Attitude Control System for Arc-Second Stabilization of 30-kg Micro Astronomy Satellite

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ABSTRACT

This study focuses on the development of a precise attitude control system for small satellites. In general, conventional methods used for attitude control in standard-sized satellites are not applicable to small satellites because of constraints of power consumption, space requirements, and mass. In addition, small satellites are more greatly affected than standard-sized satellites by attitude disturbances because of their relatively small moment of inertia. Although magnetic disturbance is considered negligible in standard-sized satellites, it is dominant in small satellites. To realize precise attitude control in small satellites, the satellite should use an attitude control method that satisfies the abovementioned constraints and reduces the effect of magnetic disturbance. This study proposes a new method to solve these problems. Through an example of an astronomical observation mission using small satellites, it is demonstrated that precise attitude control is feasible in small satellites.

1. INTRODUCTION

In recent years, small satellites having small mass and volume have attracted increasing interest because they can be developed to realize various space missions at low cost within a short period. Some small satellites have been targeted at sophisticated missions such as remote sensing and astronomical observations. In 2003, CubeSat satellites developed at several universities including the University of Tokyo were launched. These satellites weighed around 1 kg and had a volume of 10 cm × 10 cm × 10 cm, and they were developed using commercial off-the-shelf (COTS) materials; they were used by universities worldwide to perform practical space science missions. After the success of these satellites, nano- and microsatellites were proposed for more sophisticated objectives such as remote sensing and astronomical observations. Examples of these missions include Pico-satellite for Remote sensing and Innovative Space Missions (PRISM) and Nano-Japan Astrometry Satellite Mission for INfrared Exploration (Nano-JASMINE). PRISM is a remote sensing nanosatellite weighing 8.5 kg that was developed at the University of Tokyo and launched in 2009. Its objective was to capture images with 30 m resolution, for which its attitude had to be stabilized to an accuracy of 0.001 rad/s. Nano-JASMINE is an astrometry nanosatellite that was developed at the Intelligent Space Systems Laboratory (ISSL), University of Tokyo, in cooperation with the National Observatory of Japan (NAOJ). Its objective was to accurately estimate the positions of stars and to update star catalogues, for which its attitude, too, had to be stabilized to a high accuracy. To satisfy the mission requirements, the spin rate of the satellite was controlled to an accuracy of 4×10^{-7} rad/s, which was difficult to achieve using conventional sensors and actuators. Figure 1 shows the relationship between satellite mass and the requirement for attitude stabilization. In the case of conventional standard-sized satellites, many satellites can achieve precise attitude stabilization (gray group in Figure 1). Nowadays, however, small satellites are also used for sophisticated missions that would previously be performed by standard-sized satellites. Therefore, small satellites also require precise attitude stabilization (orange group in Figure 1). Previously, many studies have focused on precise attitude control for conventional standard-sized satellites. These methods are now being applied to small satellites; however, some of them are unsuitable for standards satellites because of constraints such as power consumption, mass, and space requirements. This study clarifies these constraints and problems and proposes new methods to solve some of these problems with the objective of realizing precise attitude control for nano- and microsatellites.

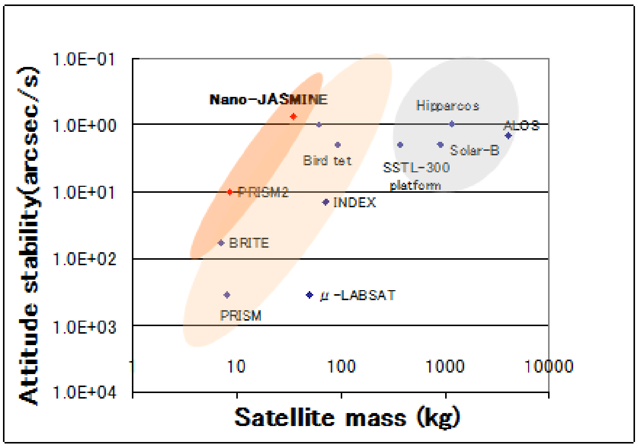


Figure 1*. Relationship between satellite mass and attitude stabilization of a satellite.*

2. Overview of ADCS in Nano-JAMSINE

This study focuses on Nano-JASMINE as an example of small satellites that require precise attitude control. As mentioned above, Nano-JASMINE is an astrometry nanosatellite that was developed by the ISSL in cooperation with the NAOJ. Nano-JASMINE weighs 35 kg and has a volume of approximately 50 cm × 50 cm × 50 cm. Table 1 lists its specifications. Nano-JASMINE will be launched into a sun-synchronous orbit in 2013. It will then perform an all-sky survey during an operational period of approximately two years. Its objective is to measure the three-dimensional positions of stars to an accuracy of three milli-arcseconds (mas) by performing stellar parallax measurements. Nano-JASMINE uses a charge-coupled device (CCD) driven by time delay integration (TDI) to obtain the star images. The use of TDI enables Nano-JASMINE to track and observe a large number of faint stars. Now, to capture the star images using TDI, the spin rate of Nano-JASMINE has to be synchronized with the TDI scanning rate to an accuracy of half the size of one CCD pixel (its view angle is approximately 740 mas) during the exposure time (approximately 8.8 s). Thus far, such high-accuracy attitude stabilization has not been accomplished in any small satellite weighing less than 50 kg.

Table 1. Specifications of Nano-JASMINE

Item	value
Size	508 × 508 × 512 mm^2
Mass	35 kg
Orbit	Sun-synchronous Orbit
Mission	Infrared astrometry
Focal length	1.67 m
Diameter	5 cm
Detector	CCD in TDI method
Attitude rate requirement	4×10^{-7} rad/s (TDI scanning direction)
	2×10^{-6} rad/s (The other direction)
Sensor	Sun sensor, Magnetometer, FOG, STT
Actuator	RW, MTQ, Magnetic Canceler

In general, although small satellites afford the above-described advantages, namely, low development cost, short development period, and applicability to various space missions, they are unsuitable for missions with strict requirements because of constraints such as power consumption, mass, and space requirements. In particular, precise AOCS is difficult to achieve in small satellite for the following two reasons. (1) The effect of attitude disturbances is stronger in small satellites than in standard-sized ones because of their smaller moment of inertia. Magnetic attitude disturbance is the dominant attitude disturbance for low Earth orbit (LEO) small satellites. (2) Some conventional methods are unsuitable for application to small satellites because of constraints such as power consumption, mass, and space requirement. For example, rate estimation using precise gyro sensors such as fiber optic gyroscope (FOG) and ring-laser gyroscope (RLG) cannot be applied because of the abovementioned constraints.

This study focuses on magnetic disturbance and the constraints faced in small satellites for precise attitude control.

3. MAGNETIC ATTITUDE DISTURBANCE

3.1. Magnetic attitude disturbance

Nano- or microsatellites in LEO suffer from various attitude disturbances such as magnetic disturbance, air pressure disturbance, solar disturbance, and gravity gradient disturbance. In standard-sized satellites, the effect of magnetic disturbance is insignificant and therefore not considered. However, in small satellites, magnetic disturbance is the dominant attitude disturbance. This is because the magnetic moment has a relatively strong effect on such satellites owing to their small moment of inertia. Furthermore, the geomagnetic field has a large magnitude in LEO (Inamori et al., 2011(c)). To satisfy the strict attitude requirements for nano- and microsatellites in LEO, the effect of magnetic disturbance should be mitigated to achieve precise attitude control. Figure 2 shows the effect of magnetic disturbance in previous satellite missions. The horizontal and vertical axes show the satellite moment of inertia and the angular acceleration due to a magnetic field produced by magnetic disturbance, respectively. Figure 1 shows that magnetic disturbance has a larger effect in smaller satellites. Therefore, this effect should be compensated in small satellites.

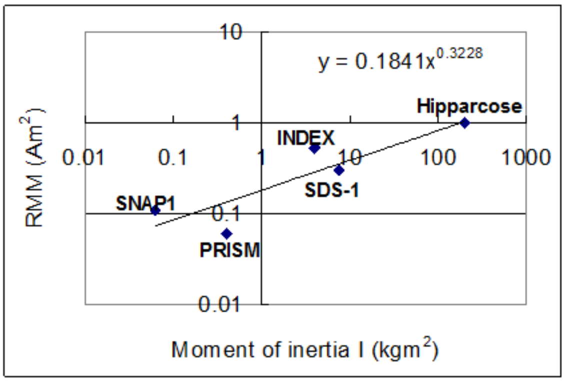


Figure 2. *Relationship between satellite mass and residual magnetic moment of a satellite.*

3.2. Magnetic disturbance compensation

Magnetic disturbance is caused by the interaction of the geomagnetic field and the residual magnetic moment of a satellite. If a satellite estimates the residual magnetic moment and compensates for it using the steady output of a magnetic torquer (MTQ), it can compensate for the effect of magnetic disturbance. Figure 3 shows an overview of the compensation of magnetic disturbance. To compensate for the magnetic disturbance precisely, a satellite must estimate the residual magnetic moment accurately and must have an accurate actuator to generate a magnetic moment. The satellite can estimate the magnetic moment using an extended Kalman filter with magnetometers and gyro sensors. This method is examined using an in-orbit satellite. Figure 4 shows the result of magnetic compensation using the remote sensing nano-satellite PRISM. Figure 4-a) shows the attitude rate of PRISM without magnetic compensation: the satellite attitude rate changes relatively rapidly because of the magnetic disturbance effect. With magnetic compensation, the satellite can stabilize the attitude precisely because of the relatively small magnetic moment.

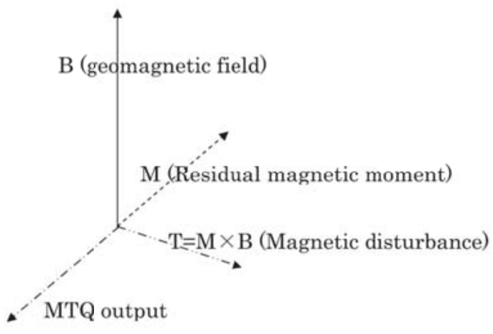
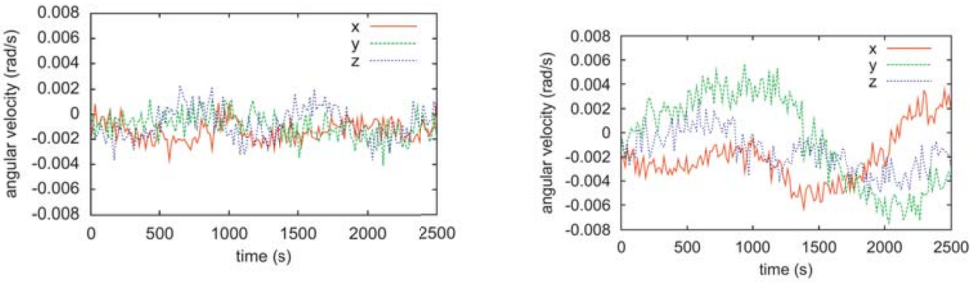


Figure 3. *Magnetic moment compensation using MTQ.*



a) b)

Figure 4*. Results of in-orbit experiments for magnetic compensation using remote sensing nano-satellite PRISM*: *angular rate of PRISM: a) without magnetic compensation and b) with magnetic compensation.*

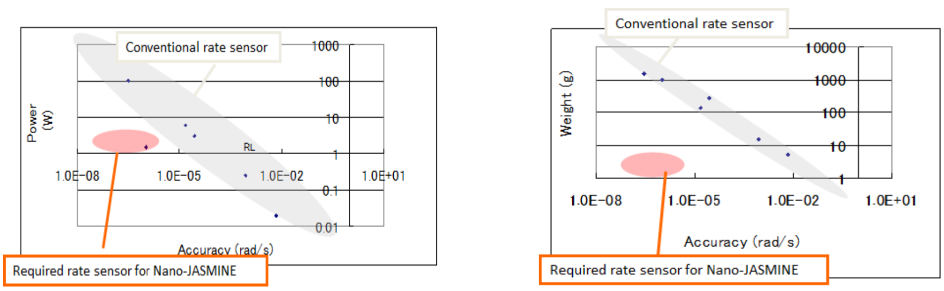
4. CONSTRAINTS OF POWER CONSUMPTION, MASS, AND SPACE REQUIREMENTS

4.1. Constraints for small satellites

Because a small satellite has strict constraints of power consumption, mass, and space requirements, some conventional methods for precise attitude control, such as rate sensing and jitter reduction of a reaction wheel (RW), are not applicable to them.

In these satellites, RWs are used as actuators for precise attitude control. Because RWs have an easily measurable speed that provides very precise control of their rotation speed, they permit very precise changes in a spacecraft's attitude. These actuators enhance the accuracy of attitude control by reducing the effect of low-frequency disturbances; however, the RWs degrade the attitude control accuracy at high frequency because of the jitter generated by the wheel imbalance and bearing irregularities. Such jitter degrades the quality of scientific data or Earth images; therefore, jitter reduction is essential for achieving sophisticated missions such as astronomical observations or remote sensing. In previous large satellite missions, tip-tilt mirrors (TTMs) and isolators were used for controlling or isolating the vibration; however, these devices are difficult to use in small satellite because of the strict constraints of power consumption, space requirements, and mass.

Further, in these satellites, conventional FOG and RLG are also difficult to use because of these constraints. Figure 5 shows the relationship between the accuracy and the power consumption as well as mass of a rate sensor. The figure shows that an accurate rate sensor for precise attitude control has a large power consumption and mass. Thus, in general, accurate rate sensors are not available for the precise attitude control of a small satellite. For example, Nano-JAMSINE requires a stabilization of 1 × 10^{-6} rad/s during missions with a 30-W power system, which is difficult to achieve using FOG and RLG, as shown in Figure 5. Therefore, a new method to determine the angular rate accurately is indispensable for small satellites.



a) b)

Figure 5*. Power consumption and weight of a rate sensor: a) power consumption vs. accuracy of a rate sensor and b) weight vs. accuracy of a rate sensor.*

4.2. Jitter reduction using small reaction wheels

In many satellites, the jitter of an RW degrades the accuracy of attitude control. To reduce the effect of jitter, TTMs and isolators are used in many satellites. For example, Solar-B, a solar observation satellite developed by the Japan Aerospace Exploration Agency (JAXA), uses a TTM. The objective of the Solar-B mission is to explore the magnetic field of the Sun, which requires attitude stabilization to an accuracy of 60 mas per 10 s. To achieve this accuracy, the effect of disturbances due to RWs should be reduced. To suppress high-frequency jitter, a TTM was mounted on a solar optical telescope. TTMs mirrors are effectively segmented mirrors having only one segment that can tip and tilt, rather than an array of multiple segments that can tip and tilt independently. By controlling a part of the satellite body using the TTM as opposed to flexibly controlling the entire satellite body, the telescope stabilization requirement can be achieved rather easily.

Both TTM and isolators are effective in reducing the effect of the jitter from wheels; however, they are difficult to use for small satellites because of the power consumption, space requirement, and mass constraints.

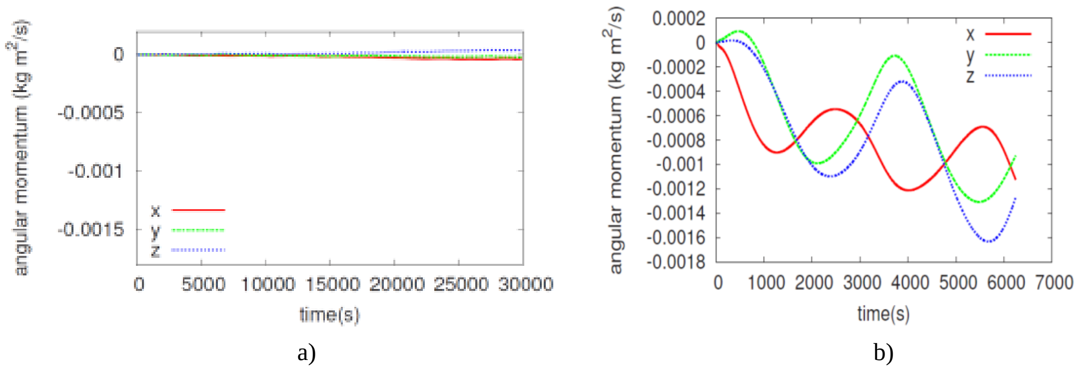
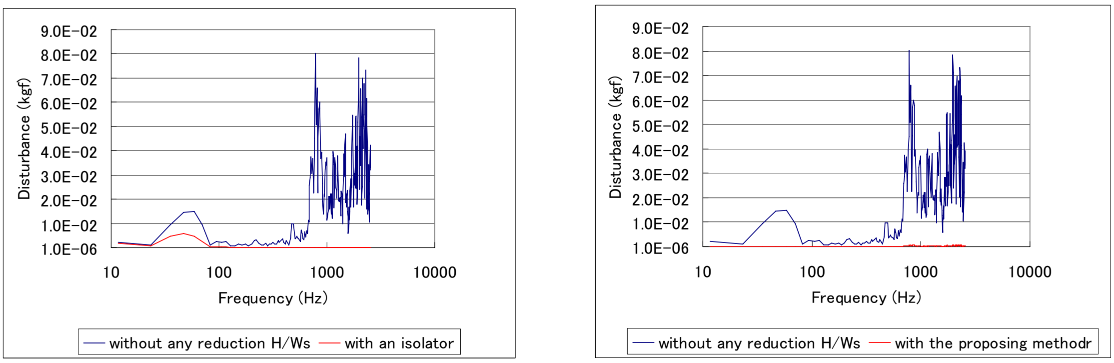


Figure 6. *Angular momentum of reaction wheels: a) with magnetic compensation and b) without magnetic compensation.*

In this study, the jitter of RWs is reduced by using small RWs, and concurrently, the magnetic disturbance is compensated using MTQs. With magnetic compensation, the satellite reduces the angular momentum of the RWs; therefore, the satellite does not need large RWs that may otherwise cause jitter. Figure 6 shows the simulation result of the RW angular momentum in orbit. In this simulation, a satellite stabilizes the attitude using RWs; therefore, the RW gains angular momentum from attitude disturbances such as the magnetic disturbance. As shown in Figure 6-b), without magnetic compensation, the RW gains angular momentum from disturbances. In order to store the angular momentum in the RW, the satellite must use relatively large RWs, which usually cause large jitter. Figure 6-a) shows the angular momentum of an RW with magnetic compensation. Because the satellite reduces compensates for the magnetic disturbance using MTQs, the RW gains a small magnitude of angular momentum. Therefore, the satellite can use a relatively small RW, which does not cause jitter. As a result, the satellite can reduce the effect of jitter without the use of conventional isolators and TTMs. In conclusion, by using this method, the satellite can achieve precise attitude control under the constraints of low power consumption, small space, and low mass. Figure 7 shows the result of jitter reduction by using a conventional method using with an isolator (a) and by using the proposed method (b). In Figure 7, in the case of the conventional method, the jitter of an RW with an isolator is calculated using experimental data and the expected transform function of the isolator. As shown in Figure 7, the isolator is effective in a high-frequency area; however, it is not effective in a low-frequency area. Therefore, the isolator cannot reduce relatively low-frequency jitter produced by a certain rotation frequency. Low-frequency jitter interacts with the detector used for observations and degrades the scientific data. By using the proposed method, jitter reduction is effective at all frequencies, and therefore, the scientific data is not degraded by jitter. In addition, by using this method, the total mass and power consumption of the satellite can be kept low through the use of small RWs; therefore, the method is useful for small satellites that have strict constraints.

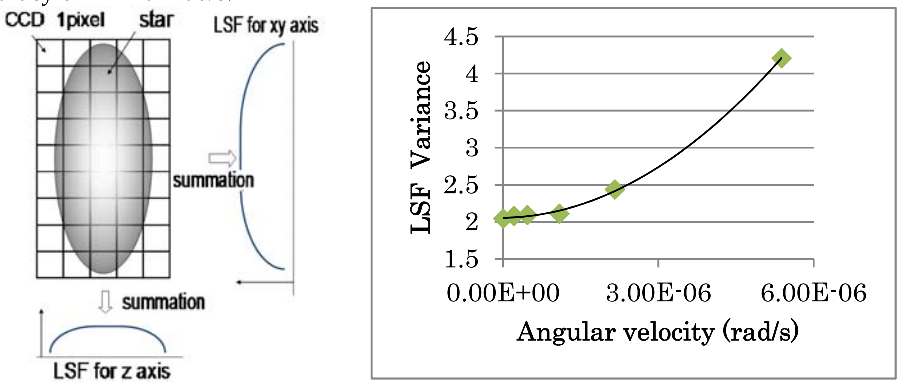


a) b)

Figure 7. *Jitter reduction of a RW: a) with an isolator and b) with the proposed method.*

4.3. Rate estimation using astronomical bodies

Small satellites cannot use precise attitude rate sensors, as shown in Figure 6. This research proposes a method for estimating the angular rate by using star images obtained from the on-board telescope. If the satellite attitude is unstable, the obtained star images are blurry and not sharp. In this method, the satellite estimates the angular velocity using the blurriness of the star images. Figure 8-a) shows how a satellite estimates the angular velocity using a star image. First, the satellite calculates the line spread function (LSF), which is a star image compressed to 2 axes (horizontal and vertical axes). The blurriness of a star can be assessed using the variance of the LSF, which changes with the satellite attitude rate. Figure 8-b) shows the relationship between the motion of the satellite and the star images. If the satellite attitude has an angular velocity, the star images obtained from the telescope are blurred in the direction of the axis of rotation. Figure 8-b) also shows the result of a ground experiment using an LED, which is used to mimic a star, and a satellite flight model. By using this method, Nano-JASMINE could stabilize its attitude to an accuracy of 4×10^{-7} rad/s.



a) b)

Figure 8. *a) Angular rate estimation using star images obtained from on-board telescope and b) relationship between attitude rate of a satellite and variance of a star image obtained from experimental data and theoretical analysis.*

CONCLUSION

In this study, we focused on the development of a precise attitude control system for small satellites. To do so, several problems had to be considered. The first problem was the effect of magnetic disturbance. Because of the small moment of inertia of a small satellite, the magnetic disturbance degraded the accuracy of attitude control. In this study, the magnetic disturbance was compensated by using the steady output from MTQs. The second problem was the constraints of power consumption, space requirement, and mass. Because small satellites are generally designed at low cost within a short period, they involve strict constraints. Therefore, some conventional methods that are used in standard-sized satellites are not applicable to small satellites. In this study, we focused on the jitter of an RW and rate estimation. To reduce the jitter of the RW, we used a small RW in conjunction with magnetic compensation. To develop a precise attitude rate sensor, we used the blurriness of star images obtained from an on-board telescope. Simulations of these methods showed that precise attitude control was feasible in small satellites.

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