			DP	PB	P	PS	ZO	ZO
	WPS	Altitude change	DN	P	P	P	PS	PS
			DZO	PS	ZO	ZO	ZO	ZO
			DP	ZO	ZO	ZO	ZO	ZO
	WPM	Altitude change	DN	P	P	PS	PS	PS
			DZO	PS	ZO	NS	ZO	ZO
			DP	ZO	NS	NS	ZO	ZO
	WPB	Altitude change	DN	P	PS	PS	PS	PS
			DZO	NS	NS	NS	ZO	ZO
			DP	N	N	N	ZO	ZO
	WPL	Altitude change	DN	PS	PS	PS	PS	ZO
			DZO	N	N	N	ZO	ZO
			DP	NB	N	N	ZO	ZO

TABLE II
FUZZY RULE (3 INPUTS 1 OUTPUT)

of the tether line between the flight unit and ground unit is set to about 75 [m]. At the beginning of the flight, the ground unit winds the line to take off the flight unit based on the fuzzy controllers.

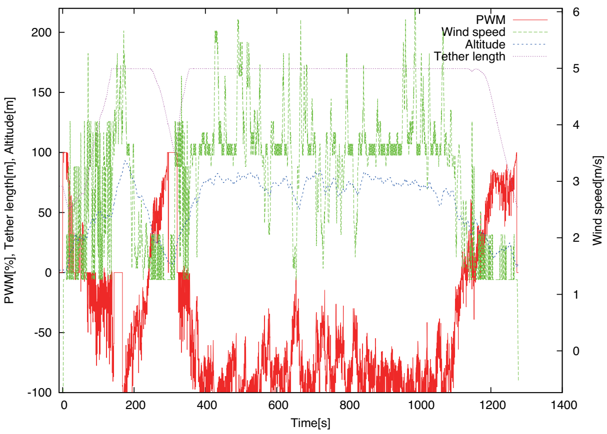


Fig. 8. Flight log (Motor power, Wind speeds, Tethered line length, Altitude) by 2-inputs 1-output fuzzy controller

Fig.8 shows the flight log of PWM duty ratio, wind speed, line length, and the altitude while the 2-inputs 1-ouput fuzzy controller with the fuzzy rules shown in TABLE I is applied. The PWM duty ratio indicates here the power to winch the tether line and φ in Eq.(3) as the control input to the winding machine. Fig.9 shows the flight trajectory based on the GPS and the barometer outputs. The green cross in the figure indicates the position of the ground unit.

Fig.8 shows that the flight unit successfully takes off at the beginning and ascends into the sky because of the high speed wind until about 190 [s]. The wind suddenly stops from 190 [s] to 300 [s], then, the flight unit goes down and the ground unit starts to wind the line. However, the motor output becomes high slowly because the altitude of the flight unit is high. This leads the flight unit to reduce the altitude a lot. Fig.9 shows the behavior of the flight unit as well. In order to avoid the undesired altitude loss of the flight unit, the controller needs information of not only wind speed and

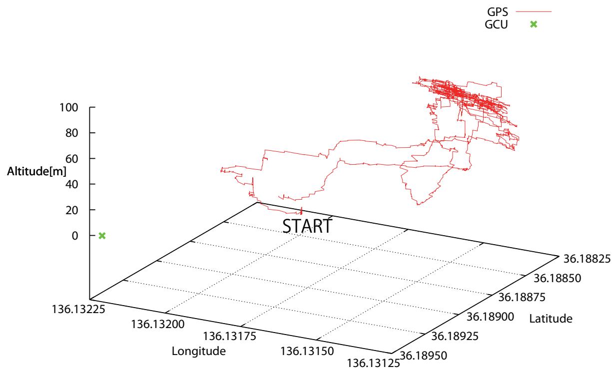


Fig. 9. Flight log (GPS, altitude) by 2-inputs 1-output fuzzy controller

altitude but also the altitude change of the flight unit.

After it recover the altitude around 400 [s], the ground unit controls the line to keep the altitude of the flight unit around 75 [m] stably. The wind stops again around 1100 [s] and the ground unit start to drag the line, then, the flight unit keeps to reduce the altitude and lands on the ground.

Figs.10 and 11 show the flight log of PWM duty ratio, wind speed, line length, and the altitude while the 3-inputs 1-ouput fuzzy controller with the fuzzy rules shown in TABLE II is applied. Fig. 11 shows the flight log from 0 [s] to 300 [s] of Fig.10. At the beginning of the flight, the ground unit

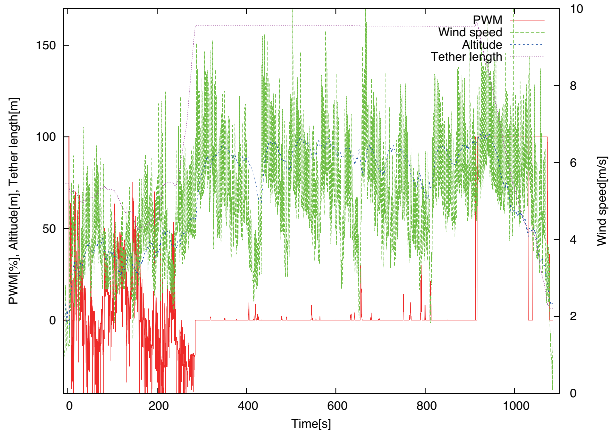


Fig. 10. Flight log (Motor power, Wind speeds, Tethered line length, Altitude) during flight of 3-inputs 1-output fuzzy controller

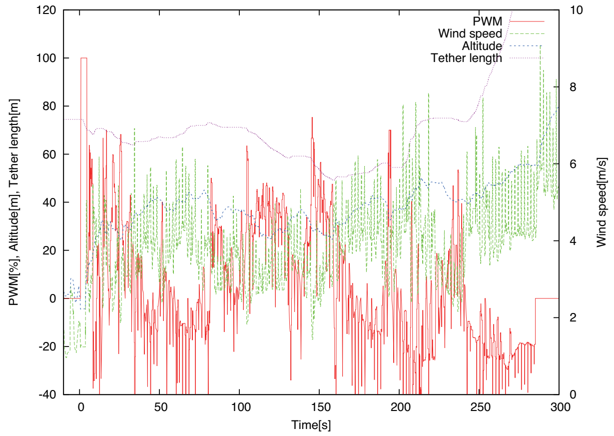


Fig. 11. Flight log (Motor power, Wind speeds, Tethered line length, Altitude) during flight of 3-inputs 1-output fuzzy controller at the beginning of the Fig.10

drags the line to take off the flight unit based on the fuzzy controller. After that, it reduces the drag force according to the wind speed measured by the flight unit and releases the line around 50 [s]. Unfortunately, the wind becomes weak around 100 [s] and 230 [s] then the ground unit drags the line to keep the altitude of the flight unit. The wind becomes strong again around 200 [s] and 250 [s] then the ground unit reduces the drag force and releases the line. As a result, the altitude of the flight unit becomes higher and higher. After around 250 [s], the wind becomes strong enough to lift the flight unit in hight altitude. The ground unit stops releasing the tether line after around 280 [s] because the max tether line is set to 170 [m]. When the wind becomes weak, the ground unit tends to increase the drag force. In case that the wind becomes strong enough in short time, the line is not dragged actually. It keeps the altitude from 70 [m] to 100 [m] stably. The line is winded by hand from around 920 [s] to land the flight unit. The winding is interrupted for a while around 1050 [s] because the motor of the winding machine becomes too hot to drag the line safely. Finally, the flight

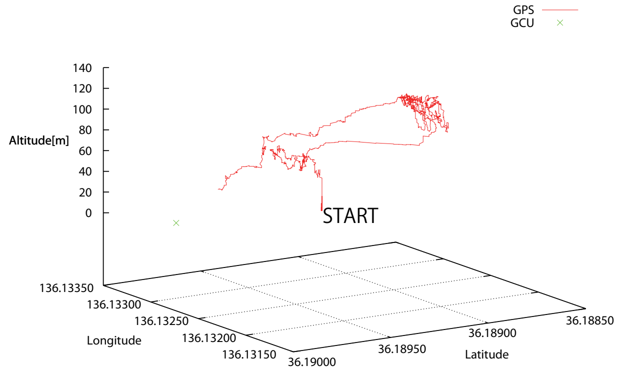


Fig. 12. Flight log (GPS, altitude) during flight of 3-inputs 1-output fuzzy controller

unit lands on the ground successfully.

Fig.12 shows the flight trajectory based on the GPS and the barometer outputs. The green cross in the figure indicates the position of the ground unit. The flight trajectory shows the flight situation mentioned above. The flight unit zips upward into the sky at the beginning of the flight and stays there for a while because of weak wind from 10 [s] to 250 [s]. After around 250 [s], the wind becomes strong enough to lift the flight unit in high altitude and the ground unit releases the line. The flight unit goes in high altitude until the length of the line reaches the limit. Then, the line is winded by hand to land the flight unit.

Those figures show that the 3-inputs 1-output fuzzy controller works fine to control the tethered flying robot successfully.

IV. Conclusions

This research aims at realizing a flying observation system which complements other information gathering systems using a balloon or an air vehicle. We proposed the kite-based tethered flying robot with long-term activity capability. This paper showed two flight controllers based on fuzzy control and the performance of our methods. One of our future work is learning the parameters of the membership functions and singletons of the fuzzy controllers.

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