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Development and evaluation of the 1/30U small-sized 3-axis attitude control module, and its application for the JEM Internal Ball Camera Robot

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ABSTRACT

In this paper, we propose the 1/30U small-sized 3-axis attitude control module. The idea of using an electrical circuit board as a structural component reduces the mass of the mechanical structure and the electrical wiring as well. Adapting the System-On-Chip (SoC) reduced the circuit area while maintaining the complexity of the electric circuit. We managed to develop an attitude control module measuring 31 mm in size and 88 g in weight. This module contains 3-axis reaction wheels, six MEMS-IMU sensors (18-axis acceleration and 18-axis gyro), and an attitude control computer. The module only requires a power supply and external serial communication. The module can also be connected to other navigation sensor. And by adding the extension circuit, this module can drive and control 12 actuators, such as micro thrusters. An on-orbit evaluation was conducted with the JEM Internal Ball Camera Robot as the control system for robot position and attitude. The robot is an autonomous maneuverable ball-shaped camera that is operated by ground operators. Twelve micro fans and the proposed module are integrated inside the robot to realize 6-axes maneuvering, and a navigation camera provides the robot's relative position and attitude to a target marker. This paper discusses an evaluation of attitude control accuracy to reveal the module's on-orbit performance.

INTRODUCTION

In this paper, we describe the development of a miniaturized all-in-one attitude control module that employs 3-axis reaction wheels, a processor, and IMU sensors.

The market for small satellites has expanded drastically in recent years, and various missions have evolved[1),2)]. Thus, we can expect a growing demand for such satellites from now on. Small commercial electronic devices have also been developed to achieve difficult missions with a small satellite. There is also a growing need for 3-axis attitude control for small satellites.

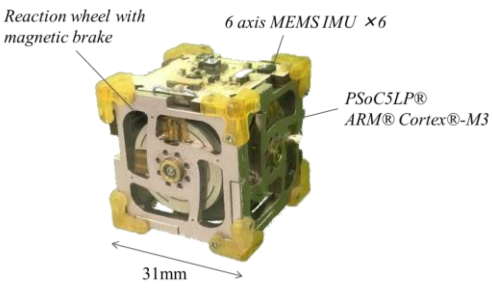


Fig. 1. Appearance of proposed all-in-one miniaturized 3-axis attitude control module

The traditional process for designing an attitude control system entailed the following: choose an attitude sensor (e.g. star tracker, gyro), a control computer, and actuators (e.g. reaction wheels (RW), thrusters)), and then combine the components into one system. Those components are usually designed individually and supplied by each manufacturer. This approach thus requires electric wires and structures for each component. This results in making the satellite heavy and large. We have developed a highly integrated 3-axis attitude control module that contains six MEMS IMU sensors (18-axis gyro and 18-axis accelerometer), 3-axis reaction wheels, and a control processor. The module measures 31 mm in size (1/30U) and weighs less than 88 g (Fig. 1).

We also describe the results of on-orbit evaluation using an application of Int-Ball[3)4)], which is a drone floating in the JEM of the International Space Station. Int-Ball supports astronauts in taking movies and images, while being controlled by a ground operator. Int-Ball was launched as a payload of the Dragon spacecraft by SpaceX Falcon 9 on June 4, 2017. The first flight control demonstration was successfully conducted in 2017. Int-Ball is equipped with the all-in-one attitude control module, 12 micro fans, and a self-localization image sensor (Phenox). The role of the all-in-one attitude control module is to determine position and attitude, control computations, and actuate with the reaction wheels and micro fans. In this paper, we describe an evaluation of reaction wheel capability.

PREVIOUS RESEARCH

The concept of a cubic integrated reaction wheel module is inspired by the "Cubli" proposed by the research group of ETHZ in Switzerland[5)6)]. The Cubli is a cubic robot that contains three reaction wheels, each equipped with a brake mechanism. Braking the rotating wheel causes the Cubli to jump up and then balance itself on a corner with the reaction wheels.

We have designed a 100-mm cubic all-in-one attitude control module that contains six MEMS sensors, a control processor, three reaction wheels, and magnetic brakes, and which possesses the ability to balance itself on a corner.[7)8)] The purpose of this research is to integrate satellite attitude control systems, such as reaction wheels, attitude sensors, and processors, and thus reduce their weight and size. To complement the lack of torque, this module has an electric magnetic brake. When braking a rotating wheel, sufficiently high torque is generated to cause the module to jump up. The structure of the wheel and magnetic brake system has scalability to miniaturize the reaction wheel module so as to enable the design of the 31-mm all-in-one module.

Integrated attitude control modules for small satellites are commonly proposed in the commercial market. For example, the XACT system proposed by Blue Canyon Technologies contains reaction wheels, ADCS including a star tracker, and attitude control processors. Our all-in-one module is much smaller than the XACT unit, and provides 1U-size small satellites with attitude control ability.

SIZE AND ANGULAR MOMENTUM

The angular velocity of a satellite relies on the angular momentum of the reaction wheel. Fig. 2 shows angular momentum vs. mass of the components. The angular momentum depends on the wheel size and mass. The solid line denotes the theoretical line when the wheel is installed inside a cube as shown in Fig. 3. The wheel is shaped like a cone.

For a small satellite, a reaction wheel should be small enough to load the mission payload. In this study, we targeted a 1U-size satellite.

The target angular velocity is more than 10 deg/sec. for a 1U-size satellite weighing 1 kg. Consider a cube made from homogeneous material. The inertia moment is defined as:

$$J = \frac{1}{6} M a^2 \quad (1)$$

where, J is the inertia, M is mass [kg], and a is the length of a cube [m].

Thus, the angular momentum of a 1 kg/1U-size cube at 10 deg/sec. is as follows:

$$L = J\omega = 2.91 \times 10^{-4} [\mathrm{Nms}] \quad (2)$$

When the wheel speed is 8000 rpm, the wheel inertia should be larger than 3.47×10^{-7} [kgm^2].

Fig. 3 shows the shape of the reaction wheel. In this case, the inertia is described by the equation below. The wheel diameter must be larger than 19 mm, with tungsten material (specific gravity = 19.25 g/cm^3). In considering the efficiency of utilizing the module in space, determine the wheel diameter to be 20 mm as follows:

$$J_{whl} = \frac{13}{160} \pi \rho r^5 \quad (3)$$

where, J_{whl} is the wheel inertia, ρ is the specific gravity [kg/m^3], and r is the wheel diameter [m].

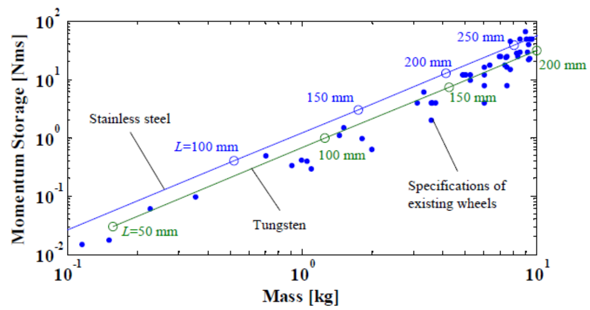


Fig. 2. Momentum storage versus mass

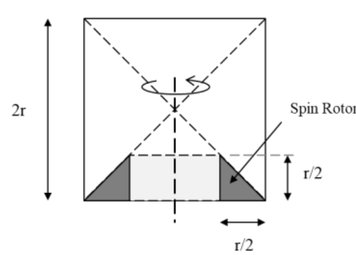


Fig. 3. Maximal arrangement within a one-package module

SYSTEM DESIGN

System design overview

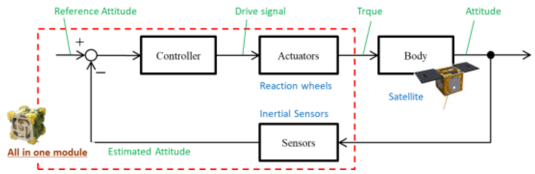


Fig. 4. The proposed system of the all-in-one module

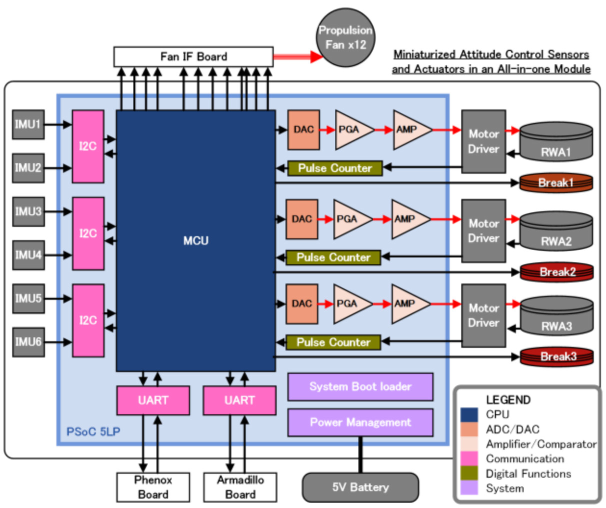


Fig. 5. System block diagram of the all-in-one module

The all-in-one module measures 31 mm in size, and is equipped with inertial attitude sensors, a control processor, and actuators. It provides the functions of attitude determination, control, and actuation (see Fig. 4). The feature of the module is that it enables a satellite control its attitude with only serial communication command and a power line. Two different wheel versions are available, one is with tungsten wheel, weighs less than 88 g, and the other is high torque version with steel wheel and magnetic brake, weighs less than 50g. A robot application is assumed by a high torque version.

The control processor is the PSoC5LP®, ARM-based System-on-Chip (SoC), equipped with programmable analog and digital circuits. The programmable circuits enable such peripheral circuits as the motor driver's reference signal and pulse counter logic to be integrated in one chip (Fig. 5). The MCU core is ARM M0 and the operating clock is up to 80 MHz, with 64-KB SRAM and 256-KB flash ROM.

The inertial attitude sensors consist of six MEMS sensor chips. Each MEMS chip has a 3-axis gyro and a 3-axis accelerometer. Each MEMS chip is connected to the I2C bus of the SoC. The sensor data is integrated in a PSoC5LP.

External communications can be connected to two UART serial communication ports—one typically used as the command and telemetry port, and the other used for such external absolute attitude sensors as STT and sun sensors.

Three reaction wheels are inside the module. Each wheel is driven by a customized Maxon EC-10 flat motor (i.e. a three-phase brushless DC motor). At maximum current, this motor generates torque of up to 0.24 mNm. The maximum speed is 16000 rpm with no load. Wheel speed can be restricted by a software limiter, and speed is restricted to 8000 rpm in the application example described below.

Performance Summary

Table 1 summarizes the performance of the module. The steel wheel version with a magnetic brake weighs 50 g and the tungsten wheel version weighs 88 g. The power consumption is 2W when one reaction wheel generates maximum torque. The recommended supply voltage is from 6V to 10V. The angular momentum is 1.35 mNms@8000 rpm.

Table 1. Performance summary

Wheel performance	3 axis
Wheel inertial moment	1,030 gmm^2 (tungsten wheel)
Wheel speed	<16,000 rpm
Maximum torque	0.239 mNm
Sensors	6-axis MEMS IMU × 6
Gyro range	±250 deg/s (configurable)
Gyro noise	0.008 deg/s/$\sqrt{}$Hz
Gyro Bandwidth	< 250 Hz (configurable)
Accelerometer range	±2 g (configurable)
Accelerometer noise	250 μg/$\sqrt{}$Hz
Accelerometer bandwidth	< 218 Hz (configurable)
Mechanical features	
Weight	88 g (tungsten version) 50 g (steel version)
Size	31 mm Cube
Electrical features	
Voltage supply	6-10V
Power consumption	2W @one wheel with max. torque

Sensors

Six MEMS IMUs are installed in the module as attitude determination sensors. Compared to such highly accurate gyro sensors as the fiber optical gyro, the chip's MEMS sensor itself is not very accurate. By taking the average of multiple sensors, random noise is reduced.

Electric circuit design

The fundamental system structure is based on the 100-mm module presented above. When the reaction wheels are miniaturized, it is difficult to maintain the 100-mm cubic module structure. As empty space in a 1-inch module is strictly limited, electrical wires and the electric circuit cannot be settled inside it.

Instead of using an aluminum alloy, this module uses an electric PCB board as part of the mechanical structure. The area is sufficiently large to mount electric chips by using the three sides of the cube for the electric board. And the other three sides of the cube are used for the reaction wheels. Three boards are manufactured simultaneously and then connected with a flexible PCB circuit. This flexible PCB enables the boards to be deployed during soldering, and then folded into the cube structure.

The module is assembled as per the following process: connect the motor flexible cable to the PCB board (Fig. 6), fold the panels into a cube, and then clamp a screw on each corner.

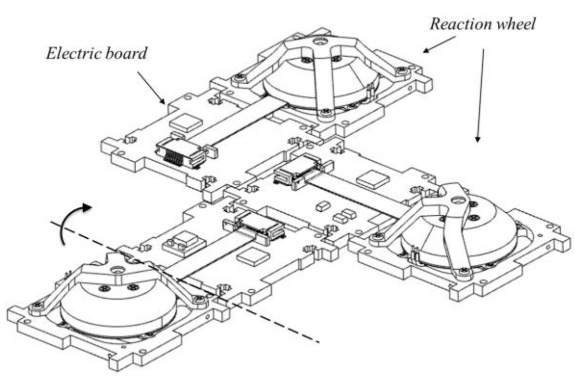


Fig. 6. Module development plan

(All parts are connected and folded into a cube.)

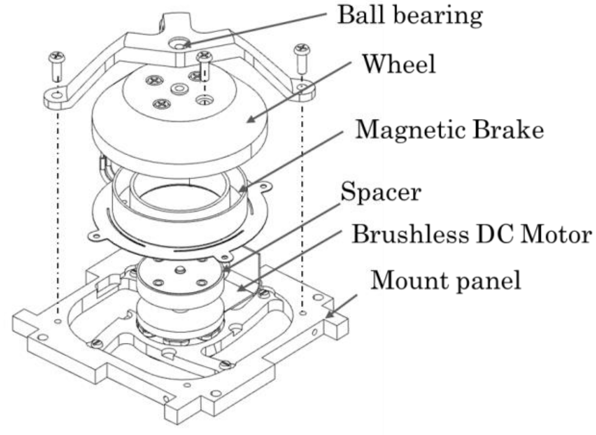


Fig. 7. Structure of a wheel with a magnetic brake

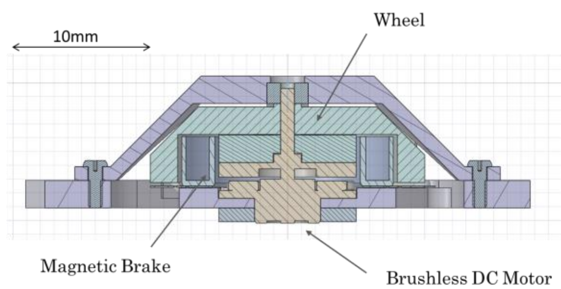


Fig. 8. Cross-sectional view of a wheel

Wheel design

We have two versions of the wheel structure. One type is a high momentum wheel version that uses a wheel made of tungsten. The other type features a magnetic brake that enables the generation of high torque.

In the tungsten model (i.e. normal model), the wheel is made of tungsten. The inertia of the wheel is 1030 gmm^2, which exceeds that required in the SIZE AND ANGULAR MOMENTUM section. It enables a small satellite of 1 kg/1U size to rotate higher than 10 deg/sec.

When the wheel is miniaturized, the motor torque becomes smaller. For an application that requires high torque, we propose the high torque model, in that the magnetic brake is used to instantaneously generate high torque. We consider the application for a modular robot that moves on the earth or an asteroid, where environment with gravity. Related ideas are also published, such as MINERVA[9)], Cubli[5)6)], and M-Blocks[10)]. The extremely high integration of actuators in this module offers the advantage of smaller size than that of any other modular robot. The wheel is made of steel, and its attached magnetic brake is applied to brake the wheel. Torque of at least 42 mNm is thus generated. This torque is sufficiently high to make the module wake up and roll around on the ground in a 1G gravity environment. Fig. 9 shows how the module wakes up and rolls.

Fig. 7 and Fig. 8 show the structure of the wheel. The motor is mounted on an aluminum panel, and a brake is installed concentrically with it. The wheel is supported by an upper ball bearing and the motor shaft. The gap between wheel and a brake is adjusted with a thin spacer block. The normal model is not equipped with a magnetic brake but the structure is the same. The wheel is shaped like a cone so as not to interference each other with the next wheel.

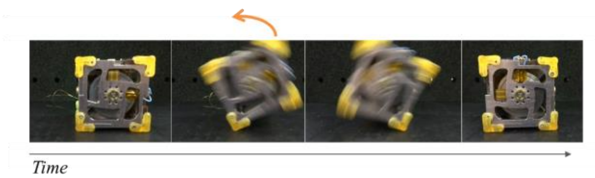


Fig. 9. How the module rolls with the magnetic brake and wheel

Wheel speed detection

Wheel speed is detected by counting the hall sensor pulse width. Three hall sensors are installed inside the EC-10 flat motor and connected to the BLDC motor driver. Two of these sensors are used by the system to detect wheel speed and rotation direction. Fig. 10 shows an example of the logic circuit used in detecting the pulse width. In a typical BLDC motor, three hall sensors are used to detect speed. However, there are insufficient hardware resources in SoC (due to the selected package) to connect three hall sensors from each motor. At least two sensors are needed to detect wheel direction. In the module, two hall sensors are used to detect both wheel direction and wheel speed.

When the wheel speed is slow, the wheel pulse duration is longer than control cycle. In that case the main control program may fail to read correct wheel speed. One hall sensor outputs one pulse per electric rotation. When two hall sensors are used, two pulses are obtained in each rotation (see Fig. 10 below). With one hall sensor, the limit speed is 150rpm and with two sensors its 75 rpm. Compare to one hall sensor, speed detection with two hall sensors is better choice to avoid such errors.

In a typical satellite control system, reaction wheels are used with bias rotation, wheel speed read errors will not occur.

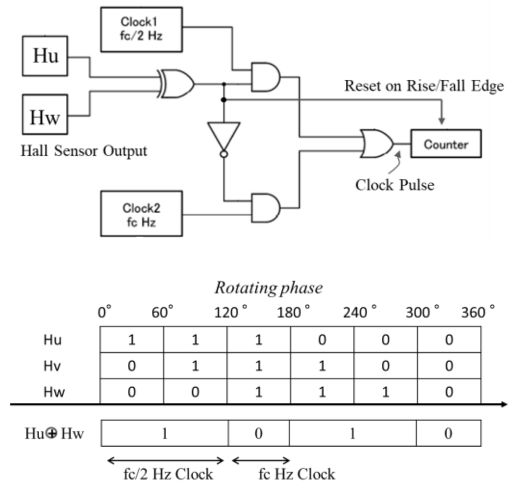
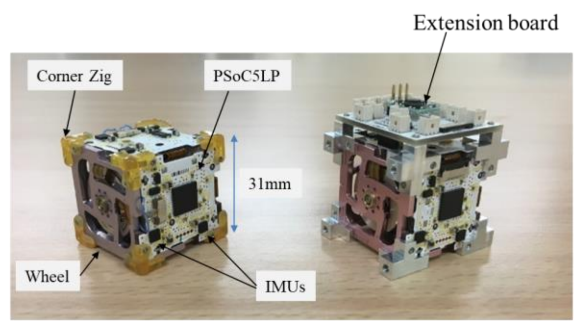


Fig. 10. Wheel speed detection logic

System extensibility

The all-in-one module has an extension port and thus can drive external thrusters such as micro fans through an external driver circuit. The port is directly connected to the GPIOs of PSoC5LP. The drive signal is 3.3V TTL and up to 12 lines are available. This extensibility makes the module flexible and easy to apply in various types of systems. For most small satellite applications, all control systems are typically integrated in one module so as to make the system simple.

An extension board can be mounted on top of the module (Fig 11). Each corner of the module is clamped with a corner zig, and the extension board is also mounted and clamped with screws on it.



(left)Fundamental module (right) module with extension board

Fig 11. The all-in-one module with an extension board

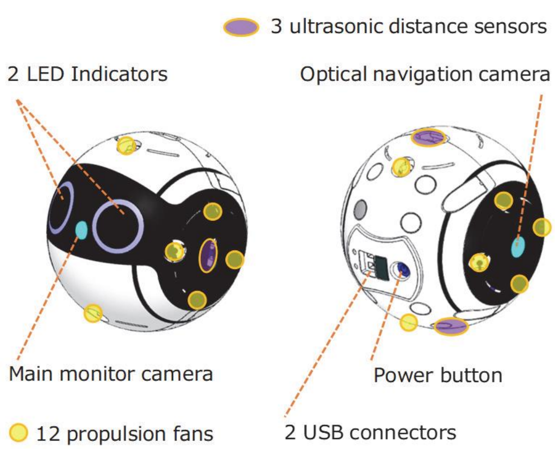
EXAMPLE OF INT-BALL APPLICATION

Introduction of the Int-Ball

The JEM Internal Camera Robot or "Int-Ball" is a drone floating in the JEM of the International Space Station[3)4)]. Int-Ball supports astronauts in taking movies and images, while being controlled by a ground operator. It was launched as a payload of the Dragon spacecraft by SpaceX Falcon 9 on June 4, 2017. The first flight control demonstration was successfully conducted in the JEM pressurization section.

Fig. 12 shows the appearance of Int-Ball. It is shaped like a sphere and less than 150 mm in diameter. The size is defined based on ISS safety requirements. LEDs are installed in the "eyes" that indicate operating status: blue indicates camera operation and red indicates control system trouble. Two cameras are mounted: one used to take images and make broadcasts to ground operators in real time, and one used for vision-based navigation. The navigation camera (called Phenox) detects a 3D target marker and calculates its relative position and attitude to the marker. Sensing data is sent via the serial communication port to the all-in-one module, which then determines attitude and position.

Int-Ball moves using 12 micro axial flow fans. Each fan thrust force is approximately 1 mN. Fig. 13 shows the vectors of fan thrust direction, thereby generating not only thrust force but also control torque so that Int-Ball's six degrees of freedom or its attitude and position can be fully controlled with 12 fans. Micro fan thrusters are also available in case of required unloading of the reaction wheel's angular momentum.



(A) Appearance of Int-Ball and the functions of each part

(B) A photo of the Int-Ball in first flight checkout

Fig. 12. Appearance of Int-Ball (The first evaluation was made in July 2017.)

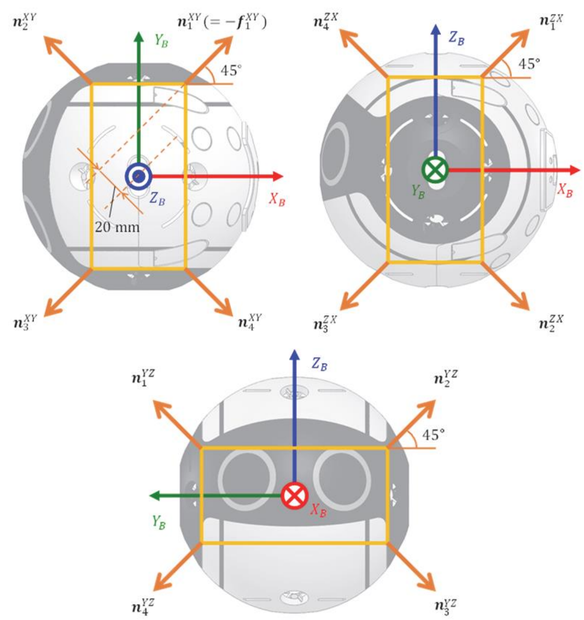


Fig. 13. Geometry of propulsion fans

On-orbit evaluation

The all-in-one attitude control module was evaluated with Int-Ball in the JEM pressurized area. Fig 14 shows the attitude control results with only wheels. Int-Ball initially maintains its position and attitude with fan control. Wheel control begins at approximately -1.4 sec., and then the reference attitude is commanded to roll around the roll axis -10 deg at 0 sec.

The reaction wheel speed is at up to 760 rpm, with angular velocity of 2.82 deg/sec. In this evaluation case, control was conducted with only the reaction wheels. The standard deviation σ of roll axis attitude is 0.0294 degree in 10 sec. The accuracy of control stability relies on the accuracy of gyro sensors and the attitude estimation accuracy of vision based navigation board.

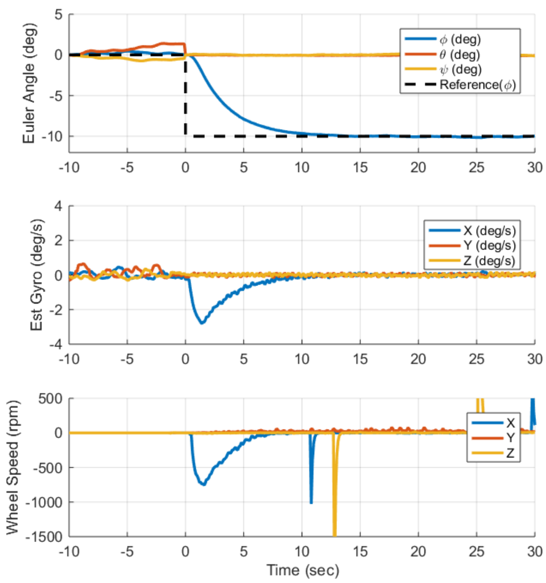


Fig 14. Wheel control results

(Top: Euler angle; middle: angular velocity; bottom: wheel speed. Wheel control starts at -1.4 s, reference attitude is commanded to roll -10deg at 0 s.)

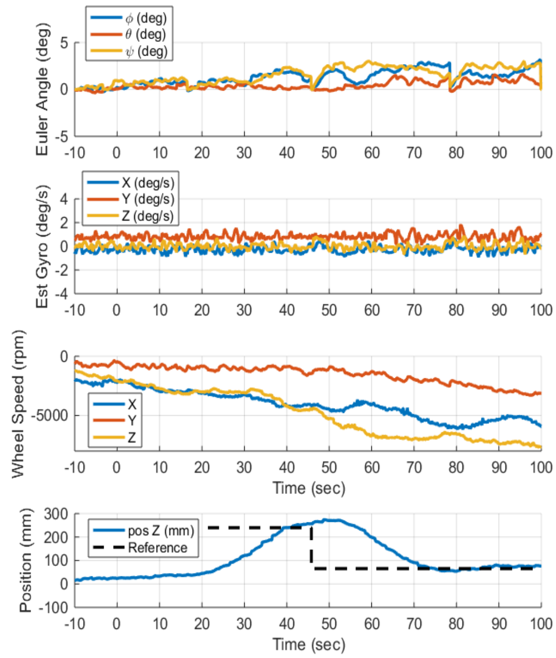


Fig 15. Results of control with fan thrusters and wheels (Commanded maneuvering Z axis direction ± 200 mm while maintaining attitude)

In Fig 14, the reaction wheel speed indicates non-contiguous values at 11 sec., 13 sec., 25 sec., etc. This is due to an error of the wheel speed pulse counter. When the wheel speed is slower than 75 rpm, the counter pulse duration becomes longer than the control process cycle, so that the main control program may fail to read out the correct wheel speed. This erroneous wheel speed data is nullified in control software. This figure shows the raw telemetry including the error signal. In a satellite control system, reaction wheels are typically used with bias rotation, but in the case of Int-Ball, the reaction wheel used without bias rotation due to the setup. With bias rotation, wheel speed read errors do not occur.

When position is controlled using the fans, the dispersion of thruster force and misalignment cause a disturbance torque, thereby making the accuracy of attitude control worse. Fig 15 shows the evaluation results of fan and wheel simultaneous control. In this case, the commanded Z position is ±200 mm, while maintaining attitude with the wheels. The standard deviation σ of roll axis was 0.345 degree in 10 sec.

Future works

Int-Ball was evaluated inside the JEM pressurized area. For a small satellite, the module should be guaranteed to withstand the vacuum environment, mechanical vibration at launch, and thermal/radiation environments. These topics are now being discussed for processing.

CONCLUSION

In this paper, we proposed the 1/30U small-sized 3-axis attitude control module. The idea of using an electrical circuit board as a structural component reduced the mass of the mechanical structure and electrical wiring as well. Adapting the System-On-Chip (SoC) reduced the circuit area while maintaining the complexity of the electric circuit. An attitude control module measuring 31 mm in size and 88 g in weight was developed. This module contains 3-axis reaction wheels, six MEMS-IMUs (18-axis acceleration and 18-axis gyro), and an attitude control computer. The angular momentum is 1.35 mNms@8000 rpm per axis. The module only requires a power supply and external serial communication. Moreover, this module can drive and control 12 actuators such as micro thrusters by adding an extension circuit. The results of an on-orbit evaluation with Int-Ball—a camera robot floating inside the JEM—were also described.

For a small satellite, the all-in-one module should be guaranteed to withstand the vacuum environment, mechanical vibration at launch, and thermal/radiation environments.

Acknowledgments

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