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A PDA-Controlled Pico-Satellite, Cute-1.7, and its Radiation Protection

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ABSTRACT: A PDA-controlled picosatellite, named Cute-1.7, is being developed at Laboratory for Space Systems, Tokyo Institute of Technology and looking for a launch opportunity in 2005. PDAs, short for Personal Digital Assistants, and their peripheral devices are used as the primary computer and its interfaces in the satellite. The design of the satellite is based on the CubeSat standard, a 10cm cube of 1kg mass. The goal of our project is to facilitate small satellite development by allowing future small satellites to rely on high performance and easy-to-use commercial components, such as PDAs and Compact Flash card cameras. Secondary purpose of this project is to offer experiment opportunity of advanced magnetic torquers control algorithm in space, taking advantage of well-known operating system running on a PDA. Magnetic torquers is considered suitable for controlling small satellites so there are much work on advanced control algorithm of magnetic torquers, such as three axis stabilization.

INTRODUCTION

The second CubeSat of Laboratory for Space Systems, Tokyo Institute of Technology is being developed and looking for a launch opportunity in 2005. The satellite is named Cute-1.7 after the first one, named CUTE-I. 'CUTE' stands for '*Cu*bical *T*okyo Tech *E*ngineering Satellite.'

The Cute-1.7 project has two goals. The first one is to facilitate future microsatellite development by demonstrating a new design methodology. To realize it, there are three aspects to consider; reliable use of high performance and low cost commercial devices in space, practical SatelliteCore concept proposed here, and satellite disposal after the end of mission.

The second goal of the project is to share experiment opportunities using real satellite with space engineering researchers, students, and others. Cute-1.7 satellite is equipped with three magnetic torquers and has program upload functionality in order to enable on-orbit experiment about advanced control algorithm. Variety of those algorithms are proposed [3, 4].

In this paper, concepts and missions of Cute-1.7 picosatellite project is explained before description on radiation protection system and radiation test is given.

CONCEPTS AND MISSIONS

SatelliteCore Concept

When a new satellite is developed, several bus components, such as attitude sensors, a housekeeping unit, and mission systems are integrated. This is an effective way of development of satellites, but a more effective way should exist in the case of picosatellites. That is the SatelliteCore concept.

A satellite bus system is enclosed in a box. This box is a functional core of satellite, termed the "*SatelliteCore*". Then another box, called *a mission container*, is attached to the SatelliteCore to form a complete satellite. The SatelliteCore provides electrical power (3.3V, 5V, and unregulated) and USB connection to the mission container. Only a mission container is necessary to be newly developed when building a new satellite. This way of development will allow satellites with various missions, as in Figure 1, to be built in short period, avoiding repeated redesigning of bus systems.

Since the CubeSat standard is followed by many developers and adoption of the standard is likely to allow more launch slots to be found, the dimensions of the SatelliteCore is based on CubeSat standard[1]. The combination of the SatelliteCore and a mission container is a double CubeSat or larger.

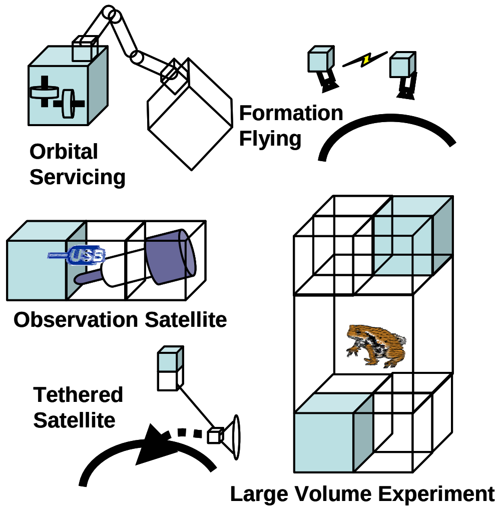

Figure 1 SatelliteCore Concept

It is easily noted that resulting satellites does not always have optimal features, such as attitude control capability, total mass. However, the SatelliteCore concept is intended to optimize cost and time because picosatellites have advantages of low cost, short production time, frequent access to space and therefore quick outcome, rather than other performance.

Laboratory for Space Systems, Tokyo Tech is currently developing two CubeSats. One is a single CubeSat for demonstration of the SatelliteCore bus system and attitude control experiment and the other a double CubeSat for performance evaluation of the avalanche photodiode (APD) charged particle detector. The development of the latter one is initiated by a request from a laboratory developing the detector. This detector will be put in a mission container, which will be connected to the SatelliteCore.

Use of PDA and its Peripherals

Use of commercial-off-the-shelf devices are accelerated in space applications. Our previous

CubeSat, CUTE-I, was all composed of commercial grade parts. Especially, its FM transmitter and receiver, which are commercial handheld transceiver, have functioned without any error for more than a year. Having this experience and having the objective to facilitate satellite development, in Cute-1.7 project, we are trying to be at the extreme end in terms of use of commercial products in a satellite. Cute-1.7 will depend on commercial finished products rather than only on commercial grade electric parts.

Its main computer is Personal Digital Assistant (PDA) in Figure 2, size of which is about 100mm x 70mm. Figure 3 shows thirty functional blocks in Cute-1.7. Thirteen blocks out of thirty rely on finished products sold at ordinary electric goods store, for example PDAs, memory cards, USB hub, digital cameras, handheld transceivers. In addition, PDA's operating system is Windows CE.NET 4.1 and primary communication line is USB, making the system friendly to potential satellite users.

Figure 2 Main Circuit Board of Hitachi NPD-20JWL

Of course, enough evaluation is required to make the total system reasonably reliable. Radiation protection circuitry and radiation test are some of methods to do so. In addition, careful study on how a failed component would affect other components is to be done in order to enhance survivability. We do not follow the convention of requiring extremely high reliability when developing a picosatellite.

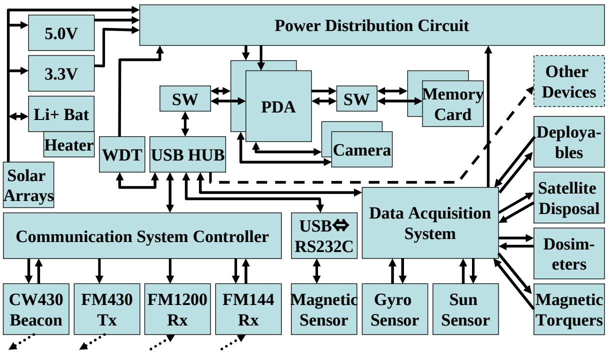

Figure 3 System Block Diagram

Attitude Control Experiment

To demonstrate various attitude control algorithm, such as three-axis stabilization, detumbling, and spin-up, with only magnetic torquers, Cute-1.7 is equipped with three magnetic torquers placed orthogonal to each other. Each torquer is a coil without iron core, whose dimensions are 50mm × 80mm × 4mm. Maximum magnetic moment is designed to be 0.037Am^2. Magnetic torquers have potential to be most useful actuator for such a tiny satellite. A magnetic torquer has no moving parts, requires only electricity and has structural simplicity. Nevertheless, control algorithm is a challenge, and therefore, it requires more study. Cute-1.7 will be a test bed for advanced magnetic torquer control, having capability of uploading control software.

The satellite's attitude determination system is composed of a three-axis gyrosensor, a three-axis magnetometer, a sun sensor and an earth sensor. The gyrosensor is a combination of three ADXRS gyroscopes by Analog Devices. The magnetometer is

HMR2300 by Honeywell. The sun sensor is of most primitive type that is photodiode arrays, S6560 by Hamamatsu Photonics, attached to the surface of the satellite. Earth sensor is a CMOS camera, FlyCAM-CF by Animation Technology, with a fisheye lens. Before making decision, other configurations of attitude sensor system was considered.

A star sensor seemed to be a preferable option because three-axis attitude determination is possible only with a star sensor. However, the area covered by the earth is an important consideration for low altitude picosatellite with less attitude control capability. At the altitude of 800km, the apparent diameter of the earth is 125°, which means that one fourth of a sphere about a satellite is covered by the earth. When a star sensor points to the earth, it cannot provide any data on attitude.

A CCD camera earth sensor with fisheye lens attached was also considered and selected finally. For the first idea, an ordinary camera with 50° of field of view was considered but was found that it can detect the edge of the earth image 36% of a sphere about a satellite. The larger field of view the camera has, the more effective area the sensor has. When the field of view is extended to 180° with a fisheye lens, the earth sensor can work as much as 75% of arbitrary attitude. This is equal to the percentage in the case of a star sensor.

Having the comparable size of the field of view, the earth sensor has advantage because a camera for star sensor should be so sensitive that it might be damaged by the light from the sun while one for earth sensor is not.

Table 1 Coverage of Earth and Field of View

Type of Image	Field of View	
	180° (Fisheye)	50°
Whole Edge	7%	0%
Part of Edge	68%	36%
Earth w/o Edge	0%	10%
No Earth	25%	54%

Message Box Functionality

Through the experiences of using amateur radio frequency to operate CUTE-I, CUTE-I operators recognized that cooperation with radio amateur community is important. A lot of telemetry data from CUTE-I owes contribution by radio amateurs. Cute-1.7 will have functionality as an on-orbit message box open to public with uplink in 1200MHz band and downlink in 430MHz band.

Since the satellite is planned to be inserted into low earth orbit, footprint of the satellite will not be so large and long distance communication via the satellite will not be possible. However, Cute-1.7 will enable communication between radio operators who are not in the same footprint simultaneously by storing and forwarding uploaded messages. Messages received by the satellite is stored and downlinked repeatedly for certain duration.

Satellite Disposal System

Cute-1.7 will be equipped with satellite disposal system. Small satellites are the satellites that are designed for short lifetime, and that are likely to be used as satellite constellation. The number of them should be large. Since the size of the proposed picosatellite is comparable to the smallest size catalogued by U.S. Space Command, it might be untraceable. The issue of satellite disposal may not, therefore, be left untackled. Guidelines by the Inter Agency Space Debris Coordination Committee (IADC) are requiring all satellites in low-Earth orbit to be de-orbited within no more than 25 years.

First, the use of air drag by a deployed balloon was considered. But simulation resulted in that a balloon with cross section of $110m^2$ would be required for the satellite to reenter in 20years. The mass of the balloon would be more than 1kg with the material density of the balloon $0.1kg/m^2$. It clearly means that this option is unrealistic for the proposed satellite.

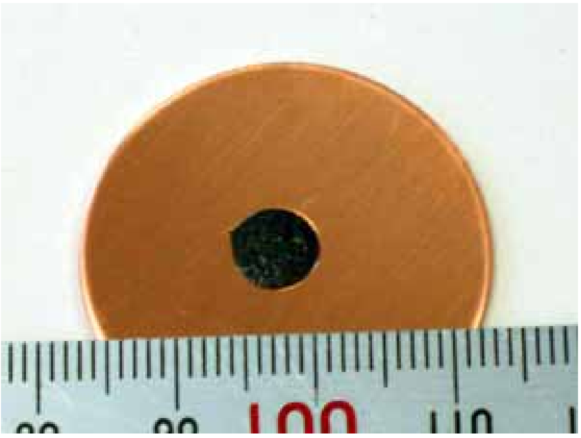

Figure 4 Prototype of Electron Emitter

Alternatively, the use of electrodynamic tether was studied. Simulation resulted in that a 100m electrodynamic tether with 0.2mA current flowing can deorbit the satellite in 25years, assuming the tether is always perpendicular to earth's magnetic field. Because a 100m tether does not generate enough voltage to achieve self-sufficiency, an additional power supply will be used to increase potential of the anode. The satellite deorbit system consists of a carbon nanotube electron emitter, a tether, a high voltage power supply and a tether end deployment mechanism. A prototype of the electron emitter, shown in Figure 4, is resin containing carbon nanotubes, pasted on the surface of a copper disk and its performance is being evaluated. Development of other parts is going as well.

RADIATION PROTECTION CIRCUIT

Radiation protection system of PDA consists of a double watchdog timer and over current protection. Assumption on which its design is based is that there is only a point affected by radiation over the circuitry at a time.

To prevent PDA from halting because of single event latch-up (SEL) or single event upset (SEU), double watchdog timer, shown in Figure 5, is used. When a SEL occurs, electric devices can only be recovered by power cycling. Although SEL can be detected by monitoring current consumption, current consumption of a computer varies depending on its CPU load. Simple thresholding is not always effective. Therefore, use of watchdog timers to initiate power cycling is decided. A watchdog timer is also capable of recovering a computer from system freezing caused by SEU. SEU is not destructive phenomenon but can cause software to freeze. When a computer freezes, power cycling can solve it as well.

Double watchdog timer is a combination of two watchdog timers and is able to protect itself. One is a watchdog timer in Loop 2 including the main computer and USB connection. Any failure in the devices surrounded by dashed lines in Figure 5 causes the watchdog timer to cut power to the main computer and others. The other watchdog timer is in Loop 1 to cut power to the real-time clock, DS2417, in case that the real-time clock does not work properly. Assuming that one failure happens simultaneously at most, this pair of watchdog timers can always protect the system. Any devices in Loop 3 are controlled and cut power, when necessary, by the main computer.

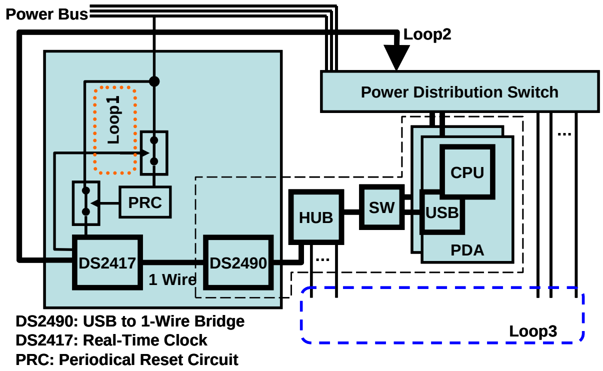

Figure 5 Double Watchdog Timer

RADIATION TEST

Radiation test was conducted using proton beam with energy of 60MeV and lower at Research Center for Nuclear Physics in Osaka University. PDA as a whole rather than a CPU was tested. Wide beam was used to cover about a quarter of PDA's circuit board.

Test Setup

Figure 6 is a block diagram of test setup. A PDA, NPD-20JWL by Hitachi, was irradiated by proton beam. The PDA ran two application programs during the test as shown in Figure 7. One was monitoring program that was continuously accessing its memory and communicating with PCs, which saved communication log to record errors during irradiating. The other was watchdog timer clear program that periodically cleared the counter of the watchdog timer. Before testing PDAs, beam profile and intensity were measured. Beam intensity was not uniform. It was 3×10^7protons/cm^2/s in higher intensity area and about 1×10^5protons/cm^2/s in lower area as shown in Figure 8.

During radiation tests, the above-mentioned two programs are running and the double watchdog timer is connected to the PDA, which is the device under test. The PDA communicates with PC in operators' room, showing whether the PDA works properly. When any error occurs, communication between the PDA and the PC is stopped but is expected to recover in a certain time if the watchdog timer works and the PDA is not damaged. Data sent by the PDA to the PC can be compared with the correct data in order to detect error data.

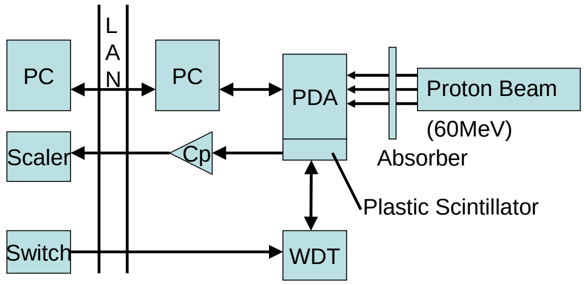

Figure 6 Radiation Test Setup Block Diagram

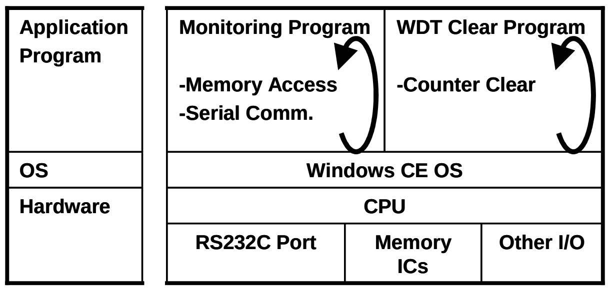

Figure 7 PDA System Configurations

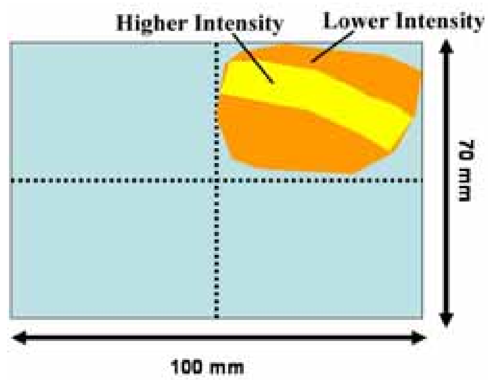

Figure 8 Beam Profile

Results

Fourteen tests with different parameters were conducted as listed in Table 2. Hard error here means an error unrecoverable by power cycling by the watchdog timer. Four PDAs are used. Test 1 to 9, where PDA1 was used and dose rate were 3×10^7proton/s/cm^2 resulted in no error.

In test 10, PDA 1 stopped sending data at 690s and did not recover despite power cycling by the watchdog timer. After replacing PDA1 with PDA2, test 11 was started. Data sending was interrupted three times; the first two interruptions at 110s, 580s was followed by recovering of PDA and the last one at 1075s resulted in unrecoverable error. Using PDA3, test 12 with the same parameters as test 10 reproduced the similar result with sooner unrecoverable error. With PDA 4, test 13, which is the same as test 11 except for lower dose rate, showed several unexpectedly changed bytes sent by the PDA at 180s, 2610s, and 2903s, but was finished without either restarting or unrecoverable error. Using the same PDA, test 14 showed unexpected byte changes at 260s and 685s as in test 13, and was halted because of mishandling.

Discussion

There are three error modes observed in those tests; 1)bit flip in data sent from PDA to PC, 2)communication between PDA and PC halted, and recovered by a watchdog timer (WDT), and 3)communication between PDA and PC halted, and not recovered by WDT. Error mode 1 indicates SEU in not critical data. But it should be noted that a computer system, rather than a single CPU or a memory chip, was irradiated in this experiment, and therefore a single observable error can have different causes, especially for error mode 2 and 3.

Error mode 2 can be a result of the following scenarios:

(2-a) SEL caused over current and voltage drop of power supply, or OS freezing. If the WDT initiated before PDA was destroyed, power cycling recovered PDA.

(2-b) SEU caused OS or only the WDT clear program to freeze and then WDT initiated power cycling before PDA restarted properly.

(2-c) SEU caused temporary delay in accessing memory chips or I/O devices, which can be recovered without doing anything, and then WDT initiated unnecessary power cycling before PDA restarted properly.

For error mode 3, possible scenarios are:

(3-a) SEL permanently damaged PDA.

(3-b) SEU caused only the monitoring program to freeze. Therefore, communication stop is observed but WDT does not initiate power cycling, resulting in no recovery.

(3-c) SEU caused bit flips in ROM, which stores OS and data essential to reboot. Thus, the PDA cannot restart even if the WDT works.

Both modes can be caused by both SEU and SEL. Although SEU results in error mode 3 as in (3-b) and (3-c), (3-b) is ruled out because none of PDAs could restart after each experiment. As it is difficult to distinguish real cause of each observed error modes, recoverable errors are interpreted as SEU and unrecoverable errors as SEL. Cross section was calculated as shown in Figure 9.

The resulting plot of cross section shows that SEU cross section is $\sim10\times10^{-10}$cm^2, and SEL, $\sim10\times10^{-11}$cm^2. In 800km circular orbit and in 330km-480km orbit, SEU would occur once every two years and once every thirty years respectively. Those probabilities are low enough for Cute-1.7 to function correctly for about a year. It has been concluded that use of PDA in Cute-1.7 is justified in terms of proton induced single event effects. In addition, it was demonstrated that the double watchdog timer protected PDAs as it is designed to do.

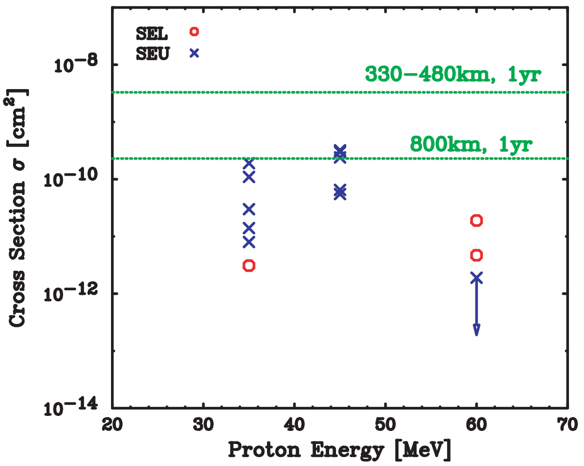

Figure 9 Cross Section for PDA

Table 2 Radiation Test Log

Test	Block No.	E/ MeV	Rate/* p/s/cm^2	Time/ s	Result** (E1,E2,E3)
1	F-1	60	3×10^7	2000	No Error
2	F-2	60	3×10^7	2000	No Error
3	F-3	60	3×10^7	2000	No Error
4	F-4	60	3×10^7	2000	No Error
5	B-2	60	3×10^7	2000	No Error
6	B-1	60	3×10^7	2000	No Error
7	B-1	60	3×10^7	2000	No Error
8	B-4	60	3×10^7	2000	No Error
9	B-3	60	3×10^7	2000	No Error
10	F-2	60	3×10^8	2000	(0, 0, 1)
11	F-2	35	3×10^8	2000	(0, 2, 1)
12	F-2	60	3×10^8	2000	(0, 0, 1)
13	F-2	35	3×10^7	3000	(3, 0, 0)
14	F-2	45	3×10^7	2000	(2, -, -)

*: Unit of Dose Rate is protons/s/cm^2.

**: E1, E2, and E3 is error mode 1, 2, and 3.

CONCLUSIONS

We have explained concepts and missions of a picosatellite, Cute-1.7, where PDA and its peripherals are used to build a satellite to reduce development time. To ensure PDAs can function in space, radiation protection circuitry was developed, and radiation test at RCNP, Osaka University was conducted. Test results showed that PDAs have low probability of SEU or SEL, which is acceptable.

Also the SatelliteCore concept is introduced, based on which Cute-1.7 and its derivative are being developed. The concept is optimized in terms of cost and time, which are attractive points of picosatellites, sacrificing other performances. In fact, that derivative of Cute-1.7 will be a satellite for demonstration of a newly developed APD charged particle detector.

Other missions including satellite disposal system using the carbon nanotube electron emitter and message box functionality to serve amateur radio community are described.

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