Reliable and Robust Implementation of Attitude Determination and Control Subsystem and Initial Flight Operation Result of 50 kg-class Interplanetary Spacecraft PROCYON

Takahiro Ito [(1)(*)], Satoshi Ikari[(2)], Toshihiro Nakatani[(2)],
Masataka Fujimoto[(2)], Kaito Ariu[(2)], Kenshiro Oguri[(2)],
Takaya Inamori[(2)], Shinichiro-Sakai[(1)], Yasuhiro Kawakatsu[(1)], and Ryu Funase[(2)]

(1) Japan Aerospace Exploration Agency (JAXA)
(2) The University of Tokyo
(*)Mailing address: 3-1-1 Yoshino-dai, Chuo-ku, Sagamihara, Kanagawa, Japan
Phone number: 81-50-3362-8447
Email address: ito.takahiro@jaxa.jp
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ABSTRACT

PROCYON (PRoximate Object Close flYby with Optical Navigation), which is developed by the University of Tokyo in collaboration with JAXA, is a 50 kg-class interplanetary spacecraft (categorized as "micro-sized spacecraft"). After an Electric Delta-V Earth Gravity Assist (EDVEGA), PROCYON flies toward an asteroid. PROCYON has two main mission objectives. The first objective is to demonstrate indispensable technologies of a micro-spacecraft bus system for deep space exploration. This includes communications, attitude/orbit determination and control, heat-control, and solar power generation in deep space environment. The second objective is to demonstrate advanced deep space exploration technologies that range over communication using a high-efficient X-band amplifier, precise orbit determination by Very Long Baseline Interferometry (VLBI), and flying-by observation of an asteroid using optical navigation. In September 2013, PROCYON was selected as one of secondary payloads for the 26th H-IIA launch. After the short-term development (one year and three months), PROCYON was launched with Hayabusa-2 in December 2014.

In order to meet the mission requirements, the attitude determination and control subsystem (hereafter "ADCS") of PROCYON has one fiber optical gyro (FOG), one star tracker (STT), and five sun aspect sensors (SAS). Regarding actuators, it has four reaction wheels (RW; one of which is aligned with skew-axis) and eight cold gas jet thrusters (CGJ; only used for unloading and orbit control). Figure 1 shows the external view of PROCYON. Compared to large missions, realizing the redundant system is more difficult to PROCYON due to the resource restriction in terms of spatial and electric-power issues. Hence, PROCYON has no backup FOG and STT onboard.

With regard to the operation, the critical term is particularly on the launch day. At first, PROCYON begins its attitude control for spin rate dumping several hundred seconds after the separation from the rocket. PROCYON has to succeed in rate dumping control even under the worst separation condition. The worst assumption is that 10 deg/s (0.57 Nms) is given in a certain direction while the compensable angular momentum by four RWs is between 0.50—1.02 Nms, which may cause saturation of RWs and finally fall the attitude into out of control. Next, it starts sun-search until detecting the sun, and after that, sun-pointing control begins. At this point, PROCYON has to succeed in sun-pointing control and start solar charging within one hour because without sun light its inner battery can provide electricity for only one hour. Moreover, it has to continue sun-pointing control at least for several hours as all earth stations in Japan for telemetry-command operations for deep space missions are assigned for the other missions during that period. Therefore, the sequence from rate-dumping control to sun-pointing control has to run automatically. The difficult point is that although it is the first time for PROCYON to work in space environment, highly reliable and robust implementation is required on this automatic sequence because its success is critical for its survival.

To pursue the reliability and robustness, following measures are taken. In terms of reliability, software/hardware is carefully verified through the whole sequence from the separation to sun pointing control. For the verification, simulation environment called "SILS (Software in the Loop Simulator)" and "HILS (Hardware in the Loop Simulator)" is applied. SILS is the closed-loop

simulator for the software verification, which can verify not only ADCS software but also other subsystem software (that enables whole software verification). In contrast, HILS can verify not only software but also communication hardware between onboard computer and component drivers. From the viewpoint of robustness, the whole sequence from the separation to sun pointing control is designed to complete even when one component of ADCS breaks down. To achieve this, FDIR (Fault detection, isolation and recovery) functions are built in the system. Further, sun-pointing control by using a maneuver path planning technique is implemented in case that one of four RWs is broken and the initial separation condition is the worst assumption.

PROCYON was launched in 3rd December 2014. After 5.5 hours from the separation, the telemetry-command started and we confirmed that the sequence until sun pointing control ran successfully in orbit as shown in Figure 2. The attitude dynamics during this sequence was almost the same as simulated by SILS. However, the result also shows that one thing we did not consider in the design is the feature of the RWs that has the dead time for 0.5 second (though the control period is 1.0 second), which caused hunching around the target attitude. However, it disappeared soon after another torque distribution method was applied. Another significant feature is that disturbance reduced the angular momentum of PROCYON by 0.03 Nms for the first 5.5 hours while it gave no negative effect on the attitude control.

This paper first introduces mission objectives of PROCYON and then describes implementation requirements on reliability and robustness that are unique to a secondary payload. Next, we explain a design of the attitude determination and control subsystem in addition to its verification process. We also report the initial flight operation results, and finally evaluate the designs and verification process. The practical information summarized in this paper will be useful for not only nano/micro satellite community but also those who are interested in low-cost space missions and efficient development.

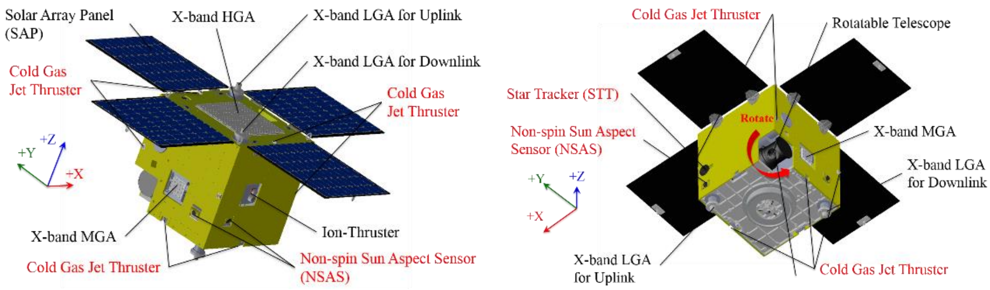

Figure 1 External view of PROCYON.

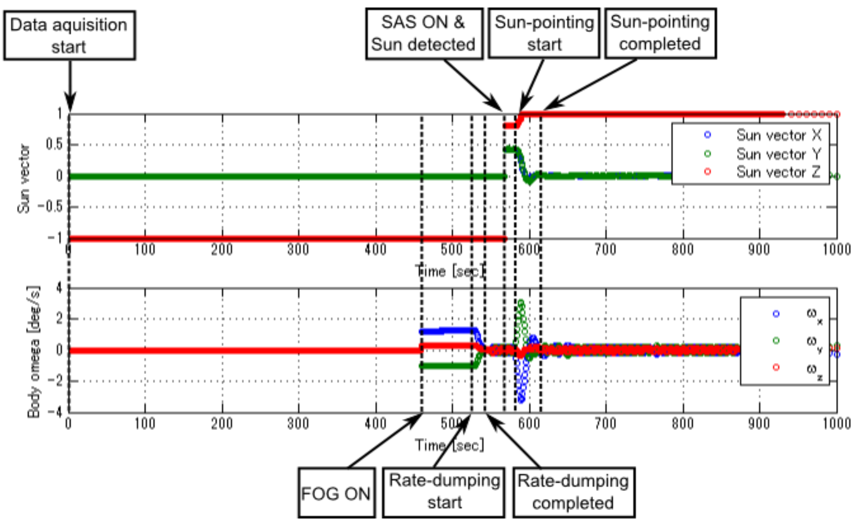

Figure 2 Flight result of the automatic attitude control sequence.