CANYVAL-X Mission Development Using CubeSats

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1 Introduction

Current space telescopes have a single structure, and consequently, their focal length cannot be increased sufficiently. Sometimes, this problem may prevent the improvement of the resolution of the telescope. To solve this problem, the concept of virtual telescope has been proposed. A virtual telescope consists of two spacecraft: one has a lens system and the other has a detector system. By using formation flying, the two spacecraft can be simplified as a virtual telescope system. Then, their relative orbit distance can serve as a baseline for the virtual telescope system [1, 2]. The most important issue in a virtual telescope is to perform inertial alignment with respect to a celestial object and to maintain it in space. Inertial alignment means that the relative position and relative attitude of the two spacecraft are simultaneously aligned with a target.

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Yonsei University's Astrodynamics and Control Laboratory (ACL) and NASA's Goddard Space Flight Center (GSFC) have collaborated in a study to resolve the abovementioned limitation of existing space telescopes. In this study, they developed and demonstrated the core technology of a virtual telescope with the CANYVAL-X (CubeSat Astronomy by NASA and Yonsei using Virtual telescope ALignment eXperiment) mission.

2 Overview of CANYVAL-X Mission

The CANYVAL-X mission consists of two CubeSats: one serves as the lens satellite and the other as a detector for satellite movement in a virtual telescope. The primary mission objective of CANYVAL-X is to build an inertial alignment system for the virtual telescope with respect to the target object (the Sun) during a few minutes by using two CubeSats, Tom (2U) and Jerry (1U). The secondary mission objective is to provide an opportunity for CubeSat development and flight operation by students. The objective of this mission is not to observe the Sun directly but to test the required technology for the virtual telescope system in space. The experimental result can be used for subsequent science demonstrations such as CANYVAL (CubeSat Astronomy by NASA and Yonsei using Virtual telescope ALignment) [2] and the Solar X-ray Imager mission [3]. The two CubeSats for the CANYVAL-X mission will be launched in June 2016.

3 Core Technologies for CANYVAL-X Mission

For constructing vision alignment in space, first, Tom needs the position information of Jerry in the Earth-centered inertial (ECI) frame. Next, Tom approaches Jerry and maintains a distance of 10–50 m, which allows the operation of the vision alignment system. Finally, Tom and Jerry will perform inertial alignment by using relative orbit control. To minimize orbit control, the two CubeSats will be launched as one entity from a CubeSat deployer. Then, Tom and Jerry will be separated by a satellite separation device when the mission conditions are satisfied. For these sequences, Tom and Jerry use the (1) vision alignment system, (2) relative orbit determination system, (3) relative orbit control system, and (4) satellite separation system.

3.1 Vision Alignment System

This mission uses a vision alignment system that can determine the relative position and relative attitude between the two CubeSats simultaneously. In this system, laser

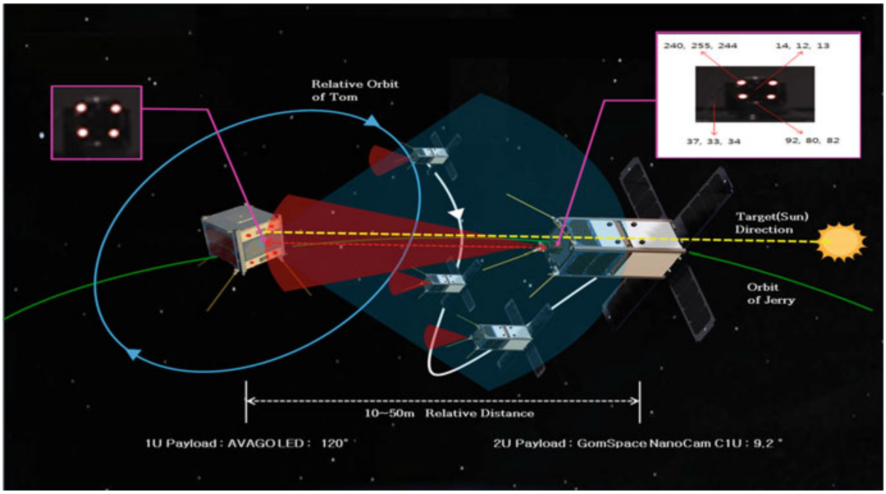

Fig. 1 Concept of inertial alignment system of CANYVAL-X

beacons are installed in Jerry and one visual camera is installed in Tom. Tom detects the laser diode projection images to determine the relative position and relative attitude between the two CubeSats. In the vision alignment mode, Jerry will fix its attitude for the laser diodes on Jerry such that they look at the Sun. Then, Tom will interrupt this line between Jerry and the Sun and will maintain the inertial alignment between Jerry, Tom, and the Sun for a few minutes. For this purpose, Tom will fix its attitude with respect to the Sun and will control its position in the transverse plane of Jerry and the Sun alignment by using the reaction wheels and thrusters (Fig. 1).

3.2 Relative Orbit Determination System

If Tom wants to approach Jerry, it needs to know Jerry's current position, velocity, and time information. The two CubeSats can each determine the absolute orbit by using GPS. After calculating the absolute orbit, Jerry sends the information to Tom via a UHF crosslink. Then, Tom receives this data along with the differential. UHF communication is also used for telemetry and telecommands between the ground station and the CubeSats. For this purpose, the main frequencies of the two satellites were selected to have a difference of 0.02 MHz. This difference can be identified by the ground station, and it enables communication with the same UHF transceiver (Fig. 2).

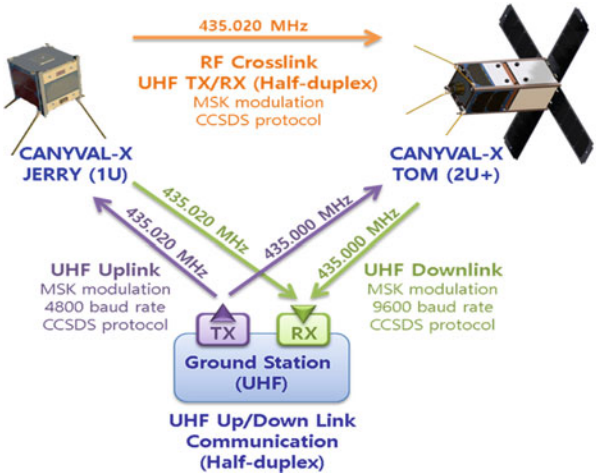

Fig. 2 CANYVAL-X communication system

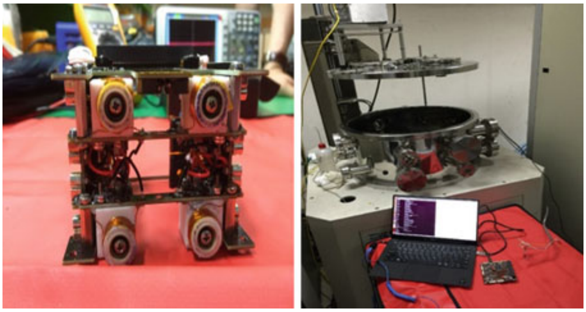

Fig. 3 Configuration (*left*) of mCAT and vacuum test setting (*right*)

3.3 *Relative Orbit Control System*

For orbit control in close proximity, Tom uses a micro cathode arc thruster (mCAT), a low-thrust electric propulsion system developed by the George Washington University [4] and tested by NASA's GSFC. The thruster system has four nozzles. The maximum impulse of each nozzle is 0.05 mNs. To obtain sufficient impulse, the four nozzles are located on the same axis of the body frame. If Tom needs to perform orbit control, it first uses a three-reaction-wheel system for attitude control for thrust direction and then fires the proper thrust in each sampling time step. Figure 3 shows the configuration of mCAT and the result of plasma firing in a vacuum chamber at 25 Hz.

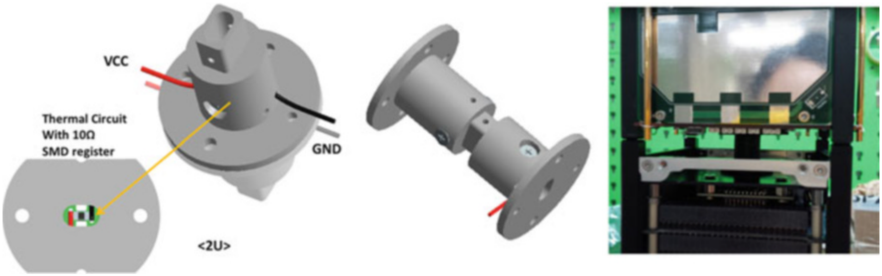

Fig. 4 Separation device system

3.4 *Satellite Separation System*

If Tom and Jerry are not one entity, they will gradually move away at a rate of 4.55 km/rev because of orbital perturbations. A separation device system is used to tie the two CubeSats. Each satellite has a separation device mounted on the z-axis of the body frame. Tom's mounting system consists of an electrical wire and 10-Ω heat resistor. The two satellites are bound by using a high-tension dynamo wire that melts easily under high temperature (Fig. 4). Tom sends a command to initiate the switch at a voltage of 7.8 V. Then, the heat resistor is heated, thereby melting the wire and disconnecting the system. Consequently, Jerry's kill switch spring ejects Tom. This separation device is activated when the attitude of the coupled satellite is oriented and aligned in a proper direction to minimize the relative distance between the satellites after separation (Fig. 4).

4 Spacecraft System

The CANYVAL-X mission needs to develop two cube satellites for testing the basic technologies of a virtual telescope in orbit. Limited resources are available for its development. Consequently, the development philosophy of this mission follows the proto-flight philosophy, in which one proto-flight model is developed (Fig. 5). The CANYVAL-X system uses many COTS (commercial off-the-shelf) products and several devices that were developed in-house, such as the solar panels, magnetic torquers, separation device, deployer devices, coarse and fine sun sensors, and thruster assembly. The mission lifetime is 3 months, and both CubeSats need a three-axis attitude control system and absolute orbit determination system. The flight software of Tom and Jerry are developed in the free RTOS (real-time operation system) for embedded system programming, which is simple and robust. An I2C (inter-integrated circuit) via a PC-104 connector serves as the main data communication system. PWM, UART, and SPI are used for sensor data connections and actuator control. Fig. 6 shows a system interface diagram of the two CubeSats.

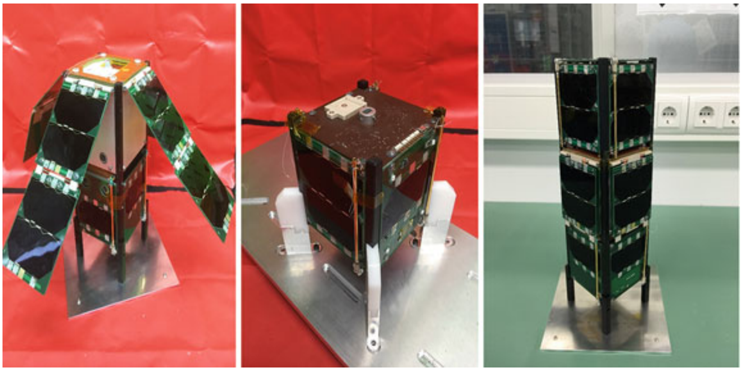

Fig. 5 Configuration of Tom (*left*), Jerry (*middle*), and coupled Tom and Jerry (*right*)

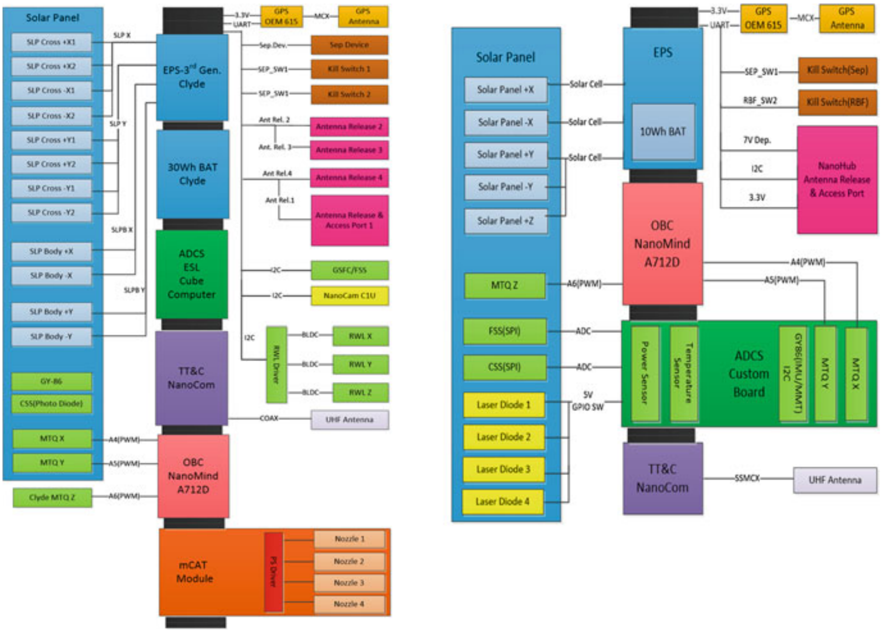

Fig. 6 System interface diagram of Tom (*left*) and Jerry (*right*)

4.1 *Jerry (1U)*

In this mission, Jerry serves as a marker for vision alignment. Jerry's payload consists of laser LEDs with 120° field of view. In the vision alignment mode,

Table 1 System performance of Jerry

Properties	Value	
	Requirements	Performance
Mission lifetime	3 months	
Payload	Laser diodes	
Payload field of view	>15.5°	120° (±60°)
Relative orbit control	N/A	
Relative orbit determination	N/A	
Attitude control	<5°	<5°
Attitude determination	<5°	<5°
Frequency	UHF	435.020 MHz
Uplink rate	4.8 kbps	4.8 kbps
Downlink rate	9.6 kbps	9.6 kbps
Link margin	>4.00 dB	>5.51 dB
Protocol	CSP (CubeSat space protocol)	
Mass	<1.33 kg	0.81 kg
Power generation	1.8 W	2.0 W
Deployment	Antenna	

Jerry turns on its LEDs and orients itself with respect to the Sun for the vision alignment system. For the three-axis attitude control, Jerry uses magnetic torquers for attitude control in each axis. X- and Y-axis controls are performed using rod-type magnetic torquers, and Z-axis control is performed using a PCB-type torquer. Four photodiodes serve as a coarse sun sensor and one fine sun sensor; these are located on each solar panel for attitude determination. Jerry sends the position, velocity, and time information of the ECI frame to Tom every 5 min using intersatellite links with a UHF crosslink. Tom uses this data for differential orbit determination for relative orbit determination. Table 1 shows the system characteristics of Jerry.

4.2 Tom (2U)

Tom's payload consists of a visible camera for detecting Jerry's laser beacon. It has a 610–660 nm bandpass filter to eliminate ambient light. Tom mainly uses a three-reaction-wheel assembly for attitude control. It also has magnetic torquers for each of the three axes to dump the angular momentum of the wheels. For precise attitude determination in the vision alignment mode, it uses the fine sun sensor developed by the GSFC. Tom performs many mission procedures. In particular, mCAT, the reaction wheel system, GPS, and camera are activated simultaneously in 10 min to perform the inertial alignment of the virtual telescope with respect to the Sun.

Table 2 System performance of Tom

Properties	Value	
	Requirements	Performance
Mission lifetime	3 months	
Payload	Visible camera	
Payload field of view	>7.50°	9.22°
Relative orbit control (20 m)	<1 m	<1 m
Relative orbit determination	±10 cm	±10 cm
Attitude control	<1°	<1°
Attitude determination	<1°	<1°
Frequency	UHF	435.000 MHz
Uplink rate	4.8 kbps	4.8 kbps
Downlink rate	9.6 kbps	9.6 kbps
Link margin	>4.00 dB	>5.51 dB
Protocol	CSP (CubeSat space protocol)	
Mass	<2.66 kg	2.25 kg
Power generation	2.2 W	2.5 W (normal) 13.0 W (pointing toward sun)
Deployment	Antenna, solar panel	

To accomplish this, Tom generates sufficient power using a cross-type solar panel. To prevent interference with the UHF antenna, Tom's solar panels use a double deployable system. Table 2 shows the system characteristics of Tom.

5 Environment Tests

The development philosophy of CANYVAL-X mission follows PFM (proto-flight model) philosophy. PFM philosophy is conducting "proto-flight" environment test levels and durations with FM (flight model). The "proto-flight" test levels are equal to the "qualification" levels, while the "proto-flight" durations are equal to the "acceptance" duration. The characteristics and levels of the test level follow document ISILaunch09 campaign [5].

The test range of thermal vacuum is −10 to 40 °C (inner temperature) which contains on-orbit thermal simulation. The cycles of worst hot case and worst cold case were repeated two times for each CubeSat (Fig. 7). Table 3 shows characteristics details of the thermal vacuum test.

Tom and Jerry are tied with separation device system when they are in the CubeSat deployer. Therefore, the vibration test also has to be performed by one entity (Fig. 8). The main tasks of vibration consist of acceleration (quasi-static) test

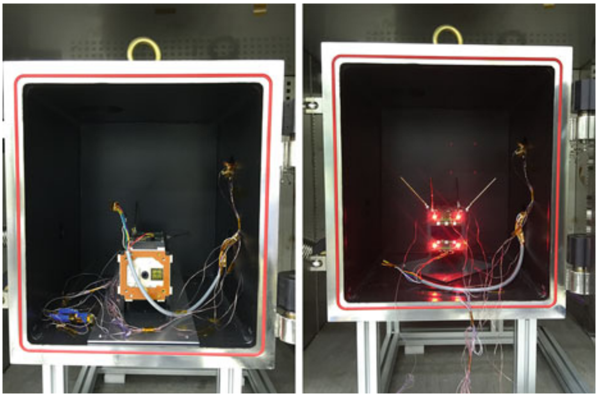

Fig. 7 Thermal vacuum test Tom (*Left*) and Jerry (*Right*)

Table 3 Characteristics details of thermal vacuum test

Properties	Value
Number of cycle	2 times
Soak duration (dwell time)	2 h
Temperature range	$-15 \sim +40\ ^\circ$C
Temperature transition rate	$\leq 2\ ^\circ$C/min
Stabilization condition	$\leq 3\ ^\circ$C/h
Pressure	$\leq 10^{-5}$ Torr

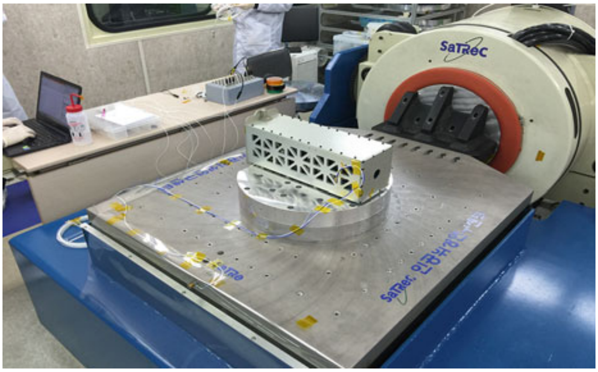

Fig. 8 Vibration test

and random vibration test. In addition, low-level sine sweep test was conducted before and after main tasks for searching the change of natural frequency. Table 4 shows characteristic details of the vibration test.

Table 4 Characteristic details of vibration test

Properties	Value
Resonance survey test level	
Directions	X, Y, Z
Type	Harmonic
Amplitude	0.4 [g]
Frequency range	5–2000 [Hz]
Sweep rate	2 [oct/min]
Tolerance	Alarm level: ±3dB Abort level: ±6dB
Acceleration test level	
Directions	X, Y, Z
Acceleration	+18.75 [g]
Centrifuge	30 [sec]
Sine burst	≥5 [cycles at full level]
Random vibration test level	
Directions	X, Y, Z
20 [Hz]	0.026 [g^2/Hz]
50 [Hz]	0.16 [g^2/Hz]
800 [Hz]	0.16 [g^2/Hz]
2000 [Hz]	0.026 [g^2/Hz]
RMS acc.	14.1 [g]
Duration	60 [sec/axis]

6 Conclusions

This study presents the concept and system of the CANYVAL-X mission. Tom and Jerry contain the basic technologies necessary for a virtual telescope. This study verifies that Tom and Jerry are well developed to satisfy the system requirements. The two CubeSats are ready to be launched and operated in 2016. The CANYVAL-X mission will serve as a baseline for a virtual telescope, which is expected to be the next-generation space telescope.

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