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Microgravity Experiment for Attitude Control of A Tethered Body by Arm Link Motion

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1. Introduction

Tethered satellite systems (TSS) offer various attractive potential applications in space, and therefore, they have been an object of study for over two decades (Rupp & Laue, 1978). In these studies, the tether extension strategy utilizes the gravity force and/or the centrifugal force associated with the orbital motion. Typically, it is assumed that the tether is to be extended for about 20-100km along the local vertical. Mass, elasticity, and deflection of the tether cannot be neglected in such a case. The TSS is then characterized by various dynamical effects including three dimensional rigid body dynamics, swinging and vibration, in-plane and out-of-plane motions of the tether, transverse vibrations of the main satellite, and so on. Due to these diverse dynamical effects, the TSS can become unstable. Therefore, at an early stage, active tether tension control has been recognized to be indispensable. Since then, various control approaches have been proposed, including both linear regulators (Bainum & Kumar, 1980) and nonlinear control methods (Pines, D. J. et al, 1990), control strategies employing thrusters, tension in the tether line or motion of the offset of the tether extending point have been investigated (Modi, V. J. et al., 1992).

Tethered Space Robot (TSR), which is connected to a mother spacecraft through a piece of tether, is a new type of space robot system proposed in the previous work (Nohmi et al., 2001). TSR differs significantly from the TSS studied so far, mainly in three aspects. First, we assume that the tether is to be extended for a relatively short distance, 10-100m. Second, we do not envision gravity force and/or centrifugal force influencing tether extension. Rather, we will employ tether extension strategy assisted by an initial translation momentum of the subsystem. Third, we envision the tethered subsatellite to be a multi-body system. Major consequence of the multi-body nature is that its attitude can be controlled under tether tension by its own link motion, instead of reaction wheels, jet, or thrust. When attitude control of the subsystem is possible, robotic motion can be achieved by employing methods borrowed from free-flying space robots studies: the generalized Jacobian matrix based approach (Umetani & Yoshida, 1989), or the virtual manipulator approach (Vafa & Dubowsky, 1990).

This paper discusses attitude control of a tethered space robot based on experimental results under microgravity condition by capsule dropping (at Microgravity Laboratory of Japan; <http://www.mglab.co.jp/index.html>) and by parabolic flight (at Diamond Air Service corporation; http://www.das.co.jp/new_html/index-static.html). Section 2 describes experimental device for a tethered space robot. Section 3 explains algorithm for attitude

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control of experimental device of a tethered space robot. Section 4 and section 5 describe microgravity experiment and experimental results, respectively.

2. Attitude control for a tethered space robot

2.1 Design for a tethered space robot

Attitude control of a tethered space robot is based on torque caused by tether tension. Therefore, it is impossible to control attitude around the axis along tether tension. The vertical axes with respect to tether tension can be possible. Figure 1 shows a simple model, which consists of one rigid arm link and one rigid base, and those are connected by one spherical joint. Since tether tension caused no torque, the tethered subsystem is in equilibrium when the mass center of the base, the tether attachment point, and the tether are located on a straight line. $O-xyz$ denotes an inertial frame fixed to a tether extension point. $O-012$ denotes the body fixed frame, whose origin is fixed to the center of the spherical joint, and the 2 axis is along tether extension line at the equilibrium condition. Link motion can obtain torque acting on the base around the 0 axis and the 1 axis, then attitude control around those axes is possible.

2.2 Experimental device for a tethered space robot

Experimental device for a tethered space robot is shown in figure 2, which is developed based on the design as shown in figure 1. Tether is attached to the end of the arm link. All equipments including batteries are mounted on the base without external cables. The parameters are: total mass of the robot is about 4.5kg, scale of the base is 261x261x82mm, and length of the arm link is 100mm, respectively.

Electrical circuit on the experimental device are shown in figure 3. Angular velocities (ω_1 and ω_2) of the base around the 0 axis and the 1 axis are measured by two gyro sensors, respectively. The arm link is actuated by two motors around the 0 axis and 1 axis, respectively. Arm link angle around the 0 axis and 1 axis (ϕ_1 and ϕ_2) measured by potentiometers, respectively.

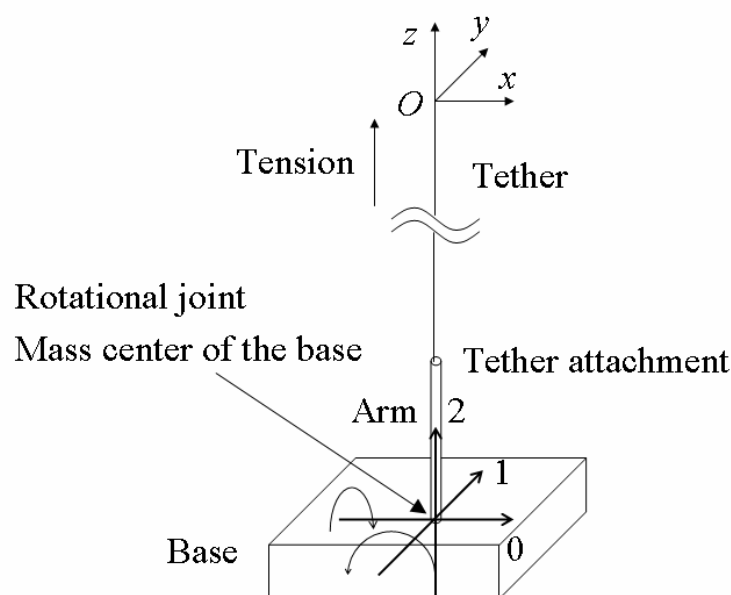


Fig. 1. Simple model for a tethered space robot

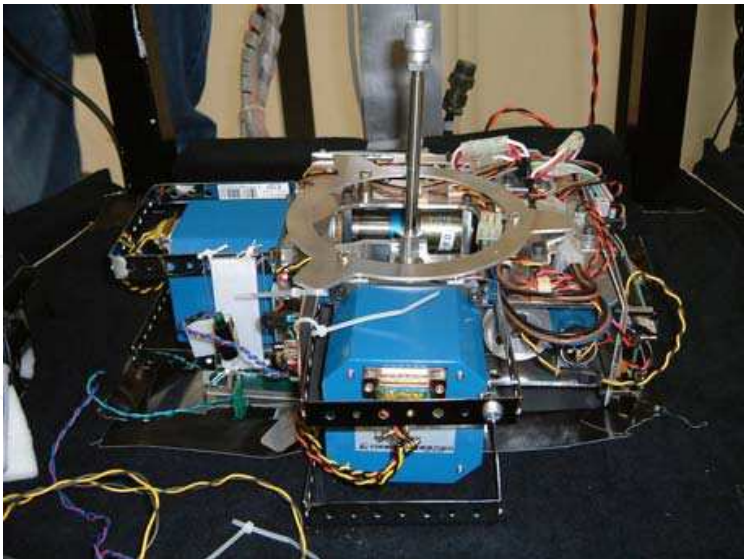


Fig. 2. Experimental device for a tethered space robot

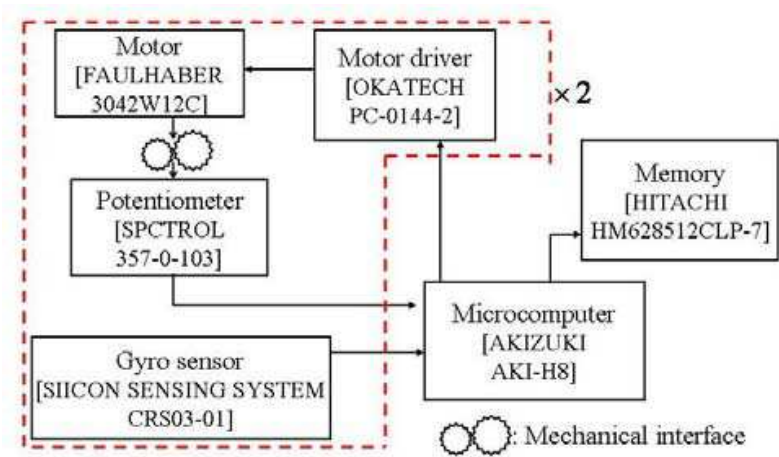


Fig. 3. Electrical circuit on the experimental device

2.3 Joint mechanism for arm link

Joint mechanism consisting of 5 rotational joints as shown in figure 4 was employed for the experimental device. Joint 0 and joint 1 are actuated by motors, respectively. Joint a, joint b, and joint c are passive joints. Then, two actuators along the 0 axis and the 1 axis can control arm link motion around the 0 axis and the 1 axis, respectively.

3. Control algorithm

3.1 Tether tension torque

Figure 5 shows rotational motion of the simple model for a tethered space robot, in case of deviating from the equilibrium. Here, \boldsymbol{p} denotes position vector of the tether attachment point with respect to the origin of O-012. \boldsymbol{p}_r and \boldsymbol{p}_i denote vectors along the 2 axis and the y axis, respectively, and $\|\boldsymbol{p}_r\| = \|\boldsymbol{p}_i\| = \|\boldsymbol{p}\|$. $\boldsymbol{\omega}$ ($= [\omega_0 \ \omega_1 \ \omega_2]^T$) and \boldsymbol{n} denote vectors of angular velocity and tether tension, respectively. Since it is difficult to measure tether motion, control algorithm is designed under assumption that tether length is long enough compared to scale of a tethered subsystem,

and also tether tension is constant, that is, n is constant. Also, assuming that arm link mass can be neglected compared to the base mass, tether tension torque τ_r can be written as:

$$\tau_r = p \times n = -n \times p_r - n \times (p - p_r) . \tag{1}$$

The second term in the right hand of equation (1) can be changed by arm link motion.

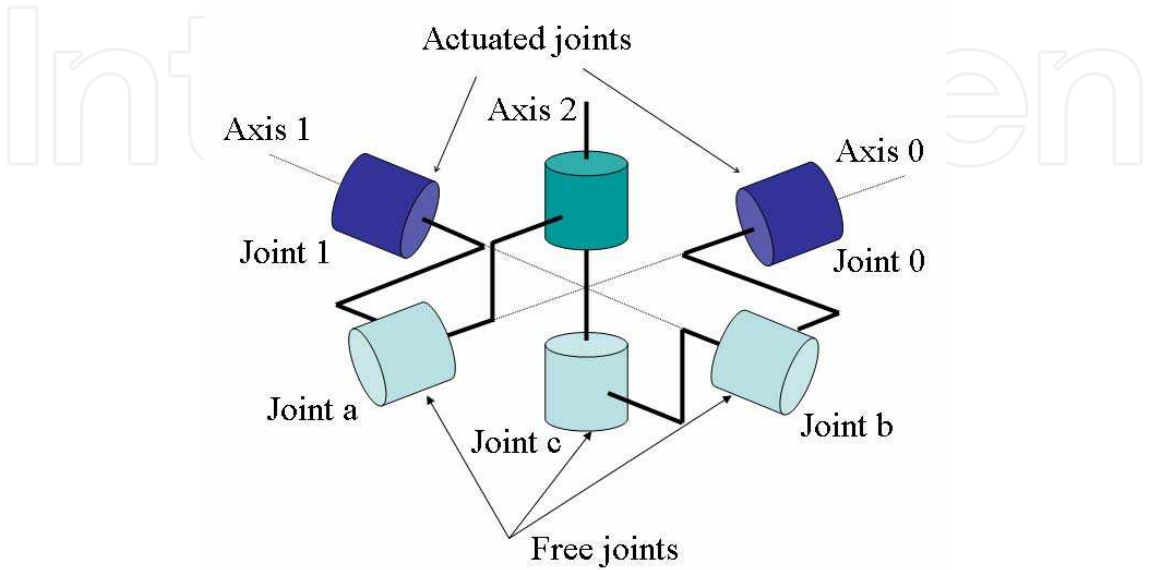


Fig. 4. Joint mechanism for the experimental device

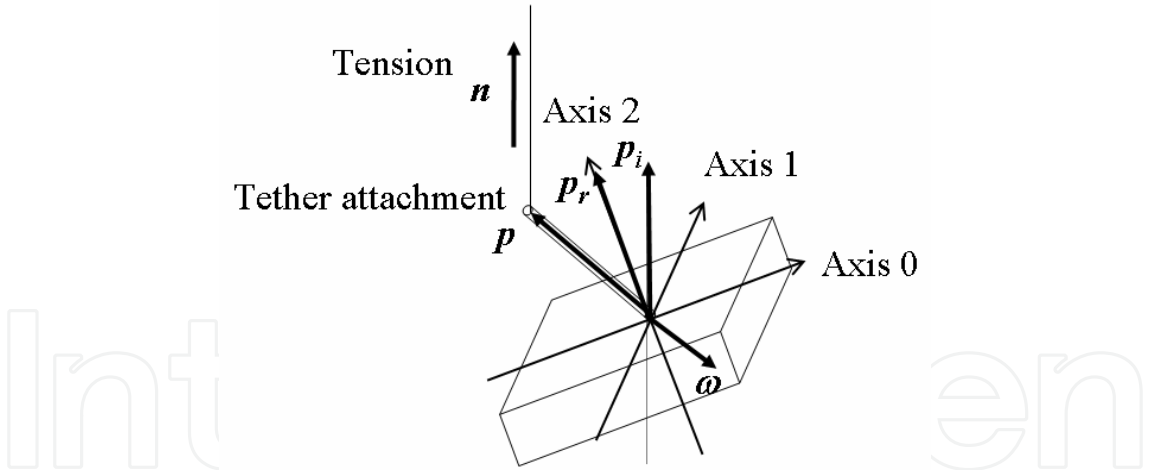


Fig. 5. Tether tension torque acting on the simple model

3.2 Arm link motion control

The tethered subsystem is in the equilibrium when $p_r = p_i$. When arm link motion generates (A) torque acting in direction to stable attitude; and (B) torque damping rotational motion, the PD control for rotational motion of the subsystem is possible. In order to employ the PD control, feedback information of attitude and angular velocity of the base are needed. Gyro sensors of the experimental device measures angular velocity, however it is difficult to obtain accurate attitude. Then, attitude angle (θ_1 and θ_2) around the 0 axis and the 1 axis are assumed:

$$\theta_i = \int \omega_i dt, (i = 0, 1). \quad (2)$$

Also, assuming $\theta_1, \theta_2, \phi_1, \phi_2 \ll 1$,

$$p - p_r = l \begin{bmatrix} \phi_1 & -\phi_0 & 1 \end{bmatrix}^T. \quad (3)$$

where l denotes arm link length ($= \|p\|$). From equations (2) and (3), equation (1) can be rewritten as:

$$\ddot{p} = -n \times p_r - n l \begin{bmatrix} \phi_0 & \phi_1 & 0 \end{bmatrix}^T. \quad (4)$$

Employing the following control equation of arm link motion:

$$\begin{bmatrix} \ddot{\phi}_0 \\ \ddot{\phi}_1 \end{bmatrix} = k_p \begin{bmatrix} \theta_0 \\ \theta_1 \end{bmatrix} + k_d \begin{bmatrix} \omega_0 \\ \omega_1 \end{bmatrix}. \quad (5)$$

where k_p and k_d are control gains, equation (1) can be expressed as:

$$\ddot{p} = -n \times p_r - n l k_p \begin{bmatrix} \theta_0 \\ \theta_1 \\ 0 \end{bmatrix} - n l k_d \begin{bmatrix} \omega_0 \\ \omega_1 \\ 0 \end{bmatrix}. \quad (6)$$

In the right hand of equation (6), the first term is torque by base motion; the second term is (A) torque acting in direction to stable attitude; the third term is (B) torque damping rotational motion, respectively. Then, basic characteristics of the control approach can be summarized as follows:

- without control ($k_p = k_d = 0$): the base performs rotational vibration motion due to tether tension torque;
- P control ($k_d = 0$): rotational vibration frequency is high, since tether tension torque is large compared to that in case (a);
- D control ($k_p = 0$): rotational vibration can be damped;
- PD control: damping time is short compared to that in case (c), since frequency is high as well as that in case (b).

4. Microgravity experiment by capsule dropping

4.1 Experimental facility

Micro Gravity Laboratory of Japan (MGLAB) provides a high-quality and stable microgravity environment, which is $10^{-5}G$ order, equivalent to that in space. The experiment capsule is dropped, and a high-quality microgravity environment is created for approximately 4.5 seconds with minimal turbulence. The capsule measures 900mm in outer diameter and 2,280mm in height, and the payload space available for users is 720mm (radius) \times 885mm (height), with a maximum weight of 400kg (max. weight loaded by users).

4.2 Experimental device for deployment

In order to perform microgravity experiments for a tethered space robot at MGLAB, experimental device for tether extending mechanism as shown in figure 6 was developed.

The torque transmission device (permanent wave torque) of tether reel can apply constant tension on tether during deployment and retrieval. The load cell measures tension by pushing tether between pulleys, and the encoder measures tether length by rotation of tether reel, respectively.

Deployment mechanism for the robot in MGLAB was designed under consideration of the microgravity experiment sequence of capsule dropping, which is transition from condition under gravitational field to that under the microgravity. Figure 6-(a) shows the initial condition under gravity, and the robot is set on the plate supported by springs. These springs are pressed by the robot mass due to the gravity. When it becomes the microgravity condition, these springs are extended because the gravity force due to the robot mass becomes to be zero, and then the robot is deployed as shown in figure 6-(b). During deployment, tether tension reduces deployable velocity of the robot, then the robot stops to be deployed, and begins to be retrieved.

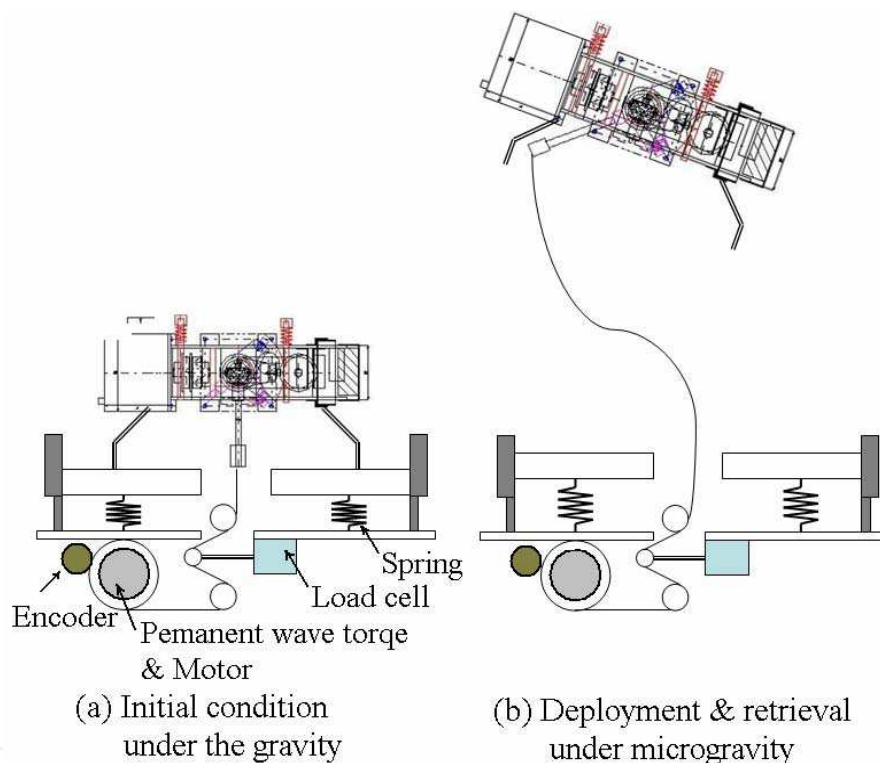


Fig. 6. Deployment mechanism for capsule dropping experiment

4.3 Experimental results and discussion

The experimental results in following three cases are shown in figure 7.

- i. P control: $k_p = 2$ and $k_d = 0$, $n = 100$ [gf],
- ii. D control: $k_p = 0$ and $k_d = 2$, $n = 60$ [gf],
- iii. PD control: $k_p = 3$ and $k_d = 3$, $n = 60$ [gf].

The desired attitude of the base was set as $\theta_0 = \theta_1 = 0$. Figures show time histories, where L denotes tether length, and n denotes load cell data, respectively. Rotation angles around the 0 axis and 1 axis were measured by gyro sensors in case (i), and angular velocities were

measured in cases (ii) and (iii), respectively. In graphs of gyro sensors ω_0 and ω_1 or θ_1 and θ_2 , and potentiometers ϕ_1 and ϕ_2 , dark solid line shows average of 100ms for filtering noise. Here, load cell data in case (ii) was failed to be recorded. It was microgravity condition from $t = 0\text{s}$ to $t = 4.5\text{s}$, and large motion at $t \sim 4\text{s}$ was due to collision of the robot against to the plate after retrieval. The following characteristics of the attitude control have been confirmed. It is noted that rotational vibration motion of the base attitude could not be suppressed in case of the P control because of $k_d = 0$, and that its amplitude was increasing.

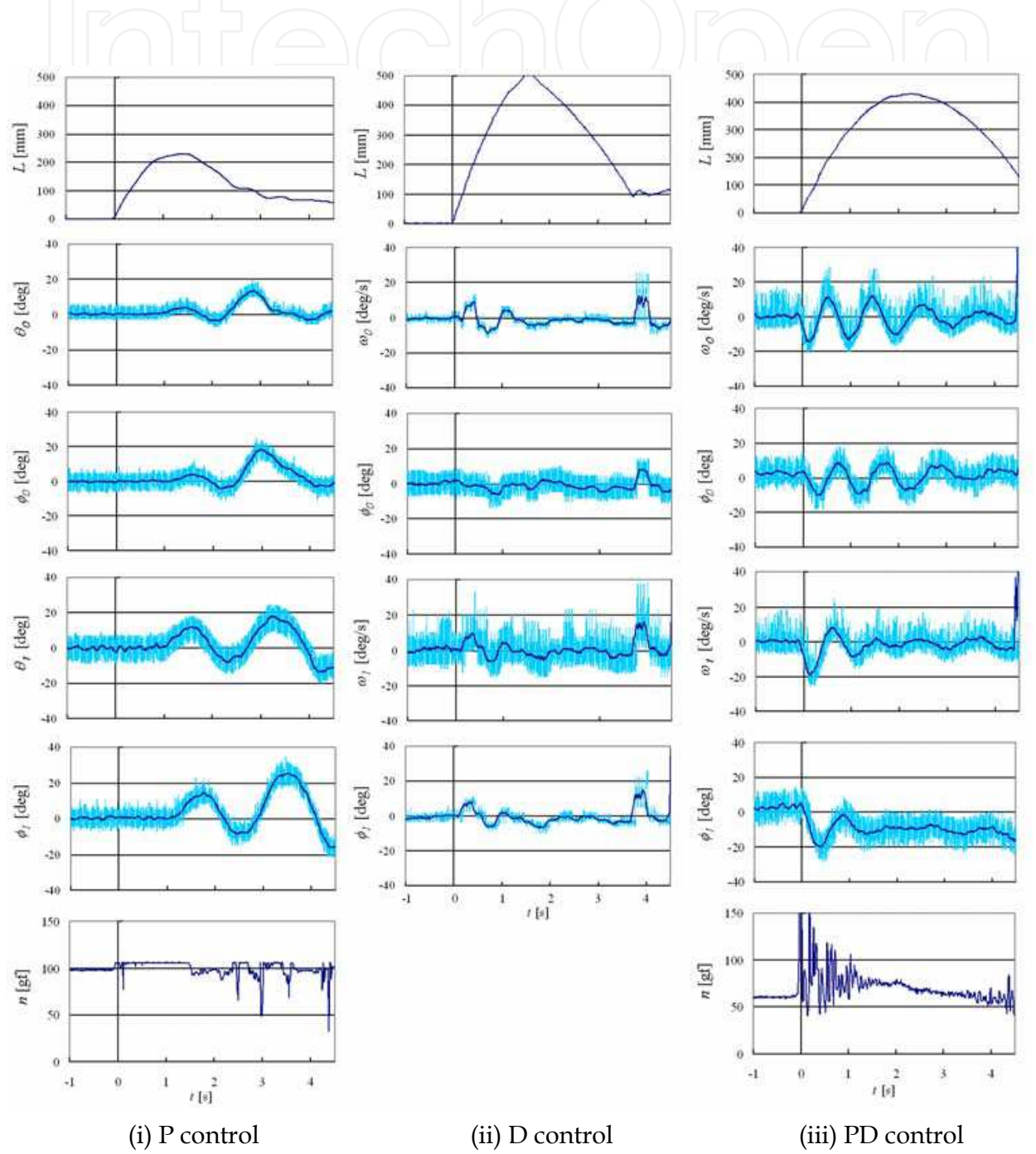


Fig. 7. Microgravity experimental results by dropping capsule

In case of the PD control, rotational vibration motion was damped. Also, rotational vibration motion could not be observed in case of the D control. Hence, it can be considered from these results that the P control excites rotational vibration motion of the base.

In order to examine the characteristic of the P control, figure 8 shows control input and arm link angle, and also tether tension in case (i). It is noted that tether tension changed large discontinuously when arm link angle was peak value. And, it is also noted that arm link angle was behind the control input. Then, it can be said that the P control excites rotational vibration motion of the base due to these reasons.

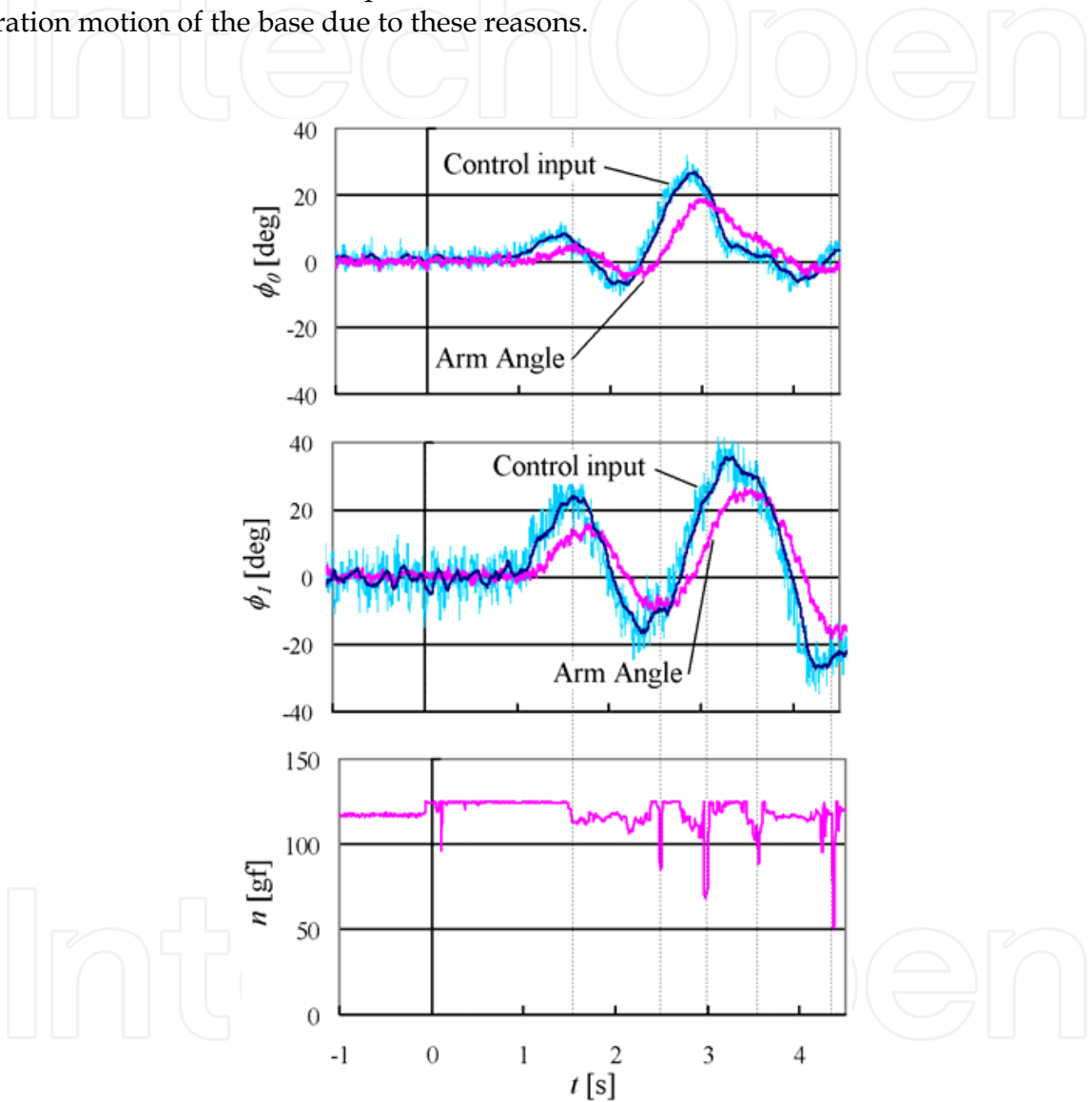


Fig. 8. Arm link motion in case (i) P control

In order to confirm that the D control is suitable for the developed experimental device than the PD control, experiment was performed in case that the P control and the D control are employed in the 0 axis and in the 1 axis, respectively. Figure 9 shows its result. It is noted that rotational vibration motion could be observed in the 0 axis with the P control, and rotational vibration motion could not be observed in the 1 axis with the D control.

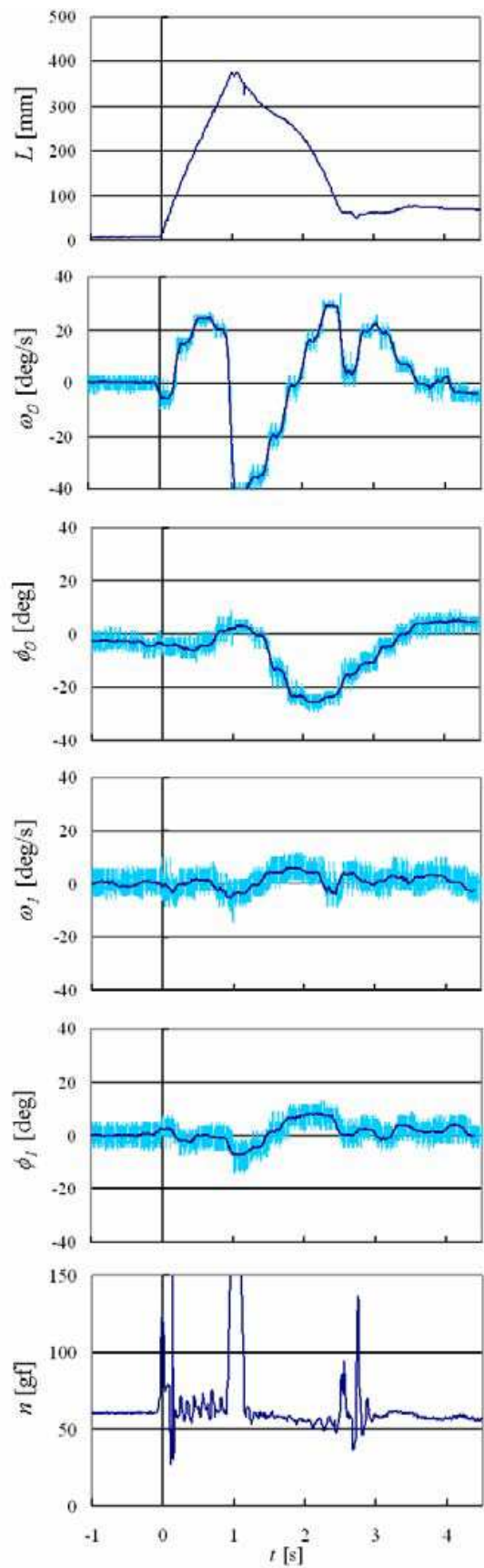


Fig. 9. Compare the D control and the Pcontrol

5. Microgravity experiment by parabolic flight

5.1 Experimental facility

Parabolic flight by the airplane provides microgravity condition, which is performed by Diamond Air Service Corporation in Japan. Microgravity condition is provided in the cabin of the airplane for approximately 20 seconds. Maximum acceleration error is 0.05 G in the vertical direction, 0.01 G in the back and forth, also from side to side, respectively. Scale of the cabin used for the experiment is about $1.5 \times 1.5 \times 4.8$ [m].

5.2 Experimental setting

At the parabolic flight experiment, the experimental device was deployed in the vertical direction in the cabin by constant length tether. Then, a pilot operates the airplane for creating microgravity condition within 0–0.05G in the vertical direction, that is, tether tension was applied at random.

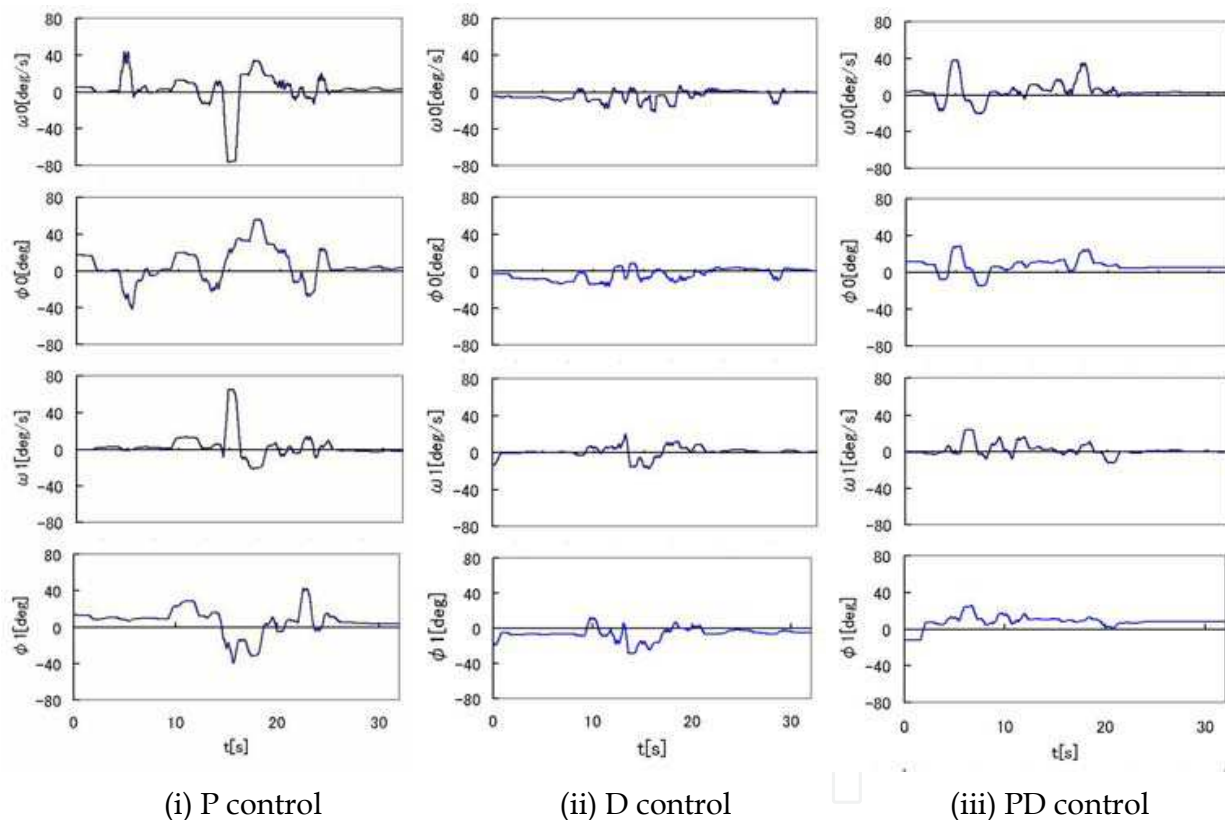


Fig. 10. Microgravity experimental results by parabolic flight

5.3 Experimental results and discussion

The experimental results in following three cases are shown in figure 10.

- i. P control: $k_p = 1$ and $k_d = 0$,
- ii. D control: $k_p = 0$ and $k_d = 1$,
- iii. PD control: $k_p = 1$ and $k_d = 1$.

The desired attitude of the base was set as $\theta_0 = \theta_1 = 0$. Figure shows time histories of the angular velocities of the base ω_0 , ω_1 , and ϕ_0 , ϕ_1 , respectively. The following characteristics of the attitude control have been confirmed. Large rotational motion of the base attitude was observed in case of the P control because it could not be suppressed due to $k_d = 0$. Rotational motion was the smallest in case of the D control, which is better result than that in case of the PD control. Hence, it can be considered that the P control excited rotational motion of the base, since arm link motion changes tether tension, and tether tension excites motion of the tethered subsystem.

6. Conclusion

This paper has described the microgravity experiment of the attitude control for a tethered space robot. A simple model model, which is suitable for attitude control by arm link motion of the multi-body subsystem, and its dynamics have been explained, and also the control equation has been derived. Microgravity experiment was performed in order to confirm and evaluate the attitude control. Experimental device for a tethered space robot is perfectly autonomous and has no external cables, and connected to only tether.

For the microgravity experiment by dropping capsule, tether extending mechanism was designed to apply constant tension on tether, and deployment device was designed under consideration of the experimental sequence. In the microgravity experiment by parabolic flight, tether length was kept constant, and small random tension was applied utilizing characteristics of parabolic flight. The two kinds of microgravity experiment were successfully performed.

It is noted from the microgravity experimental results that the D control can suppress rotational motion of the base, and the P control has possibility to excite rotational motion. The PD control also has such possibility. However it can suppress rotational vibration.

7. Acknowledgement

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