ON FORMATION DEPLOYMENT FOR SPINNING TETHERED FORMATION FLYING AND EXPERIMENTAL DEMONSTRATION

Koji Nakaya(1), Masafumi Iai(1), Osamu Mori(2), Saburo Matunaga(1)

(1)*Tokyo Institute of Technology, 2-12-1-I1-63 O-okayama, Meguro-ku, Tokyo, 152-8552, Japan*
(2)*ISAS/JAXA, 3-1-1 Yoshinodai, Sagamihara-city, Kanagawa, 229-8510, Japan*
E-mail: Koji.Nakaya@lss.mes.titech.ac.jp

ABSTRACT

This paper discusses a ground experimental demonstration on formation deployment for spinning tethered formation flying. The spinning tethered formation flying is the system that rotates around the center of mass of it under the condition that each spacecraft is connected by tethers. Therefore the system can achieve formation deployment using tether tension as well as thrusters. Most of the past studies about the system focused on theoretical studies. However it is important to evaluate it experimentally. In this paper, we introduce an experimental set-up using two-dimensional micro-gravity simulators to evaluate the formation deployment, and discuss results of the experimental demonstration.

1. INTRODUCTION

In resent years, tethered formation flying has been proposed [1]-[5]. The formation flying consists of some spacecrafts connected by tethers as shown in Fig. 1. In generally, spacecrafts of formation flying need so much fuel to precisely keep the required relative position and attitude, and their lifetimes become to be short. However, in the tethered formation flying, spacecrafts can save fuel using appropriate tether tension to achieve precisely formation keeping. This feature is the advantage of the tethered formation flying.

There were some studies on the tethered formation flying as shown in the following part. Mori treated spinning tethered formation flying as a kind of a tethered service satellite system, and proposed feed-forward tether tension control for the formation control [1]. Quadrelli studied spinning tethered formation flying to achieve a space interferometer for deep space [2]. Kim et al. developed control law for NASA's SPECS mission [3]. Matunaga proposed the tethered formation flying to deploy and maintain large membrane structures such as a solar sail spacecraft [4]. Nakaya discussed formation deployment for the spinning tethered formation flying in terms of required maximum thrust and tether tension. He developed formation control for the system based on a virtual structure approach [5]. However these studies mentioned above mainly focused on theoretical approaches. There were few papers that treated the tethered formation flying experimentally in the past studies. The tethered formation flying system has never been operated on orbit. Therefore it is important to evaluate the system using a ground experiment system beforehand.

In this paper, a ground experimental demonstration on formation deployment of the spinning tethered formation flying is discussed. As the experimental demonstration, formation deployment dealt with in [5] is considered. This paper is organized as follows. In section 2, the outline of the ground experimental demonstration is mentioned. In section 3, formation control architecture is explained. The control is based on the virtual structure approach described in [5]. In section 4, ground experiment set-up is introduced. In section 5, results of the experimental demonstration are referred. In section 6, conclusions are mentioned.

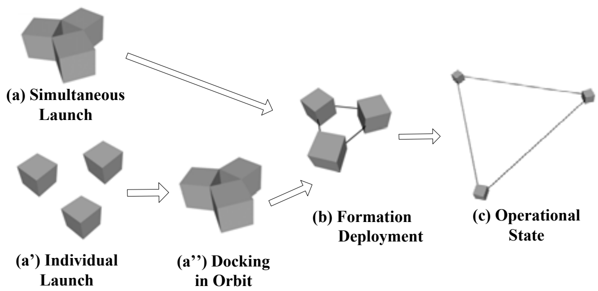


Fig. 1. Spinning Tethered Formation Flying

2. OUTLINE OF EXPERIMENT

An outline of the ground experiment is explained in Fig.2. The formation consists of three spacecraft simulators and it rotates around its center of mass with initial spin radius r_s and angular velocity ω_s. The formation then deploys to the final condition in two-dimension; spin radius r_e and angular velocity ω_e. The formation assumes to keep an equilateral triangle during its deployment. The position, velocity, attitude and angular velocity of each spacecraft simulator, and tether tension and length are measured to evaluate and consider the formation deployment motion.

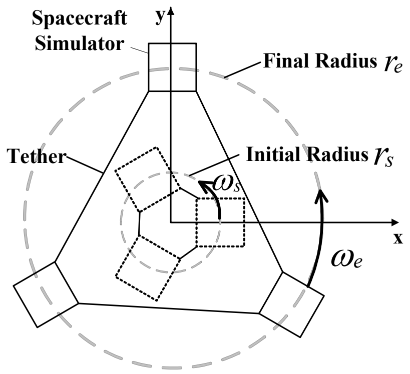


Fig. 2 Outline of the Experiment

3. CONTROL METHOD

3.1 Virtual Structure Approach

A virtual structure approach is one of approaches for conventional multi-spacecraft formation control. In this approach, the control is derived in three steps. First, the desired dynamics of the virtual structure is defined. Second, the motion of the virtual structure is translated into the desired motion for each spacecraft, and finally, tracking control for each spacecraft is derived [5]-[7].

3.2 Control Method

Application of the virtual structure approach to the spinning tethered formation flying is explained in detail in [5]. Therefore the control method is briefly mentioned in this paper. Fig.3 is a virtual structure model for the system. The virtual structure consists of three rigid bodies that are placed 120 degrees apart on a circle. The center of mass (c.m.) of the virtual structure and that of each rigid body are assumed to be connected by a massless rod. $\{\mathbf{v}\}$ is the body-fixed coordinate system attached to the c.m. of the virtual structure. $\mathbf{v}_3$ represents the spin axis of the entire system.

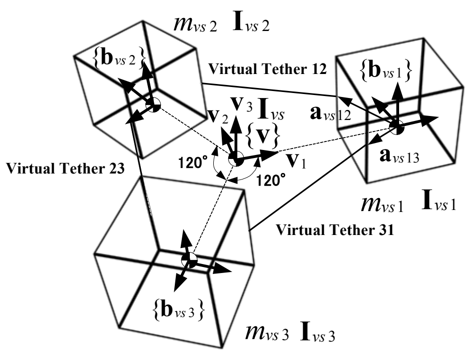


Fig. 3. Virtual Structure Model

For the spinning tethered formation flying system, we can derive a characteristic control method as shown in the following. Because the system rotates around c.m. of the whole system under the condition that spacecrafts are connected by tethers, the system can control the spin radius using only tether tension and centrifugal force while the system must use thrusters to control out-of-plane motion and spin angular velocity as shown in Fig.4. (Out-of-plain motion is ignored in case of a two-dimensional experiment.) This is an especially important feature of the formation flying.

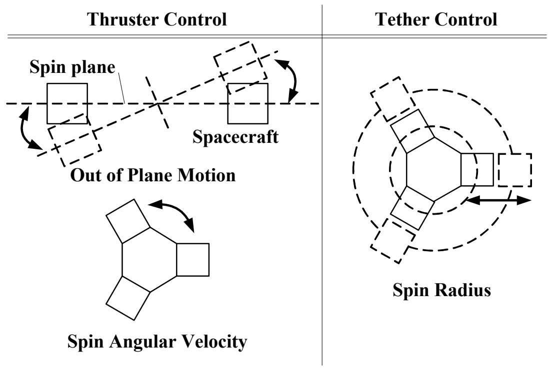


Fig. 4. Control Target of Thruster and Tether

Control of thrusters, wheels and tethers is explained in the following parts. The control assumes to be derived in the three-dimensional case.

Thruster control: thrusters are used to control spin angular velocity and out-of-plane motion. Thruster control is considered in the coordinate system $\{\mathbf{v}\}$ as shown in Fig.5. Let $\mathbf{r}'_j$, $\mathbf{r}'_{cm}$ represent projections of $\mathbf{r}_j$, $\mathbf{r}_{cm}$ onto the $\mathbf{v}_1\mathbf{v}_2$ plane. $\mathbf{r}_j$ means the position of spacecraft j, and $\mathbf{r}_{cm}$ means the position of the c.m. measured in the coordinate system $\{\mathbf{v}\}$. Thruster control is derived as follows.

$$\mathbf{f}_{cnt\,j} = \{\mathbf{i}\}^T f_{cnt\,j} = \{\mathbf{v}\}^T \begin{bmatrix} \dfrac{(\hat{r}_j \times r_j^d)\times \hat{r}_j}{\left|(\hat{r}_j \times r_j^d)\times \hat{r}_j\right|}(K_\theta \theta + K_{\dot{\theta}}\dot{\theta}) \\ -K_r r_{j3} - K_{\dot{r}}\dot{r}_{j3} \end{bmatrix} \quad (1)$$

where $\hat{\mathbf{r}}_j = \mathbf{r}'_j - \mathbf{r}'_{cm}$, and K_θ, $K_{\dot{\theta}}$, K_r, $K_{\dot{r}}$ are controller gains, θ means the angle between $\mathbf{r}_j^d$ and $\hat{\mathbf{r}}_j$, and r_{j3} represents the out-of-plane displacement of the spacecraft j.

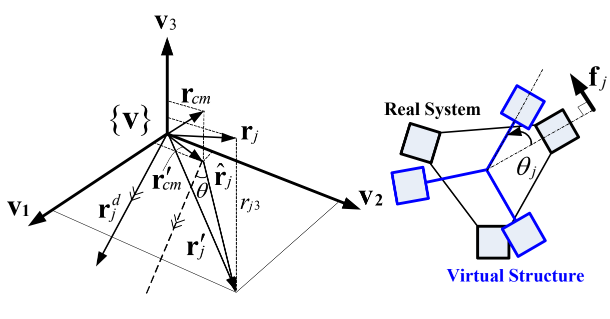


Fig. 5. Definitions for Thruster Control

Wheel control: the control is derived as follows.

$$\mathbf{t}_{cnt\,j} = -K_e \varepsilon_e - K_\omega(\omega_j^{B_j/I} - \omega_j^{B_j/I^d}) \tag{2}$$

where ε_e is the relative quaternion , and K_e and K_ω are controller gains.

Tether control: the control is derived as follows.

$$f_j = f_j^d + K_L(L_j - L_j^d) + K_{\dot{L}}(\dot{L}_j - \dot{L}_j^d) \tag{3}$$

where K_L and $K_{\dot{L}}$ are controller gains. f_j^d means the equilibrium tension for keeping the present spin radius [1].

$$f_j^d = \frac{M_j d(\omega_{vs}^{d2} - \ddot{d}/d)\sin\pi/6}{\sin\pi/3 + \sin\pi/3} = \frac{M_j d(\omega_{vs}^{d2} - \ddot{d}/d)}{\sqrt{3}} \tag{4}$$

where d represents the desired spin radius.

4. GROUND EXPERIMENTAL SYSTEM

Fig.6 shows a schematic diagram of the ground experimental system. The system consists of a 3m*5m flat floor, three spacecraft simulators and a position determination subsystem (PDS) using a CCD camera. A reel mechanism can be installed on the spacecraft dynamics simulator.

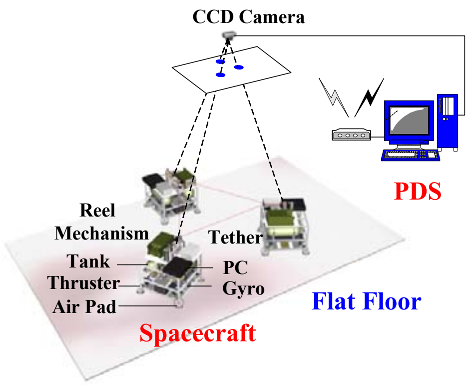


Fig. 6. Schematic Diagram of Experimental System

4.1 Spacecraft Dynamics Simulator

Fig.7 represents the spacecraft simulator. This simulator is floated on the flat floor by air-bearings using air pads to simulate 2-D micro-gravity motion. The simulator has eight thrusters to control position and attitude. It has no wheels for attitude control. The attitude is controlled using thrusters. Air tanks on the simulator supply air for thrusters and air-bearings. Attitude of the simulator is measured by an on-board gyro, and position is acquired from the position determination subsystem via wireless LAN. In other words, this simulator has no cabling for any communication or air supplying to achieve complete 2-D micro-gravity environment. Fig.8 represents the system configuration of the simulator. Each spacecraft simulator has a laptop PC to acquire various sensor data from the gyro and the reel mechanism, to communicate with the PDS and to control devices. Table 1 shows specifications of the simulator. The laptop PC controls the thrusters and the reel mechanism at intervals of 60 msec.

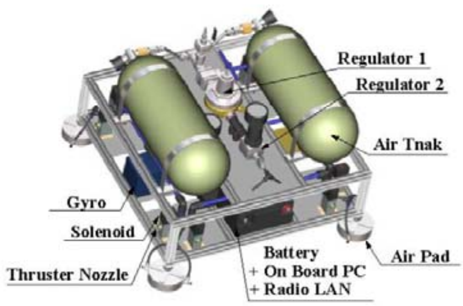


Fig. 7. Spacecraft Simulator

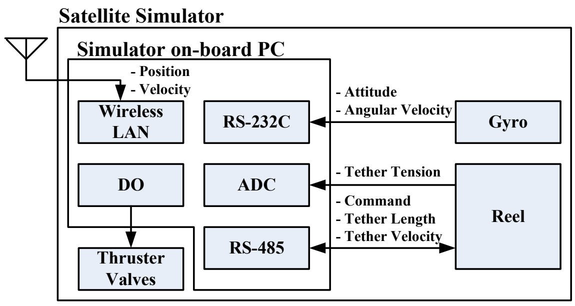


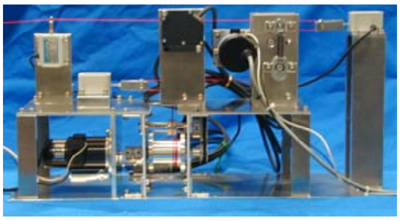
Fig. 8. Spacecraft Simulator System

Table 1. Specifications of Spacecraft Simulator

Size	0.6*0.6*0.69 [m]
Wight	42 [kg]
Moment of Inertia	2.3 [kgm^2]
Pressur in Air Tank	150 [kgf/cm^2]
Volume of Air Tnak	8.6 [l]
Control Cycle	60 [ms]
Communication Rate	10.0 [Mbps]

4.2 Reel Mechanism

The reel mechanism is used for tether tension control. Functions of the reel mechanism include reel in/out, tension control, measurement of tether length. Fig. 9 shows the reel mechanism and its system. The mechanism has two DC motors to control inner and outer tether tension. Inner tension is controlled to be more than 0 N to prevent the tether from being untied state. Tether length is measured by encoder of the Motor A. The mechanism also has a level winder to reel in/out tether equally on a rotating spool. Each motor has a motor driver, which consists of a DC motor driver circuit, MPU and a RS-485 Interface circuit. The reel mechanism communicates with the spacecraft simulator using the RS-485 serial communication line. MPU controls motors at intervals of 2 msec.



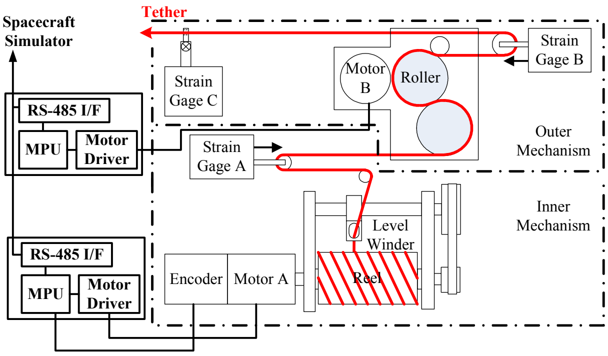


Fig. 9. Reel Mechanism System

4.3 Control System

Fig. 10 represents a control system block diagram of the spacecraft simulator and the reel mechanism for the ground experiment. In this experiment, the virtual structure dynamics is computed offline, and distributed to each simulator. Since the simulator does not have wheels to control its attitude as we mentioned in the explanation on the spacecraft simulator, the simulator uses thrusters to control its attitude. Therefore, position control and attitude control are switched every control cycle.

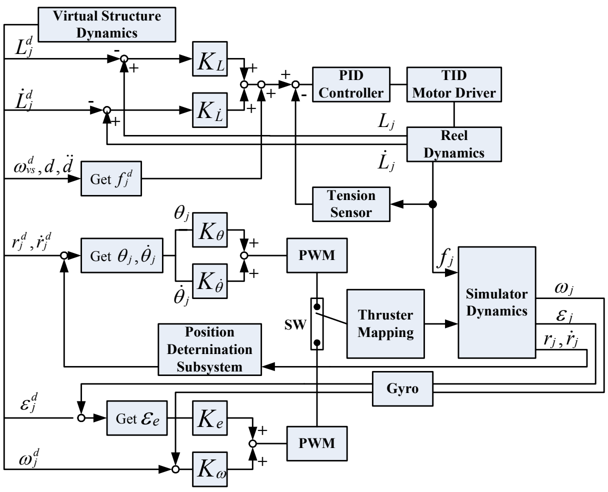


Fig. 10. Control System Block Diagram of Ground Experimental System

5. EXPERIMENTAL DEMONSTRATION

5.1 Results of the experiment

We conducted the experimental demonstration with the condition shown in Table 2. Fig.11 shows time series images of the experiment. Trajectories of each spacecraft simulator are indicated in Fig.12(a). A trajectory of the center of mass is also shown in the figure. The motion of the c.m. was occurred during the formation deployment because the formation control, as shown in Eqn. 1, applied to the system did not have a function to adjust the c.m.. We expect that a slight slope of the flat floor caused the motion of the c.m. Fig.12(b) shows trajectories of each spacecraft simulator looked from the c.m., where the solid lines indicate trajectories of simulators and dotted lines indicate desired trajectories acquired from the virtual structure motion. From this figure the formation was deployed as planned.

Table 2. Experimental Condition

Initial Radius r_s	**0.6 m**
Final Radius r_e	**0.9 m**
Initial Angular Velocity ω_s	**0.18 rad/s**
Final Angular Velocity ω_e	**0.18 rad/s**
Deployment Duration t_{dep}	**10 sec**

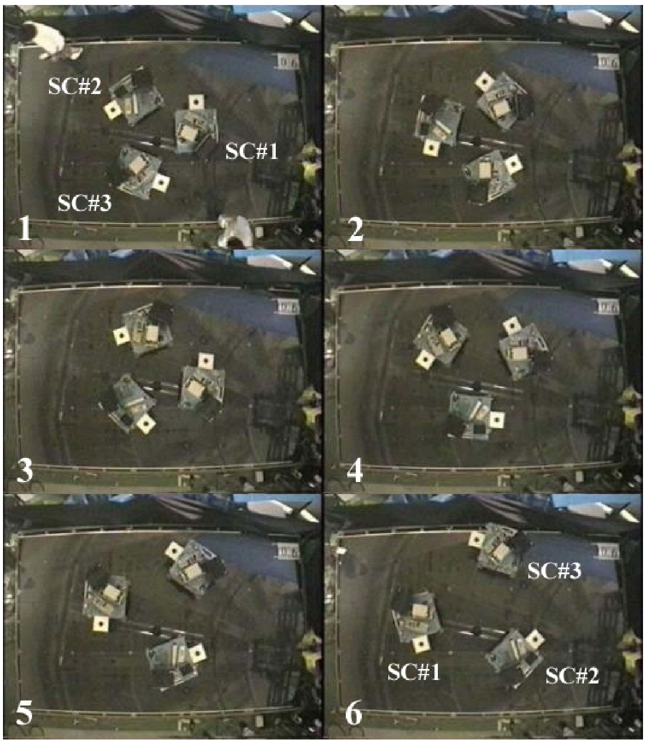
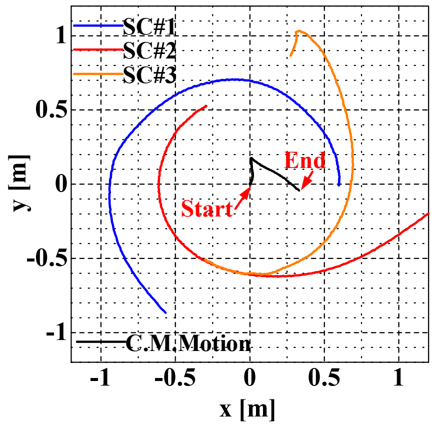
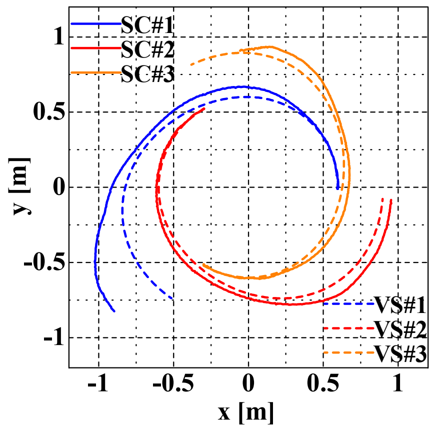


Fig. 11. Ground Experiment of Formation Deployment



(a) Inertia Coordinate



(b) {v} Coordinate

Fig. 12. Trajectory of Spacecraft Simulator

Fig.13 shows the attitude of the simulators during the experiment. It is clear that all simulators surely followed the attitude commands from the virtual structure. Fig.14 indicates the tether tension, and Fig.15 shows the tether length of the simulator #2. The dotted lines in the figures indicate command values of the tether tension and length. In both figures, the values after 20 sec. decrease rapidly. The reason is that simulator #3 was caught in a edge of the flat floor (Fig.11 No.6) and the tether length between simulator #2 and #3 is shorter than its command. From Eqn. 3, tether tension command then decreased as shown in Fig.14 These figures show that the reel mechanism worked adequately.

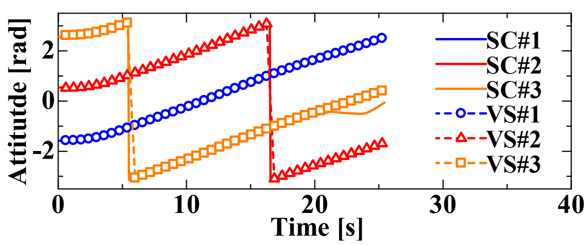


Fig. 13. Attitude of Spacecraft Simulator

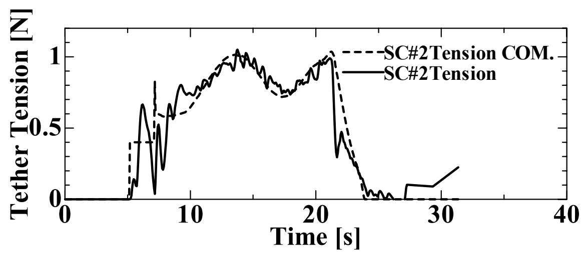


Fig. 14. Tether Tension of Simulator #2

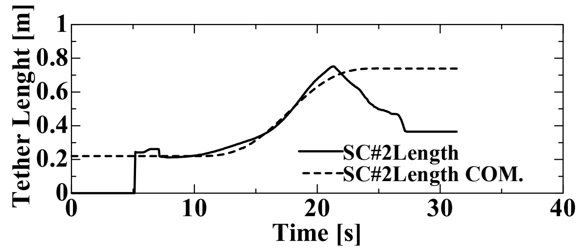


Fig. 15. Tether Length of Simulator #2

5.2 Discussion on Improvements for the Experimental System

From the experimental demonstration, it becomes clear that the ground experimental system has capability to conduct and evaluate the experiment on formation deployment of the tethered formation flying. However the experimental system is not complete. The following points must be improved.

Control Gain Tuning

Fig.12(b) and Fig.13 indicate the displacement between real and desired values. These phenomena caused by mistuning of controller gains concerned with the reel mechanism. In particular, it is experientially clear that tuning of K_L and $K_{\dot{L}}$ of Eqn. 3 is extremely important. Therefore, we must tune the gains to conduct the precise experiment.

Thsuter Control

Tether zero tension condition that occurs when distance between spacecraft simulators is too shorter than the desired distance as shown in Fig.14 and 15 must be escaped because formation is uncontrollable in the condition. Appropriate thruster use is considered to avoid the condition. Therefore the functions for avoiding the zero tension condition as well as controlling the position of c.m. must be included in the thruster control.

6. CONCLUSION

In this paper, the ground experimental system, that is needed to experimentally study the tethered formation flying, and experimental demonstration for the formation deployment are explained. The experimental system consists of the 3m*5m flat floor, three spacecraft dynamics simulators and the position determination subsystem. The reel mechanism that is able to control tether tension can be installed on the spacecraft dynamics simulator. Reference commands for spacecraft simulators and tether reel mechanisms are derived using the virtual structure approach, which is one of various strategies and approaches for conventional multi-spacecraft formation control. From the experimental demonstration, it is clear that the ground experimental system constructed here has capability to acquire various data and sufficiently evaluate the experiment on formation deployment of the tethered formation flying. The improvements to be made in the experimental system are also discussed.

Acknowledgments

We are grateful to Mr. Kuniyuki Omagari, Mr. Hideyuki Yabe and Mr. Shinji Masumoto of Tokyo Institute of Technology for giving us valuable advice. On numerous occasions they helped operations for the ground experiments.

References

1. Mori, O., Matunaga, S., Coordinated Control of Tethered Satellite Cluster Systems, AIAA Guidance, Navigation, and Control Conference and Exhibit, AIAA 2001-4392, Montreal, Aug.6-9, 2001.

2. Quadrelli, M., Modeling and Dynamics Analysis of Tethered Formations for Space Interferometry, AAS/AIAA Spaceflight Mechanics Meeting, Santa Barbara, CA, February 11-14, 2001.

3. Kim, M. and Hall, C. D., Control of a Rotating Variable-Length Tethered System, 13th AAS/AIAA Space Flight Mechanics Meeting, Ponce, Puerto Rico, February 9-13, 2003.

4. Matunaga, S., Mori, O., Nakaya, K., Iai, M., Omagari, K and Yabe, H., et al. New Spinning Deployment Method of Large Thin Membranes with Tether Control, 54th Congress of the International Astronautical Federation, Bremen, Germany, Sep.29-Oct.3, 2003, IAF-03-A.4.01.

5. Nakaya, K., Iai, M., Omagari, K., Yabe, H. and Matunaga, S., Formation Deployment Control for Spinning Tethered Formation Flying -Simulations and Ground Experiments-, AIAA Guidance, Navigation, and Control Conference and Exhibit, AIAA 2004-4896, Providence, Aug.16-19, 2004.

6. Beard, R. W. and Hadaegh, F. Y., A Coordination Architecture for Spacecraft Formation Control, *IEEE Transactions on control systems technology*, Vol. 9, No. 6, 2001, pp.777-790.

7. Ren, W. and Beard, R. W., Virtual Structure based Spacecraft Formation Control with Formation Feedback, AIAA Guidance, Navigation, and Control Conference and Exhibit, AIAA 2002-4963, Monterey, CA, August 2002.