



Article Experimental Examination of Automatic Tether Winding Method Using Kinetic Energy in Tether Space Mobility Device

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Abstract: Tethers (strings and wires) are used in various mechanical systems because they are lightweight and have excellent storability. Examples of such systems include elevators and cranes. In recent years, the use of tethers in special environments, such as outer space, is expected, and various systems have been proposed. In this study, we propose a mobility system using a tether that moves a human by winding a tether attached to a wall. However, the method has a problem whereby the attitude of the human can lack stability during the winding of the tether. We developed the attitude control method of the Tether Space Mobility Device during tether winding while focusing on fluctuations in the rotational kinetic energy of systems. The effectiveness of the control method was shown using numerical simulation. In this paper, the proposed control system is installed in the experimental device for validating the numerical simulation model. Then, we verified the effectiveness of the proposed control method through experiments using an actual system. The experimental results confirm that the angular velocity of the Tether Space Mobility Device converges to 0 deg/s when control is applied. In addition, it was shown that the proposed control method is effective for automatically winding the tether.

Keywords: motion control; tether; winding method; space robot

1. Introduction

In September 2021, for the first time in the history of space development, all-civilian and all-private spacecraft orbited the Earth. Private spaceflight is still in the development phase, but it will become more common in the future. With more people staying in space, we need to think about how to move efficiently and safely in a space station. The expansion of human-occupied space facilities, such as the International Space Station, is expected to increase this tendency. In addition, the general contractor Obayashi Corporation in Japan has announced the "Space Elevator Construction Concept" to construct a space elevator by 2050 [1]. Because it is assumed that the interiors of such occupied space facilities will have microgravity conditions, a special means of mobility is needed for humans to perform efficiently.

The use of space tethers in such a space environment has been proposed [2]. Since space tethers were first proposed by Tsiolkovsky, space tethers have been widely used in space missions such as attitude stabilization, momentum exchange, and space elevators. Many space tether concepts have been proposed, and missions have been carried out [3]. Tethers have the advantages of being lightweight and compact. A compact tether system has been proposed for microgravity environments [4]. For instance, a tethered robot system was developed for use under microgravity conditions [5]. Furthermore, an extension method based on the Lorentz effect was proposed, and its control method was developed [6]. Furthermore, a number of tethered deorbiting missions were proposed [7,8]. A system using net-shaped tethers has been developed [9]. In addition, there is also a system proposal



Citation: Nirayama, K.; Takehara, S.; Takayama, S.; Ito, Y. Experimental Examination of Automatic Tether Winding Method Using Kinetic Energy in Tether Space Mobility Device. *Automation* **2022**, *3*, 364–377. https://doi.org/10.3390/ automation3030019

Academic Editor: Felipe Martins

Received: 11 May 2022 Accepted: 18 July 2022 Published: 19 July 2022

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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). using a tether for the safety of astronauts [10]. As shown in these studies, the tether is useful as an actuator in space. However, the flexibility and elasticity of space tethers creates problems. Therefore, there are many development items as research themes. Moreover, many proposals for using tethers have been proposed in other fields. There has been research on the use of tethers for automatic landing [11], anti-vibration, and energy supply for helicopters [12]. In addition, there are Remotely Operated Vehicles in the deep sea [13].

We developed the Tether Space Mobility Device (TSMD) for facilitating human mobility within an occupied space facility in a microgravity environment [14]. This system was proposed by us as a tool for humans to move by using the tether as an actuator. Figure 1 shows the concept of the TSMD. The tether is shot out from the TSMD, and the end of the tether is attached to the target point. Then, the tether is wound into the TSMD by an actuator, pulling the operator toward his or her desired destination. However, because this system only uses the tension in the tether for movement, as shown in Figure 2a, when the center of gravity of the target user moves away from the line of action of the tension, a moment due to the tension is applied, as shown in Figure 2b, and the problem of rotational motion occurs. Therefore, it is necessary to adopt a control method to suppress this rotational motion. For cable control, cooperative control is applied to the gantry robot under tension [15]. There is research on the design of the control system with the observer to suppress the vibration of the crane [16] and the design of the control system to move the load of the crane [17]. Regarding tension control, research on applying fuzzy PID to an automatic winding machine to control tension [18] and a method of controlling the tension of a machine for feeding paper has been proposed [19]. There is a study that controls the tension by feedback control for the tethered space-tug system [20]. In the above research, control under the condition that tension acts the system is examined. However, in the proposed system, when the tether is wound up, and the human is moved, there is a time when the tether undergoes deflection due to the inertial force of the human, and the tension becomes zero. Then, the tension is generated again by winding the tether. In other words, it is the system in which there is a time when there is no tension used for control, and control is not possible.

In this study, we focused on the kinetic energy related to rotation and developed an attitude control method that converges the angular velocity during the winding of the tether to 0 deg/s. Then this control method has been shown to be effective by the numerical simulation model [21].

In this paper, we designed and built the proposed control system. This system was installed in the experimental device for validating the numerical simulation model. Therefore, we targeted the TSMD motion during the winding of the tether and verified the attitude control method by focusing on the kinetic energy related to rotation using actual machine experiments. Furthermore, the usefulness of the proposed method is shown in the results obtained using a numerical simulation model.



Figure 1. Concept of the TSMD.



Figure 2. Drawbacks of the TSMD. (a) Moment of force; (b) Rotational motion.

2. Control Method for Winding Up the Tether

This section provides an overview of the winding tether control method we developed. Details are given in [21]. The proposed control method focused on the change in kinetic energy related to the rotation of the rigid system and applied a control method [22] that converges the angular velocity of the rigid system generated during tether recovery to 0 deg/s. This form of control automatically achieves optimum winding of the tether based on the motion of the TSMD.

First, the conditions under which the tension of the tether attenuates the rotational motion of the rigid system are derived. Figure 3 shows the TSMD model with the tether stretched. Here, no relative motion is assumed between the TSMD and the unit for simulating the influence of the weight of a human body (hereinafter referred to as the rigid body). The symbols in the figure are defined as follows:

- *T* : Tension of the tether
- φ : Angle formed by the *X* axis and the tether
- *I* : Moment of inertia of the TSMD
- G-X'Y' Body coordinate system with the center of gravity G of the rigid body as the origin
- w : Distance from the tip of the inlet to *G*
- α : Angle of the tip of the inlet in the object coordinate system
- θ : Rotation angle of the rigid body



Figure 3. Model of the TSMD when the tether is stretched [21].

The equation of motion for the rotational motion of the rigid system in Figure 3 is given by:

$$I\theta = wT\sin(\varphi - \theta + \alpha) \tag{1}$$

The kinetic energy E_{θ} related to the rotational motion of the rigid system is given by the following equation:

$$E_{\theta} = \frac{1}{2} I \dot{\theta}^2 \tag{2}$$

It can be seen that when $E_{\theta} \rightarrow 0$, $\theta \rightarrow 0$ from Equation (2). The following equation is obtained by differentiating Equation (2) with respect to time and substituting Equation (2) for Equation (1):

$$\dot{E}_{\theta} = I\dot{\theta}\ddot{\theta} = wT\dot{\theta}\sin(\varphi - \theta + \alpha)$$
(3)

Here, from $T \ge 0$ and w > 0, the following relations hold:

$$T = 0 \quad \theta \sin(\varphi - \theta + \alpha) \ge 0$$

$$T > 0 \quad \dot{\theta} \sin(\varphi - \theta + \alpha) < 0$$
(4)

When *T* is switched as follows,

$$\dot{E}_{ heta} \le 0$$
 (5)

and the passage of time makes $E_{\theta} \rightarrow 0$ and $\theta \rightarrow 0$. Moreover, because α is the TSMD and the human unit are fixed at 90 deg by a joint in this paper, it has the following value:

$$\alpha \approx 31.57 \deg$$
 (6)

Next, consider the winding tether control rule that satisfies Equation (4). Let l be the length of the tether that has not been collected inside the rigid body and let r be the target value for the length of the tether. For simplification, the transfer function from r to l is given by Equation (7).

$$G(s) = \frac{1}{(\tau_l s + 1)^2}$$
(7)

Therefore, the acceleration \hat{l} of the tether length is given by the following equations:

$$\ddot{l} = k_{l1}(r-l) - k_{l2}\dot{l}$$
(8)

and

$$k_{l1} = \frac{1}{\tau_l^2}, \ k_{l2} = \frac{2}{\tau_l}, \ \tau_l > 0$$
 (9)

Moreover, *r* is determined as follows with reference to Equation (4):

$$\begin{cases} r = d + u_{+} & \dot{\theta}sin(\varphi - \theta + \alpha) \ge 0\\ r = d + u_{-} & \dot{\theta}sin(\varphi - \theta + \alpha) < 0 \end{cases}, \ u_{+} \ge 0, \ u_{-} \le 0 \tag{10}$$

where *d* is the distance from the origin of the global coordinate system to the tip of the suction port, and u_+ and u_- are control inputs when $\theta \sin(\varphi - \theta + \alpha) \ge 0$ and $\theta \sin(\varphi - \theta + \alpha) < 0$, respectively. In this paper, let $u_+ = 0.01$, $u_- = -0.06$, and $\tau_l = 0.1$. By defining *r* as in Equation (10), when tension increases the kinetic energy of the rigid system, the tether flexes to counteract the tension, and when the tension reduces the kinetic energy of the rigid system, the tether is stretched so that tension is applied. By repeating this, the angular velocity of the rigid system can converge to 0 deg/s over time.

3. Experiment

3.1. Experimental Setup

In this paper, the experimental setup for validating the proposed control method was built by adapting various sensors into the experimental setup for validating the numerical simulation model. A photograph of the experimental device is shown in Figure 4, and the system details are given in Figure 5. The device requires an actuator that winds the tether to create movement and satisfy the functions discussed in Section 1. In this experiment, a motor was used as an actuator, and the experimental device was equipped with a reel to wind the tether. The motor winds the tether while adjusting the rotation speed according to the state of motion of the device. Therefore, the device is equipped with a motor that is capable of controlling the rotation, a gyro sensor, and a distance sensor. The adapted gyro sensor and distance sensor are shown in Figure 6. For the gyro sensor, we adopted CRS03-02S (Silicon Sensing Systems Ltd, Hyogo, Japan), which has a proven track record in space. For the distance sensor, we adopted VL53L1X (STMicroelectronics Ltd, Geneva, Switzerland.). This sensor is very small. The size of the distance from the sensor is 4.9 $[mm] \times 2.5 [mm] \times 1.56 [mm]$. In addition, conventional distance sensors that use infrared technology may be affected by the reflectance of the object, but this sensor starts from the time it takes for the projected photons to reflect on the object and return. Technology to directly measure the distance was adopted. Therefore, it is possible to measure the absolute distance without being affected by the color and reflectance of the object. Figure 7 shows a photograph of the control system board. This platform was newly created for the construction of the control system. The sensor data were recorded in a database for later review. Because this device was designed to be used by humans, it was equipped with a dummy human unit that simulates the mass of a TSMD user. In this experiment, floating the device using gas pressure reduces the frictional force with the experimental table, simulating a two-dimension microgravity state [23]. An Mbed NXP_LPC1768 was used as a microcomputer to control the rotation. Table 1 shows the specifications of the experimental equipment. The flat experimental table was made from a smooth glass plate $(1.5 \text{ m} \times 3 \text{ m}).$



Figure 4. Experimental setup of TSMD.



Figure 5. Schematic of experimental device.



(a)

(b)

Figure 6. Adapted Sensor. (a) Gyro sensor; (b) Distance sensor.



Figure 7. Control system board.

Weight of TSMD [kg]	0.8
Size of TSMD [mm]	$170 \times 95 \times 179$
Weight of human imitate part [kg]	7.9
Size of human imitate part [mm]	220 imes 190 imes 242
Length of inlet [mm]	40
Total weight [kg]	8.7
Moment of inertia [kgm ²]	0.088

Table 1. Specifications of experimental device.

3.2. Initial Conditions

Figure 8 shows the initial state and initial position of the experimental device. In the initial state, the relative angle of the TSMD and the human unit is 90 deg. In the initial position, the tether was extended 1.5 m from the center of the flight table short side and parallel to the flight table. Zero-point correction for each sensor was conducted at the initial position in each trial. The zero point of the gyro sensor was determined by measuring the output voltage 100 times when the experimental device was stationary and finding the average value. The zero point of the range sensor was determined by averaging the values measured 50 times under stationary conditions. Zero-point correction for the wireless motion sensors was conducted using a dedicated IMU-Z Viewer GUI.



Figure 8. Schematic of experimental setup.

3.3. Method of Measuring Feedback Data

When attitude control is applied, it is necessary to measure φ , θ , θ , and d and to use them as feedback signals, as described in Section 2. Here, the measurement method for these values is described. Here, θ was measured using a gyro sensor and θ was obtained by the trapezoidal integration of the measured value. Figure 9 shows the state during the experiment. The coordinate system was based on the center of the flight table short side, $O^E - X^E Y^E$; the *x*-coordinate of the suction port tip, x_{E1} ; and the *y*-coordinate of the suction port tip, y_{E1} . The coordinates are obtained by the following equation:

$$\begin{cases} x_{E1} = x \cos \theta \\ y_{E1} = 0.75 - y \cos \theta \end{cases}$$
(11)

Therefore, *d* is obtained by

$$d = \sqrt{x_{E1}^2 + y_{E1}^2} \tag{12}$$

The obtained value of *d* is applied to determine φ using the following equation:

$$\varphi = \sin^{-1} \frac{y_{E1}}{d} = \cos^{-1} \frac{x_{E1}}{d}$$
(13)

Feedback of these values allows energy control possible.



Figure 9. State of the experiment.

3.4. Initial Winding Velocity

In this experiment, the tether was initially set in an extended state. If the attitude control method is applied immediately after the start of the experiment and $i \approx 0$ in Equation (8), then Equation (8) is represented by the following equation:

$$l \cong k_{l1}(r-l) \tag{14}$$

For there is no motion in initial state, the angular velocity is zero. Then $\theta \sin(\varphi - \theta + \alpha) \cong$ 0. Therefore u_+ is applied as the control input. Further, because $d \cong l$ immediately after the start of the experiment, Equation (14) is converted to the following equation:

$$\ddot{l} \cong k_{l1}u_+ \tag{15}$$

In Equation (15), because l > 0 for $k_{l1} > 0$ and $u_+ > 0$, the tether is extended, not wound up. In this experiment, it was decided to set the initial winding speed to V_i . A schematic diagram of the winding speed is shown in Figure 10, where T_i represents the time to start the energy control. As shown in Figure 10a, the tether was wound at a constant initial speed V_i until T_i had passed, and attitude control began to be applied after T_i had passed. In addition, as shown in Figure 10b, the simplest method to continue winding the tether at a constant winding speed V_i was also tested. The winding acceleration until the winding speed reached V_i was 2.39 m/ s^2 , which is the maximum value that the motor used can produce. V_i was set to 0.10 m/s and T_i was set to 1.0 s when applying attitude control. In addition, the device moved while maintaining a relative angle of 90 deg between the TSMD and the human unit without considering disturbance. The measurement time of the movement was set to 6.0 s based on the time when tether winding was started.



Figure 10. Outline of initial winding velocity. (a) With control; (b) Without control.

4. Discussion

In this section, we discuss the effectiveness of attitude control based on the experimental results. A numerical simulation model proposed in the literature [21] is used for comparison because the experimental setup is affected by friction and gravity acting on the tether. First, the effect of control is verified by the experimental results and simulation results. Furthermore, the effectiveness of the proposed method is shown by comparing the results under attitude control.

First, the control effect is examined based on the experimental results. Figure 11 shows the time history of the angular velocity obtained from the experimental results. It can be seen that from 0 to 1.3 s, the angular velocity without control increased rapidly and then decreased rapidly. Because the angular velocity is never negative between 1.3 and 6.0 s but remains a constant positive value, the TSMD continues to rotate counterclockwise. This indicates that the rotational motion is excited by the tension in the tether in the initial state, and the rotational motion is not controlled. In contrast, with control, the TSMD moves in a similar manner from 0 to 1.3 s, but after that, the angular velocity settles at a constant value at around 1.5 s. Then, due to the tension in the tether generated by the attitude control, the angular velocity begins to decrease again and converges to about 0 deg/s after 3.2 s. The rapid change in angular velocity after 5.7 s with attitude control was caused by the device approaching the edge of the flight table and is thus not related to control performance.



Figure 11. Time history of angular velocity (experimental results).

Next, the effect of control is examined based on the numerical simulation results. Figure 12 shows the time history of the angular velocity in the numerical simulation, and Figure 13 shows the shape of the system at each time step. From Figure 12, it can be seen that from 0 to 1.3 s, the angular velocity under both conditions increases rapidly and then decreases rapidly to a negative value. In contrast to the experimental results, the reason

the values became negative under both conditions can be considered to be the lack of frictional force. After that, the angular velocity without control converges to a constant value after 1.3 s and then remains at almost the same value. This indicates that the TSMD continues to rotate in the same direction as the initial rotation. In contrast, with control, the angular velocity becomes negative and then increases and converges to about 0 deg/s after 2.9 s. This is because the tension in the tether was induced multiple times by the energy control, which controlled the rotational motion. The generation of this tension can also be confirmed from by shape of the system in Figure 13. The tether without control is not greatly deformed from the start of winding to about 1.5 s, and the tether is moving while being greatly deformed after 1.5 s so that it is not stretched again. In other words, it can be considered that the TSMD is moved by only the inertial force. Conversely, the tether under the condition of attitude control deforms in a manner similar to that when there is no energy control from 0 to 1.5 s. However, the tether under attitude control does not deform significantly from 1.5 to 3.0 s, and the deflection of the tether is eliminated. This is because the winding speed of the tether is automatically adjusted by the attitude control. After that, the deflection of the tether caused by the rotational motion of the TSMD is eliminated by attitude control. It can also be seen that the TSMD is moving when its rotation is suppressed. The difference between the experimental and numerical results may be due to the influence of the frictional force between the TSMD and the flight table. However, it is considered that this difference does not affect attitude control since this difference also exists under uncontrolled conditions.

Therefore, the effect of attitude control on the rotational motion of the TSMD is to automatically change the winding speed in both the experimental and numerical results.



Figure 12. Time history of angular velocity (numerical results).

Next, to verify the attitude control from the viewpoint of the control mechanism, the timing of the control input was examined. Figures 14 and 15 show the time histories of the control input and angular velocity in the experimental and numerical results, respectively. In Figures 14 and 15, the following common tendencies can be seen. At 1.0 s, when control starts, control input u_- causes the tether to stretch, and the tension acts in a direction that reduces the kinetic energy. After that, the control input switches from u_- to u_+ when the angular velocity shows a negative value and the control input u_+ prevents an increase in kinetic energy. Then, the angular velocity is stable at negative values. Switching the control input from u_+ to u_- generates tension in the tether. The tension, which acts in a direction that reduces kinetic energy, increases the angular velocity, which converges to approximately 0 deg/s. Regarding the number of times the control input is switched, it can be seen that in the experimental results, the control input is switched to u_- from 1.8 to 1.9 s in the experimental results. Because the control input is switched depending on the sign of the conditional expression $\dot{\theta} \sin(\varphi - \theta + \alpha)$ in Equation (10), the reason is obtained from

the time history of $\theta \sin(\varphi - \theta + \alpha)$. Figure 16 shows the time history of $\theta \sin(\varphi - \theta + \alpha)$. When the control input becomes u_- , it can be seen that $\theta \sin(\varphi - \theta + \alpha)$ becomes negative from 1.8 to 1.9 s. At other times, the control input is switched depending on the sign of $\theta \sin(\varphi - \theta + \alpha)$. It can be seen that the control input is switched appropriately. Because the sign of $\theta \sin(\varphi - \theta + \alpha)$ is determined by the angular velocity θ and the angles θ and φ , the reason the sign changes twice between 1.6 and 2.1 s is that the angle θ changes due to the sudden change in angular velocity θ and φ from 1.4 to 2.1 s.



Figure 13. Comparison of system shape. (a) Without control; (b) With control.



Figure 14. Time history of angular velocity and control input (experimental results).



Figure 15. Time history of angular velocity and control input (numerical results).



Figure 16. Time history of $\theta \sin(\varphi - \theta + \alpha)$ (experimental results).

Therefore, the control target of converging the angular velocity of the TSMD to about 0 deg/s over time is achieved. In addition, attitude control is realized by a similar mechanism both experimentally and numerically. Based on these results, the effectiveness of attitude control is established.

5. Conclusions

In this study, as fundamental research on a TSMD system designed to be used under microgravity conditions, an attitude control method was adapted. The proposed method aims to automatically achieve optimum winding of the tether based on the motion of the TSMD. This control method was verified only by the numerical simulation model. Then, an experimental device based on the proposed control system was designed. A control system was implemented by a gyro sensor and a distance sensor. Therefore the effectiveness of the proposed attitude control method was reduced. Using this method, the angular velocity, which is the control target, could be set to 0 deg/s. This indicates that stable automatic winding of the tether was realized by using rotational energy. In future work, the proposed control will

be implemented using a Kalman filter instead of a distance sensor. Because the distance sensor cannot be used unless the wall is flat, it is not preferable to use it in a structure with a complicated shape. Moreover, the calculation of distance using the accelerometer has an error caused by two integrations. So, a Kalman filter will be used to solve these problems. In addition, disturbance experiments related to human movement as the device is used will be conducted.

Author Contributions: Conceptualization, S.T. (Shoichiro Takehara); Experiment, Y.I., K.N. and S.T. (Satoshi Takayama); Numerical simulation, Y.I. and S.T. (Satoshi Takayama); Writing—original draft preparation, K.N. and S.T. (Shoichiro Takehara); Writing—review and editing, K.N. and S.T. (Shoichiro Takehara). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Japan Society for the Promotion of Science, KAKENHI grant number JP26820075.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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