Attitude Determination and Control System for the PROCYON Micro-Spacecraft

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This paper describes development strategies and on-orbit results of the attitude determination and control system (ADCS) for the world’s first interplanetary micro-spacecraft, PROCYON, whose advanced mission objectives are optical navigation or an asteroid close flyby. Although earth-orbiting micro-satellites already have ADCSs for practical missions, these ADCSs cannot be used for interplanetary micro-spacecraft due to differences in the space environments of their orbits. To develop a new practical ADCS, four issues for practical interplanetary micro-spacecraft are discussed: initial Sun acquisition without magnetic components, angular momentum management using a new propulsion system, the robustness realized using a fault detection, isolation, and recovery (FDIR) system, and precise attitude control. These issues have not been demonstrated on orbit by interplanetary micro-spacecraft. In order to overcome these issues, the authors developed a reliable and precise ADCS, a FDIR system without magnetic components, and ground-based evaluation systems. The four issues were evaluated before launch using the developed ground-based evaluation systems. Furthermore, they were successfully demonstrated on orbit. The architectures and simulation and on-orbit results for the developed attitude control system are proposed in this paper.

Key Words: Micro-Satellite, Interplanetary Spacecraft, Attitude Determination, Attitude Control

Nomenclature

\- q: quaternion
\- \omega: angular rate
\- u: Sun direction vector
\- L: angular momentum
\- e: control error
\- T: torque
\- A: distribution matrix
\- E: identity matrix
\- K: control gain
\- t: time

Subscripts

\- i: inertial frame
\- b: body frame
\- tg: target
\- rw: reaction wheel component frame
\- s: sampling interval
\- Po: proportional control of the angular rate control mode
\- Pp: proportional control of the pointing control mode
\- Dp: differential control of the pointing control mode
\- Pr: proportional control of the three-axis control mode
\- Dr: differential control of the three-axis control mode

Abbreviations

ADCS: attitude determination and control system
CGJ: cold-gas jet
FDIR: fault detection, isolation, and recovery
FOG: fiber-optic gyro sensor
RW: reaction wheel
SAS: Sun aspect sensor
STT: star tracker

1. Introduction

The world’s first nano-satellite called CubeSat XI-IV was developed by The University of Tokyo and launched in 2003.1) Since the success of this nano-satellite, an increasing number of nano- and micro-satellites have been developed and applied all over the world. These satellites have been used for practical earth observations and science missions by some venture companies and laboratories. To realize these missions, the requirements for attitude stability of Earth-orbiting satellites have become more precise and accurate.2,3) For example, the attitude stability requirement of Nano-JASMINE, which is a 35 kg astrometry satellite reaches 740 mas in 8.8 s.3)

On the other hand, there have been few micro-spacecraft for interplanetary exploration missions developed, and a bus system for these interplanetary spacecraft has not yet been demonstrated. For example, the first Japanese micro-deep-space spacecraft, UNITEC-1, which was launched in 2010, did not have an active attitude control system because the mission was only a simple communication test in deep space.
space. The development high-performance and low-cost interplanetary micro-spacecraft is needed for more frequent deep-space exploration. In order to realize the development of a micro-spacecraft bus system for deep-space exploration, The University of Tokyo and Japan Aerospace Exploration Agency (JAXA) developed the 50-kg-class PROCYON interplanetary spacecraft, which was launched on December 3rd, 2014. In addition to demonstrating the bus system, PROCYON was also supposed to perform a close flyby observation of an asteroid. PROCYON requires robustness for the long-term operation and precise three-axis stabilization for orbit control maneuver and the optical navigation.

This paper describes the development strategies and on-orbit results of an attitude determination and control system (ADCS) for interplanetary micro-spacecraft. In particular, four issues for realizing interplanetary micro-spacecraft are discussed: initial sun acquisition without magnetic components, angular momentum management without magnetic actuators, requirements for increasing the robustness of the ADCS, and precise attitude control. The first three issues come from the differences in the environments between low earth orbit and interplanetary orbit and are related to the survivability of micro-spacecraft in a deep-space environment. The four issues have already been demonstrated for large spacecraft; however, they have not been demonstrated for micro-spacecraft. The reliability of micro-spacecraft components has yet to be proven, and it is especially limited due to their weight, size, and cost. Development strategies to overcome these issues under limited resources are important for future micro-spacecraft.

In this paper, the ADCS for PROCYON, which can solve these four issues, are introduced. Firstly, details of the four issues are discussed in Section 2. Secondly, the overview of PROCYON itself is introduced in Section 3. Next, the requirements and architectures of the ADCS are described in Section 4. Section 4 also discusses the details of the reliable and precise ADCS and FDIR system without magnetic components. Section 5 provides simulation results for ground-based tests. The tests verified that the ADCS can solve the four issues before launch. Finally, on-orbit results are provided in Section 6. They demonstrate that the ADCS can solve the four issues on orbit. These flight data will help the development of the attitude control system for future interplanetary micro- and nano-spacecraft missions.

2. Technical Issues in Realizing Interplanetary Micro-spacecraft

Here, details for the four issues are introduced. The first two issues, initial Sun acquisition without magnetic components and angular momentum management without magnetic actuators, are related to the magnetic environment. For Earth orbiting micro-satellite, magnetic sensors and actuators are generally used to obtain initial stabilization soon after separation due to their high reliability. The magnetic components are also used for wheel unloading operations, since they do not require fuel. For example, PRISM, which is an 8.5 kg remote-sensing satellite launched in 2009, has successfully controlled its attitude using magnetic sensors and actuators. Nano-JASMINE uses these components for coarse attitude control, wheel desaturation, and the recovery operation from safe mode due to their high reliability. Although magnetic components are attractive for micro-satellites, interplanetary spacecraft cannot use these components because they fly in interplanetary orbits far from a geomagnetic field. Large deep-space probes commonly use propulsion systems for reaction control; however, no highly reliable and safe propulsion systems are currently available for micro-spacecraft. In addition, the fuel capacity of a micro-spacecraft is more limited than a large spacecraft. Therefore, the development of a new small propulsion system and a new reliable attitude control system without magnetic components is required.

The third issue, robustness of the ADCS, is related to the difficulty that interplanetary spacecraft face regarding power generation. Since they fly far from the Earth, much larger communication power is needed compared to Earth-orbiting satellites. In addition, propulsion during practical deep-space exploration (e.g., an ion thruster operation) requires larger power consumption. Thus, body-mounted solar cells, which are widely used for Earth-orbiting micro-satellites, are not sufficient for practical interplanetary micro-spacecraft. Therefore, a large solar paddle should be equipped. An ADCS for spacecraft without body-mounted solar cells must have high reliability and robustness since small failures of the ADCS will result in failure of the spacecraft itself. Therefore, the development of a new reliable fault detection, isolation, and recovery (FDIR) system without magnetic components is required for limited size micro-spacecraft. The developed FDIR system actively uses function redundancy instead of component redundancy to observe the weight and size limitation.

The fourth issue, attitude control accuracy, is important for advanced space exploration such as scientific observations, optical navigation, and orbit control. The development strategy of precise ADCS is similar to that of Earth-orbiting micro-satellites. The contributions of this paper towards this issue are on-orbit demonstrations of the newly developed ADCS for interplanetary micro-spacecraft and comparisons between the on-orbit results and ground-based simulations. Ground-based simulations are also important for the first three issues; thus evaluation systems for interplanetary spacecraft are developed. Many ground-based tests were performed to verify the developed ADCS and FDIR system.

3. Configuration of PROCYON

PROCYON’s mission has two objectives. The first is to demonstrate the micro-spacecraft bus system for practical deep-space exploration. The second is to demonstrate an asteroid close flyby. To realize these objectives despite the size and mass constraints, requisite minimum components are installed on PROCYON. The external view of PROCYON is shown in Figs. 1 and 2. PROCYON has only one solar panel at the Plus Z (PZ) plane. This plane should face towards the
Sun to generate electric power during most times of operation. For communication with ground stations, PROCYON has three types of antennas: low-gain antenna (LGA), middle-gain antenna (MGA), and high-gain antenna (HGA). The LGA has wide directionality near 90°. On the other hand, the MGA and HGA have narrow directionality in order to achieve high bitrate communication in deep space. The half-power angle of the MGA is 15°, and that of the HGA is 1°. PROCYON also carries an ion thruster and cold-gas thruster propulsion system (I-COUPS), which was newly developed for this project. I-COUPS integrates an ion propulsion system and multiple cold-gas jet systems. The fuel for these propulsion systems is Xenon, which is supplied from the same tank. This gas-sharing system realizes a lightweight propulsion system. Two telescopes are mounted on PROCYON. One of them is used for asteroid observation; not only for close flyby, but also for optical navigation. The telescope has an active scan mirror that enables it to keep gazing at the asteroid, which rapidly moves through the field of view. The other telescope observes the geo-corona around the Earth.

4. Overview of ADCS for PROCYON

4.1. Requirements
In order to achieve the mission objectives of PROCYON, the ADCS must satisfy some requirements. The first is the requirement for power consumption. The solar panel must face the Sun within one hour after separation to generate enough power before the battery is discharged. The second is the requirement of clearly imaging a star for optical navigation. This requires a pointing accuracy of 0.2° and attitude stability of $6.0 \times 10^{-3}$ deg (3σ) during 10 s of exposure time. The third is the requirement for angular momentum management. The solar radiation pressure torque or the ion thruster disturbance torque will increase the angular momentum of the spacecraft, and this angular momentum accumulates in the reaction wheels. Scheduled unloading is needed because the wheels have a limitation in spin rate. The fourth is the requirement for survivability. The on-orbit mission time is over two years. During the two years, PROCYON should remain in a Sun-pointing attitude even if any one of the attitude components is broken. All of the technical requirements mentioned above have to be built into the system using very-limited resources and a short development period. To summarize the requirements, we defined the success criteria for the attitude control system of PROCYON as follows:

- **Minimum-1**: Success of Sun-pointing attitude control to generate electric power
- **Minimum-2**: Execution of rough three-axis attitude control for high-rate communication and orbit control
- **Full-1**: Achievement of the required accuracy, being $6.0 \times 10^{-3}$ deg (3σ) for 10 s
- **Full-2**: Management of the angular momentum to desaturate the wheels without a magnetic component
- **Advanced**: Sustain of the Sun-pointing attitude even if any one of the components fails

These success criteria relate to the four issues discussed in Section 2, and all criteria were evaluated on orbit.

4.2. Architecture of ADCS
The structure of the ADCS for PROCYON has been designed to achieve the requirements stated earlier, and the architecture designed is described in this section. In order to develop the ADCS quickly, the PROCYON project chose to reuse components from other spacecraft, as done with many other space projects. According to the spacecraft’s size and performance, Hodoyoshi-3 and -49; which are Earth remote-sensing satellites developed by The University of Tokyo, are selected. Attitude sensors and actuators mounted on Hodoyoshi satellites, such as the Fiber-optic gyro sensor (FOG), Sun aspect sensor (SAS), Star tracker (STT), and Reaction wheel (RW), were reused for PROCYON; except for the magnetic sensors and actuators, which are not able to be used in deep space. Only the RW was modified to reinforce vacuum tolerance. Although most of the components were reused from Hodoyoshi satellites, the algorithms of the attitude control systems were newly developed due to some differences in the design concept. For example, the attitude control system for the Hodoyoshi satellites strongly depends on the magnetic components. The requirement of robustness is also different because the Earth-orbiting micro-satellites can easily survive, even in a tumbling situation. To evaluate the newly developed algorithm, we also reused the test environment for the attitude control system of the Hodoyoshi project with a slight modification. The overview of the ground-based evaluation systems is described in Section 5.
If the RW is the only actuator mounted on PROCYON, wheel unloading or angular momentum management, cannot be performed. In the case of a large spacecraft, propulsion systems are used for angular momentum management instead of magnetic actuators. However, a highly reliable thruster system for micro-spacecraft has not yet been demonstrated on orbit. Hence, a new cold-gas jet (CGJ) propulsion system, I-COUPS, was developed to perform angular momentum management.

The specifications of the sensors and actuators mounted on PROCYON are provided in Table 1 and Table 2. To get a wide field-of-view, five SASs are installed on PROCYON. Each SAS is placed on one panel of PROCYON, except the Minus Z (MZ) panel, which is on the opposite side of the solar panel. Four RWs are installed on PROCYON for redundancy. Three RWs are aligned in each axis of the body-fixed frame and the fourth RW is aligned to the skew direction. PROCYON has eight CGJ thrusters to generate three-direction torque and two-direction thrust for angular momentum management and orbit control. The specifications of the STT show that the requirement of pointing accuracy, which is 0.2 deg, is satisfied using only the STT. On the other hand, the specifications of the FOG indicate that the random noise and bias of the FOG are too large to achieve the stability required, which is $2.0 \times 10^{-3}$ deg for 10 s. In order to reduce these noises, two software filters (i.e., a low-pass filter (LPF) and extended Kalman filter (EKF)) are implemented.

### Table 1. Sensors mounted on PROCYON.

| Observable | Specifications |
|------------|----------------|
| FOG        | 3-axis angular rate: Random noise: $4.7 \times 10^{-4}$ deg/s Nominal bias: $2.8 \times 10^{-3}$ deg/s Weight: 980 g Power consumption: 3.5 W |
| SAS        | 2-axis Sun angle: Accuracy: 1 deg Field-of-view: 100 deg x 100 deg Sampling rate: 2 Hz Weight: 48 g Power consumption: 0.16 W |
| STT        | 3-axis attitude: Accuracy: 0.02 deg (Boreisigt) : 0.002 deg (Cross axes) Field-of-view: 8 deg x 8 deg Sampling rate: 1 Hz Weight: 516 g Power consumption: 2.5 W |

### Table 2. Actuators mounted on PROCYON.

| Observable | Specifications |
|------------|----------------|
| RW         | Spin rate of wheels: Maximum spin rate: 6000 rpm Maximum angular momentum: 0.45 Nm/s Maximum angular acceleration: 300 rpm/s Sampling rate: 1 Hz Weight: 1050 g Power consumption: 3.5 W (3500 rpm) |
| CGJ        | Thrust: $20.85 \pm 0.85$ mN Specific impulse: $24.1 \pm 0.95$ s Delay: $0.7 \pm 0.1$ s |

### Table 3. Attitude mode of PROCYON.

| Mode                  | Sensor | Algorithm       | Unloading |
|-----------------------|--------|-----------------|-----------|
| Rate damping          | FOG    | Rate stabilization | $\times$ |
| Sun search            | FOG    | Rate control     | $\times$ |
| Sun-pointing          | NSA    | Pointing         | $\bigcirc$ |
| Three-axis stabilization | STT   | Quaternion FB   | $\bigcirc$ |
| Precise three-axis stabilization | STT   | FOGLPF         | $\bigcirc$ |
| Precise three-axis stabilization | STT-FOG EKF | Quaternion FB | $\bigcirc$ |

*Actuator used in all modes is RW.

### 4.3. Attitude mode definition

During the PROCYON mission, the attitude control process can be separated into three phases; Sun-pointing, coarse three-axis stabilization, and precise three-axis stabilization. Sun-pointing phase requires that the solar panel faces towards the sun with an accuracy of 5 deg. The rotation angle around the Sun vector is not specified during this phase. The coarse three-axis stabilization phase requires that the three-axis angle error be smaller than 0.5 deg for maneuvering the ion thruster direction or pointing the directive antenna towards the Earth. The precise three-axis stabilization phase requires a three-axis stability of $6.0 \times 10^{-3}$ deg (3σ) for 10 s for optical navigation. To satisfy the requirements of these phases, three attitude modes were defined using the same name with the phases: Sun-pointing mode, coarse three-axis stabilization mode, and precise three-axis stabilization mode. Unloading using the CGJ is enabled in these three modes. In addition, two modes called “rate damping” and “Sun search” are also defined for initial stabilization and Sun detection. The attitude modes, sensors and algorithms used in each mode are summarized in Table 3. The details of the algorithms in the table are discussed in the next section.

### 4.4. Attitude determination algorithms

The architecture of the attitude determination system is shown in Fig. 3. The system calculates five state variables: the angular rate of the spacecraft $\omega_h$, the angular momentum of the spacecraft $L_h$, the sun vector in the inertial frame $u_s$, and in the body-fixed frame $u_{sb}$, and the quaternion that represents the coordinate transformation from inertia to the body-fixed frame $q_{(2b)}$. These state variables are used for attitude control. The angular rate $\omega_h$ is basically obtained from the FOG via software LPF. The FOG LPF calculates the time average of FOG outputs to cut the random high-frequency noise in the FOG measurements. The angular rate $\omega_h$ is obtained from the STT-FOG EKF instead of the LPF when PROCYON is in the precise three-axis mode. The STT-FOG EKF implemented on PROCYON is usually used Kalman filter described in Lefferts et al. The EKF estimates the bias in the FOG and the quaternion $q_{(2b)}$. The quaternion $q_{(2b)}$ is also provided from the quaternion propagator. This algorithm integrates the kinematics relationship between the angular rate $\omega_h$ and the quaternion $q_{(2b)}$, which is shown as Eq. (1), to estimate the next-step quaternion if the new quaternion cannot be obtained from the outlier rejecter system, which detects and rejects the anomalous value output from the STT.
If the new quaternion is provided by the outlier rejector system, the estimated quaternion will update to the new quaternion obtained by the outlier rejector. In the precise three-axis mode, the quaternion is also provided from the EKF instead of the quaternion propagator. The Sun vector on the body-fixed frame $\mathbf{u}_b$ is calculated by the Sun sensor integrator, which estimates the Sun vector using the data from five SSSs. The Sun vector on the inertia frame $\mathbf{u}_i$ is calculated using the Sun vector on the body-fixed frame $\mathbf{u}_b$ and the quaternion $\mathbf{q}_{2b}$.

### 4.5. Attitude control algorithms

Figure 4 illustrates the architecture of the attitude control system. The attitude controller calculates the control torque on the body-fixed frame $\mathbf{T}_b$ to stabilize the attitude. The torque is generated by one of the three PID controllers: spin rate controller, pointing controller, and three-axis controller. The control period of these controllers is 0.5 s. The controller is chosen depending on the attitude mode. The spin rate controller uses only the estimated angular rate $\omega_b$ as the controlled object. The controlled error vector using the angular rate PID controller is calculated as follows:

$$\mathbf{e}_{\omega} = \mathbf{q}_{2b} - \mathbf{q}_{2i}.$$  

The control torque $\mathbf{T}_b$ in the body frame in the spin rate controller is obtained as follows:

$$\mathbf{T}_b = K_{P\omega} \mathbf{e}_{\omega}. \quad (3)$$

On the other hand, the controlled object using the pointing controller is not only the body-fixed sun vector $\mathbf{u}_b$, but also the angular rate $\omega_b$. The angular rate $\omega_b$ is applied for the derivative term in the PID pointing controller. Due to this construction, an angular rate around the target vector can be controlled. The controlled error vectors using the pointing PID controller are calculated as follows:

$$\mathbf{e}_{P} = \omega_{i} - \omega_{b}. \quad (2)$$

The control torque $\mathbf{T}_b$ in the pointing controller is obtained as follows:

$$\mathbf{T}_b = K_{P\omega} \mathbf{e}_{P} + K_{D\omega} \mathbf{e}_{D\omega}. \quad (6)$$

Similarly, the quaternion $\mathbf{q}_{2b}$ and angular rate $\omega_b$, which is applied for the derivative term, are used in the PID three-axis controller. The controlled error vectors for the three-axis PID controller are obtained as the following equations:

$$\mathbf{e}_{P} = \begin{bmatrix} q_{b2i1} \\ q_{b2i2} \\ q_{b2i3} \\ q_{b2i4} \end{bmatrix}, \quad \mathbf{e}_{D\omega} = \begin{bmatrix} q_{b2i1} \\ q_{b2i2} \\ q_{b2i3} \\ q_{b2i4} \end{bmatrix}.$$  

The control torque $\mathbf{T}_b$ in the three-axis controller is obtained as follows:

$$\mathbf{T}_b = K_{P\omega} \mathbf{e}_{P} + K_{D\omega} \mathbf{e}_{D\omega}. \quad (9)$$

In Eqs. (5) and (8), the derivative terms are obtained as the angular rate; however, the derivation of the Sun vector and the quaternion are also calculated in each controller for redundancy.

The unloading controller detects the unloading demand and controls CGI valve opening and closing. When a CGI valve is opened, it is expected that the attitude will oscillate because large torque near 6 mNm is generated. To follow such momentary disturbance torque, the torque generated by the CGJs is estimated and compensated as a feedforward controller. The gyro-effect torque is also estimated and compensated for better stabilization. Finally, the calculated torque $\mathbf{T}_b$ is distributed to the four RWs. The degrees of freedom of the RW are four. This is more than enough to control the three-axis spacecraft. Using this extra degree of freedom, all the RWs can generate a pure moment.
follows:

\[ T_{rw} = A_{rw}^{T} T_b = A_{rw}^{T} (A_{rw} A_{rw}^{T})^{-1} T_b, \tag{10} \]

where \( A_{rw} \in \mathbb{R}^{3 \times 4} \) is the distribution matrix of the RWs and is composed of the rotation axis vectors of the four RWs in the body frame. The superscript PI is pseudo-inverse operation. In the attitude control system for the PROCYON, it is implemented not only Eq. (10), but also in Eq. (11),

\[ T_{rw} = A_{rw}^{T} T_b - (E - A_{rw}^{T} A_{rw}) \frac{L_{rw;tg}}{I_b}. \tag{11} \]

Equation (11) shows the optimal angular momentum distribution.\(^{11} \) This method controls the angular momentum of the RWs to the target angular momentum \( L_{rw;tg} \). This method prevents cancelation of the angular momentum in the RWs.

4.6. FDIR system

One of the challenges for the ADCS is to construct a FDIR system without magnetic components for interplanetary micro-spacecraft. The fault detection system is implemented in the outlier rejeter for the STT and other component drivers to check the health of each component. They monitor the communication line between the on board computer (OBC) and the components (e.g., health flags reported from the components, rejection frequency of the outlier rejeter, and communication failures). When a component anomaly is detected, the power of the component is turned off to reset it. Several minutes later it is turned on again, and the component’s health is confirmed. After several resets, if the situation cannot be changed, it is considered the component has some types of failure, and the attitude system will change the modes and parameters to ignore the component failure. For example, if the STT has a failure, the control mode is set to the Sun-pointing mode to maintain power generation from the solar cells. If one RW is broken, the RW coordinate transform matrix \( A_{rw} \) is changed to ignore the broken RW, and the attitude control is continued using the other three RWs.

In the FDIR system, function redundancies are actively used for fault recovery instead of component redundancies since micro-spacecraft are extremely limited in terms of size, mass, and cost. The component redundancy implemented for the PROCYON is only the fourth RW. As mentioned in the previous section, the PID controllers calculate the angular rate as a derivation of the Sun vector and the quaternion. Thus, if the FOG has a failure and the angular rate is not obtained, the PID controller calculates derivative terms instead of the angular rate from the FOG, and stable attitude control will be maintained. If all SASs cannot detect the Sun, the Sun vector on the body-fixed frame \( u_b \) is estimated from the Sun vector on the inertia frame \( u_i \) and the angular rate \( \omega_b \), assuming that \( u_i \) changes slowly in the interplanetary orbit. Using this function, PROCYON can maintain a rough Sun-tracking attitude if the SAS in the PZ plane experiences a failure.

5. Ground-based Evaluation

It is needed to carefully evaluate the ADCS algorithms before launch. Construction of a reliable evaluation system is also required, but it is difficult and takes a long time. Therefore, our project again chose to reuse the ground-based evaluation system of the Hodoyoshi project, in which a software-in-the-loop-simulator (SILS) and a hardware-in-the-loop-simulator (HILS) were used to evaluate the attitude determination and control algorithms.\(^{12} \) The SILS and HILS were modified for more useful and practical evaluation. This section describes the evaluation method using SILS and HILS.

5.1. SILS

The SILS is an attitude simulator constructed using only software on a standard computer, as Fig. 5. The SILS includes attitude dynamics calculations, disturbance calculations and component noise models to emulate the behavior of the PROCYON on orbit. It also includes the embedded software of PROCYON to evaluate the algorithms. The advantages of SILS are its convenience and short calculation time. SILS can run quickly on a standard laptop. Therefore, it is useful for software-bug fixing, gain adjustments and evaluation of the robustness of the algorithms. The SILS used in the Hodoyoshi project was modified for the PROCYON project. In the case of Hodoyoshi, the embedded software run on the SILS was only ADCS software. However, for PROCYON, most of the software embedded on PROCYON is run on the modified SILS. Due to this modification, it was possible to verify all subsystem software including the main software architecture.\(^{13} \) Additionally, the modified SILS can be used for evaluating communications between subsystems software (e.g., the behavior of the power switching control when the attitude mode is changed or the flow of commands to the ADCS software from a ground station and the telemetry to the ground station from the ADCS software). The modified SILS enabled the PROCYON’s software for the ADCS and other subsystems to be developed quickly.
5.2. HILS

The SILS is a convenient and useful simulator. However it cannot emulate the behavior of the communications between the real components mounted and the on-orbit computational time. In contrast, the HILS is not so simple and provides an environment of a hardware layer evaluation. The HILS shown as Fig. 6, consists of simulator software on a standard computer and embedded software on the OBC. The two computers are connected via wires that are compatible with flight wires. The software operated on the computers is same as SILS, but the interface of the HILS between the simulator software and embedded software is more similar to the on-orbit configuration. A disadvantage of the HILS is a long simulation time because HILS is a real-time simulator used with a real OBC. The on-board computational time and communication software of the components are evaluated using the HILS. In addition, the final integration test with other subsystems was performed using the HILS. An important point for simple development of the HILS is unification of the communication protocol and wiring for mounted components. Fortunately, the communication protocol selected for all of the attitude components installed on PROCYON was a commonly used serial communication standard using RS-422 wires. This selection shortened the development time of the HILS.

5.3. Simulation results for the initial sequence

The initial Sun acquisition sequence on launch day, which is the most critical moment for the PROCYON, was tested under nearly 100 conditions, which included the worst separation rate case obtained by the launch condition and various one-component failure cases, to verify the robustness of our ADCS and FDIR system. In the worst case, the norm of the initial angular rate reaches 12 deg/s. All tests have shown that the ADCS can achieve a Sun-pointing attitude even in the worst separation rate case or the component failure cases. In this section, two results obtained using the SILS are shown as examples.

The first example is a nominal case and shown in Fig. 7. In this case, the initial angular rate was \((1 \ 1 \ 3)\) deg/s and the initial Sun direction was \((-0.35 \ 0.001 \ -0.94)\). The ADCS programs works 400 s after the OBC switched on. During this 400 s, the OBC is initialized and the components are powered on. After that, the spin rate stabilization control is executed until the spin rate is reduced to zero. When the rate stabilization finishes, the Sun search mode starts and the spacecraft rotates with a constant rate until the Sun is detected by each SAS. If one of the five SASs detects the Sun, the Sun-pointing mode is executed in order to point the PZ plane towards the Sun. Figure 7 shows that this sequence is fully executed within 10 min.

The second example is an anomaly case. The initial conditions are same as the first case, but it is assumed that the communication between the OBC and the FOG has failed. Figure 8 shows the initial Sun acquisition sequence when the FOG is not used. The rate stabilization is not executed because the angular rate cannot be estimated. However, the Sun-pointing control is executed successfully except for the spin rate stabilization around the Z-axis. In this case, the failure of the FOG was detected by the FDIR functions and the PID gains were changed to use the derivation from...
the Sun vector instead of the angular rate obtained from the FOG. The reason of the residual spin around the Z-axis is that the derivation of the Sun vector cannot calculate the angular rate around the Sun direction. This residual spin is not critical because the solar panel can be kept pointing at the Sun. The FDIR functions for other components have been evaluated in a similar way.

5.4. Simulation results for precise three-axis mode

Simulations for the precise three-axis mode have also been demonstrated using the SILS in order to evaluate the attitude accuracy of the ADCS. The results are shown in Fig. 9. The top figure expresses the error between the target and the estimated attitude, and the bottom figure shows the variation of the error during a 10 s time frame. The requirement of the pointing accuracy is 0.2 deg. The attitude stability requirement is 6.0 \times 10^{-3} \, \text{deg} (3\sigma) during 10 s for optical navigation and 2.0 \times 10^{-2} \, \text{deg} during 100 s for the geo-corona imager. These stability requirements are illustrated in the figure as red lines. The simulation results show that the pointing accuracy and stability requirements are satisfied. These simulation results are compared with flight data in Section 6.2.

6. On-orbit Results

PROCYON was launched on December 3rd 2014, and the initial signal acquisition and other initial health checks were successfully performed on orbit. This section describes the on-orbit behavior of PROCYON’s ADCS.

6.1. Initial Sun acquisition soon after separation

The initial Sun acquisition after separation from the HII-A rocket is reported in Fig. 10. It is similar to the results of the SILS shown in Fig. 7: the initial Sun acquisition sequence was successfully performed, and the minimum success criterion-1 was achieved on orbit. Fortunately, the initial spin rate was \(1.2 \, -1.0 \, 0.3\) deg/s, which was much smaller than the worst assumption. PROCYON could charge the battery for the long journey to the asteroid because of successful initial Sun acquisition.

6.2. Three-axis stabilization

Sun-pointing was successfully achieved as described above. For the next step, three-axis stabilization was demonstrated and a MGA communication experiment was performed. In order to point the MGA towards the Earth, a 40-deg maneuver is needed in the three-axis stabilization mode. The on-orbit results of this experiment are shown in Fig. 11. The top figure illustrates the quaternion \(q_{123}\), and the bottom figure shows the Sun angle when viewed by the SAS placed on the PZ plane. The attitude was changed in increment of 10 deg to point the MGA toward the Earth. When the Sun angle reached 40 deg, the MGA faced the Earth and MGA communication was demonstrated. Finally, the attitude came back to the initial Sun-pointing attitude. This result verified that minimum success criterion-2 was completed on orbit. PROCYON can control its attitude freely for long-distance communications, conduct orbit control using ion
shows that the requirement was satisfied. In the case of PROCYON, the requirement for using the mission telescope, more precise attitude stability is required. In order to prevent such a dangerous situation, the total angular momentum of the PROCYON and RWs is controlled to maintain pointing towards the Sun. This angular momentum management method is discussed in Hayashi et al.\textsuperscript{14}) In the case of PROCYON, the angular momentum is managed to maintain two constraints. The first one is that the angular momentum around the Z-axis should remain larger than 0.1 Nm. The second one is that the angle between the Sun and the angular momentum should be kept smaller than 30 deg. The angular momentum is changed by not only solar radiation pressure torque, but also the torque generated by the ion thruster. The cause of ion thruster torque is the misalignment between the thrust vector and the center of mass. The magnitude of the torque is estimated from on-orbit data as \((-0.8, 0.0, 2.0) \times 10^{-6}\) Nm when the ion thruster is in acceleration mode and as \((-1.4, 0.0, 0.0) \times 10^{-5}\) Nm when the ion thruster is in the plasma ignited mode without acceleration. During ion thruster operation, the variation in angular momentum should be predicted and controlled using CGJ to satisfy the two constraints described above.

In actual operation, angular momentum management was performed by a combination of on-orbit detection and ground-based CGJ control. Operators predict the angular momentum variation from solar radiation pressure and ion thruster operation. The CGJ control timing and required control value are obtained from the prediction, and the information is uploaded to PROCYON. Several minutes before the CGJ control data is uploaded, the angular momentum detection system is turned on to prevent misdetection. When the angular momentum reaches the threshold, the CGJ is automatically controlled using the uploaded control value, and the detection system is then turned off.

Figure 13 illustrates the on-orbit results of angular momentum management during ion thruster operation. Firstly, the angular momentum around the Z-axis and X-axis were controlled as large magnitude on the opposite side of the predicted torque direction. During acceleration using the ion thruster, the angular momentum became smaller due to the disturbance torque generated by the ion thruster. Near the point of 120,000 s, the X-axis angular momentum was controlled by CGJ operation. After 140,000 s, the Z-axis angular momentum was controlled by CGJ operation to maintain the angular momentum larger than 0.2 Nms. Figure 13 shows that the two constraints were satisfied over two days of ion thruster operation. Criterion-2 was also successfully accomplished on orbit. These results also verify the capability of orbit control using ion thrusters on micro-spacecraft.

6.4. FDIR

Finally, the on-orbit results of the implemented FDIR system are explained. In this case, all four RWs suddenly became uncontrollable because the power control unit stopped
the electric power supply to the RWs. Figure 14 shows the RW reset count, the angular rate obtained by the FOG, and the Sun angle given by the SASs. The failure occurred in the coarse three-axis mode, and the Sun angle was controlled as 40 deg. The FDIR system detected the RW failures from communication errors, and the RWs were reset. However, the failure did not recover until after resetting three times. Since the reset count reached the threshold, the FDIR system decided to change the attitude control mode from three-axis mode to the safe Sun-pointing mode. In the mode changing sequence, the power control unit that failed was reset, and then the power control unit was recovered. After that, PROCYON could maintain the Sun acquisition safely since the power supply to the RWs was recovered. This flight data verified that the PROCYON achieved the advanced success criterion.

7. Conclusions

This paper describes an attitude determination and control system for the world’s first interplanetary micro-spacecraft, PROCYON. Four technical issues for interplanetary micro-spacecraft were focused on in this paper: initial Sun acquisition without magnetic components, angular momentum management without magnetic actuators, the requirement of a more robust ADCS, and precise attitude control. In order to overcome these issues, a reliable and precise ADCS and FDIR system without magnetic components were proposed. In addition, ground-based evaluation systems were developed to verify the systems before launch.

For the first two issues, which come from the fact that magnetic components cannot be used in interplanetary orbit, a new small propulsion system and a new reliable attitude control system without magnetic components were developed. The initial Sun acquisition control without magnetic components was tested applying many initial parameters using the developed ground-based evaluation system. For the robustness mentioned as the third issue, the developed FDIR system actively uses function redundancy instead of component redundancy to observe the serious resource limitations of micro-spacecraft. The FDIR was also tested using the ground-based evaluation systems to verify that the system can achieve Sun acquisition even if one of the components fails. In order to satisfy the attitude accuracy for the fourth issue, an EKF- and LPF-based attitude determination system was developed. The accuracy of the developed ADCS was simulated using the ground-based evaluation system. The simulation results verified that the ADCS accuracy satisfies the requirement.

Furthermore, the developed ADCS and FDIR system were successfully demonstrated on orbit. The flight data shows that the proposed systems successfully resolved the four issues. Angular momentum management using the newly developed propulsion system was also demonstrated on orbit during ion thruster operation. The minor differences between the flight data and simulation results for precise three-axis control indicates the mismatching of components in the simulator. Although degradation of the on-orbit accuracy is not a big problem for the PROCYON mission, model calibrations and gain tuning should be studied for more accurate attitude stability as a theme of future work. For interplanetary micro-spacecraft, this is the first success regarding practical attitude control for advanced interplanetary operations. The development strategies and flight data proposed in the paper will help the advancement of future micro- and nano-interplanetary missions.

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