Development Status of Microsatellite HIBARI for Demonstration of Variable Shape Attitude Control

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ABSTRACT

We are developing a 50kg class microsatellite “HIBARI”. The main technical mission is the demonstration of a novel attitude control method called “Variable Shape Attitude Control (VSAC)”. VSAC is based on an idea to utilize a reaction torque generated by changing the shape of the satellite itself by driving solar array paddles with actuators. HIBARI is planned to be launched in fiscal year 2021 under “Innovative Satellite Technology Demonstration Program” led by JAXA. We are currently developing the EM of HIBARI and describes them in this paper. Specifically, the results of missions, systems, and various tests are shown and the validity is derived.

可変形状姿勢制御衛星ひばりの開発状況について

摘要

東工大では50kg級可変形状姿勢制御（VSAC：Variable Shape Attitude Control）実証衛星ひばりの開発を行なっている．VSACは太陽電池パドルを回転駆動させ発生した内部トルクで衛星本体の姿勢を変更する制御方式である．ひばりはJAXA革新的衛星技術実証2号機に採択され，2021年度内に打ち上げ予定である．現在EM開発フェーズであり，本稿ではひばりのミッション，各サブシステム概要，各種試験結果および開発スケを示した．

1. INTRODUCTION

In recent years, the number of micro/nano satellites and CubeSats has increased due to the miniaturization of electronic devices and the sale of dedicated components, and we can see a paradigm shift in the utilization of these small satellites for various business and scientific purposes. The mission requirements have become more advanced, such as astronomical observations, constellations and deep space exploration. However, there is a technical limit to the requirements that can be met by small satellites at present. This is especially noticeable in the attitude/orbit control systems and optics, as it is difficult to mount control moment gyro(CMG), propulsion systems and large observation systems due to limitation of volume and electric power. In order to solve this problem, it is necessary to make the on-board equipment multifunctional or downsize. We are paying attention on multi-functionalization, and are trying to realize a new control method to control the attitude/orbit by changing the shape of the satellite on orbit. The microsatellite HIBARI has an engineering mission to demonstrate this control method on orbit[1,2,3]. This satellite is currently under EM development and will be launched into low earth orbit by JAXA's “Innovative Satellite Technology Demonstration Program” in fiscal year 2021. This paper describes the mission, system and development status of the HIBARI.

2. VARIABLE SHAPE SYSTEM

By changing the system shape on orbit, three main things can be made possible as follows:

(1) attitude control using anti-torque generated by shape change[4,5,6,7].
(2) Orbit/attitude control by shifting to desired shapes and changing the external environmental forces such as atmospheric drag.
(3) Change of satellite function according to mission.

Figure 1 shows the concept of attitude control called VSAC (Variable Shape Attitude Control) of (1). The attitude of the satellite body is controlled by using a part of the system (e.g. solar array paddle) as a rotary drive actuator. Since this method does not require motor drive at all times, it has better energy efficiency than conventional wheels. Also, by increasing the mass of the driving structure, the attitude change angle can be increased. This enables agile attitude control as the inertia of the system is increased, which makes stability control easier than previous methods. In addition, by using control under Non-Holonomic constraints, the satellite attitude can be changed while restoring the shape. By repeating such nonholonomic sequence, it is possible to change to any 3-axis attitude, exceeding the limit of the attitude change angle due to the drivable range of the paddles.

Figure 2 shows the concept of orbit/attitude control described in (2). Generally, atmospheric resistance and solar radiation pressure are considered as control disturbances. However, it is possible to control the orbit/attitude by paying attention to the fact that the amount and direction of these disturbances change depending on the system shape. By actively changing the shape and utilizing these external forces, orbit/attitude control can be made possible. For example, it can be applied to de-orbit and formation flight utilizing atmospheric resistance in low earth orbit. Also, external torque can be used for unloading of Reaction Wheel.

(3) can be applied not only to changing the observation mode due to deformation of the optical system, but also to thermal control by creating sunshade and changing the surface area. This will not be demonstrated on this satellite, but will be demonstrated on Transformable Spacecraft proposed by JAXA/ISAS[8].

In this satellite, the driving object for changing the shape is a solar array paddle with a power generation function, realizing a more multifunctional actuator. This will lead to system simplification, cost reduction, and mission diversification.

3. MISSION DESIGN

We set the success criteria in Table 1 with the agile and large-angle attitude control as the main mission of HIBARI. In the minimum success, we confirm that the attitude changes actively by driving the paddles with motors. In full success, we confirm the agility of VSAC. The performance target is 20deg/10sec (maneuver 20deg within 10sec). This is the performance equivalent to CMG for microsatellite. In Extra Success, the performance target is agile attitude change of 40deg/10sec, stable attitude control of 300arcsec/1sec (keep the attitude change within 300 arcsec or less for 1sec), and large angle attitude change of 40deg or more using non-holonomic characteristics. In addition, stable control is performed in combination with RW, and the target is 300arcsec/10sec. In addition, we will also demonstrate orbit/attitude control using atmospheric resistance as extended operation.

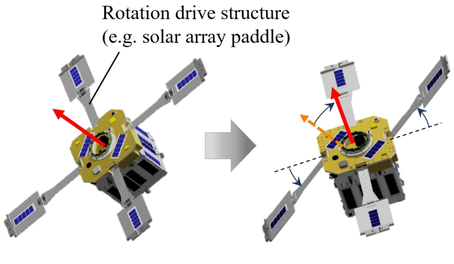


Fig 1: Concept of VSAC

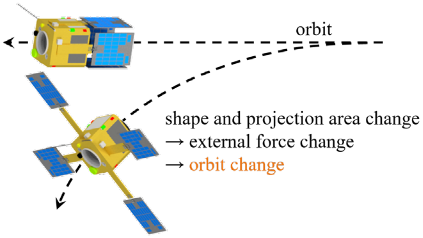


Fig 2: Orbit Control using External Force

Table 1: Success Criteria

Level	Mission
Min.	• Confirm attitude change predicted by variable shape function of motor drive
Full	• VSAC ○ Agility: 20deg/10sec ○ Pointing Accuracy: 5deg
Extra	• VSAC ○ Agility: 40deg/10sec ○ Stability: 300arcsec / 1sec ○ Large-Angle Maneuver using Non-Holonomic Control: 40deg • Cooperative control with RW ○ Stability: 300arcsec / 10sec • confirmation of orbit/attitude change with controlled atmospheric resistance

4. MODE OF OPERATION

Figure 3 shows the mode transition of HIBARI. The satellite first performs detumbling and spin-sun pointing using MTQ as critical modes. After establishing communication with the ground, we check out each device such as camera and RW. After that, the paddle is deployed while monitoring with a wide-angle camera. Since the deployment involves motor drive, it is positioned as a part of minimum success.

After the paddle is deployed, zero momentum sun pointing using MTQ is performed to prepare for the mission. In mission mode, VSAC only experiments are performed first, and then cooperative experiments with RW are performed. These are carried out in the shade due to the requirement of STT accuracy and thermal stability. Also, Nadia Pointing is set as the nominal mode when driving RW.

When power shortage or device anomaly is detected during operation, the satellite autonomously shifts to safe mode and performs processing according to the anomaly while sun pointing.

Furthermore, when the battery voltage becomes lower than the threshold value, the battery protection mode is entered. In this mode, all power except the battery are cut off, and the attitude will not be controlled.

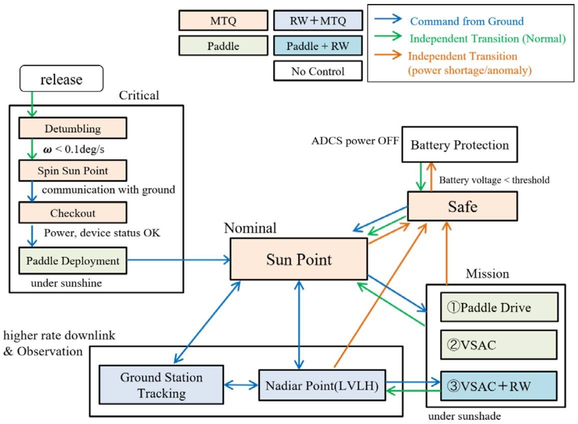


Fig 3: Mode Transition Diagram

5. SYSTEM DESIGN

Figure 4 shows the HIBARI system diagram. The subsystem consists of the following: CDH (Command & Data Handling), COMM (Communication), ADCS (Attitude Determination & Control System), EPS (Electric Power System), Camera system, Structure and Thermal.

A common MPU is placed in each subsystem, which monitors the inside of each system. Then, CDH monitors each system's MPU. By making the MPU common, development costs are reduced, defects are simplified, and the burden of CDH system is reduced. Through the radiation test, this MPU has determined that there is no permanent radiation damage.

Other equipment is basically selected based on radiation tests and on-orbit performance. Most bus devices meet the CubeSat standard, and we are developing a standard bus applicable to CubeSat.

Figure 5 shows an external view of HIBARI. The paddle is folded to meet the loading requirements of the Epsilon rocket, and its size is 600 x 600 x 500mm. The satellite bus has a mass of 35 kg, with four paddles mounted, weighing 2.5kg each.

The planned orbit is a sun-synchronous orbit with an altitude of 560 km and Local sun time at descending node of 9:30.

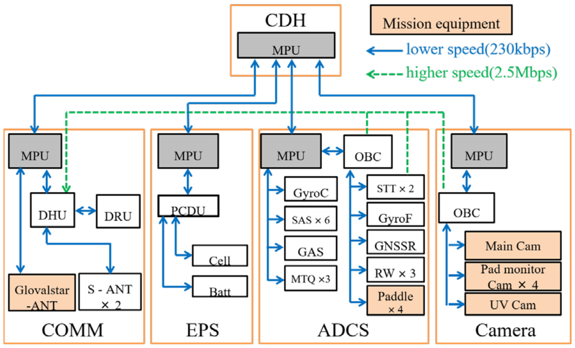
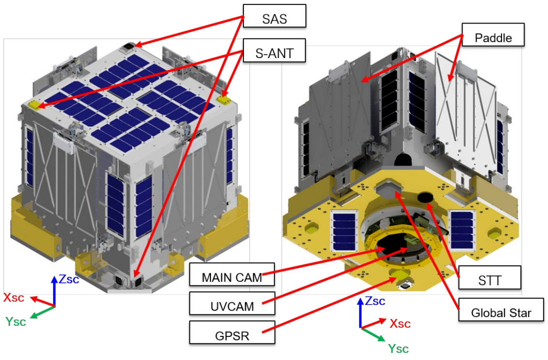
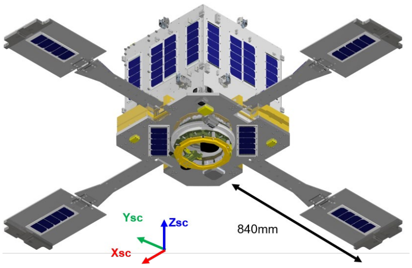


Fig 4: System Diagram



(a) Launch Configuration



(b) On-orbit Configuration

Fig 5: External View of HIBARI

5.1 Structure

The structural system is designed to meet the requirements for mass, center of gravity, rigidity, envelope area from rocket, and layout requirements for each device. As a result of the eigenvalue analysis, the machine axis direction is 45.7 Hz and the machine axis orthogonal direction is 86.5 Hz, which satisfies the rocket requirements. During the strength analysis of static load, sine wave, and random load was performed, the stress distribution was as shown in Figure 6, and it was confirmed that the safety margin exceeded 0 in all cases.

Figure 7 shows the internal structure of the paddle drive unit. The internal actuator is housed in a box and connected to the satellite structure to protect it from the external environment. It is necessary for the satellite to detect the rotation of the output shaft, including the backlash of the planetary gears, and determine the origin of the motor. Therefore, in addition to an encoder for the motor control, an absolute encoder is used on the output shaft side. As shown in Figure.8, the paddle is deployed by the hinge and motor drive.

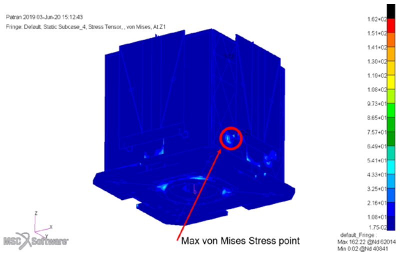


Fig 6: Strength Analysis

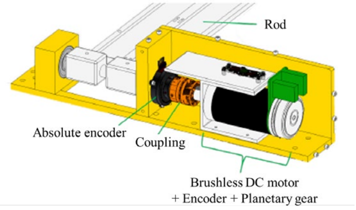


Fig 7: Paddle drive structure

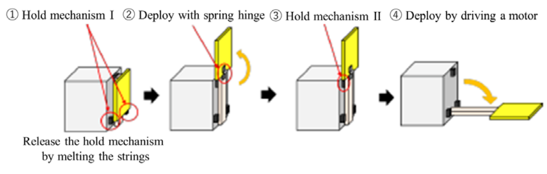


Fig 8: Paddle deployment sequence

5.2 CDH&COMM

The CDH collects and confirms HK (House Keeping) data of each subsystem, manages operation mode, and processes command and telemetry. The abnormality of each subsystem is detected from the HK data, and the operation mode is switched according to it. It also manages the satellite internal time and regularly synchronizes the time with each subsystem.

There are two types of communication devices, S band and Global Star communication. The S-band is a nominal communication system that receives commands from the ground and sends HK data and experimental data to the ground. For command reception and HK data transmission, in order to establish communication regardless of the attitude of the satellite, two transmitting and receiving antennas are installed so that the entire sky can be covered. Also, the receiver is always turned on so that commands can be received even when an error occurs. Since the transmission of experimental data is a high bit rate communication, ground station tracking is required. Global Star is used for demonstration of real-time communication with the ground for future sudden astronomical observation.

5.3 ADCS

The ADCS is composed of a coarse attitude system with a highly reliable MPU and a fine attitude system with a OBC capable of high-speed computation. Each device is purchased or developed as shown in Table 10. The coarse attitude system is used for backup of the precise attitude system when reliability is required more than the accuracy in critical mode or safe mode. The precise attitude system is used during missions where accuracy is required. Each of them performs attitude control processing as shown in Figure 9, and is designed so that the coarse system functions as a backup even if the fine system freezes or fails.

The data in ADCS is basically processed as telemetry via CDH, but a huge amount of data is acquired during a mission, so a high-speed communication line that can be directly sent to the COMM system is separately prepared (green line in Fig 4).

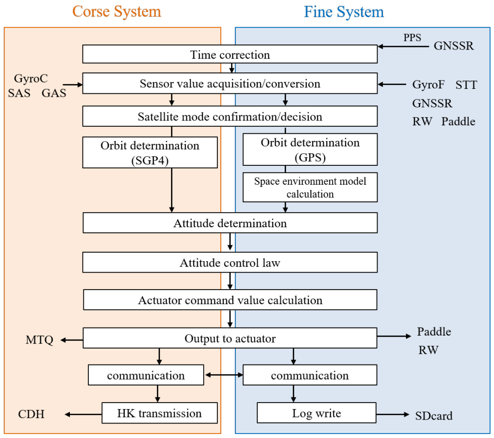


Fig 9: ADCSMain loop processing

6. TESTING

6.1 BBM/EM Elec Integration Test

We conducted BBM electrical integration test by CDH system, communication system, EPS, ADCS. Figure 10 shows the situation during the test.

The following items were confirmed.

- Supply appropriate power from EPS to each subsystem device and operate for a long time.
- MPU of each subsystem can acquire HK data from each device
- CDH MPU can acquire and process HK data from each subsystem MPU.
- The HK data processed by CDH can be transmitted by COMM and received by the simulated ground station without loss.
- Simulated mission data can be transmitted from CAM-OBC to the simulated ground station.

- CDH can receive the command sent from the simulated ground station and send the command to MPU of each subsystem.

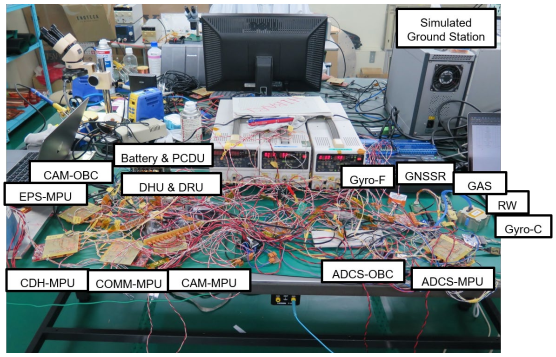


Fig 10: BBM test configurations

6.2 Paddle Deployment/Driving Test

A paddle deployment test using BBM was performed and it was confirmed that it could be deployed on the ground. In the deployment test, the effect of the weight of the paddle of the BBM cannot be ignored, so the paddle was hung with a gut for gravity compensation. During the test, the panel was folded by hand and then released. At this time, the rod is fixed. The time history of the deployment angle of the spring hinge was obtained by motion-capturing this behavior using OptiTrack. Figure 11 shows the appearance of the actual test at this time.

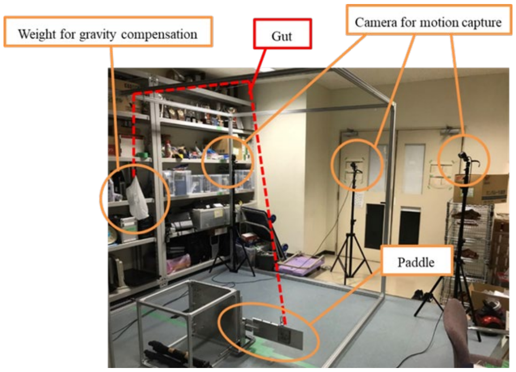


Fig 11: Paddle deployment test

6.3 Antenna Pattern Test

In HIBRI, the shield environment of communication radio waves fluctuates in orbit as the paddle is deployed and driven. Therefore, we measure antenna patterns according to various satellite shapes (paddle angles) and confirm that a sufficient line margin can be secured. Figure 12 shows the appearance of the test configurations. The paddle can simulate the shape before and after deployment (paddle angle 0deg, +90deg, -90deg). The antenna is mounted at a position corresponding to the actual configuration, and the radiation pattern is measured in an anechoic chamber.

As a typical measurement result, Figure 13 shows the radiation pattern of the transmitting antenna when the paddle angle is at 0deg and +90deg. Attitude angle represents the angle of deviation from the normal of the antenna mounting surface, and is measured on two planes, horizontal and vertical. In consideration of the line calculation, it was found that a line of 10 kbps communication was established in any attitude when the paddle angle was 0deg, but it was found that it was established only in a limited range at +90 deg. This is because the paddle has a non-negligible effect as a radio wave shield. Since the angle is always +90deg when the paddle is deployed, it is necessary to make a design change so that the paddle does not act as a shield in order to ensure a secure line, and it is currently under consideration. In addition, in other cases, it was confirmed that it is likely that a sufficient line would be established for both the uplink and downlink.

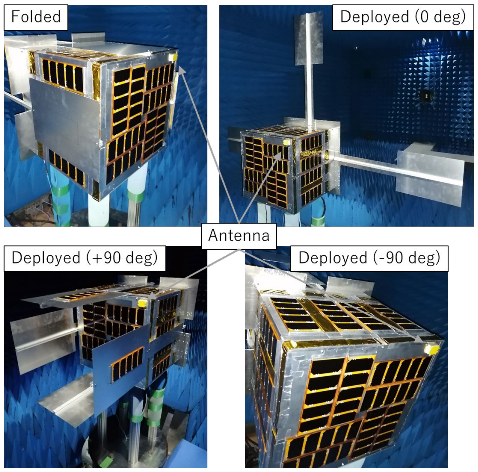


Fig 12: Antenna pattern test configurations

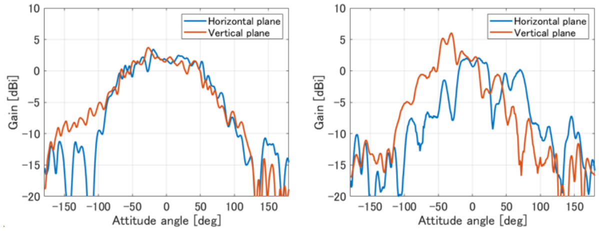


Fig 13: Antenna pattern test results of Tx antenna (left: deployed 0deg, right: deployed +90 deg)

7. DEVELOPMENT PLAN

Figure 14 shows the development schedule. Currently, development is delayed due to the influence of COVID-19, but we are planning to conduct an EM vibration test in September and an EM thermal vacuum test in

November. After that, we will shift to FM development and launch within FY2021.

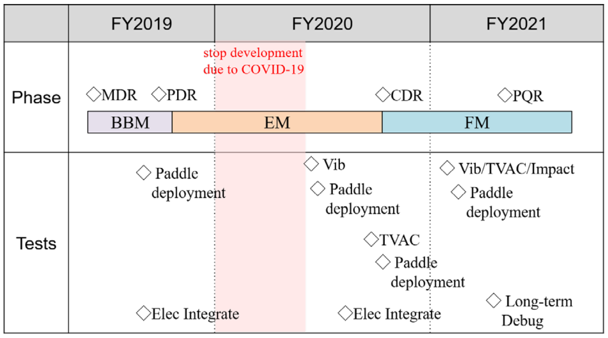


Fig 14: Development schedule

8. CONCLUSION

We are developing a 40kg microsatellite "HIBARI", which will demonstrate a novel attitude control method called VSAC. This paper described the mission, system, and various tests. HIBARI is planned to be launched within FY2021. Currently in the EM development phase, and we are planning on developing the FM this year.

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