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Experimental verification of the position and attitude control law between two objects using multiple coils

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Abstract

The target of this research is a relative position and attitude control method of re-configurable space structure without reaction wheels (RW) but using magnetic force with multi-dipole system. This technology can be widely applied to docking phase of such space structures that can architect large structure, such like SSPS for example, which restructuring themselves by assembling basic structural units. Such docking technology can be one of the key technologies as "autonomous rendezvous and docking" which is advocated in NASA's strategic plan. One remarkable benefit of this system is that this doesn't limit mission term because it never requires any types of fuel, while the RW needs thruster to release the accumulated angular momentum. Using Thruster means that this system needs fuel and limits the life of the system due to this point. Another benefit is that the torque generated from the magnetic moment can control position and attitude at a time and it can realize independent control on each axis including rotation. Therefore authors have focused on current control of dipoles which produce strong nonlinear magnetic forces and proposed a way of control to the strong nonlinear electromagnetic system Feasibility of this method and controllability had been investigated, then the series of position and attitude control simulation in 3D which enables a relative position and attitude control by using only magnetic force with multi-dipole system were shown in our previous study. Here in this paper, experimental verification of our control method are carried out to see if the magnet forces can works out the correction of position and attitude at a time as calculated manner, then good agreement of both are obtained and verified the efficiency of our proposing control law.

1. INTRODUCTION

In architecture of a large space structure field, one of the hopeful way is assembling some very simple and small units to function into one large structure. The point is that one unit can't function as a system but just simple and all have same structure. Then once these are assembled, they can function as a system. Further, this way of architect enables itself into having variety in function by transforming its configuration like **Figure 1**.[1]

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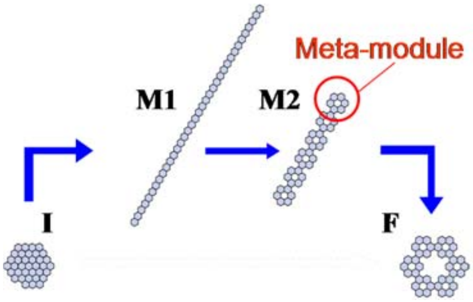

Figure 1. Hierarchical modular structure[1]

Many of such projects have been proposed and a large focal length space telescope is one of the example shown in **Figure 2**. This concept shows small segments are assembled into a large aperture telescope mirror. Then **Figure 3** shows a small project as a first step of realizing this large and innovative aperture telescope[2,3]. This project is proposed by Caltech and Surrey Univ. to make a small space telescope which can transform its configuration from a short focal length one (the middle figure in this picture) into a large focal length one by two 10cm square and 30cm height CubeSats. Each can move to the right-hand neighbor or left hand neighbor of the center CubeSat. Of course opposite transforming way is possible, too.

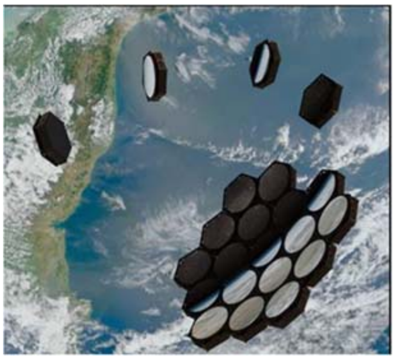

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Figure 2. Concept for constructing a large aperture telescope mirror from self-assembling segments

Figure 3. Autonomous assembly of a reconfigurable space telescope (AAReST)

Main project of this is of course a verification of a space telescope, but another aspect is verifying autonomous docking to change its structural configuration. This technology can be versatile for the docking of space structures and this is the point our research is focusing on. Then the electromagnetic devices have chosen as a hardware to realize this scenario. The reason of applying this system is commented later.

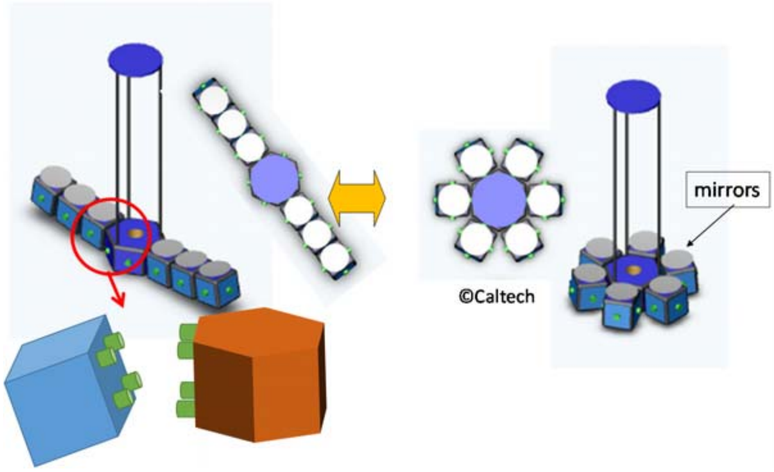


Figure 4. docking of daughter sat and parent sat by four dipole system

So the docking of one daughter sat and one parent sat is focused on because generality can be kept on a release and docking with any of two.
Four dipoles are installed on one satellite and two satellites are controlled by the generated pulling force and repulsive forces. Control forces are decided by current of each dipole.

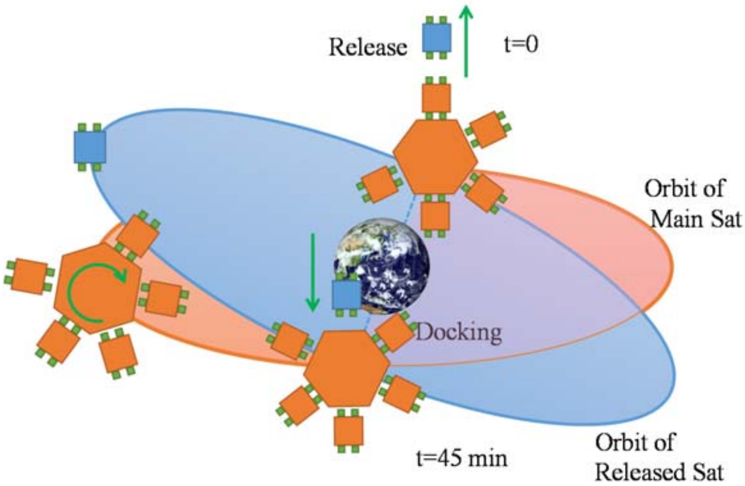


Figure 5. Orbit of satellites (ideal release)

Image of their behavior for docking on the orbit is like **Figure 5**. From macro view, once a daughter satellite is released, it will be back after 45 min. During this time, Parent sat (we call it as Sat2 here) rotates some degree to face Sat1's new docking surface.
But in actually, the disturbance by solar wind, drug, magnetic force from the earth etc… may affect its orbit, so the control for this is required when the two body is going to dock.

2. RESEARCH OBJECIVE

As far as docking by using light weight and simple structure, while there has been some researches to use electromagnetic force for controlling translation or attitude control between two bodies, there are almost no research to control translation and rotation at a time. If any, it is using RW for attitude control[4~14] which mean it needs thruster. In other words, it needs fuel so the term of satellite's operation is limited by this reason.

Then the use of some pairs of electromagnetic device to control attitude and translation at a time is suggested to realize no limit for operation life time[11]. The point of this proposal is multi electromagnet system can generate torque, so this can be used as actuation force for attitude control. Here we summarize the research objective as follows

- Suggestion of position and attitude control at a time by multiple electromagnetic dipoles only.

However already the hardware for this kind of docking had developed by SURREY University[16,17], their electromagnet system uses just constant current as far as it goes. This means their docking will cause collision and will much affect to its attitude as disturbance. So the difference of research point by authors is to solve this collision problem by proposing control technique, that is to say, realizing very soft docking and no collision.

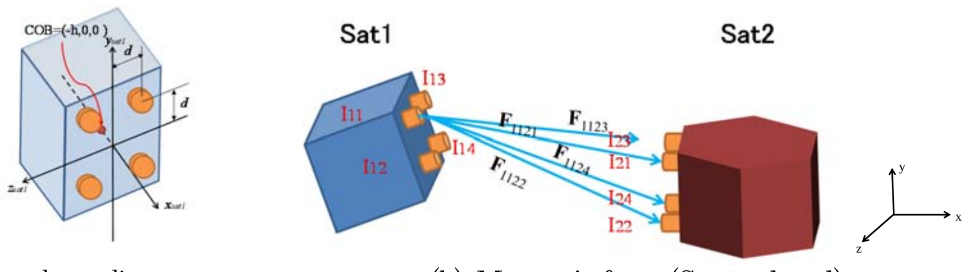
Authors have suggested and formulated the control law in planer system[11], and expanded it into 3D system to obtain six DOF control (position and attitude) independently. Then its verification by numerical calculation was also done[18].

As a series of the research, here in this paper reports the experiment verification about followings.

1. Sphere of electro-magnetic influence for docking
2. Identification of a hardware parameters (Stiffness of a coiled cable)
3. Position and attitude control by only electro-magnets

3. FORMULATION OF CONTROL BY ELECTROMAGNET

This chapter explains out view of our proposing control law. **Figure 6** shows the coordinate about two bodies. Magnetic force is generated between each coils, so the total number of the combination is 16 in this figure and the summation of them works as actuation.



(a) Local coordinate (b) Magnetic force (Sat1 related)

Figure 6. Coordinate and magnetic forces

Then, two assumptions are implemented to make the formulation of the magnetic forces as simple in a range of it doesn't lose generality.

Assumption 1)

(Attracting or repulsive force) $\propto$ (distance)$^{-2}$

Assumption 2)

Neglect the torque generated by the dipoles, but express it as the moment of arm.

Regarding with Assumption1, generally the magnetic force is inverse proportion to 4th order of distance エラー! 参照元が見つかりません。, but basic structure of force formulation is same. So the assumption doesn't lose its generality. As for Assumption 2, both the torque and the moment of arm have same structure, so this assumption keeps generality, too.

Non-linear state equation is expressed as Equation (1) ~ (3) by using previous assumption.

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{Bf} = h(\mathbf{X}) + g(\mathbf{X}, \mathbf{I}) \tag{1}$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{eye} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1} \end{bmatrix} \mathbf{f}(\mathbf{x}, \mathbf{I}) \tag{2}$$

Here, $\dot{\mathbf{X}} = [\mathbf{x}, \dot{\mathbf{x}}]^T$

$$\mathbf{f}_{1i} = \mathbf{F}_{1121} + \mathbf{F}_{1122} + \mathbf{F}_{1123} + \mathbf{F}_{1124} = \sum_{j=1}^{4} \frac{\mathbf{r}_{1i2j}}{\left|\mathbf{r}_{1i2j}\right|} \frac{\alpha I_{1i} I_{2j}}{\left|\mathbf{r}_{1i2j}\right|^2}; \quad i = 1, 2 \tag{3}$$

r shows relative displacement and the coil constant α is a function of permeability μ_i, turns of coil N_i, and projection area of dipole $\mathbf{A}_i$. Especially the term of the magnetic force is consisted of the square term of current, so independent 3DOF control in planer system needs four dipoles, and 6DOF in 3D system needs 7 dipoles. This is the feature of this control system.

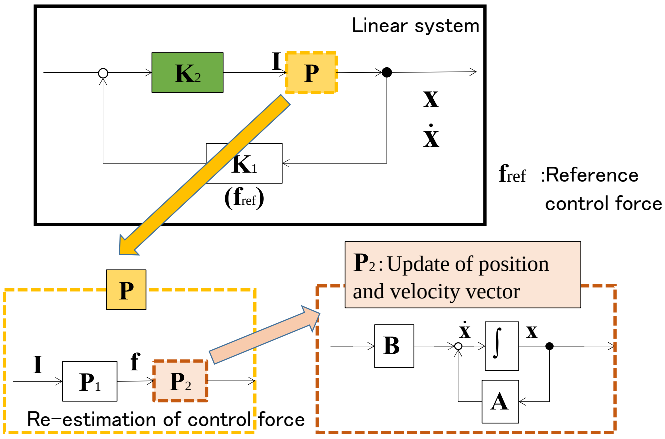


Figure 7. Linearization of electromagnetic control

Then **Figure 7** shows linearization scenario of the basically strong nonlinear system by electromagnetic forces. First, a reference force matrix $\mathbf{K}_1$ is obtained to realize moderate control without collision of linear system, just like critical damping system. Then decide current **I** which realize the previous reference force, and then calculate actual magnetic force ($\mathbf{P}_1$) then update the satellites positions vector ($\mathbf{P}_2$).

4. IDENTIFICATION EXPERIMENT

4.1. Experiment system

This chapter explains the experiment hardware and its results.

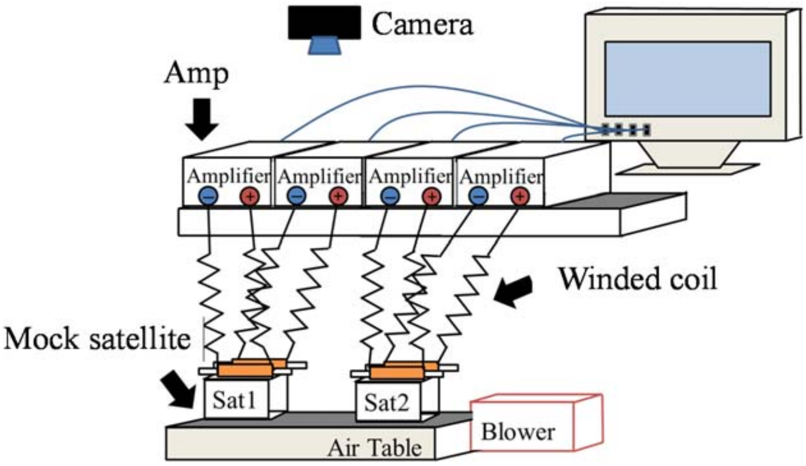


Figure 8. Experiment system

Figure 9. Dipole and winded cables

Figure 8 shows the out view of the experiment system. Two cube sat mock are put on the air table which can realize zero friction. Here Sat2 is fixed because the parent satellite usually has superior control system and it can be considered as fixed to the coordinate in actual operation. Two solenoids are installed on it as **Figure 9** (top), and each solenoid has 1500 turns with 1 [mm] diameter bronze coil. Core material is iron with 110 [mm] length with 10 [mm] diameter. PC calculates current data, and this is transferred to each solenoid through amplifier. Coils are connected to each amplifier by very soft winded cable like **Figure 9** (bottom) to reduce the influence of stiffness by this cable as much as possible.
Table 1 shows the mass property of each satellite mock and coil's property. Although mass is smaller than the actual satellite, authors adapted this just because of the measurement time to make the docking finish earlier. In actual operation in space, it is true that the position and attitude control will need more time but this is only due to the larger moment of inertia, and this has little affection to the scenario of the verification of the proposing control method, so the small mass is adapted this time.

Table 1. Mass property of each satellite and coil's property

Mass	0.657
Moment of inertia [kgm2]	1.0
Coil constant $\alpha = f(\mu_i, N_i, \mathbf{A}_i)$	0.0048
I_{max} [A]	2.0

4.2. Stiffness of a coiled cable

As explained in previous section, solenoid coils are lined to the amplifier by winded cable. However this coil is very soft, this have some amount of stiffness, so measurement of this stiffness is needed and then implement this value into the proposing control model. **Figure 10** shows that the simulation of the behavior of Sat 1, in which the appropriate stiffness value is implemented, matches well to the experiment. This experiment is carried out with two cases under constant current.

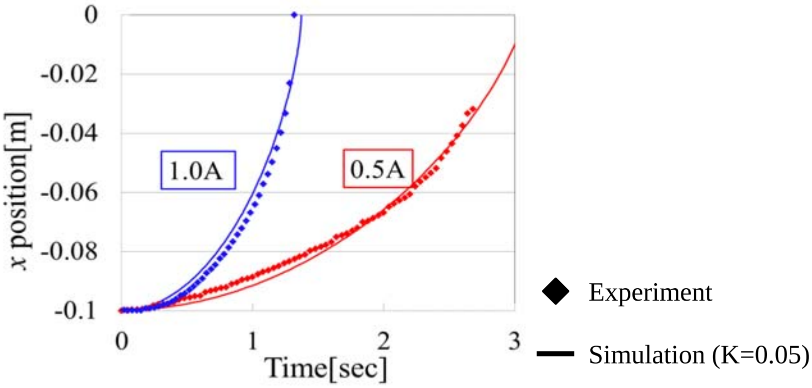


Figure 10. Decision of the stiffness of winded cable

From this results, K=0.05 gives the good agreement to both the 1.0 [A]model and 0.5[A] model, so this value is used in the following argument.

4.3. Sphere of electro-magnetic influence for docking

Then, the sphere of electro-magnetic influence for docking is investigated. Grey colored region in **Figure 11** is effectively electromagnetic force is working and successfully docked. Here, the case that pair dipoles docked by residual field but misaligned was defined as failure. This results shows electromagnetic force is useful within 0.25 [m] in maximum under 40 [W] energy. Further, it is obvious that as relative distance in initial state is larger, it allows larger angle modification however time for docking requires much more. This tendency is also obtained from simulation.

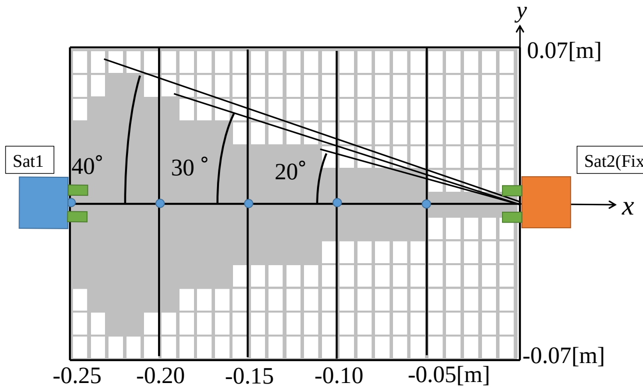
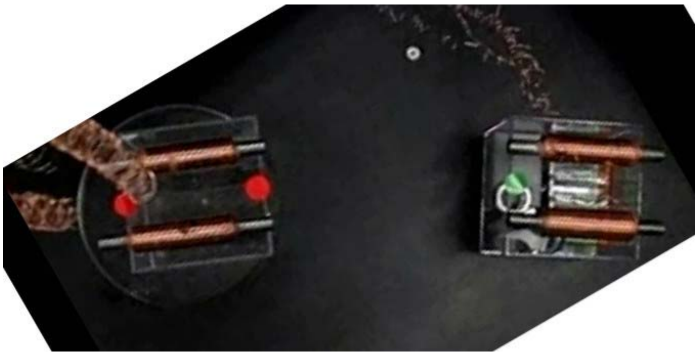


Figure 11. Sphere of electro-magnetic influence for docking

4.4. Control experiment

This section explains about control experiment. **Figure 12** and **Table 2** shows the initial state of experiment and each position is measured by the red or green marker on the mock satellite. Input current is the data derived from the proposed control law.



Left: Sat1 Right: Sat2

Figure 12. Experiment of electromagnetic force (Initial state)

Table 2. Initial state of Sat 1

x_1[m]	0.25
y_1[m]	0.10
θ_1[m]	0.10

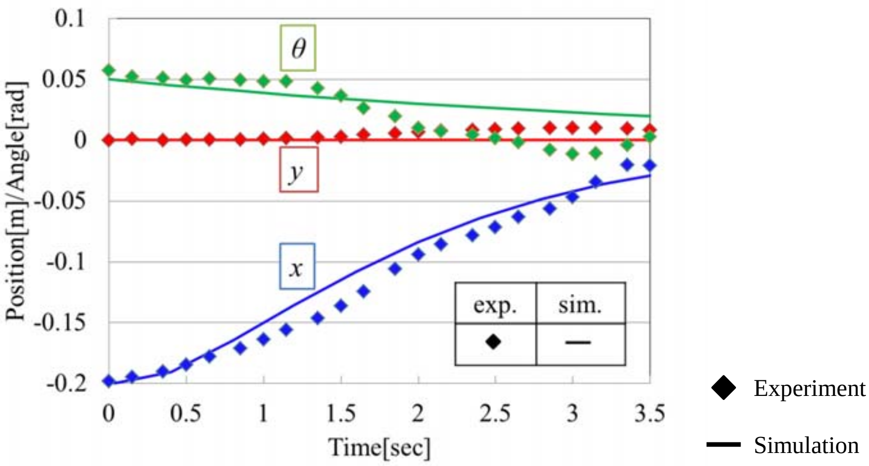


Figure 13. Result of controlling electromagnetic force

Figure 13 shows the time history of position/ angle by experiment and simulation. Although the problem of difficulty to set initial state or disturbance by air flow, generally good agreement is obtained. From this, controlled current can generate enough force to modify its attitude. The behavior of the satellite also shows this system produces reasonable actuation phase such like acceleration phase at the beginning of its behavior, and slowing down phase near the end of docking. These control scenario can be seen in both the simulation and experiment.

However this comparison has larger error in the end of the docking which is after 2.5 [sec] in this case. This shows the influence of residual field, as to say, the current amount is very small in this phase, so the control force is mostly dominant of residual field force. This influence continues until the collision. While treating this residual field is difficult in actual operation, this no collision control would be progressed if this influence of the residual field is implemented into the simulation model.

Still some problems are remained to be solved, the experiment verification of modifying position and attitude at a time by only the magnetic force is outstanding result.

5. DISCUSSIONS AND FUTURE WORKS

Here considers more reason about the difference between experiment and simulation. Of course the first assumptions affects largely to it, more possibility can be considered on coupling coefficient of inductance. This value means the percentage of magnetic flow which is moving from one solenoid to another one. This coefficient of an actual solenoid changes momentarily, so this parameter should be chosen appropriately time by time. This means more accomplished magnetic flux model is needed to better simulation and control, and then this will improve controllability.

Another difficulty in experiment is that the control in simulation is difficult in convergence when the relative displacement is very small. The reason of this can be considered that torque for attitude modification is expressed as (Magnetic force x arm), so the value of torque becomes smaller than the magnetic force in translation. This unbalance comes from the assumption 1 which mentioned in chapter 3. As actual expression of electromagnetic force in translation as it is inversely proportional to the 4^{th} order of relative displacement, with combination of correct expression of torque (reduction of assumption 2), would the incommensurable difference between force and torque smaller. So the reducing this assumption may bring better effect in control formulation.

Putting above all together, more brushed up model after reducing assumptions in chapter 3 and applying actual magnetic formulation would improve the proposing control method. Then introducing optimum method to minimize the influence of residual field by handling this proposal as an initial guess would be the next step for autonomous control technique. Here summarizes the future works.

- Reduce the assumptions and applying actual magnetic formulation
- Investigate optimum installing configuration
- Introduce optimization method to minimize the influence of residual field by handling this proposal as an initial guess.
- Development of test bed with less disturbance.

6. CONCLUSIONS

Experiment hardware to realize simultaneous control of position and attitude only by electromagnetic force was designed and set up which is consisted of 4 dipoles per each satellite. Then following phenomena became obvious.

- Parameters of experiment hardware is obtained and implemented into the simulation model.

- Sphere of electromagnetic control in effect was obtained. From the results, it becomes obvious that the far distance allows larger angle modification although time for docking requires much more.
- Proposing control method by only electromagnetic force enables the modification of displacement and attitude at a time, and good agreement with simulation is obtained on the behavior of a cube sat.

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