A06. Attitude and Orbit Control System of OMOTENASHI Spacecraft considering Power Constraints

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Abstract

OMOTENASHI spacecraft has very strict power constraints, both instantaneous power and battery capacity. Considering those constraints, an attitude and orbit control scheme during orbital maneuver was developed. That is, torque commands to the reaction wheels are limited during the propulsion heaters are used. When attitude error exceeds the threshold, the propulsion heaters are switched off and the torque command limit becomes nominal. If the battery voltage decreases below the limit, the orbital maneuver is suspended and attitude change to a sun point attitude is conducted autonomously. In this article, outline of the control scheme and some test results using a simulator are reported.

OMOTENASHI 探査機の消費電力制限を考慮した姿勢軌道制御系

概要

OMOTENASHI 探査機は、その瞬時電力およびバッテリー容量の双方の点で制約が厳しい。これらの制約を考慮した軌道変換中の姿勢軌道制御方式を開発した。すなわち、推進系のヒータを使用中はリアクションホイールの制御トルクを制限するが、姿勢誤差が閾値を超えた場合には推進系ヒータを停めて姿勢制御トルクをノミナル値に戻す。またバッテリー電圧が閾値以下になった場合には軌道制御を中断し、太陽指向姿勢に変更して充電を行う。本稿では、制御則の概要とシミュレータを用いた検証結果を報告する。

1. Introduction

NASA planned to launch thirteen secondary payloads on board Space Launch System (SLS) Artemis-1 (former name was EM-1) [1], with Orion Spaceship, on a non-interference no harm basis, to increase the scientific and exploration capability of the SLS. Each payload is a CubeSat class payload. OMOTENASHI which stands for Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor is one of those CubeSats. Its main mission is to demonstrate ultra-small technologies for moon landing [2][3]. Because CubeSats are relatively small and inexpensive, they will enable low cost and quick exploration. Therefore, those technologies will promote the participation of industry, academia, and even individuals in exploration.

To realize a lunar lander within 14 kg and 6U CubeSat size, some new technologies had to be developed. For example, the propulsion system by which whole 14 kg spacecraft can land on the moon surface could not be realized within 6U size. Therefore, minimization of the landing mass is essential, that is, the separation of the spacecraft in orbit before landing is needed. To cancel the orbital velocity of about 2500 m/s, a small solid rocket motor is used, considering its specific impulse and mass structure ratio. Since the thrust of a solid rocket motor can not be changed after manufacturing, a sophisticated trajectory design before the RM ignition and a precise orbit determination are needed to decide the ignition timing.

The short time development was another difficulty. The planned launch date was 2018 when OMOTENASHI was selected as the secondary payload of SLS EM-1 in 2016. About two-years development was required. Therefore, we used off-the-shelf instruments as much as possible. For the Attitude and Orbit Control System (AOCS) of OMOTENASHI, an attitude control unit called XACT and propulsion units called MiPS are used. Though those components were imported from U.S., we developed high-level control software running on an On Board Computer (OBC).

In the following sections, mission sequence, spacecraft configuration, functions of AOCS software, and its test results using the simulator are described, focusing on the orbital maneuver scheme.

2. Mission sequence

During launch, CubeSats are housed inside individual deployers which are attached in Orion Stage Adapter (OSA). Each CubeSat shall be powered off with three inhibits while ascending. After flying out from the deployer, OMOTENASHI spacecraft, which consists of Orbiting Module (OM), Rocket Motor (RM), and Surface Probe (SP), initiates attitude acquisition sequence, in order to make body-mounted solar cells face the sun. The orbital maneuver to put into lunar impact orbit (which is called DV1) will be performed by a cold gas jet propulsion system at about 24 hours from the launch. The amount of DV1 will be about 15 m/s.

Trajectory correction maneuver (TCM) might be performed if DV1 execution error is big.

After four or six days from the launch (it depends on launch date and trajectory), a-few-tens-minutes before the lunar impact, the spacecraft will start the landing preparation sequence, that is, the attitude change for deceleration (which is called DV2) and spinning up for the attitude stabilization during solid rocket motor firing. The deceleration of DV2 will be 2500 m/s. Soon after the ignition of the rocket motor, RM+SP is separated from OM. After DV2 is completed, SP lands on the moon surface. Though there is no proactive separation mechanism between SP and RM, SP might separate from RM by the impact shock on the surface. SP is designed to survive for six minutes at shortest on the surface. We will recognise that the landing is successful if the signal from SP continues after expected landing instance. Fig. 1 shows the outline of the mission sequence.

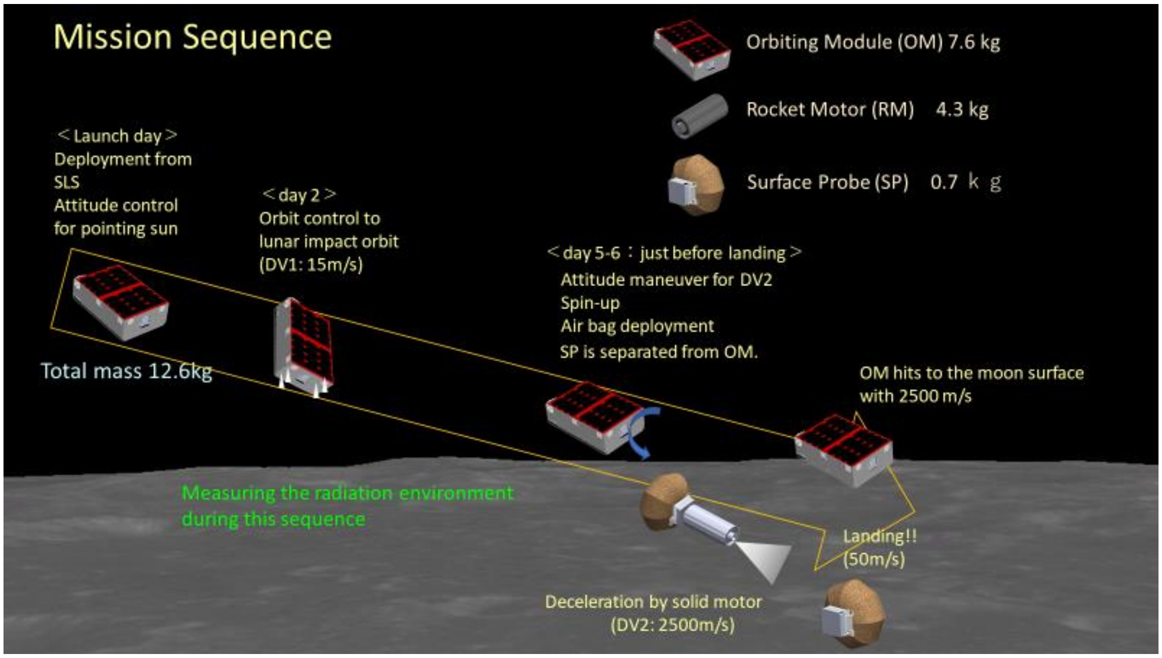


Fig.1 Mission sequence of OMOTENASHI

3. AOCS of OMOTENASHI

3.1 Spacecraft configuration

The external appearance and the perspective view of the spacecraft are shown in Fig. 2.

OM has solar cells on +Y surface, secondary batteries, a Power Control Unit (PCU), OBC, an Attitude Control Unit (XACT), two gas-jet propulsion units (MiPS), separation mechanisms, a communication system (COM) including antennas, etc. XACT which was manufactured by Blue Canyon Technologies has four Sun Aspect Sensors (SAS), a STar Tracker (STT), 3-axis Inertial Measurement Unit (IMU), three Reaction Wheels (RW), and a control processor. Each unit of MiPS which was manufactured by Vacco Industries has four thrusters, two axial and two tangential. Therefore, OMOTENASHI has total of eight thrusters as shown in Fig. 3. MiPS uses R-236fa liquefied gas as a propellant. Therefore, heater power is needed to vaporize the propellant and generate thrust.

RM consists of a motor case with solid propellant, nozzle, nozzle closure with optics for laser ignition, and separation guides from OM.

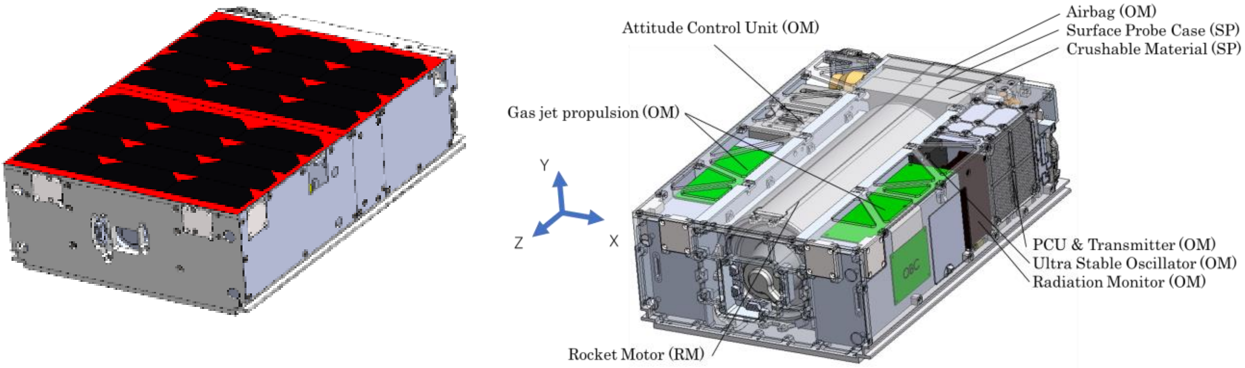
SP has shock absorption mechanisms to cope with 50 m/s impact velocity. We use a crushable material which is inserted between the SP instrument box and RM. The crushable material will reduce the shock acceleration within 8500G (1G=9.8m/s). To stand the high impact acceleration, SP instrument box is filled with epoxy.

3.2 AOCS functions

To realize the mission, the following AOCS functions are need [4].

1. Sun pointing attitude control

To keep power generation, +Y surface of the spacecraft should be faced the sun, except while orbital maneuver. This function has to be conducted without any commands from ground stations. XACT has autonomous sun acquisition and pointing function.



(a) External view (b) Perspective view

Fig. 2. CG model of the spacecraft

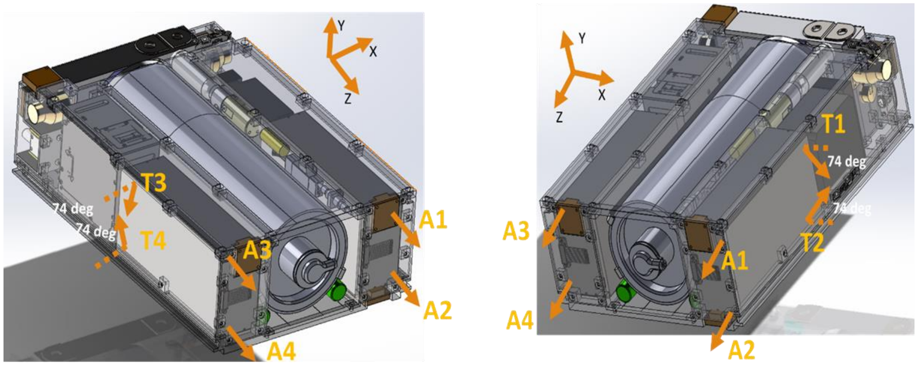


Fig. 3 Thruster allocation of MiPS

2. Three axis attitude control

During orbital maneuver, both DV1 and DV2, +Z axis of the spacecraft should be pointed to the designated direction. And in the nominal operation, the sun pointing is realized using three axis attitude control function, to optimize the attitude around the sun considering communication link and Earth and moon avoidance angle of STT. XACT has also three axis pointing function.

3. Angular momentum management

To keep the rotational speeds of RWs within allowable limits, angular momentum should be controlled. Because XACT is developed for earth orbiting satellites, it is designed to use Magnetic TorQuers (MTQ) for momentum management. However, outside Earth's magnetosphere, MTQ cannot be used. Therefore, we developed momentum management law using MiPS, which is realized by OBC software.

4. Orbital maneuver

To conduct DV1 or TCM, we have to control MiPS firing time, while keeping the proper attitude. The firing time and the attitude will be commanded to MiPS and XACT, respectively, based on the trajectory design on ground. However, because MiPS heater needs large electric power, charging is sometimes required during DV1. Therefore, we developed an autonomous control software running on OBC. The software is watching the battery voltage and if the voltage goes down to the threshold, it stops MiPS firing and change the attitude to point sun. After the battery voltage goes up to the upper threshold, the spacecraft changes its attitude for the orbital maneuver and restarts MiPS firing.

Since MiPS heater power uses most part of PCU supply capacity, the power consumption of RWs, that is, their control torques should be reduced during MiPS firing. On the other hand, torque limitation causes attitude error by MiPS thrust disturbance. Therefore, the software monitors attitude error and if it becomes larger than the threshold, it stops MiPS firing, switches off the heater, and cancels RW torque limitation.

This sophisticated software is the main topic of this article and we describe it in detail in the following sections.

5. Spin up for DV2 attitude stability

While the rocket motor firing, spin stabilization is required. Therefore, spinning up to 5 Hz (TBD) is needed. This function will be realized by the commands to MiPS, in an open loop manner.

AOCS control modes are summarized in Table 1 and its state transition diagram is shown in Fig. 4.

Table 1 AOCS control modes

	OBC control	MiPS	XACT				
			Control mode	RW	STT	SAS	IMU
Stand by	STNBY		N/A				
Rate dump	RateDump	use	Sun Point				use
Sun acquisition	NCNT		Sun Point	use		use	use
Three axis	NCNT		Fine Reference Point	use	use		use
RW unloading	UnLoad	use	Fine Reference Point	use	use		use
Orbit Maneuver	OMV	use	Fine Reference Point	use	use		use
Spin up/down	SPIN	use	Off				

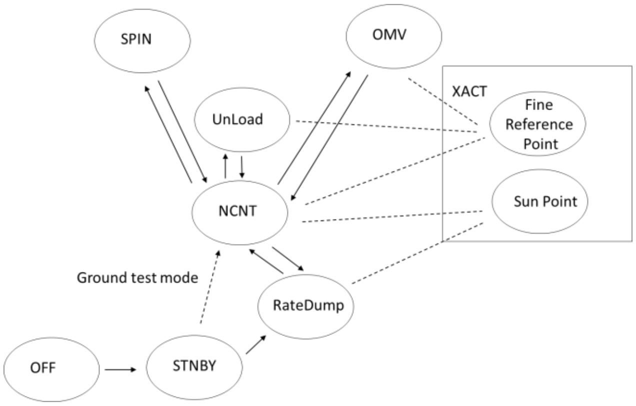


Fig. 4 AOCS state transition diagram

3.3. Constraints for AOCS

To realize functions described in section 3.2, there are some constraints.

1. XACT and MiPS are off-the-shelf commercial products. Though some project-specific parameters are adjusted, no modifications of functions or performances are allowed. OBC software should read telemetries from instruments and send commands to them. No additional interface exists.
2. PCU can provide limited power. The power consumption of RW full torquing and the heater power for MiPS firing are not compatible. Exclusive use is necessary.
3. Considering OBC computational power, only addition, subtraction, and comparisons can be used in AOCS algorithm. Therefore, we use XACT and MiPS functions as much as possible, that is, arrange types of variables to those of XACT and MiPS commands and telemetry (ex. uint8, uint32, int16, int32, float32) to avoid typecast and floating-point processing. Moreover, no proportional control but stepwise control (table lookup) is used.
4. AOCS algorithm is working with other OBC algorithms such as command and telemetry handling, time management, and FDIR functions. It is realized on ITRON-based real time OS.

3.4. Orbital maneuver algorithm

The orbital maneuver mode, which is used for DV1 and TCM, consists of six control phases as shown in Table 2. After AOCS_ATT_OMV command is received, the spacecraft changes its attitude to “intermediate attitude” in which Y axis faces sun and whose displacement angle with the orbital maneuver attitude is minimum (MNV1). Then goes to the orbital maneuver attitude (MNV2). While the battery voltage is higher than the threshold, A1 and A4 thrusters are fired (DV). However, if the angular momentum exceeds the upper limit, a couple of thrusters to compensate it are fired. (MOM_ADJUST). Since RW control torque is restricted in DV and MOM_ADJUST phases, the attitude will drift. Therefore, if the attitude error exceeds the threshold, the propulsion heaters are switched off and RW torque becomes nominal (ATT_ADJUST). If the battery voltage goes down to the lower threshold, the orbital maneuver is suspended and changes to “intermediate attitude” to charge the batteries (CHARGING). After the batteries are charged to the upper threshold voltage, MNV2 is conducted and the spacecraft restarts DV phase.

The flowchart of the algorithm is shown in Fig. 5. Due to MOM_ADJUST and ATT_ADJUST phases, the efficiency of the orbital maneuver will decrease and it causes longer orbital maneuver time. Though MOM_ADJUST is inevitable because of the thrust disturbance, ATT_ADJUST can be optimized to arrange control torque of RMs.

Table 2 Control phases for the orbital maneuver

Control Phase	Description	MiPS	XACT	DV efficiency
MNV1	Maneuver from present attitude to intermediate attitude	OFF	RW full torque	0 %
MNV2	Maneuver from intermediate attitude to DV attitude	OFF	RW full torque	0 %
DV	Nominal DV (A1 and A4 thruster firing)	Heater high power	RW limited torque	100 %
MOM_ADJUST	Angular momentum adjust	Heater high power	RW limited torque	About 50%
ATT_ADJUST	Attitude adjust using RW	Heater off	RW full torque	0 %
CHARGING	Maneuver from DV attitude to intermediate attitude	OFF	RW full torque	0 %

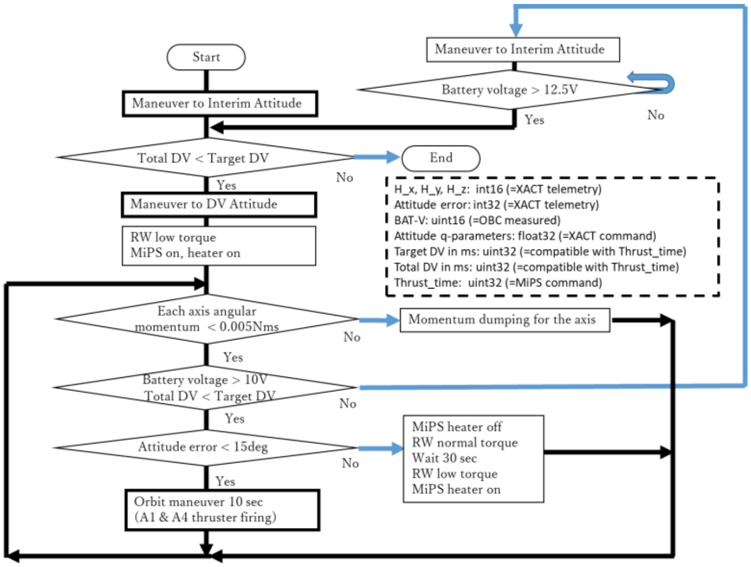


Fig. 5 Orbital maneuver algorithm

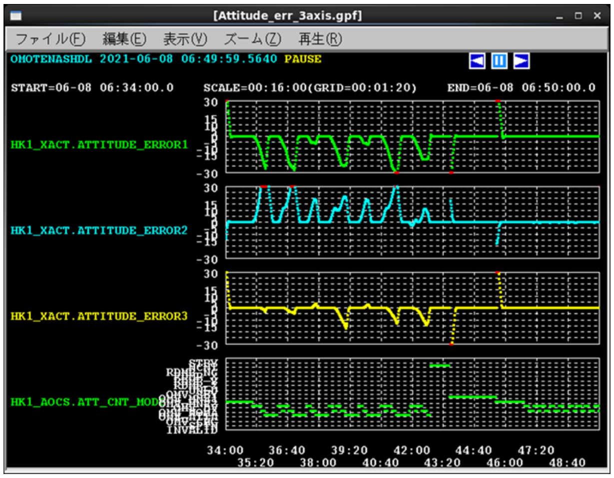


Fig. 7 Attitude during orbital maneuver
(Thrust unbalance, 0 mNm RW control torque)

4. Performance tests using simulator

In order to check behavior of the algorithm and find optimum RW torque, we conducted Static Closed Loop Tests (SCLT) with Ground test Model (GM) of OBC, PCU, COM, and batteries. [5]

Fig. 6 shows an example of the attitude during the orbital maneuver, with nominal thrust and zero RW torque. ATT_ADJUST occurred about once per two minutes. Because its duration is 30 sec, time efficiency of the orbital maneuver is about 75 %. Fig.7 shows an example with thrust unbalance and zero RW torque. In this case, ATT_ADJUST occurred about seventh per eight minutes and it corresponds about 56 % time efficiency. Fig. 8 and 9 show the case that 0.2 mNm RW torque is allowed. No ATT_ADJUST occurred in both cases. The 0.2 mNm torque needs about 7.8 W in three RWs total. If additional power is allowed, the efficiency will be improved almost 100 %.

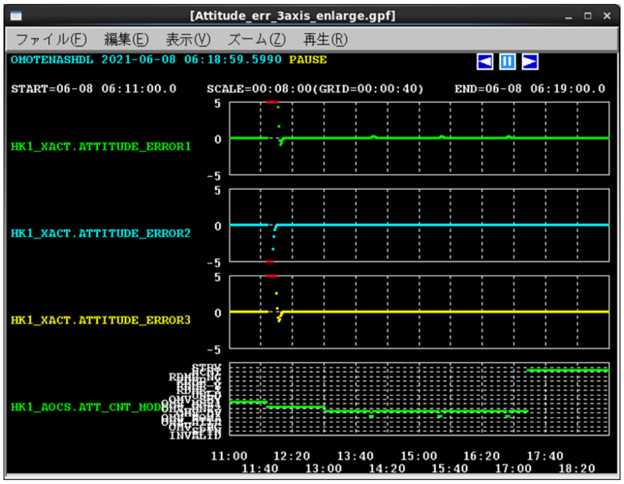


Fig. 8 Attitude during orbital maneuver
(Thrust nominal, 0.2 mNm RW control torque)

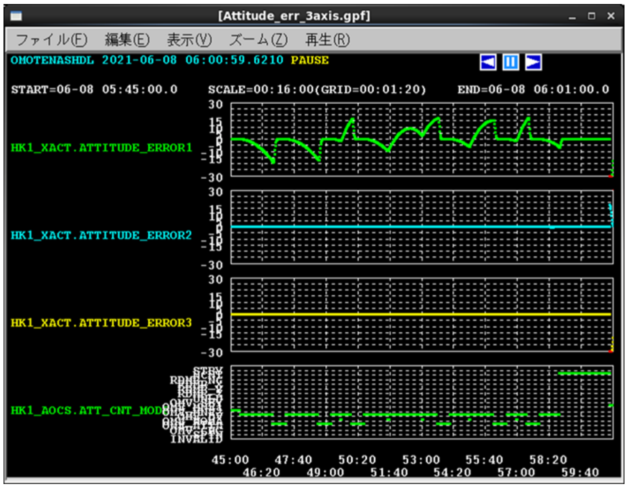


Fig. 6 Attitude during orbital maneuver
(Thrust nominal, 0 mNm RW control torque)

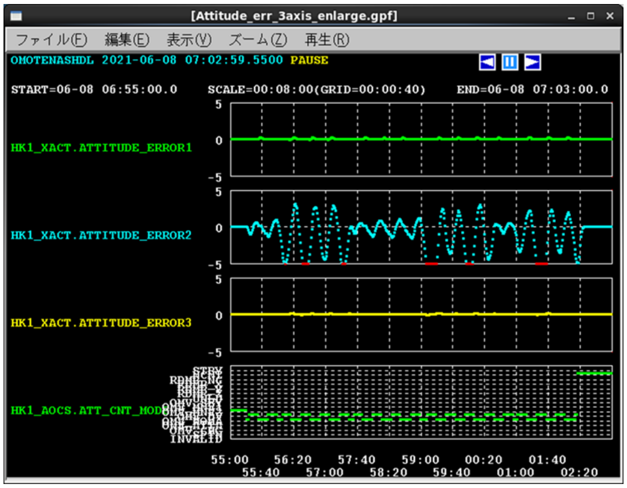


Fig. 9 Attitude during orbital maneuver
(Thrust unbalance, 0.2 mNm RW control torque)

We have to be careful that the instantaneous power does not exceed PCU capacity. But if it is allowable, the reduction of the orbital maneuver time is very attractive. Though the additional power reduces the discharge time, that is, the time for thrusting, the effect is smaller than the increase of thrust time efficiency in general. Therefore, we are now considering to allow small control torque during orbital maneuver.

5. Conclusion

We developed an autonomous orbital maneuver algorithm and confirmed it using SCLT simulations. We found that the time efficiency of the orbital maneuver will be improved by adding small torque of RW control. Because RW control torque for the flight software can be changed by commands, we are now analyzing the optimum parameters, though the spacecraft has already handed over to NASA in July 2021 [6].

Acknowledgments

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