A Preliminary Study on Attitude Control System with High Accuracy for KOSEN-1 as Innovative-2

○Nobuto Hirakoso*[1], Ryuta Onozuka*[1] ,Riku Tomizawa*[1],
Yamato Mutou*[1],Taku Takada*[2],and Kazumasa Imai*[2]
*[1]National Institute of Technology, Gunma College
*[2]National Institute of Technology, Kochi College

Abstract

In this report, an attitude control system for 2U cubesat KOSEN-1 as Innovative-2 is described. The authors conduct the attitude detection system using GPS and omnidirectional camera to measure the relatively direction between moon and the satellite. Then a fluctuation between the relatively lunar direction defined as nominal and actual lunar direction on capturing image is corresponded as the satellite attitude angle. Moreover a dual reaction wheel system consisted of two reaction wheels is proposed, then each other reaction wheel is rotated as opposite direction of rotation with a time rag as control variable.

Key Words: Antenna Deployment Mechanism, Dual Reaction Wheel, Attitude Control System, Cubesat

革新的衛星技術実証２号機 KOSEN-1 における高精度姿勢制御系に関する試作研究

○平社信人*[1]，小野塚隆太*[1]，富澤陸*[1]，
武藤大和*[1]，高田拓*[2]，今井一雅*[2]
*[1] 群馬工業高等専門学校 *[2] 高知工業高等専門学校

概 要

本講では，革新的衛星技術実証２号機 KOSEN-1 に関する試作研究として、超小型衛星の高精度姿勢制御系について述べる．姿勢角検出システムとして，GPS による地球中心座標系から見た月と衛星位置より，衛星から見えるべきノミナルの月の相対方位を算出するとともに，全方位カメラを用いて撮像データより解析した衛星から見た月の相対方位を計算し，ノミナルの月方位と観測された月方位の差異より姿勢角を特定する手法を提案する．また，姿勢制御系として，超薄型の２基のリアクションホイールを同軸上に配置し、それぞれ逆極性の角速度を、タイムラグを持たせながら角速度を与えることで、衛星を高精度に姿勢制御させるデュアルリアクションホイールシステムについて述べる．

1. Introduction

Recently, some small satellites called as “cubesat” have been developing significantly by organizations such as universities, technical colleges and private companies. Then the cubesat would be applied to not only observation mission and technology demonstration mission but also some business of the space market. Furthermore the development cost and term, launching cost for the cubesat are so lower comparing with other usual large satellites. In future, it would be considered that small satellite business would develop to divercity. Moreover, the cubesat can be conducted for special mission which conventional satellite cannot be achieved, the cubesat can be treated some innovative technology which conventional satellite cannot be treated. Now it is given an opportunity of confirmation of such innovative technologies as Inovative-2 project planning by JAXA and will be launched in around 2020 as Technology demonstration test satellite. In this launching, a high accuracy attitude control system to observe Jupiter’s decametric radio emission[1][2] by the innovative cubesat being 2U-size (200mm×100mm: ×100mm) is conducted in collaboration with other technical colleges[2][3]. Then image of the innovative satellite named KOSEN-1 by the authors is shown in Fig.1. Here, it is necessary that Jupiter’s emission is observed as a frequency of 20MHz corresponding to a 7.2m long dipole antenna. In this report, antenna deployment mechanism for 7.2m dipole antenna with attitude control system of the body is conducted.

In this report, at first introduction for this research is described. In chapter 2, the cubesat treated in this report is explained as implemental component, system diagram

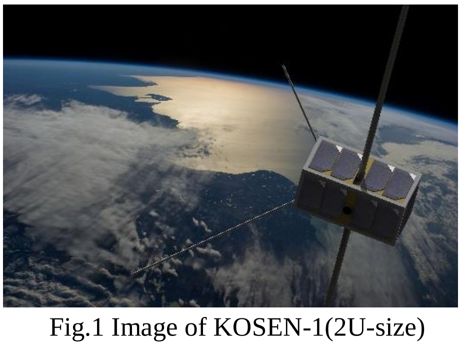

Fig.1 Image of KOSEN-1(2U-size)

and control flow. Then to observe Jupiter's emission[1], the dipole antenna deployment mechanism by using plate spring is described in chapter 3. Next, in chapter 4, attitude detection system[3][4] utilized image processing by omnidirectional camera capturing lunar image. Then high accuracy attitude control system with dual reaction wheel system[3][5] for the "cubesat".as KOSEN-1 is described in chapter 5. Finally, proposed attitude control system with antenna deployment mechanism is estimated and obtained results are concluded in chapter 6.

2. Cubesat KOSEN-1 outline

2.1 KOSEN-1 mission

In this chapter, outline of the cubesat named as "KOSEN-1" is exolained. In this cubesat, three subjects for innovative technologies are given as following:

(1)Attitude Control System with high accuracy for 2U-size cubesat

(2)On board Computer by small Linux microcomputer board

(3)Demonstration for antenna deployment technology of Jupiter's emission

To conduct these given subjects, a dipole antenna deployment mechanism with length being 7.2m are proposed by the authors. Then to compensate the satellite attitude with antenna deployment, the authors conduct a novel attitude control system with the attitude detection system by using omnidirectional camera and a dual reaction wheel system.

2.2. Implemental component for the cubesat

Next, configuration of implemental component of the cubesat is explained. Aspect of implemental component is indicated as Table 1 and outline of the configuration of the component is shown in Fig.2. Then CubePiBoard including Rasberry-Pi-ZERO as on board computer is treated by the authors.

Table 1. Aspect of implemental component

Part Name	Size	Number
OBC(CubePiBoard)	80㎜×80㎜×15㎜	1
Power Control Board	80㎜×80㎜×15㎜	1
LoRa Module(Mounted on the Power Control Board)	24㎜×17㎜×3㎜	1
Batteries	77㎜×22㎜×22㎜	2
Communication Board(CubeCom)	56㎜×56㎜×15㎜	1
Transceiver(302A-RU)	60㎜×82㎜×15㎜	1
DRW	φ80㎜×25㎜	2
Driver Unit for DRW	46㎜×38㎜×20㎜	2
Jupiter Radio Antenna Deployment System	80㎜×80㎜×38㎜	2

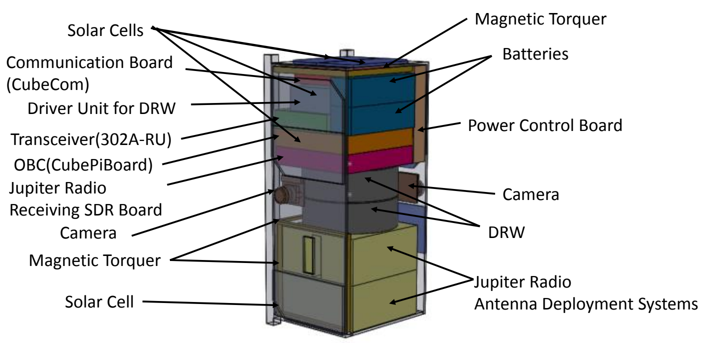

Fig.2 Outline of the configuration of the component

2.3. System diagram for the cubesat

In this section, system diagram with component for the cubesat is explained. The system diagram for the cubesat KOSEN-1 is indicated as Fig.3. Moreover, aspect of the constructed attitude control system is explained. Fig.4. shows aspect of block diagram of the attitude control system for KOSEN-1.

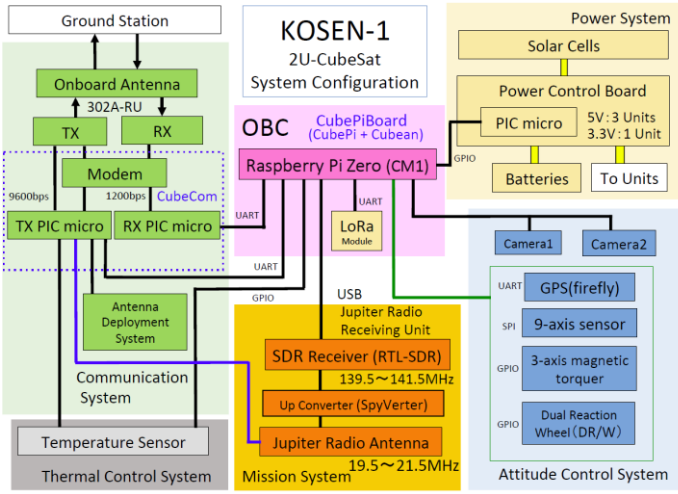

Fig.3 System diagram for KOSEN-1

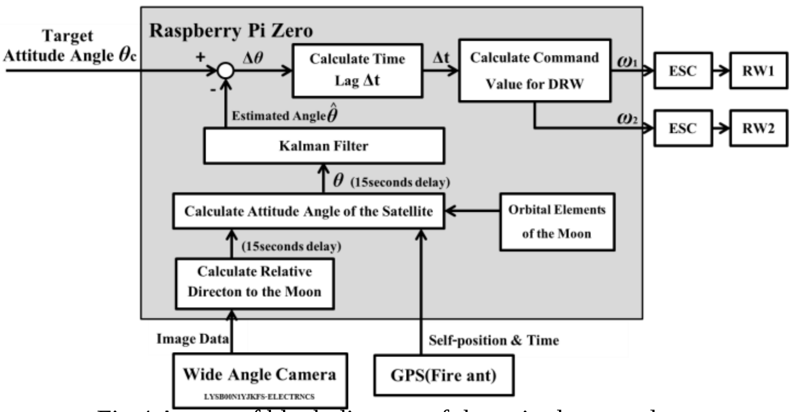

Fig.4 Aspect of block diagram of the attitude control system for KOSEN-1

3. Dipole antenna deployment mechanism

3.1. Antenna deployment mechanism by plate spring

In this section, the outline of the proposed antenna deployment mechanism is described. It is needed that the cubesat equips 7.2m dipole antenna inside before being launched into the outer space. Fig.5 shows the aspect of antenna deployment of the cubesat. In this cubesat calling as KOSEN-1, it is required that a dipole antenna of length being 7.2m equips to catch the Jupiter's emission with a frequency of 20MHz. However, it is difficult for 2U size cubesat that such long dipole antenna deploys because of traditional antenna deployment mechanism bringing link type without sufficient mechanical strength. Therefore, the authors propose an innovative antenna deployment mechanism with using plate spring of convex tape type which the restoring force for the plate spring is brought as expansion force of the antenna deployment.

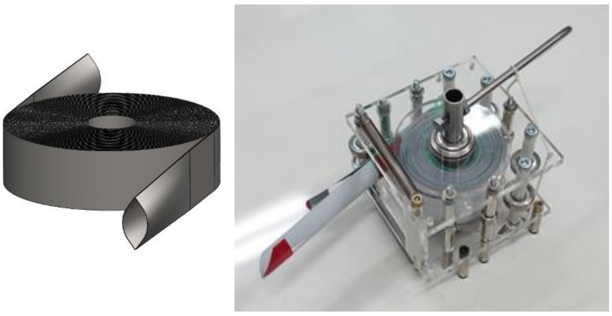

Fig.5 Antenna deployment device

3.2. Aspect of plate spring

Next, aspect of plate spring is described in this section. Fig.6 shows the cross section of the plate spring. Further, a preliminary experiment for the antenna deployment is executed. At the result, it is confirmed that the proposing antenna deployment with plate spring can develop with smoothing and quickness. Then the antenna deployment mechanism needs no electric power and that bring space saving.

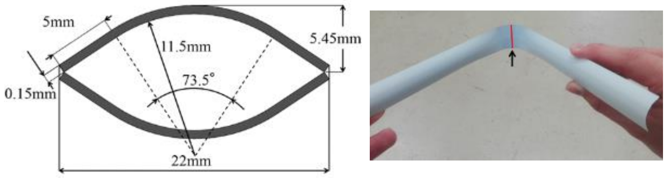

Fig.6 Cross section of the plate spring

4. Attitude detection system

4.1.Attitude detection system with omni-directional camera

In this chapter, an attitude detection system with omni-directional camera for the cubesat is described. In this report, it is needed that high accurately attitude control system to observe Jupiter's decametric radio emission. The authors conduct attitude detection system for the cubesat to control the attitude with high accuracy even if some disturbance would be given with the dipole antenna deployment. There are some traditional attitude detection system such as a star-tracker and a sun-sensor and so on. However, it is impossible that the cubesat implements the normal attitude control device because of the cubesat having few electric power and few space to equip of many functional devices.

Then the subject of attitude control system with high accuracy for such cubesat is applied as innovative technology. Then to find relatively direction between moon and the satellite, the attitude detection system by using image processing with omni-directional camera is treated, the satellite is provided to satisfaction of the problem of the space and the electric power. Fig.7 shows aspect of analyzing relatively direction between the satellite on orbit and the moon. And to analyze the image processing, Raspberry-Pi zero as On Board Computer is used. Then an experiment for the attitude detection to verify the effectiveness of proposing attitude detection system is executed and obtained result are evaluated.

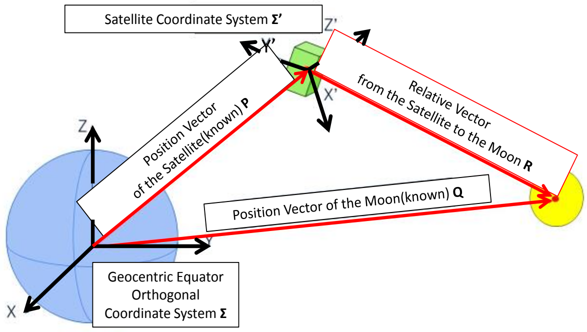

Fig.7 Relatively direction between cubesat and Moon

4.2. Attitude detection Procedure

In this section, the attitude detection procedure is introduced. The aspect of procedure of analyzing for the attitude detection is sown in Fig.8(left hand). At first, it is measured by GPS that the satellite position as x, y and z axes around inertial geocentric coordinate system and time. Fig.8(right hand) shows the aspect of analyzing procedure and captured image by an omnidirectional camera with the cubesat. Next, the point of capturing image of Moon is calculated as the elevation angle α [deg] and the azimuth angle β [deg] by using percentage of pixel numbers. Then attitude angle for the satellite is specified as the gap between nominal point and capturing point for elevation and azimuth. The procedure of attitude detection of the cubesat is as following:

(1)Detection for the satellite position and the time by GPS measurement

(2)Decision for nominal lunar direction by analyzing time from GPS data

(3)Capturing image by omnidirectional camera

(4)Analyzing lunar direction from capturing image

(5)Analyzing between actual lunar direction and nominal lunar direction as pixel number

(Comparing procedure (2) with procedure (4), Seeing Fig.8)

(6) Analyzing attitude angle as azimuth and elevation angle by differential for lunar direction data of procedure (5).

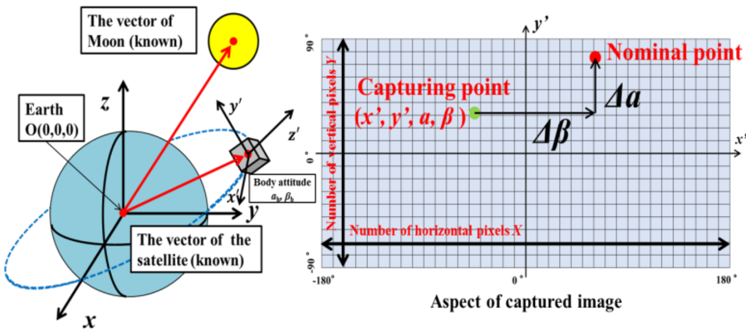

Fig.8 Aspect of process for the attitude detection (Satellite position and lunar position, Image processing)

4.3. Formulation for the omnidirectional camera

In this section, formulation for the omnidirectional camera treated is introduced. At first, to find the relatively lunar direction, the authors formulate the direction vector viewing from the capturing camera as attitude detection device. Then the viewing characteristics of the using omnidirectional camera (Raspberry pi Camera module with Wide-Angle Lens-160deg) is revealed. Next, formulation for the direction on the capturing image is conducted. Here, Rx, Ry and Rz as vector components around each angle of x, y and z axis are defined. Then the direction vector component is obtained as following equation.

$$\begin{cases} Rx = \dfrac{\cos\varphi \cdot \sin\theta}{\sqrt{1-\sin^2\varphi \cdot \sin^2\theta}} \\ Ry = \dfrac{-\sin\varphi\cos\theta}{\sqrt{1-\sin^2\varphi \cdot \sin^2\theta}} \\ Rz = \dfrac{\cos\varphi\cos\theta}{\sqrt{1-\sin^2\varphi \cdot \sin^2\theta}} \end{cases} \quad (1)$$

where θ is represented as roll angle, φ is represented as pitch angle. The capturing image with the grid line plotted at interval of 15-degrees for roll angle around x-axis and pitch angle around y-axis is illustrated in Fig.9. Then, diagonal viewing angle for the image is corresponding to160 degree. It is find that the direction vector for the omnidirectional camera is available.

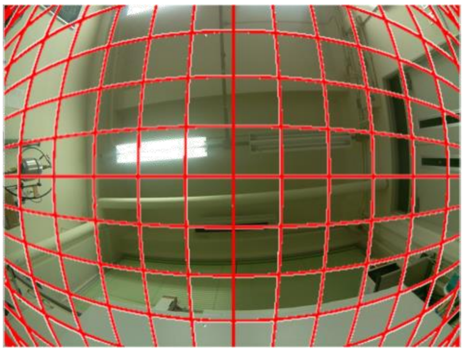

Fig.9 Capturing image with grid of formulation

4.4. Preliminary experiment for attitude detection system

Next, a preliminary experiment on ground of attitude detection system by using omnidirectional camera (Raspberry pi Camera module with Wide-Angle Lens-160deg) and Raspberry pi ZERO as OBC is explained. The experimental setup is shown in Fig.10. To verify the effectiveness of the proposed attitude detection system, a performance evaluation test on ground are executed. Then obtained results are evaluated. Next, the experimental condition is shown in Table 2. The experiment on ground is executed at location of Maebashi city, Gunma Pref.

Table 2. Experimental Condition

	Experimental Condition	
Time	2019/01/20 19:58（Japanese Time）	
Observation Point	Latitude:36.38deg	Longitude:139.02deg

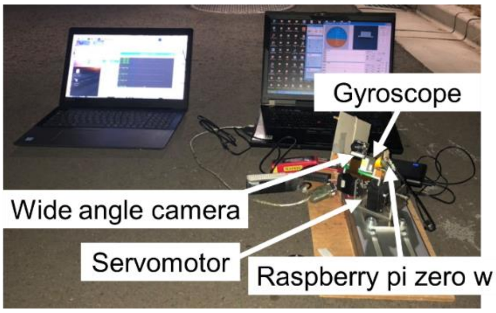

Fig.10 Experimental setup

4.5. Experimental result of attitude detection

In this section, experimental result for the attitude detection is described. Fig.11 shows the experimental capturing image with analyzing the lunar position, it is shown in Fig.12 that experimental capturing image with the grid line plotted at interval of 15-degrees for roll angle around x-axis, pitch angle around y-axis and with yellow lines as roll angle and pitch angle for the lunar direction. Moreover, Table 3 shows the analyzing results as nominal and specifying lunar direction. At the result, it is found that the proposing on-board attitude detection system for the ultra-small satellite bring effective function with high accuracy. Then the authors conclude that constructing the prototype attitude detection system is available for the cubesat.

Fig.11 Capturing image of the Moon

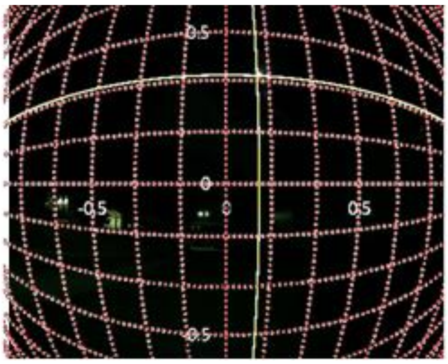

Fig.12 Analyzing image (Experimental Result)

Table 3. Experimental Results

	Azimuth Angle	Elevation Angle
Nominal	**96.7[deg]**	**46.0[deg]**
Specifying	**96.5[deg]**	**47.5[deg]**
Fluctuations	**0.2[deg]**	**-1.5[deg]**

5. Attitude Control System with Dual Reaction Wheel System

5.1. Aspect of dual reaction wheel system

In this chapter, dual reaction wheel system for attitude control system of the cubesat is described. The outline of dual reaction wheel system with comparing as normal reaction wheel system is shown in Fig.13. Then dual reaction wheel system proposed by the authors is explained. In the dual reaction wheel system, two reaction wheels are located on one axis and then each reaction wheel is rotated as opposite rotation direction with time rag. Hence, the torque conducted as acceleration and deceleration for the body are introduced at the same time. Therefore it is possible the attitude control system for the cubesat with the dual reaction wheel system is achieved with quick response and high accuracy.

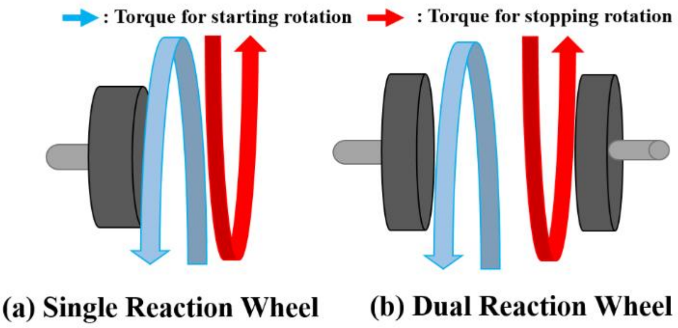

Fig.13 Aspect for dual reaction wheel system

5.2. Formulation of dual reaction wheel system

In this section, formulation for the attitude control system with dual reaction wheel system is described. The motion equation for the attitude of cubesat is represented as the Euler equation for rigid body rotation problem:

$$\begin{cases} I_x\ddot{} + \Omega^2\left(I_y - I_z\right) - \Omega\left(I_x - I_y + I_z\right)\dot{\psi} = M_x \\ I_y\ddot{\theta} = M_y \\ I_z\ddot{\psi} + \Omega^2\left(I_y - I_z\right)\psi - \Omega\left(I_x - I_y + I_z\right)^{\cdot} = M_z \end{cases} \quad (2)$$

where I is momentum of inertia of the cubesat, M is the external torque, and theta is the body angle of the cubesat on the orbit. Then motion equation for attitude behavior with dual reaction wheel system is obtained as following equation.

$$I\ddot{\theta} + I_i\dot{\omega}_1 + I_i\dot{\omega}_2 = 0 \quad (3)$$

where, index i is represented as the number of each reaction wheel system and $\ddot{\theta}$ is represented as angular acceleration to control the body attitude. Then $\dot{\omega}_1$ is represented as the angular acceleration for the first reaction wheel to start the rotation of the body, $\dot{\omega}_2$ is represented as the acceleration for the secondary reaction wheel. Then the time history of the attitude angle for the body is introduced as following equation.

$$\theta(t) = \theta_0 + \frac{I_i}{I}\int_{t_0}^{t_1}\omega_1(t)dt - \frac{I_i}{I}\int_{t_0+\Delta t}^{t_1}\omega_2(t)dt \quad (4)$$

where θ_0 is the initial body angle, ω_1 and ω_2 are represented as angular velocity command input for each reaction wheel. Next, the control input command as angular velocity of time history for each reaction wheel is shown in Fig.14. Then the time rag Δt between ω_1 and ω_2 rising is introduced as following equation.

$$\Delta t = \left(\frac{\omega_1}{-\omega_2} + 1\right)\left(t_1 - t_0\right) - \frac{I_i}{I}\cdot\frac{\left(\theta - \theta_0\right)}{\omega_2} \quad (5)$$

Therefore, the proposing dual reaction wheel system is achieved to the accurately attitude angle of the body with setting appropriative time rag Δt as control input variable.

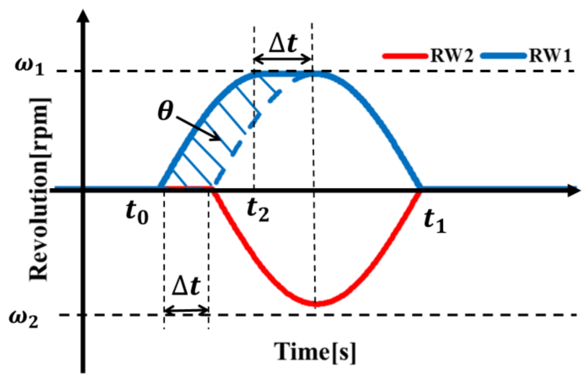

Fig.14 Input angular velocity command of dual reaction wheel

5.3. Experiment setup for dual reaction wheel system

In this section, attitude control experiment with dual reaction wheel system is described. To confirm the effectiveness of the proposing dual reaction wheel system, attitude control experiment is executed. The experimental device for attitude control system with dual reaction wheel system is shown in Fig.15, the equipment list by using the experimental setup for dual reaction wheel system is listed in Table 2.

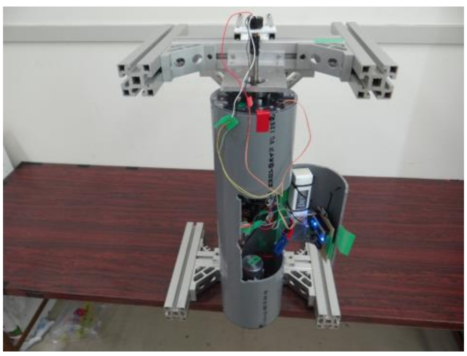

Fig.15. Experimental setup for dual reaction wheel system

Table 2. Equipment list

Conponet	Product name	Manufacture
EC motor	118896	MAXON
Motor driver	230572	MAXON
Conputer	Mbed-LPC1768	ARM
Potentiometer	HSM22-S	ETI systems

5.4. Experiment for dual reaction wheel system

In this section, the attitude control experiment with proposed the dual reaction wheel system is described. Then to verify the effectiveness of proposing the dual reaction wheel system, a step response with amplitude being 10 degree is treated as the experimental condition. Fig.16 shows angular velocity history for each reaction wheel system as command input to control the attitude of body being 10 degrees. Then the rotation direction between reaction wheel 1 and reaction wheel 2 is opposite revolution direction with the time rag Δt treated as control variable to achieve the control for the body angle. Here, the attitude control system with dual reaction wheel system is treated as feed-forward control system then the control input variable Δt is introduced by some trial tests to find trend the body angle.

Next, the attitude control experiment with 10 degrees step response is executed. The experimental result as history of the body angle with dual reaction wheel system is shown in Fig.17. As the result, it is found that the proposing attitude control system for the small satellite with dual reaction wheel system has the function of high accuracy and high response. Therefore the authors conclude the proposing attitude control system with dual reaction wheel system is available.

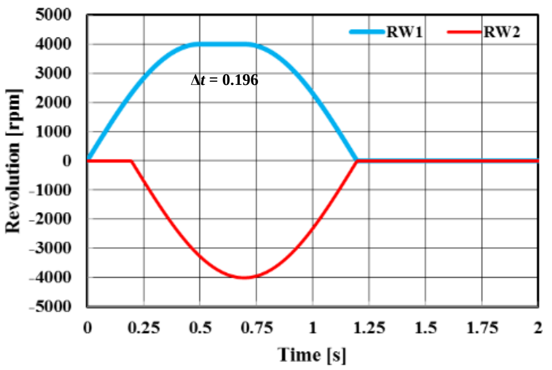

Fig.16. Control input command as each angular velocity

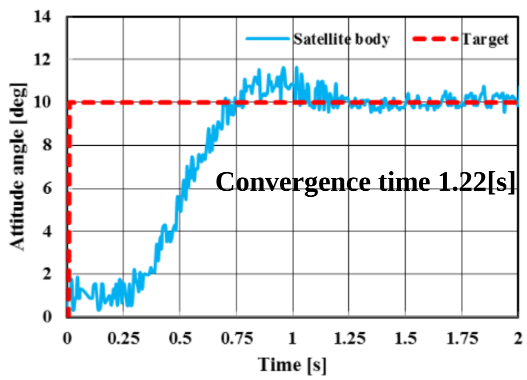

Fig.17. Experimental result

6. Conclusion

In this report, an attitude control system for 2U cubesat KOSEN-1 as Innovative-2 is explained, the subject of the innovative technology for the cubesat is described. In this report, attitude control system as one of the subject of innovative technology for the cubesat is conducted. Then the dipole antenna deployment mechanism by using plate spring is proposed for the cubesat to observe Jupiter's emission. Then attitude detection system using GPS and omnidirectional camera to measure the relatively direction between moon and the satellite are introduced. Then a fluctuation between the relatively lunar direction defined as nominal and actual lunar direction on capturing image is corresponded as the satellite attitude angle. Moreover a dual reaction wheel system consisted of two reaction wheels is introduced where each reaction wheel is rotated as opposite direction of rotation with a time rag as control variable. Then to verify effectiveness for the above innovative technologies constructed by the authors, each performance evaluation experiment is executed. At the result, it is found that each proposed component is available for the cubesat as KOSEN-1.In future work, Kalman filter to correspond the time delay with attitude detection and calculation and image processing would be conducted.

Reference

[1]M.Imai, A.Lecacheux, T.E.Clarke, C.A.Higgins, M.Panchenko, J.Dowell, K.Imai, A.I.Brazhenko, A.V.Frantsuzenko, and A.A.Konovalenko, "Beaming structures of Jupiter's decametric common S-bursts observed from LWA1, NDA, and URAN2 radio telescopes", The Astrophysical Journal, Vol. 826, number 2, pp.176, 2016.

[2]K.Imai, N.HIrakoso, T.Takada, K.kitamura, M.Imai, KOSEN-1 Team, Charles A.Higgins. James R. Thieman, k.Imai NASA Radio JOVE Team, NIT, Kochi, NIT, Guma, Kochi-CT, NIT,Tokuyama College, University of Iowa, Middle Tennesee State University of Maryland Baltimore County, "Development of KOSEN-1 Cubusat for Jupiter's decametric radio observation"SGEPSS2019

[3]R.Tamura, M. Ando, K. Shimazu, T.Takada, K.Kitamura, K .Imai, N. Hirakos," A Study on Attitude Control System with Dual Reaction Wheel System for Ultra-Small Satellite of Observing Jupiter's Decametric Radio Emission"ISCS 2018

[4]N.hirakoso, K.tajima, Ando.mizuki. A.matsumoto, Y.shigemathu"Study on Specification of Attitude Angle for Small Satellite by Lunar Outline Extraction" SICE 2016

[5]S.Obuchi, R.Tamura, M.Ando, K.Kitamura. J,Nakaya. T.Takada, K.Imai, Y.Hirama Y.Shigematu, N.Hirakoso, "An Experimental Study on Attitude Control System for Small Satellite by using Dual Reaction Wheel" SAMCON2019