Modelling and Design of Tether Powered Multicopter

Seiga Kiribayashi[1], Jun Ashizawa[1], and Keiji Nagatani[2]

Abstract— **Recently, micro unmanned aerial vehicles (MUAVs), particularly multicopters, are expected to use for rescue missions and investigations in all over the world. However, currently, its working time is quite short, typically 20 minutes or less, to conduct real missions. To extend the flight time, and to prevent jumping out from the flight area caused by incorrect operations, it is considered to use an electrical cable as a tether to supply electric power for multicopter flight. To realize the system, a selection of the cable is very important. Therefore, in this research, we model electrical devices, such as motors and ESCs on the multicopter, and discuss an optimal cable selection. In this paper, we propose our cable selection method, and introduce our power-feeding-tether system that can be carried by Unmanned Ground Vehicles.**

I. INTRODUCTION

Micro Unmanned Aerial Vehicle (MUAV), particularly a multicopter, is very small, easy to control, and a lot of flexibility for mounting sensing devices. Therefore, multicopters are recently used for search and rescue missions[1][2] and investigations of infrastructures[3], such as bridges[4]. However, in case of a small-sized conventional rotary wing aircraft, small propeller size has disadvantages, low payload and short flight time (typically 20 minutes or less), caused by a decrease in efficiency, generally.

To solve the above problem, we proposed to use an unmanned ground vehicle (UGV) as a carrier of multicopter to save multicopter's battery. In 2011, we developed a UGV-Multicopter cooperation system with Prof. Kumar's group, and conducted a mapping experiment in a disaster environment[5]. In the experiment, the UGV traversed the target environment with carrying multicopter. In case that the UGV could not enter, the multicopter took off from the UGV's helipad, explored the area, and returned to the UGV's helipad. Finally, we confirmed that the proposed system had a capability to map a large disaster area.

During the above system integration, we found two problems: short flight time and landing difficulty of multicopters. In the former problem, we explained that the multicopter could be recharged when the multicopter came back to the helipad on the UGV. Theoretically, it is possible for multicopter to conduct multiple flight with such a recharging system. However, practically, recharging motion takes a time, and causes extension of the mission time. Therefore, in our system, we installed a battery recharging system on our UGV, but we did not use it. In the latter problem, Prof. Kumar's group was succeeded in developing a robust landing system for multicopters on the helipad on the UGV. However, it is difficult to guarantee 100% successful ratio. We believe that the more reliable landing system is required for practical use.

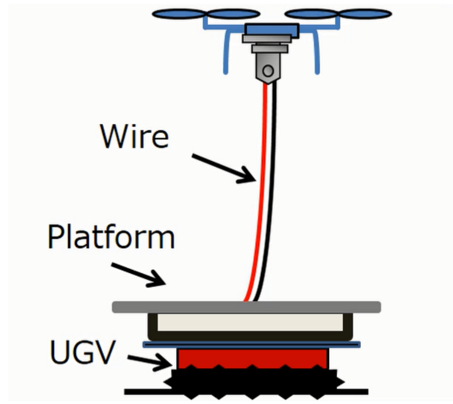

Fig. 1. Tether winding system for multicopter that is mounted on UGV

To handle the above two problems, recently, our research group proposes a Multicopter-UGV cooperative system with a "tether". The UGV mounts a special helipad for the multicopter that equips with take-up power-feeding-tether. Fig. 1 shows a concept of the idea. Once the batteries are not on the multicopter, the limitation of its operation time is limited by heavy batteries or generator on the UGV. In addition, the multicopter lands to the helipad on the UGV easily by winding up the ether forcibly. Furthermore, the tether makes a physical constraint of range of flight of multicopter, so it guarantees a safety. According to the above reasons, we have started development of a tethered multicopter system that can be carried by UGV.

In order to design such a power feeding tether, it is very important to choose an electric cable because it has a decisive impact on flight capability of multicopter. In case that tether length is over 10 m, typical multicopter requires over several hundred watts, and a voltage drop is not negligible in the power feeding tether. On the other hand, electrical cable is heavy, so it is necessary to consider the weight of the cable. However, thin and light cable is typically large ohmic value, and it generates large voltage drop. Therefore, to keep efficient flight time for tether powered multicopter, it is required to consider a choice of the cable.

In this paper, we discuss a relationship between electric cable and flight height, in other words, power loss in cable and payload. Then, we propose a design method of tether powered multicopter, particularly tether select, and evaluate the method with practical examples. Finally, we show our current status of development of a tethered multicopter

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Fig. 2. Appearance of Multicopter

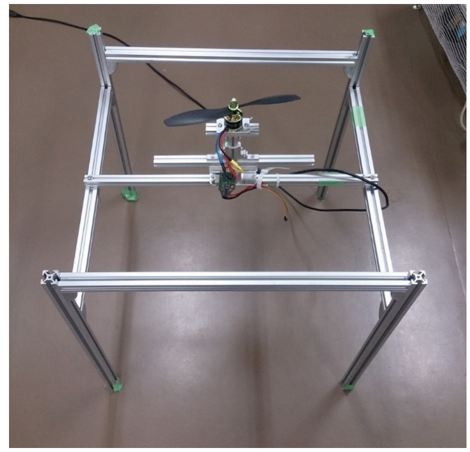


Fig. 3. Appearance of Thrust Test Bench

system that can be carried by UGV.

II. Tether Powered Multicopter

A. Proposal of tether powered multicopter system

Typically, multicopter, a multi-rotary-wing aircraft, requires large electric power to enable hovering. To obtain effective flight performance, a diameter of the propeller had better be large as much as possible. However, for use in indoor environments, the size of its body is limited. To extend its flight time, one effective way is to increase its battery capacity. However, there is a limitation on the size and weight of the battery for small-sized multicopters.

To solve the above problem, our approach is to use a multicopter with a power-feeding-tether. To allocate the battery on the ground, we can use large-sized batteries, and/or electric power generators for multicopter's power source.

When we assume a multicopter with power-feeding-tether, the maximum altitude of the multicopter is the same as the length of the tether. In case of the indoor environment, such as oil plants or disaster buildings, the length of the tether should be more than 10 m. In such cases, a problem of a voltage drop cannot negligible to keep flight altitude of the multicopter, caused by electrical resistance of the tether. The power-feeding and flight performance largely depends on the properties of power feeding tether. Therefore, the choice of tether is very important for development of multicopter system with power feeding tether.

In the following sub-sections, we models an electrical property of multicopters, current estimation through the power feeding tether, and cable selection method to enable a desired flight altitude of the multicopter.

B. Small-size Multicopter

To enable safe indoor flight, we chose a quad-rotor multicopter with 8 inch propeller for the discussion in this paper. Its outer size of each side is 470 mm, shown in Fig.2. The weight of the airframe is 1,140 g (without battery), and power for hovering is around 300 W. Usually, we fly this multicopter with a battery that voltage is around 12 V. In this case, the current for hovering requires around 25 A from the mounted battery. Even if the target multicopter is small, the 25 A is very large, and we should consider electrical cable resistance in this case.

Typically, electrical cable resistance increases in proportion to the length of power feeding cable. According to the Ohm's law, a voltage drop decreases with reducing the current in case of the constant resistance. Therefore, to earn the same electrical power, supply voltage should be large. Actually, "up-convert voltage on the power line" and "down-convert at the destination" are used for commercial power feeding system. It is possible to use such step-up/breakdown voltage devices for the power feeding tether, and some research institutes use such system, recently. However, the breakdown voltage device is typically too heavy to use for small-size multicopter. Therefore, we decided to use a high breakdown voltage motor driver, called ESC (Electrical Speed Controller), instead of mounting a voltage converter on the multicopter side.

C. Performance measurement of standard motor and ESC

In order to choose an electric cable for the power feeding tether, understanding of an electric performance of the motors and ESCs is very important. Thus, at the beginning of this research, we measured performances of the motor and ESC performances that were used in our target multicopter.

The motor used in our multicopter is categorized as a Brushless DC motor (BLDC). The type of the motor is rotated by controlling a three-phase coil current from a motor driver. To control the coil current, the current-vector-drive method is well-known for effective drive[6]. However, basically, the method requires higher calculating cost and uses for the larger electrical circuit. Therefore, typical multicopter does not use the current-vector-drive method. Instead, a square-wave-drive method is used for ESC controller mounted on hobby-use multicopters. It is a very simple method, so it is easily implemented on small multicopters with cheap devices. Generally, in case of a square-wave-drive method, the properties of the BLDC is the same as a typical (Brushed) DC motor.

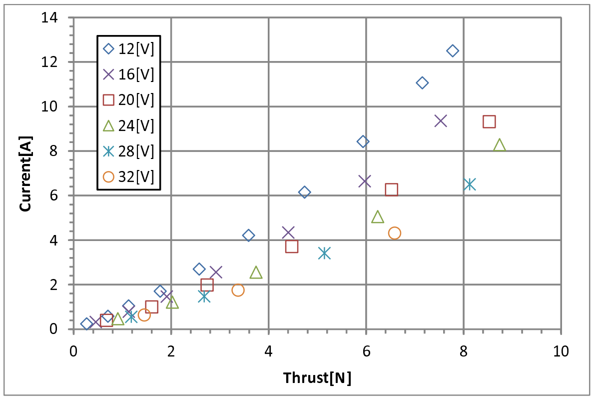


Fig. 4. Measured Thrust v.s. Measured Current

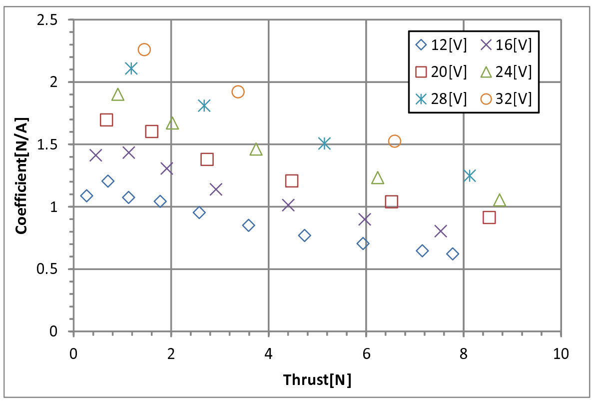


Fig. 5. Measured Thrust v.s. Thrust coefficient

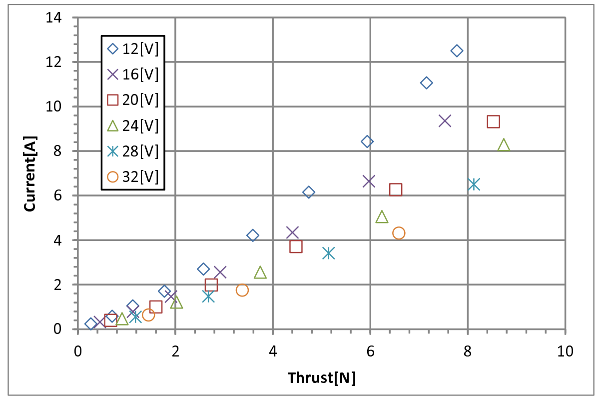


Fig. 6. Measured Thrust v.s. Measured Current

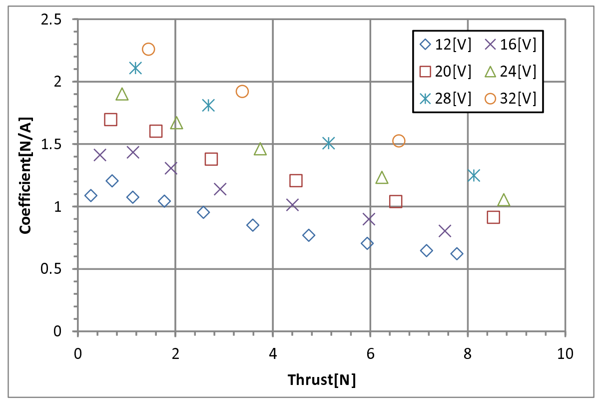


Fig. 7. Measured Thrust v.s. Thrust coefficient

To confirm the performance of a set of motor, propeller and ESC, we measured a relationship between the current and the thrust with various supply voltages and various PWM signals. Our thrust measurement bench, shown in Fig.3, was used for the measurement. It mounted a force-torque sensor to measure its thrust force and the moment force.

Fig.6 shows the result of the relationship between the output thrust and the input current. According to the result, surprisingly, the characteristics of the set of BLDC motor and ESC for multicopter were quite different from typical DC motors even if it used a square wave drive ESC. To clarify this, we created a graph of the relationship between the thrust per current and the thrust, as shown in Fig.7. Theoretically, in typical DC motors, and typical BLDC with a square-wave-drive method, the torque increases in proportion to the current, and the thrust also increases in proportion to the torque[7]. Then, the thrust should increase in proportion to the current, and the thrust coefficient should have been constant. However, as shown in the Fig.7, the thrust coefficient was not constant, in our experiment. The trend was that, according to the PWM ratio was increased, the thrust coefficient decreased. Because of space limitation, we omit results of combinations of other devices (motors and ESCs), but all devices showed the same trend.

D. Proposal of ESC and motor model

According to the discussion in the previous sub-section, a set of BLDC motor and ESC for typical multicopter does not follow a conventional DC Motor's model. Thus, it is important to model the property of BLDC motor and ESC to estimate maximum flight height of the multicopter.

Based on the relationship between the thrust and the current shown in Fig.6, it can be expressed as a quadratic approximation shown in the equation (1),

$$I_m = k_{t1} F_m^2 + k_{t2} F_m \tag{1}$$

where I_m is the motor current, F_m is the thrust, k_{t1} and k_{t2} are the members of the thrust coefficients.

Figure 8 shows the relationship between the motor voltage E_m and the thrust coefficients k_{t1} and k_{t2}. The relationships can be approximated by hyperbolic curves, as shown in (2) and (3):

$$k_{t1} = \frac{1}{k_{t11} E_m + k_{t12}} \tag{2}$$

$$k_{t2} = \frac{1}{k_{t21} E_m + k_{t22}}, \tag{3}$$

where k_{t11}, k_{t12}, k_{t21}, and k_{t22} are constant values.

Figure 9 shows a plot of measured values and estimated curves calculated by (1)-(3). It indicates that our approximation is suitable for obtaining a relationship between thrust force and current.

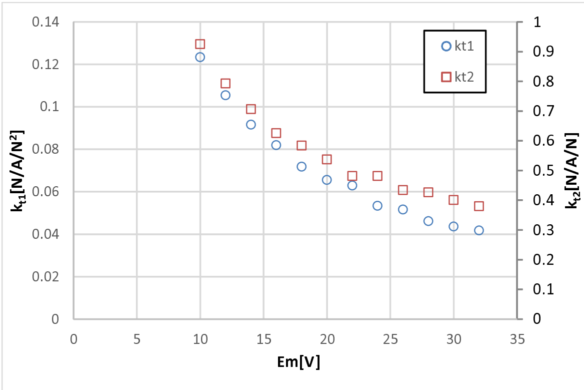


Fig. 8. Motor Voltage v.s. kt value

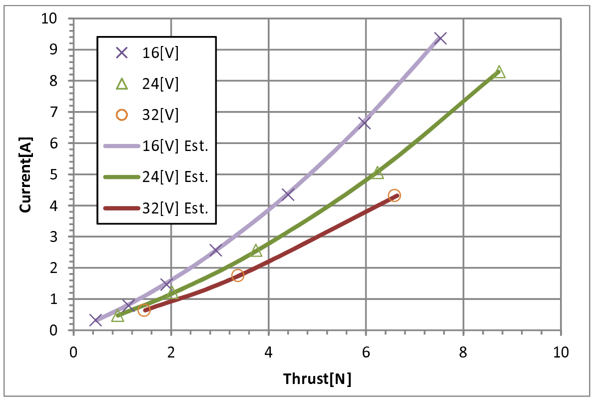


Fig. 9. Thrust v.s. Estimeted Current

In addition, we propose a model of the relationship between voltage and current of the target motor based on the measured result, shown in figure 10), in case that PWM duty is 100 %. According to the result, we assume that the motor voltage is proportional to the motor current. Therefore, the relationships can be approximated by the following equation (4):

$$E_m = I_m k_{i1} + k_{i2} \tag{4}$$

where the k_{i1} and k_{i2} are obtained from the measured values.

E. Consideration of maximum flight altitude

Now we obtained the model of ESC and BLDC motor for multicopters. The next step is an estimation of the maximum flight altitude of multicopter based on electrical/physical constraint.

Conditions of unable flight for the tether powered multicopter is in the following:

1) The required thrust exceeds the maximum thrust.
In here, the required thrust is determined by the frame weight and tether weight in the air. The maximum thrust means the total maximum thrust generated by the all propellers. Of course, the multicopter cannot fly in case that the maximum thrust is lower than the required thrust.
2) The supplied motor voltage is lower than the required motor voltage for flight.

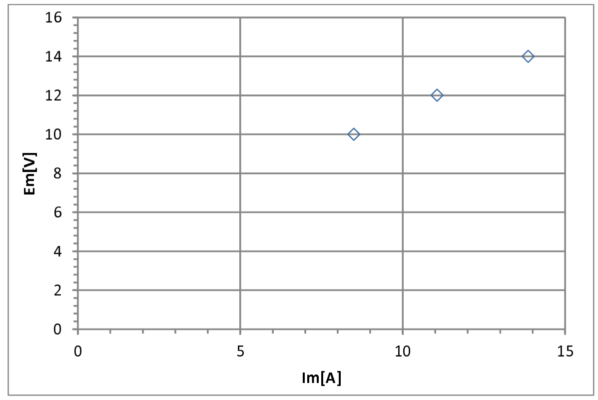


Fig. 10. Measured Current v.s. Measured Voltage

When the multicopter is hovering in fixed altitude, required thrust is constant, and the required motor voltage can be calculated by the thrust. When the supplied motor voltage becomes lower than the required motor voltage for hovering caused by the voltage drop in the cable, the multicopter cannot keep flying.
3) The supplied motor voltage is lower than the minimum rated voltage of ESC.
Even if the supplied motor voltage is higher than the required motor voltage for flight, it is impossible for multicopter to keep flying in case that the supplied voltage is out of range of ESC's operating voltage.

In order to judge whether the multicopter can fly or not, we obtain parameters in the above conditions, as follows.

[Supplied motor voltage]

The total current of the motors on airframe I_t is obtained by the number of motor n as Eq (5):

$$I_t = nI_m. \tag{5}$$

In case of the quad-copter, the n is equal to 4. Practically, during the attitude control of the multicopter, the current values for each motor are not the same. However, in here, we assume that the values are the same for simplification.

The resistance of electrical cable R_c is derived from a resistivity ρ_r Ω/m and the cable length l m. The cable includes positive and negative lines. Therefore, the total length of the cable is assumed to be doubled, as follows:

$$R_c = 2\rho_r l. \tag{6}$$

Therefore, the supplied motor voltage E_m can be derived as follows:

$$E_m = E_v - R_c I_t, \tag{7}$$

where E_v is the power supply voltage at the ground station.

[Required thrust]

The required thrust is obtained from the flight weight. The flight weight W_f is a sum of the airframe weight W_b and the cable weight in the air W_c, as follows:

$$\begin{aligned} W_f &= W_b + W_c \\ &= W_b + \rho_c h, \end{aligned} \tag{8}$$

where the ρ_c is a line density of the cable, and h is the flight height. Please keep in your mind that h is not equivalent to the cable length l.

Therefore, the required total thrust F_{treq} to keep flying is expressed by:

$$F_{treq} = gW_f + T \tag{9}$$

where g is the acceleration of gravity, and T is the cable tension from the ground station in case that it has a function to pull for taking up slack in the cable. (See the section III.) Then, the required each motor thrust F_{mreq} is obtained by the following:

$$F_{mreq} = F_{treq}/n$$
$$F_{mreq} = \frac{1}{n}\left(g(W_b + \rho_c h) + T\right). \tag{10}$$

[Maximum thrust]

Thrust F_m can be expressed by motor model and motor voltage. Concretely speaking, we can obtain F_m by using the inverse function of (1) and (11), as shown in the equation (11).

The equation (11) is a monotone increasing in case that electric resistance of the cable is equal to zero. Practically, it becomes a function that has a maximum value caused by the resistance. The maximum value is the maximum thrust of the motors.

[Required voltage to obtain a certain thrust]

Finally, required voltage for each motor E_{mreq} to obtain a certain thrust is calculated by (4) and required current I_{mreq}. The I_{mreq} can be obtained by (11) and the required thrust F_{mreq}.

According to the above, we can obtain all parameters to judge whether tethered multicopter can fly or not.

F. Cable selection for Tether Powered Multicopter

In this section, we discuss the tether selection for the actual tether-powered-multicopter system based on the approximated equations, shown in the previous section. Table I shows the specifications of electrical cable candidates in our laboratory. The cables 1 and 2 are a round shape of a cross-section cable that surface is covered by rubber. These cables are suitable for the winding mechanism because of its round shape. The difference between cables 1 and 2 is just a diameter. The cable 3 is a twisted pair cable. It is simply twisted with two single cables. Therefore, it is very light. The cable 4 is a twice of the cable 3. It is twisted with four single cables. Therefore, the cross-section shape is close to the round shape, and the resistance is decreased in comparison with the cable 3.

TABLE I
CABLE SPECIFICATION

Item	Resistivity [Ω/m]	Line density [g/m]	Cable Dia.[AWG]
Cable 1	0.0255	96	AWG18
Cable 2	0.015	119	AWG16
Cable 3	0.03	13.75	AWG20
Cable 4	0.017	27.5	AWG20 x 2

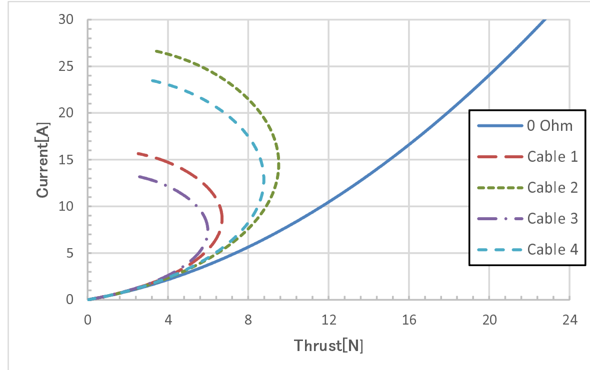


Fig. 11. Thrust v.s. Current at 32V

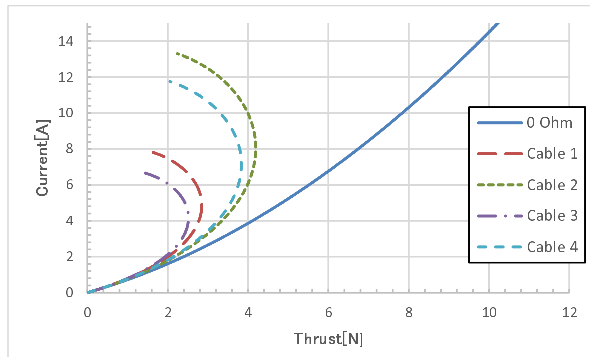


Fig. 12. Thrust v.s. Current at 16V

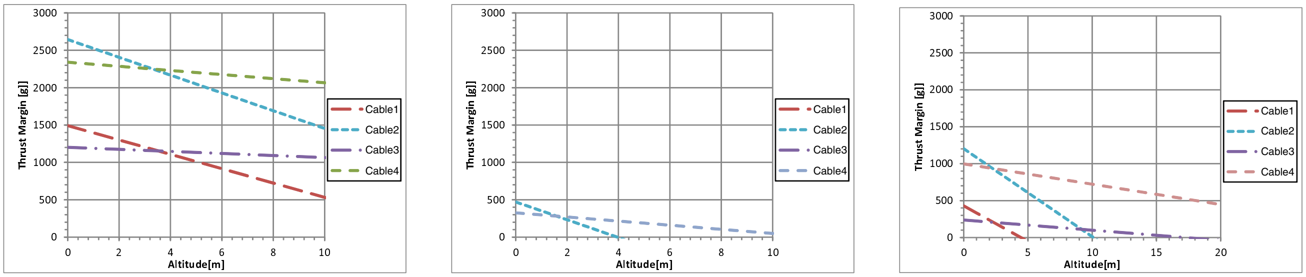
For evaluation of each cable, we simply substituted cable characteristics to Eq.(11), and observed the relationship between F_m and I_m. Fig.11 shows the result of the substitution in case that the power supply voltage E_v is 32 V and the length of cable l is 10m. Practically, we need to consider about the minimum rated voltage of ESC as shown in section II-E, but in here, we ignore this condition.

As shown in the graph, the relationship between thrust and current is a monotonic increase when cable resistance is 0 Ω. On the other hand, the thrust has a local maximal value in case that the cable resistance is larger than 0 Ω. Also, the maximum thrust tends to decrease as cable resistance increases. Fig.12 the result in case that the power supply voltage E_v is 16 V. The thrust coefficient at 16 V is smaller than at 32V, and the current at 16 V is extremely larger than at 32 V at the same thrust.

Next, we consider the voltage margin and the thrust margin from the equation of required thrust at the altitude h. The voltage margin is a result of subtracting the required motor voltage to keep its altitude from the supplied motor voltage. The thrust margin is a result of subtracting the required thrust to keep the altitude from the maximum thrust. Note that the cable tension T for taking up slack in the cable is set to 0.01 N.

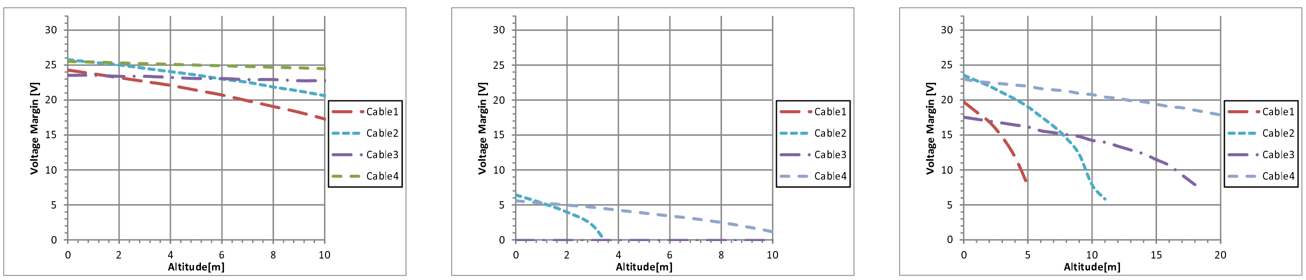
Figs.13 and 14 show the graphs of thrust margin and the

$$F_m = -\left(\frac{k_{t11}(E_v - 2n\rho_r l I_m) + k_{t12}}{2(k_{t21}(E_v - 2n\rho_r l I_m) + k_{t22})}\right) + \sqrt{\left(\frac{k_{t11}(E_v - 2n\rho_r l I_m) + k_{t12}}{2(k_{t21}(E_v - 2n\rho_r l I_m) + k_{t22})}\right)^2 + \frac{I_m}{k_{t11}(E_v - 2n\rho_r l I_m) + k_{t12}}} \quad (11)$$



(a) @ 32v, 10m (b) @ 16v, 10m (c) @ 32v, 20m

Fig. 13. Flight altitude v.s. estimated thrust margin



(a) @ 32v, 10m (b) @ 16v, 10m (c) @ 32v, 20m

Fig. 14. Flight Altitude v.s. estimated voltage margin

voltage margin.

According to the graphs, the thrust margin is simply in proportion to the flight altitude. It is obvious that the cable 1 and the cable 3 cannot generate an enough thrust to take off in case that the supply voltage is 16V. When the altitude is 0 m, the cable 2 has the largest thrust margin. However, the higher the flight altitude is, the better the cable 4 becomes. That is because the cable 2 is heavier than the cable 4.

The voltage margin has the same trend. Note that the calculation of the voltage margin was terminated when the thrust margin became at 0. Therefore, after that, the voltage became a static, as shown in Fig. 14-(c). Practically, because the minimum rated voltage of the ESC exists, the ESC might not work even if the voltage margin is greater than 0V.

According to the above, the flight condition of the tether powered multicopter is affected by the cable weight, the cable resistance, and the power supply voltage, drastically. Therefore, prior design of the tether is very important. In comparison with the four types of the cables, the cable 4 was the most suitable cable for the tether powered multicopter, because of its light weight.

III. Tether Winding Helipad-Ground-Station

In the last part of the paper, we introduce our current status of development of helipad-ground-station that has a capability to wind tether attached to the multicopter. It is supposed that the station is mounted on the UGV in the near future.

Figure 16 shows an overview of the system. One end of the tether is attached to the multicopter, and the other end is attached to the helipad-ground-station. The size of the station is 500 mm on the width, 500 mm in the length, and 350 mm in the height. A feature of the station is that it has a constant tension control system to remove the slack of the tether. The function is in the ground station side, so that the multicopter can use the system in both manual and automatic controls. The main functional elements of the station are the tension detection part and the winding mechanism.

To realize a constant tension control system to remove the slack of the tether, the tension detection mechanism is very important. Fig.15 shows a hardware CAD image around tether winder. As shown in the figure, the tether is wired through some pulleys. The pulley 2 is mounted on the link mechanism that rotate as freely. According to an increase of the cable tension, the link is rotated gradually in one

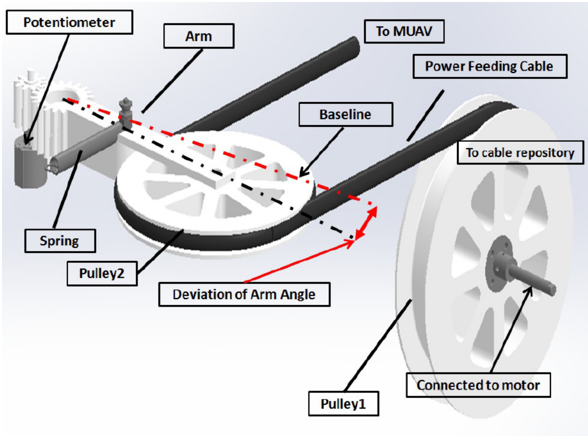


Fig. 15. Winding and Tension Measure Mechanism

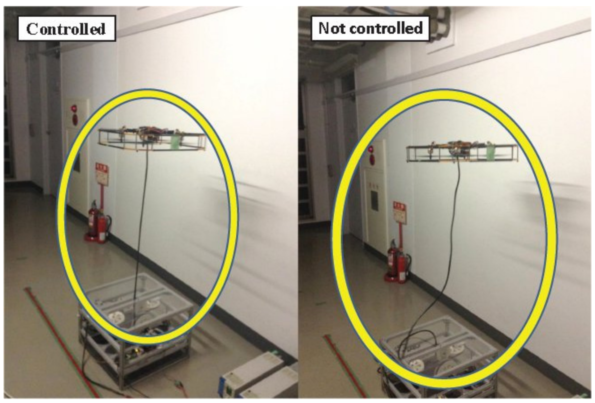


Fig. 16. Appearance of ground station and multicopter

direction by pull spring. The link axis has a potentiometer that measures an angle of the link. Therefore, a tether tension is measured by the link length, the spring rate, and the angle of the link.

To enable the winding function of tether, rubber pasted pulley 1 shown in the Fig.15, is actuated by DC motor. The tether can be both a rope and an electrical cable. In case of the electrical cable, the cable becomes high temperature because the multicopter needs a lot current through the cable. Therefore, from the point of view of heat release, the winded tether is stored in the cable chamber located at the bottom of the station loosely, not winded to a reel in order.

We conducted an initial experiment to keep flying of the multicopter with the above system with taking up slack in the cable. Figure 16 shows a typical result of the system.

IV. Conclusion

In this paper, we focused on an availability of tether powered multicopter. Particularly, we discussed the selection of the power cable for this system.

The resistance of the power cable is one of the important factors for selection of the cable. Therefore, at the beginning of this research, we focus on a modeling of the motor and ESC in the multicopter. According to our measurement experiments, we found that the thrust coefficient was not stable, unlike the typical DC motor for bhobby-used ESC. Therefore, we conducted modelling the motor and ESC. Based on the model, it is possible for us to consider the influence of the cable resistance to the motors.

The airframe of our multicopter is lightweight, and the weight of the power cable affects for thrust capability. In case that the required thrust is increased, the required current is also increased, and the loss of the cable is also increased. Therefore, in this research, we conducted a discussion of the actual tether-powered-system with four types of real cable characteristics based on the motor model and cable parameters, as shown in the section III. Consequently, we found that the possible flight height was drastically affected by the cable weight and resistance, and it was very important to choose the suitable cable for designing of the tether powered multicopter system.

In the future works, we will discuss about the cable heat that is currently ignored. Furthermore, to validate the evidence of the estimated value, we will fly our multicopter with tether powered manner. On the other hand, we plan to implement a vector control method for ESC to increase an efficiency of the multicopter flight.

Acknowledgment

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