Development of Tokyo Tech Nano-Satellite Cute-1.7 + APD II

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Abstract

The third pico-satellite "Cute-1.7 + APD II" developed by Lab for Space Systems at Tokyo Institute of Technology is currently under development. The satellite is improved version of the satellite "Cute-1.7 + APD" whitch was launched by the M-V-8 rocket on February 22, 2006. We will launch the satellite in this fall. This paper will explain the improvement and new function of this satellite.

東京工業大学における超小型人工衛星 Cute-1.7 + APD II の開発

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摘要

東京工業大学、松永研究室は現在、本研究室３機目となる超小型衛星 Cute-1.7 + APD II を開発中である。本衛星は昨年２月に打ち上げた Cute-1.7 + APD の改良型２号機であり、本年度秋のうち上げを予定している。本論文では Cute-1.7 + APD プロジェクトの説明，および 1 号機の成果報告と２号機における 1 号機から引き継いだ機能、改良点および新機能について述べる。

1.Introduction

The Laboratory for Space Systems (LSS) at Tokyo Institute of Technology (Tokyo Tech) developed a 1 kg pico-satellite, "CUTE-I", launched on June 2003 (Iai *et al*., 2004a). CUTE-I fully conducted the missions and is still transmitting its house keeping data to the Earth. This successful experiment demonstrated how students can manage the development of a satellite from the first designing steps to the effective launch and operation. Based on this satellite development procedure and acquired nano-satellite bus technology, LSS started the next satellite development project, “Cute-1.7+APD” (Iai *et al*., 2004b), pursuing the search for innovation in small satellite systems.

The Cute-1.7 + APD project has two objectives. First, facilitate future micro-satellite development by demonstrating a new design methodology, and second, provide flight experiment opportunities to space engineering researchers and students by using the highly utilizable satellite. The methodology, aiming to rapid and low-cost development, includes proactive use of high performance and low cost commercial devices in space. The Cute-1.7+APD nano-satellite is equipped with several COTS devices including widely used PDAs and handy radio transceivers. For the second purpose, this satellite contains an engineering mission shared with control engineering researchers. Three magnetic torquers and a several control programs are equipped.

The Cute-1.7 + APD, shown in Fig.1, was launched on Feb 22nd, 2006, and successfully conducted initial missions, including the effective usage of COTS devices, cooperation with amateur radio operators, retrieval of house-keeping data, and attitude determination. On May 6th, after 74-days operation, the satellite fell into a status in which the satellite does not respond to any commands from ground station. LSS investigated the cause of the situation and concluded the influence of radiation. After that, LSS have developed the second Cute-1.7 + APD with the prevention of the radiation effect. The second satellite will be launched by Indian PSLV rocket in 2007.

This paper, first, reports the flight operation results of Cute-1.7 + APD#1, the first satellite. After describing the cause of the status, we present the modification and development of Cute-1.7 + APD#2, the succeeding satellite.

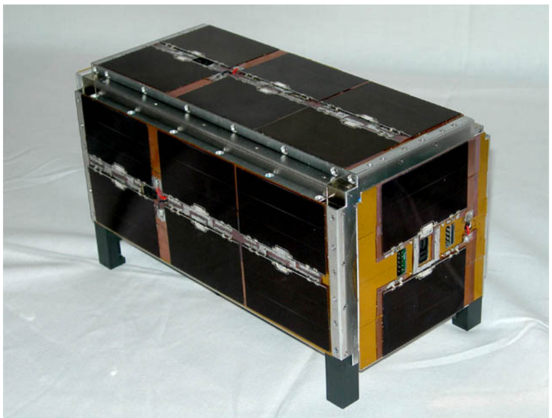


Fig.1 Cute-1.7 + APD Flight Model

2. Cute-1.7 + APD#1 Operation Results

2.1 Operation Results

The Cute-1.7 + APD#1 was launched by the JAXA/ISAS M-V#8 Rocket as a subpayload with the main payload, JAXA "ASTRO-F AKARI" satellite on February 22nd, 2006. The satellite was mounted on the B3-PL, the third stage unit of the rocket, using its separation mechanism.
After the separation from the rocket, the satellite successfully deployed its dipole antenna, and started to transmit the CW beacon including house-keeping data of the satellite. The radio reached to many amateur radio operators in all over the world at the first orbit, and LSS also received the signal in the ground station in Tokyo Tech. The house-keeping data confirmed the activation of the PDA. On March 7th, attitude data retrieval was conducted every 10ms successfully. On March 16th, as the data showed unexpected behaviour of power consumption, the operation was stalled to conduct missions and focused on understanding the situation.

Then, Cute-1.7 + APD#1 stopped accepting any uplink command in the evening March 16th when passing over Tokyo Tech, and now the satellite is not under control. Because the final operation was conducted completely without error, estimation can be that functional error had occurred in the satellite on orbit. The subsequent operations showed that the command processing system stopped its operation even though the command receiver operates its function without any problem. Therefore, the error might have been resulted from radiation damage on the command processing controller. After a careful radiation test in LSS, our team reached to the conclusion with the highest possibility of damage by the radiation.

To summarize what the satellite could conduct in the planned mission, the satellite, first, satisfied the usage of COTS devices including PDA on orbit in terms that the telemetry confirmed the operation of COTS devices. For amateur radio cooperation, Cute-1.7 + APD provided GMSK modulation method for the first time in CubeSat. The radio reached to ham operators in Japan, and LSS has received their reports. In the science module, basic operation was confirmed including the circuit around the APD sensor. Although the satellite could not fully conduct attitude control experiment, the attitude control system installed 3-axes active controller for the first time as CubeSat in Japan, and gyroscopes and sun sensor were confirmed to be in normal operation. The tether deployment mission was not conducted. LSS also found that the deployment mission had incompleteness in the proposed structure.

Cute-1.7 + APD#1 is now transmitting a continuous wave that is not modulated. The recovery operation will be continued throughout the orbit life, estimated to be 1 or 2 year. Meanwhile, the problems in Cute-1.7+APD#1 are thoroughly investigated and the satellite of the second improvement type is developed in order to achieve the missions except the tether deployment mechanism. Part of report on radiation effect on the satellite is described by Miyashita *et al.* (2005) and Omagari *et al*. (2006).

2.2 Satellite Telemetry

By referring to the change of the battery voltage recorded and downloaded since March 16th, we observed that the current consumption temporarily increased. The telemetry transmission was operated normally for a while after the uplink command analysis system stopped operating. Fig.2 shows the house-keeping data during this period. The telemetry disappears once at the evening on April 7th. About a week before the loss of signal, the voltage of the battery begins to decrease gradually. On the day of the loss, the voltage descent seems to below the operation voltage of the telemetry transmission system. Then, the satellite orbit went in eclipse for the first time on April 15; therefore, all satellite electric power could be turned off and the hard error was cancelled. Then telemetry revived on April 16 after the battery was charged again. Telemetry disappeared completely in the morning on May 6. A rapid decrease of the battery voltage was confirmed in the evening, May 5th, and over consumption of the current happened again.

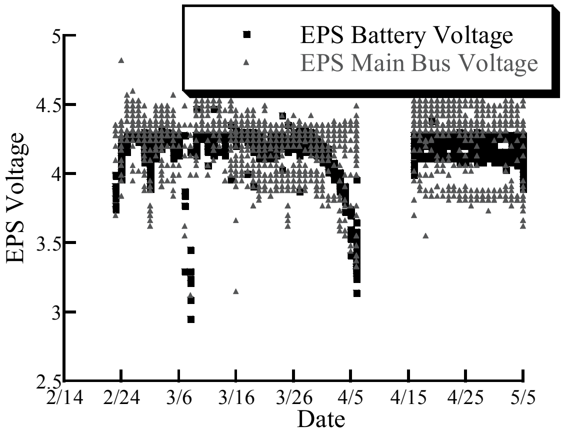
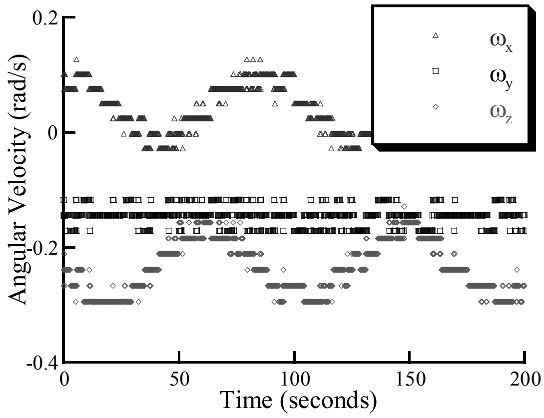
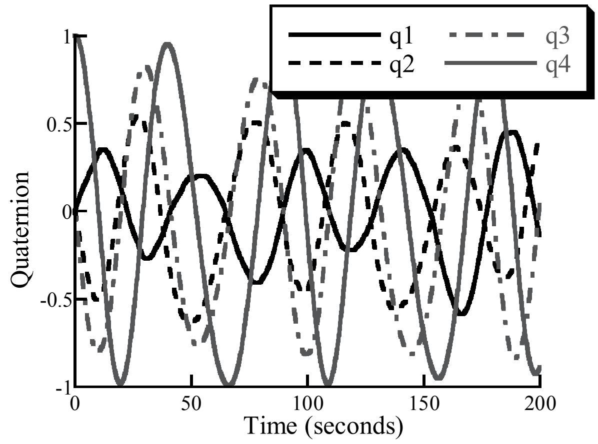


Fig.2 Flight Data of Battery and Main Bus Voltages

Fig.3 Reception reports from the world powered by google earth. Plots are the points where radio amateurs received the signal from Cute-1.7 + APD#1.



(a) Gyro Data



(b) Quaternion

Fig.4 Attitude Determination Results

2.3 Amateur Radio Cooperation

The signal transmitted from the satellite reached to many amateur operators all over the world, shown in Fig.3. Over a hundred ham operators have reported the signal reception. Trough the cooperation with those operators, the satellite received OSCAR (Orbital Satellite Carrying Amateur Radio) name. The OSCAR name uses "OSCAR (Oscar)" in a part of the name of the satellite and applies a sequence number after the name, which are assigned by AMSAT-NA. The OSCAR series satellites use amateur radio frequencies to communicate with ground stations. CUBESAT-OSCAR-55(CO-55) is issued to CUTE-I, which is the first number of "CUBASAT-OSCAR" series, and CUBESAT-OSCAR-56(CO-56) was issued to Cute-1.7+APD#1. These two satellites were admitted worldwide as amateur satellites and contributed to amateur radio operators.

2.4 Attitude Determination

The satellite's attitude determination system consists of a three-axis gyro sensor, a three-axis magnetometer, and sun sensors. The gyro sensor is a combination of three gyroscopes and the sun sensors consist of simple photodiode arrays fixed on the walls of the satellite.

The satellite uses two attitude determination methods; a geometrical method and a REQUEST (Bar-Itzhack, 1996) based method, both of which require the Earth magnetic vector and the sun directional vector. The magnetic vector and the sun vector refer to a dipole model and a circular approximation of the ecliptic plane respectively, and the satellite contains its Keplerian element calculated from uploaded TLE data.

The geometrical method uses the magnetic sensor primarily when the satellite is near the equator of the Earth, and the method rely on the sun sensor primarily when the elevation angle of the sun seen from the satellite is high. The method determines one axis of the satellite attitude at first, deriving one vector from the primary sensor in the inertial frame. To determine the other two axes, the method rotates the body frames about the first axis so that the angle between the other axes and the vector derived from the secondary sensor can be minimized. The REQUEST, expanded from QUEST, is a method to calculate quaternions recursively using angular velocity obtained by the gyro sensor.

Fig.4 shows attitude data effectively retrieved on 7th March from gyroscope at 10Hz. Fig.4(a) shows the angular velocity, and Fig.4(b) shows the quaternion computed from this data. In Fig. 4(a), ω_y shows nearly constant value of -0.15rad/s, and ω_x and ω_z behave in sin-wave motion with the shift of 90 degree. The inertial moment of Cute-1.7 + APD#1 is (2.19E-02 9.78E-03 2.18E-02) kgm^2, i.e. approximately an axisymmetric rigid body, and these motions correspond to a torque free motion of an axisymmetric rigid body spinning with nutation. The Y axis is the smallest inertial moment, and when the satellite rotates about the axis with nutation, the angular velocity of Y axis is constant while these of the other 2 axes are sin-wave motion. The nutation rate of the satellite is about 80 seconds. The spin rate of the satellite, therefore, becomes about 40 seconds from nutation speed and the inertial moment of the satellite.

The data of the sun sensor acquired on February 27 is shown in Fig. 5. The coordinate system is body fixed coordinate system. According to the data from the sun sensor, the satellite was rotating about the Y axis at this moment. The cycle of the rotation is about 30 seconds. Compared with the rotation axis given by the gyroscope data, the data shows approximately same tendencies of rotation about the major axis in the principal axes frame.

Through the Cute-1.7 + APD#1 project, the attitude determination and control system was that can be installed in micro satellite was developed, and the examination was conducted on orbit. The data of the gyro sensor and the sun sensor could be acquired. The acquisition of magnetic sensor data, attitude control experiment and attitude determination experiment, however, was not able to be conducted.

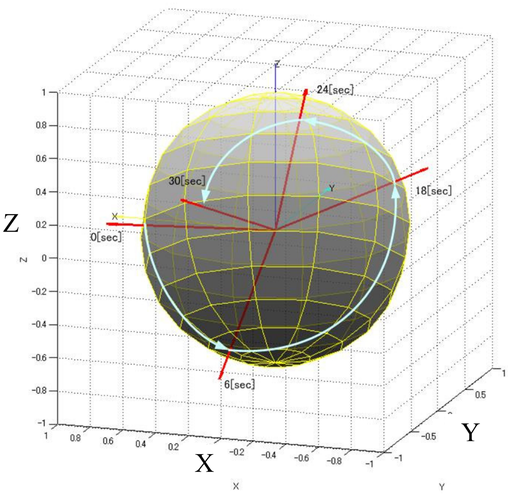


Fig. 5 Direction of the sun in body fixed coordinate system

3. Cute-1.7 + APD#2 Developments

3.1 Missions

The second satellite of Cute-1.7 + APD will conduct missions; facilitation of satellites design, attitude control experiment using magnetic torquer, amateur radio cooperation, APD sensor demonstration experiment, following the first satellite. This satellite excludes the electro dynamics tether mission.

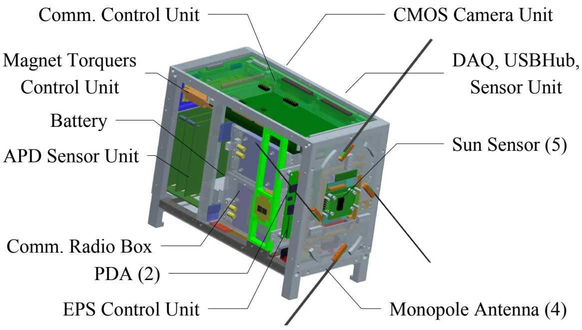


Fig. 6 Cute-1.7 + APD#2 Components Layout

Fig. 7 Cute-1.7 + APD#2 Flight Model

3.2 Project Outline

The second design of a satellite in this project started in April 2006 and is planned to be launched in 2008 by PSLV Rocket from India. This satellite uses the approximately same bus components including two PDAs, four communication channels, 3-axis gyroscope, three axis magnetic sensors, sun sensors, and a CMOS camera. The design of this satellite is shown in Fig.6 and 7. The operation results of the first satellite, however, showed a few requirements to be modified.

3.3 Modifications

The first modification includes designing a radiation tolerant circuit. In the first satellite, because of the SEL occurred in the microcomputer of communication module, the satellite became not to be able to conduct remaining missions. The 1st satellite had current watch circuit which check total current. It was mistake because the current of the SEL which occurred in one micro computer cannot reach the threshold. Therefore we added current watch circuit for each module. Second satellite can detect the SEL and restart the component. The circuit showed effective tolerance to radiation in the ground experiment.

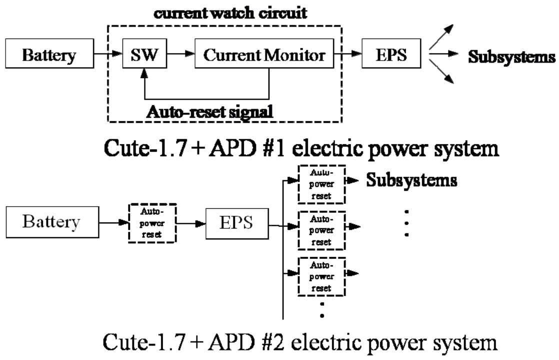


Fig.8 Modification on electric power system

Another modification is to increase the power generation of the satellite. The orbital operation showed relatively smaller power generation than the estimation, which affected operation procedure of the satellite. The power generation is enhanced by increasing the dimension of the satellite. The structural change also contributes to assembling process. As many missions were installed to the first satellite, the high dense of components and many harnesses and connectors required long time to assemble. Therefore we adopted "mother board system", which has most all connector to each subsystem and is easy to slot in subsystem boards. Though exceeding the CubeSat size, the dimension does not affect to the satellite design as the interface to separation mechanism corresponds. This satellite measures 220 x 180 x 120 mm (#2 is 226x112x133mm), weighs 3kg and generates 6.6W in average.

The attitude control system also needs improvements. In Cute-1.7 + APD#1 the magnetic sensor data was not available to determine the attitude of the satellite. The problem caused by data transfer error between bus devices needs debug. In addition, in the first satellite, each attitude sensor data, gyro sensor, magnetic sensor, and sun sensor, were not obtained at the same time. The second satellite requires the data at the same time or a time-stamp function for the precise attitude determination of the satellite. The output torque of the actuator is also increased (3 times larger). The change on the structural design and measurement of the residual magnetic field in the satellite resulted in needs for improvement of the magnet torquer. The torque is increased by dividing a coil into three and connecting parallel, which enlarge the current supply to magnet torquers.

In Cute-1.7 + APD#1, there were two attitude determination algorithms, which are geometical method and REQUEST method. For Cute-1.7 + APD #2, we added more two methods, which is used Extended Kalman Filter and Unscented Filter.

The CMOS camera also had some problems. The images were blurred because of the shutter speed. It was caused by signal processing speed by H8 micro computer. It was improved by using FIFO. In addition, the size of images was upgraded to (640 x 512) from (320 x 256).

This satellite has program update and upload functions, which is unique for nano-satellite. So we can apply many control algorisms which are suggested for magnetic torque control.

4. SUMMARY

LSS developed the Cute-1.7+APD nano-satellite, pursuing a new design methodology of nano-satellites and providing space use opportunity. The satellite was launched on Feb. 2006 and conducted initial operation, COTS devices use in space, attitude determination, and cooperation with ham operators for two months. The next satellite has been developed aiming the same objectives and using the modified design of the first satellite. The launch of the second satellite planned in 2008.

References

I. Y. Bar-Itzhack
"REQUEST - A recursive QUEST algorithm for sequential attitude determination" Journal of Guidance, Control, and Dynamics 1996 0731-5090 vol.19 no.5 (1034-1038)

Kuniyuki Omagari, Kazuya Konoue, Naoki Miyashita, Masafumi Iai, Hideyuki Yabe, Katsutoshi Imai, Kei Miyamoto, Shinji Masumoto, Thomas Iljic, Ken Fujiwara, Takeshi Usuda, Yasumi Konda, Saori Sugita, Tomio Yamanaka, Saburo Matunaga (2006)
"Tokyo Tech Second Nano-Satellite Cute-1.7 + APD and its Flight Operation Results", The 57th International Astronautical Congress. Valencia, October 2-6, 2006.

Masafumi Iai, Hirotaka Sawada, Koji Nakaya, Kyoichi Ui, Naoki Miyashita, Munetaka Kashiwa, Nobumasa Yamaguchi and Saburo Matunaga. (2004a)
"Orbital Data Analysis of Picosatellite CUTE-I," 24th International Symposium on Space Technology and Science, Miyazaki, June 1-6, 2004, 2004-f-08

Masafumi Iai, Kazuya Konoue, Koji Nakaya, Kyoichi Ui, Naoki Miyashita, Masashi Asami, Wataru Miyazawa, Kuniyuki Omagari, Yusuke Funaki, Katsutoshi Imai, Kei Miyamoto, Hideyuki Yabe, Ken Fujiwara, Shinji Masumoto, Takeshi Usuda and Saburo Matunaga (2004b)
"A PDA-Controlled Pico-Satellite, Cute-1.7, and its Radiation Protection," The 18th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 9-12, 2004.

Naoki Miyashita, Masafumi Iai, Kuniyuki Omagari, Katsutoshi Imai, Hideyuki Yabe, Kei Miyamoto, Thomas Iljic, Takeshi Usuda, Ken Fujiwara, Shinji Masumoto, Yasumi Konda, Saori Sugita, Tomio Yamanaka, Kazuya Konoue and Saburo Matunaga (2005)
"Development of Nano-Satellite Cute-1.7+APD and Its Current Status," 56th International Astronautical Congress, Fukuoka, Oct. 17-21, IAC-05-B5.6.B.06, 2005.

Naoki Miyashita, Masafumi Iai, Kuniyuki Omagari, Katsutoshi Imai, Hideyuki Yabe, Kei Miyamoto, Thomas Iljic, Takeshi Usuda, Ken Fujiwara, Shinji Masumoto, Yasumi Konda, Saori Sugita, Tomio Yamanaka, Kazuya Konoue, Hiroki Ashida and Saburo Matunaga (2006)
"DEVELOPMENT AND FLIGHT REPORT OF PICO-SATELLITE Cute-1.7 + APD", 25th International Symposium on Space Technology and Science, Kanazawa, June 4-11, 2006, 2006-f-08

Ken Fujiwara, Kuniyuki Omagari, Thomas Iljic, Shinji Masumoto, Yasumi Konda, Tomio Yamanaka, Yohei Tanaka, Masaki Maeno, Taihei Ueno, Hiroki Ashida, Junichi Nishida, Takuro Ikeda, and Saburo Matunaga
"TOKYO TECH NANO-SATELLITE CUTE-1.7 + APD FLIGHT OPERATION RESULTS AND THE SUCCEEDING SATELLITE"

Web
Cute-1.7 + APD#1
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Cute-1.7 + APD#2
http://lss.mes.titech.ac.jp/ssp/cute1.7/index.php