REMOTE CONTROL OF TARGET IN SPACE USING MAGNETIC FORCE

Masaki Nagai * **Shinichi Nakasuka** *

* Department of Aeronautics and Astronautics, University of Tokyo, Japan

Abstract: Recently, Formation Flying of satellites has been recognized as an important future on-orbit technology. It has much potential such as leading to flexibility of space mission, low cost, etc. However, conventional thrusters consume propellant fuel, which leads to high cost, high weight and restricted mission life-time. Consequently, magnetic force, which doesn't consume fuel, is widely focused to control relative position of satellites. Magnetic systems for big satellites are researched in some institutes. This paper explored that of small satellites. Particularly, it focuses on control methods for a small observation satellite which controls an optic lens remotely with electromagnet.

Keywords: Space, Magnetic fields, Remote control, Target control, Satellite, Simulation, Permanent magnet, Electromagnetic

1. INTRODUCTION

1.1 Background

Recently, Formation Flying with multiple satellites (FF) is recognized as an important technology for space missions. FF has many benefits such as realizing unlimited aperture size for sparse aperture sensing, flexibility of space mission, tolerance against single satellite failure, easier system upgrade, etc. Usage of micro or small satellites as elements of FF has such another benefit as to make it possible to implement or test the latest space technology, parts or equipment with a short preparation time.

However, the main problem of FF is its fuel consumption for maintaining or transforming the formation. It is the major cause of high cost, huge weight and restricted mission life-time of FF.

Thus, magnetic systems, which don't consume fuel, are researched as an alternative to the thruster system in these days to keep or control the formation of satellites. The merits of magnetic systems are as follows.

Renewable Fuel Source Electromagnets never consume propellant fuel. They use renewable electric power.

No Contamination Magnetic systems don't emit propellant plume which may contaminate optics or other spacecrafts nearby.

No Mechanism Electromagnets do not need movable parts which occur vibration and limit life time.

1.2 Previous Works

Strong magnetic systems such as super-conductive electromagnets or large coreless electromagnets for large satellites are researched at Massachusetts Institute of Technology (Sedwick *et al.*, 2002) (Miller *et al.*, 2002)(Kong, 2002) and Institute of Space and Astronautical Science of Japan (ISAS) (Ninomiya *et al.*, 2001), etc. Two examples are shown below.

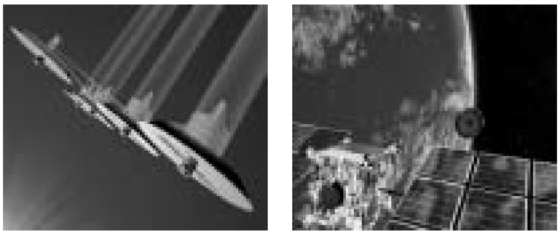

Fig. 1. TPF(Left)、XEUS(Right)

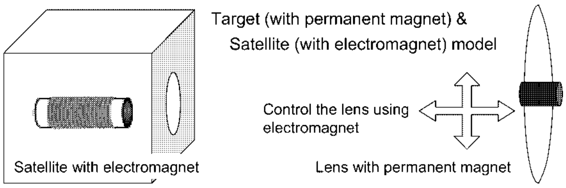

Fig. 2. An image of Target and Satellite model

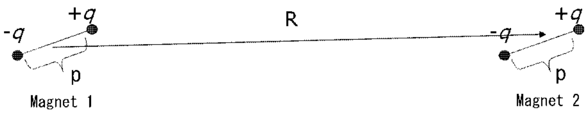

Fig. 3. Magnetic Dipole Modeling

Terrestrial Planet Finder (TPF) TPF will invest into planetary systems as far as 50 light years. It can take 100 times more detailed pictures than those of Hubble Space Telescope. The formation consists of 5 satellites that each carries interferometer. Magnetic force is studied whether it can be used to maintain the shape of the formation.

X-Ray Evolving Universe Spectrometer (XEUS) This is ESA's X-Ray Spectroscopy Mission. XEUS consists of 2 satellites at 50 meter distance and has to be controlled to an accuracy of 2mm. Electromagnetic systems are under study now at ISAS.

1.3 Objective

Large magnetic systems for large satellites over several hundred kg are well studied in these 2 projects above. The distances between satellites in these cases are as long as 50m or so. Thereby, these satellites have to carry very strong magnetic systems such as super-conductive electromagnets or large coreless electromagnets.

On the other hand, considering that small satellites are the key technologies of the future, this paper studied about control methods for small observation satellites (few kg) that control a remote lens at the distance of 1m using magnetic force. This kind of configuration which consists of satellite itself and a remote target to be controlled (e.g., optical lens) is the most likely one as magnetic control system installed in small satellites. (See Fig. 2)

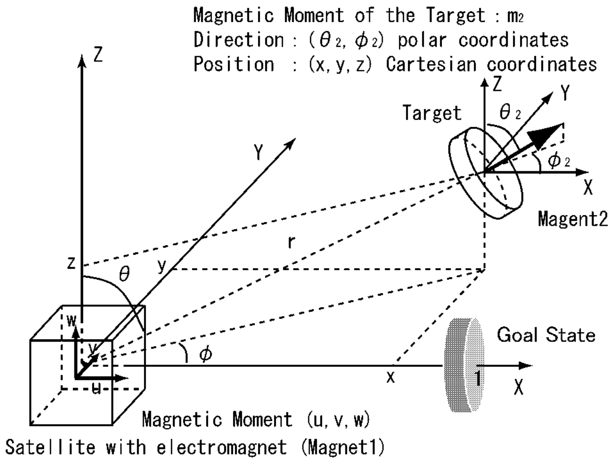

Fig. 4. Lens control model

2. MODELING AND THEORY

2.1 Magnetic Dipole Modeling

The force and torque generated by two magnets at a distance of $\boldsymbol{R}_{1\to2}(\gg \boldsymbol{p}_n)$, are known as "a far-field operation", with which each magnet can be modeled as an ideal dipole. ($\boldsymbol{p}_n$ is the length of each magnet. See Fig. 3)

This modeling makes it possible to calculate the force and torque on magnets arithmetically. Assuming $\boldsymbol{p}_n$ as very small, the translational force on magnet 2 is given as:

$$\begin{aligned}\boldsymbol{F}_{1\to2} &= q_2(\boldsymbol{B}_1(\boldsymbol{R}_{1\to2} + \frac{\boldsymbol{p}_2}{2}) - \boldsymbol{B}_1(\boldsymbol{R}_{1\to2} - \frac{\boldsymbol{p}_2}{2})) \\ &\simeq q_2(\boldsymbol{p}_2 \cdot \nabla)\boldsymbol{B}_1(\boldsymbol{R}_{1\to2}) \\ &= (\boldsymbol{m}_2 \cdot \nabla)\boldsymbol{B}_1(\boldsymbol{R}_{1\to2}) \qquad (1)\end{aligned}$$

where $\boldsymbol{m}_1$, $\boldsymbol{m}_2$ are the magnetic moment of magnet 1 and 2 respectively, $\boldsymbol{R}_{1\to2}$ is the position vector of magnet 2 from magnet 1. $\boldsymbol{B}_1(\boldsymbol{r})$ is the magnetic field made by magnet 1 at the point of $\boldsymbol{r}$.

The torque on magnet 2 is given as:

$$\boldsymbol{T}_{1\to2} = \boldsymbol{m}_2 \times \boldsymbol{B}_1(\boldsymbol{R}_{1\to2}) \qquad (2)$$

2.2 Control Model

Figure 4 illustrates the model of a satellite with electromagnetic system and a target with permanent magnets. (u, v, w) indicates the magnetic moment of the electromagnet; these three elements are input parameters. (x, y, z) and (r, θ, ϕ) indicate the position of the target center. $\boldsymbol{m}_2$ is the magnetic moment vector of the permanent magnet on the target. θ_2, ϕ_2 indicate the attitude of the target. The goal state is $(x, y, z, \theta_2, \phi_2) = (1, 0, 0, \pi/2, 0)$. Linearization about $(\theta, \phi, \theta_2, \phi_2)$ around $(\pi/2, 0, \pi/2, 0)$ yields the simplified equations as:

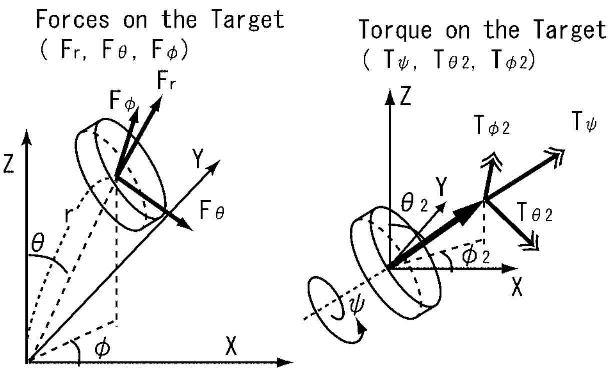

Fig. 5. Force and Torque on the Target

$$F_r = \frac{-3m_2\mu_0}{4\pi r^4}(2u + w(d\theta_2 - 3d\theta) + v(3d\phi - d\phi_2)) \tag{3}$$

$$F_\theta = \frac{-3m_2\mu_0}{4\pi r^4}(w + u(2d\theta - d\theta_2)) \tag{4}$$

$$F_\phi = \frac{3m_2\mu_0}{4\pi r^4}(v + u(-2d\phi - d\phi_2)) \tag{5}$$

$$T_\psi = 0 \tag{6}$$

$$T_{\theta_2} = \frac{m_2\mu_0}{4\pi r^3}(v + u(-3d\phi + 2d\phi_2)) \tag{7}$$

$$T_{\phi_2} = \frac{m_2\mu_0}{4\pi r^3}(w + u(3d\theta - 2d\theta_2)) \tag{8}$$

These equations include multiplicative term of states $(r, \theta, \theta_2, \phi, \phi_2)$ and input parameters (u, v, w). Therefore, straightforward control methods such as pole assignment, optimal regulator, cannot be applied simply. Of course, it could be possible to remove multicative terms by complete liniarization. But according to our study, complete liniarization has no potential to control the target.

3. CONTROL METHOD (WITHOUT EARTH MAGNETISM)

As one method to keep the relative position of a target, this paper proposes to connect satellite and the target with thin tether. (For simplicity, "Earth Magnetic Field" is abbreviated as "EM" in this paper)

With this tether, keeping u as a positive constant value and generating repulsive force on the target can make r (the distance between the satellite and the target) constant. Consequently, the system can be linearized with constant u, and linear control system design methods such as pole assignment method can be applied. In this system with constant u, the state quantities (θ, θ_2, w) and (ϕ, ϕ_2, v) are independent.

Suppose $\boldsymbol{\phi} = (\phi \quad \phi_2 \quad \dot{\phi} \quad \dot{\phi}_2)^T$ is stare variables, the equation of motion will be given as;

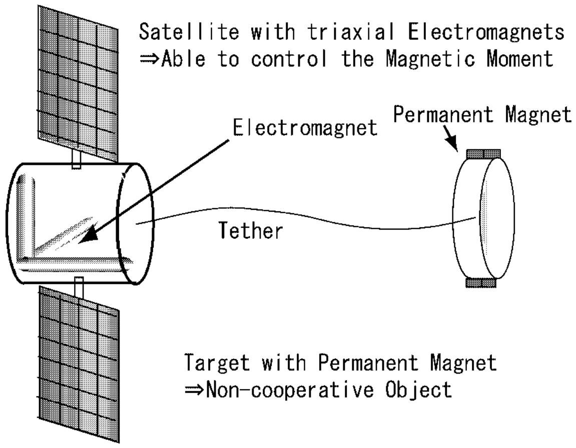

Fig. 6. The Consept of Small Earth Imaging Satellite with Magnet Control System

$$\dot{\boldsymbol{\phi}} = A\boldsymbol{\phi} + Bv \tag{9}$$

$$A = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{1}{m}\frac{3um_2\mu_0}{4\pi r_0{}^5}(-2) & \frac{1}{m}\frac{3um_2\mu_0}{4\pi r_0{}^5} & 0 & 0 \\ \frac{1}{I_T}\frac{um_2\mu_0}{4\pi r_0{}^3}3 & \frac{1}{I}\frac{um_2\mu_0}{4\pi r_0{}^3}(-2) & 0 & 0 \end{pmatrix} \tag{10}$$

$$B = \begin{pmatrix} 0 \\ 0 \\ \frac{1}{m}\frac{3m_2\mu_0}{4\pi r_0{}^5} \\ \frac{1}{I_T}\frac{-m_2\mu_0}{4\pi r_0{}^3} \end{pmatrix} \tag{11}$$

According to the other analysis, this system has controllability. Similarly, the system (θ, θ_2, w) also has controllability.

3.1 Numerical Example

This section shows the results of simulation of 20cm class pico-satellite controlling the target lens 1m away without any disturbance, measurements errors nor EM. This simulation is based on the full non-linier dynamics with magnetic dipole modeling and far-field operation. (Equation (1) and (2)) The specifications below are from (Kanairo, 2003), which is possible in standard small satellites.

- $|u|, |v|, |w| < 115\ Am^2$: Limits of control inputs
- $M = 1.92\ kg$: The mass of the target
- $u = -115\ Am^2$: The x-coordinate value of the magnetic moment of a satellite
- $m_2 = 40\ Am^2$: The magnetic moment of the permanent magnet of the target
- $\mu_0 = 4\pi \times 10^{-7}\ H/m$: Magnetic permeability of vacuum
- $I_T = 0.02348\ kg\ m^2$: Moment of inertia about the axis of symmetry of the target
- $r_0 = 1\ m$: Relative distance between the satellite and the target

Figure 7 shows the time history of state variables: $y, z, \theta_2, \phi_2, v, w$. The poles are designed as $(-0.20 \pm 0.014i, -0.019 \pm 0.005i)$. The usage of tether and

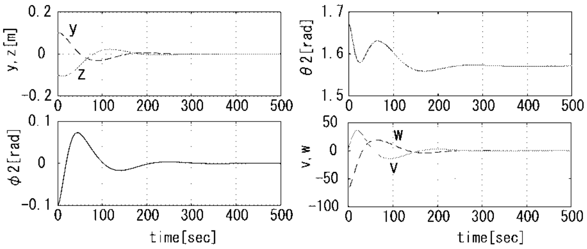

Fig. 7. The time history of $y, z, \theta_2, \phi_2, v, w$

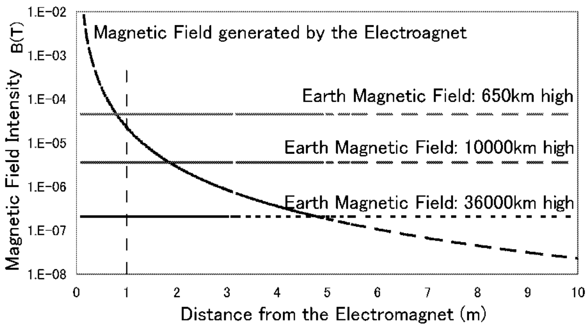

Fig. 8. The strength of electromagnet and EM

pole assignment method can stabilize the target position and attitude.

4. CONTROL METHOD (UNDER THE EXISTENCE OF EM)

4.1 The Strength of EM and the electromagnet of MotherSat.

Figure 8 shows the strength of electromagnet, which is designed in (Kanairo, 2003), and the EM.

As you can see in Fig.8, at the altitude of 650km, the EM overwhelms the magnet field of the electromagnet at the distance of 1m from satellite. It is impossible to maintain the attitude of the target against the effect of EM. A completely new way to control the target against the effect of EM is needed.

4.2 Multidimensional Magnetic Moment

This section introduces a new concept which is called "Multidimensional Magnetic Moment". For simplicity, "Magnetic Moment" is abbreviated as "MM". With this concept, Magnetic Charges is defined as 0-Dimensional (0-D) MM, Magnetic Dipoles as 1-D MM. Multidimensional MM is a concept extension of these 0-D and 1-D MM.

1-D MM consists of positive and negative 0-D MMs which are located adjacent to each other. Likewise n-D MM is defined as a combination of positive and negative (n-1)-D MM located nearly. (See Fig. 9)

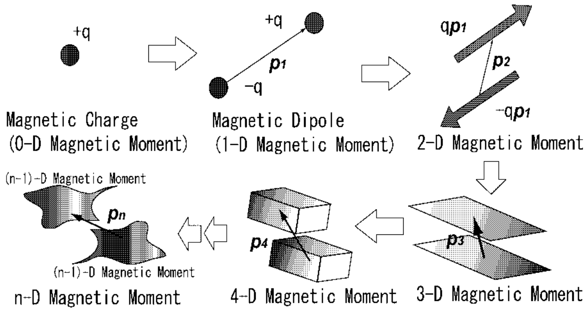

Fig. 9. The image of multidimensional MM

With the assumption that $|p_i| \ll |\boldsymbol{r}|$, magnetic field generated by m-D MM, the force and torque on n-D MM are given as:

$$B_m(r) = (-1)^m \frac{\mu q}{4\pi}(p_1 \cdot \nabla)(p_2 \cdot \nabla)(p_3 \cdot \nabla)\cdots(p_m \cdot \nabla)\frac{r}{r^3} \quad (12)$$

$$F_n(r) = q(p_1 \cdot \nabla)(p_2 \cdot \nabla)(p_3 \cdot \nabla)\cdots(p_n \cdot \nabla)B_m(r) \quad (13)$$

$$N_n(r) = \sum_{i=1}^{n} q(p_1 \cdot \nabla)\cdots(p_{i-1} \cdot \nabla)(p_{i+1} \cdot \nabla)\cdots(p_n \cdot \nabla)(p_i \times B_m(r)) \quad (14)$$

These formulae prove that n-D MM ($n \geq 2$) is not subject to the EM in two assumptions: 1) EM as locally uniform magnetic field and 2) EM as gigantic magnetic dipole.

<u>EM as uniform magnetic field</u> With the assumption that $\boldsymbol{B}(\boldsymbol{r})$ is a constant vector field $\boldsymbol{B}$, equation (13) yields $\boldsymbol{F}_n(\boldsymbol{r}) = 0$ when $n \geq 1$, equation (14) yields $\boldsymbol{N}_n(\boldsymbol{r}) = 0$ when $n \geq 2$.
Therefore n-D MM ($n \geq 2$) won't be affected by EM at all.

<u>EM as gigantic magnetic dipole</u> EM is in a sense a gigantic magnetic dipole, or 1-D MM, in a large scale. Table 1 shows the properties of force and torque, generated by 1-D MM, on dipole (1-D MM) and m-D MM.

Table 1. Force and torque on dipole and m-D MM

	dipole (1-D)	m-D MM
dipole	$F \propto p^2/r^4$	$F \propto p^{m+1}/r^{m+3}$
	$N \propto p^2/r^3$	$N \propto p^{m+1}/r^{m+2}$

The influences of EM and a typical magnetic field generated by small satellite are numerically compared in Table 2.

Table 2 shows that the influences of EM and electromagnet in case of $(p/r)^3$ are of the same order. (e.g., Torque on 1-D MM) On the other hand, influences of electromagnet in case of $(p/r)^n$ ($n \geq 4$) are far bigger than those of EM. (e.g., Force on 1-D MM, Force on 2-D MM, and Torque on 2-D MM)

Table 2. Calculated values of $q(p/r)^3, q(p/r)^4, q(p/r)^5$, which can be used to compare the influences of EM and an electromagnet)(The length of Target p=0.1)

q	height	$q(p/r)^3$	$q(p/r)^4$	$q(p/r)^5$
EM	650km	2.3E+00	3.3E-08	4.7E-16
7.9E23	10000km	1.9E-01	1.2E-09	7.5E-18
Am	36000km	1.1E-02	2.5E-11	6.0E-20
q	distence	$q(p/r)^3$	$q(p/r)^4$	$q(p/r)^5$
electro-	1 m	1.2E+00	1.2E-01	1.2E-02
magnet	2 m	1.4E-01	7.2E-03	3.6E-04
1150	3 m	4.3E-02	1.4E-03	4.7E-05
Am	5 m	9.2E-03	1.8E-04	3.7E-06
	10m	1.2E-03	1.2E-05	1.2E-07

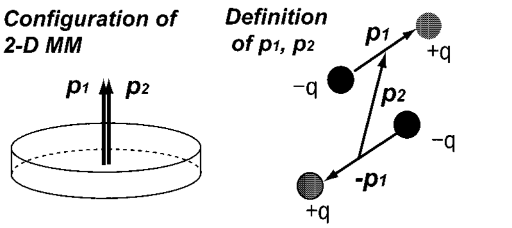

Fig. 10. The configuration of 2-D MM on the target lens

That is to say, 2-D MM is not influenced in both attitude and position from EM compared with the influence of nearby electromagnet. Therefore, mounting 2-D MM on the target instead of 1-D MM eliminates the influence of EM.

4.3 Control Method with 2-D MM

Control methods with 2-D MM on the target have been examined. (The electromagnet on the satellite is still dipole.)

2-D MM on the target As the result of another study, the configuration of 2-D MM on the target has been decided as in Fig.10.

Using this configuration, the force and the torque on the target can be written as below, using linearization about $(\theta, \phi, \theta_2, \phi_2)$ like equations (3) - (8)

$$\boldsymbol{F} = \frac{3p_1p_2q\mu}{\pi r^5}(2u + 2v(2d\phi - d\phi_2) + 2w(d\theta_2 - 2d\theta), \quad w + u(3d\theta - 2d\theta_2), \quad -v + u(3d\phi - 2d\phi_2))^T \tag{15}$$

$$\boldsymbol{T} = \frac{3p_1p_2q\mu}{2\pi r^4}(0, \quad -v + u(4d\phi - 3d\phi_2), \quad -w + u(3d\theta_2 - 4d\theta))^T \tag{16}$$

Just like the control method of chapter 3, constant u makes it possible to control the target. A numerical simulation shows that 2-D MM is useful. (The result of the simulation is not included in this paper due to space limitaion.)

5. COMPARISON OF CONTROL METHODS

Following three methods were compared in the existence of disturbance and error. Method 1 is mentioned in chapter 3, Method 2 in chapter 4.3.

Method 1 Satellite: 1-D MM, Target: 1-D MM
Method 2 Satellite: 1-D MM, Target: 2-D MM
Method 3 Satellite: 2-D MM, Target: 2-D MM

5.1 Control force of each method

Force and torque that could be generated in each method are shown below:

Table 3. Comparison between influence and disturbance in each control method

	Force (N)	Disturbance(N)	torque (Nm)	torque of EM h=650km(Nm)
1	$1.38E{-3}$		$4.60E{-4}$	$9.0E{-4}$
2	$1.38E{-4}$	$6.0E{-8}$	$3.45E{-5}$	$2.7E{-6}$
3	$1.73E{-5}$		$6.90E{-6}$	$2.7E{-6}$

As mentioned above, method 1 cannot control a target under the existence of EM, because the torque from EM overwhelms the control torque.

Although method 2 and 3 can control the target under the existence of EM theoretically, disturbance comes from the 2-D MM alignment error. The position and orientation of two dipoles of 2-D MM usually has small errors. With this 2-D MM alignment error, the effect of EM cannot be eliminated completely. Therefore EM imposes tiny torque on 2-D MM, which you can see in table 3. This paper estimated the alignment error at 0.3%. Numerical simulation result confirmed that method 2 works but method 3 doesn't under the existence of EM.

5.2 Numerical Simulation without EM

This section shows the numerical simulation of each method without EM and method no.2 with EM. This takes into account disturbance and errors, which includes sensor noise, control error, solar radiation pressure and 2-D MM misalighnment. This simulation is also base on the full non-linier dynamics with magnetic dipole modeling and far-field operation as in Section 3.1.

The results of simulations are shown in Fig. 11 and 12. Convergence times and standard deviation of state variables are estimated as below.

As a result, Method 1 is effective without EM. Although Method 3 costs convergent time and control power, the control accuracy is better.

Under the condition with EM, only method 2 works. But the standard deviations are worse than that without EM.

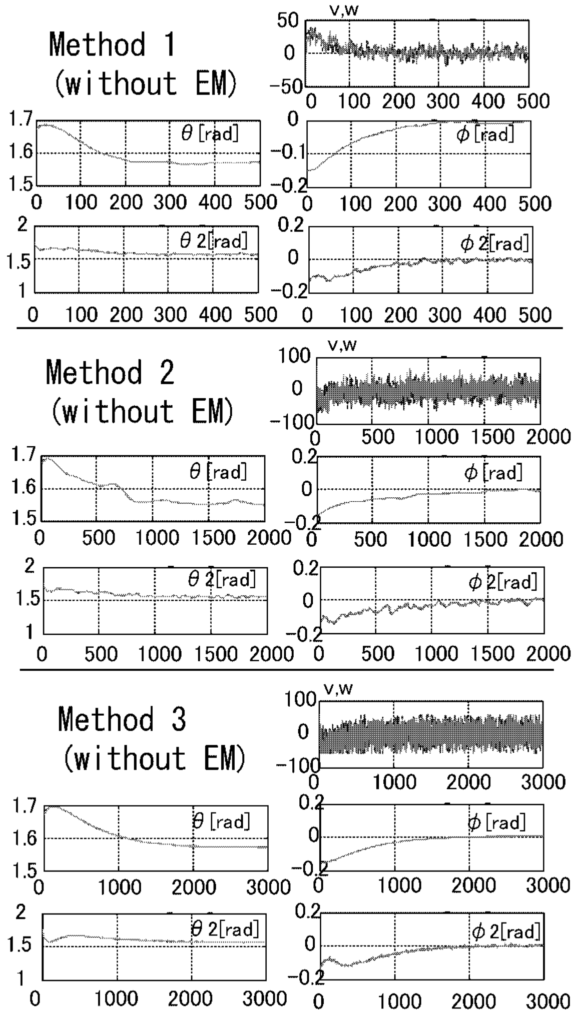

Fig. 11. Simulation of 3 methods without EM

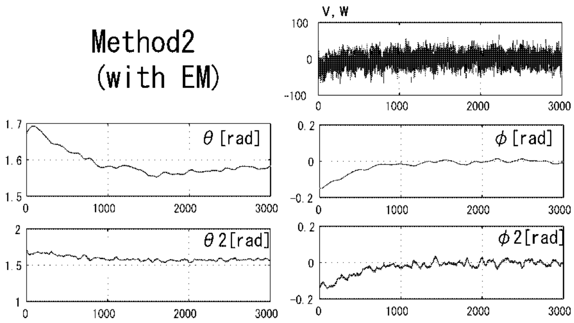

Fig. 12. Simulation of method No.2 with EM

Table 4. convergence time and standard deviation of state variables of each method

	converg-ence time	θ (rad)	ϕ (rad)	θ_2 (rad)	ϕ_2 (rad)
1	300s	0.0088	0.0088	0.0119	0.0117
2	1300s	0.0121	0.0131	0.0153	0.0152
3	2000s	0.0005	0.0016	0.0028	0.0028
2(EM)	1500s	0.0357	0.0371	0.0361	0.0381

6. CONCLUSION

Conclusion about control methods is as below;

without EM using 1-D MM and tether makes it possible to control the target.

with EM mounting 2-D MM instead of 1-D MM on a target makes it possible to control the target.

These 3 methods works even when disturbance and error exists (excluding EM). Only method 2 works under the existence of EM and alignment error. Besides, the accuracy of state variables meets the desired accuracy for PRISM satellite. (Eishima *et al.*, 2003) PRISM satellite is small observation satellite developed at University of Tokyo. PRISM uses a lens 1m away for observation and the desired positioning accuracy of the lens is 3.0 deg for θ_2, ϕ_2, 5mm for r.

This magnetic system is promising for remote-control of a nearby target with enough accuracy, even in the presence of Earth Magnetic Field.

7. ACKNOWLEDGMENT

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