Development of Total Orbital Real-Time Attitude Control Simulator for Small Satellites

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Abstract

This paper presents the overview of the mathematical simulator TORA-Sim (Total Orbital Real-time Attitude control Simulator) developed by Kyushu University and Mitsubishi Precision Co.,Ltd. used for the satellite attitude control and the simulation results for the typical small satellite application. The results have demonstrated the validity of this simulator in use for the study of the attitude control law. This simulator was used for the development of onboard software for the attitude control of the Kyushu University's small satellite "QSAT-EOS" launched last autumn.

INTRODUCTION

The missions of small and micro-satellites which are developed by universities and organizations are becoming more demanding and diversified to acquire various information. For example, the small satellite "QSAT-EOS" developed in Kyushu University has the missions such as 3-dimensional observation of a fixed point on the earth, observation of a target star, and so on. Therefore, the pointing or tracking requirements of mission instruments such as camera or antenna to the target must be taken into account in designing the attitude control system.

To design the attitude control system for small and microsatellites properly, we are developing the simulator which can simulate various attitude controls.

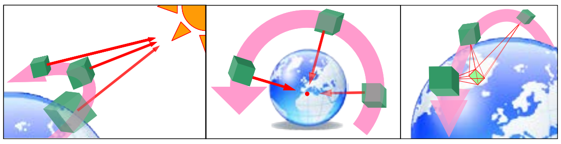
With this simulator, four attitude control modes can be designed and analyzed including the tracking control mode as mentioned above. In this paper, we describe the outline of the developed simulator and the attitude control design applied for the QSAT-EOS launched last autumn.

DEVELOPMENT TARGET

This simulator is applicable to various design phases of satellites. For instance, in the preliminary design phase of attitude control system, we can perform the basic study in control law using this simulator with ideal attitude control system (sensors, actuators, etc.). And, in the detailed design phase of the attitude control system, we can conduct more precise analysis by installing realistic sensor models and realistic actuator models of the system to this simulator.

This simulator enables design and analysis of attitude control modes shown in Fig.1 and detumbling mode after satellite separation. These modes are essential for QSAT-EOS. Therefore, the attitude control system designed by this simulator was implemented in QSAT-EOS.

We plan to improve this simulator by comparing the attitude results obtained by this simulator to the actual attitude data obtained in the on-orbit operation.



(a) (b) (c)

Figure 1: Various attitude control modes of QSAT-EOS

(a); Sun acquisition control mode, (b); Coarse geocentric pointing mode, (c); Ground point tracking mode)

DESIGN PRINCIPLE FOR THE SIMULATOR

Object modeling

The simulator consists of the following five models. We can modify details of these models in accordance with a purpose of simulation analysis.

1) Attitude estimation model
2) Attitude controller model
3) Actuators model
4) Sensors model
5) Earth's environmental model

Each model is summarized below.

Attitude estimation model

The satellite attitude can be determined by integrating data of various sensors. Depending on the purpose of the simulation analysis, we can use either output data from a simulated true attitude or an estimated attitude by the attitude estimation algorithm.

Attitude controller model

This model has independent control algorithms according to control modes. In addition, this model includes accuracy and computation delay of the satellite onboard computer.

Actuator models

Characteristics of each actuator and actuator controller are simulated by this model. We can use either the calculated command torques directly or simulated torques of realistic actuator model depending on the purpose of simulation analysis.

Sensors model

Characteristics of sensors are simulated by this model. We can use either calculated satellite attitude value or simulated measurement value of realistic sensor model depending on the purpose of simulation analysis.

Earth's environmental model

Environmental disturbance (forces and torques) is calculated by this model. IGRF model [2][3], NRLMSISE-00 model [4], and EGM96 model [2] are utilized as the geomagnetic field, Earth's global atmospheric field, and Earth's gravitational field, respectively.

Typical attitude control modes

In our simulator, the following four control modes are installed on QSAT-EOS.

1) Detumbling mode

2) Sun acquisition control mode

3) Coarse geocentric pointing mode

4) Ground point tracking mode

Control system design and analysis can be performed in each mode. Fig.2 shows a typical transition of the attitude control modes. Each mode transition is in accordance with operational plans.

Each mode is summarized below. Note that, in the below, the sensors and actuators are assumed as the design of QSAT-EOS.

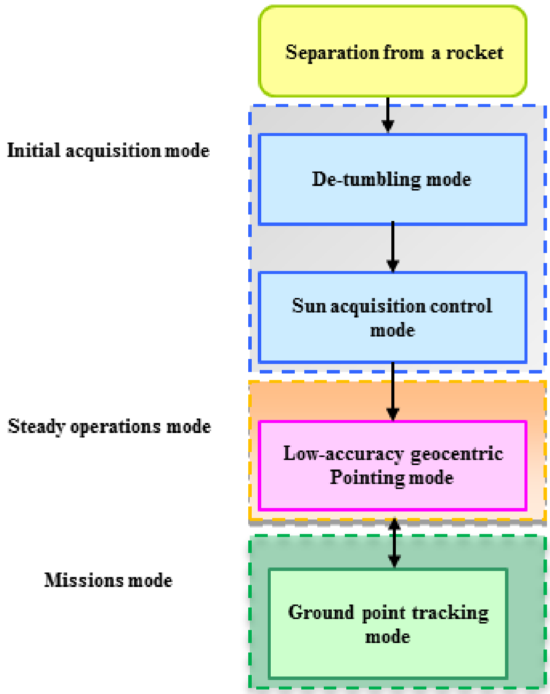


Figure 2: Typical transition of attitude control modes

Detumbling mode

At an early period right after the satellite separation in orbit, rotational motion of the satellite will be damped with magnetic sensors and magnetic torquers. In this mode, the satellite attitude is stabilized as much as sensors and communication devices are be utilized properly.

Sun acquisition control mode

In this mode, the satellite attitude is controlled to keep electric power as much as possible by utilizing sun sensors and three magnetic torquers. Arbitrary face of the satellite can be kept oriented to the sun by the control.

Coarse geocentric pointing mode

This mode keeps arbitrary face of the satellite oriented to the geocentric direction by utilizing sun sensors, magnetic sensors, rate gyros and magnetic torquers.

Ground point tracking mode

This mode keeps an antenna or payloads oriented to the desired point on the ground surface by utilizing star sensors, rate gyros and reaction wheel assemblies.

OUTLINE OF THE SIMULATOR

The simulator in this paper consists of the following four blocks.

- Attitude control block
- Generation block of satellite orbit
- Generation block of control target
- Generation block of environmental disturbance

A block diagram of these blocks is shown in Fig.3. The satellite motion in each control mode is simulated using satellite characteristics, orbital parameters (initial values of Keplerian elements), and satellite targets (attitude angle, pointing position etc.).

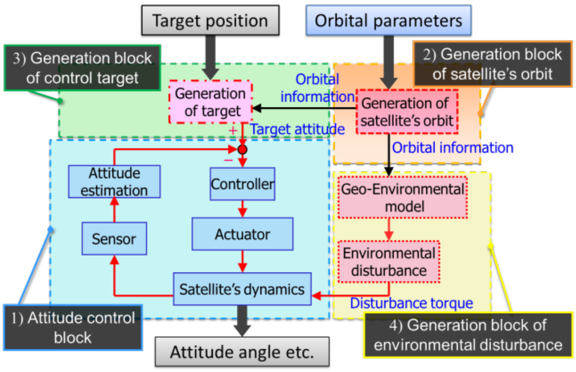


Figure 3: Block diagram of the simulator

Attitude control block

In the detumbling mode, rotational motion of the satellite at an early period right after the separation on the orbit will be damped with the B-dot control law:

$$M_i = -K\dot{B}_i^B \tag{1}$$

where M_i, K, and $\dot{B}_i^B$ represent the magnetic moment about satellite axis *i*, the gain, and the time rate of change of a geomagnetism about satellite axis *i*, respectively. $\dot{B}_i^B$ is calculated as

$$\dot{B}_{i,k}^B \approx \frac{B_{i,k}^B - B_{i,k-1}^B}{\Delta t} \tag{2}$$

where $B_{i,k}^B - B_{i,k-1}^B$ and Δt stand for the change of the geomagnetism and sampling time, respectively.

On the other hand, in the sun acquisition control mode, the low-accuracy geocentric pointing control mode and the ground point tracking control mode, the satellite attitude is controlled with the control torque u. u is determined by the following quaternion feed-back control law:

$$\begin{aligned} u = &-K_p \cdot q_e \\ &- K_d \cdot (\omega_b - \omega_d) - K_i \cdot q_{e\_i} \end{aligned} \tag{3}$$

where q_e, q_{e_i}, ω_b, ω_d, K_p, K_d, and K_i represent each component of the quaternion error, the value of integral of the q_e, current angular velocity, target angular velocity, proportional gain, derivative gain, and integral gain, respectively.

Generation block of satellite orbit

Orbital information of the satellite is necessary for the calculation of the environmental disturbance and the target attitude. At this block, the orbital information (latitude, longitude, altitude, etc.) is calculated with the initial values of the Keplerian elements. This orbital information is input to the generation block of control target and that of environmental disturbance. Note that, in this block, the sun-synchronous orbit can also be generated because an orbital perturbation is considered.

Generation block of control target

In the ground point tracking control, the direction of the ground point and the target attitude in the satellite coordinate need to be calculated. In this block, target attitude and unit vector whose direction coincides with the target direction in the orbital coordinate system are calculated from the coordinate of the target point (latitude, longitude, etc.). These calculated values are supplied to the attitude control block.

Generation block of environmental disturbance

Geomagnetism and atmospheric density are calculated from the orbital information of the satellite. In addition, the environmental disturbance is calculated from the satellite characteristics (a residual magnetic moment, mass properties, a position of the mass center, etc.). These calculated values are supplied to the attitude control block.

RESULT OF THR SIMULATION AND ANALYSIS EXAMPLE OF THE ATTITUDE CONTROL SYSTEM

For an example of the attitude control system design and analysis by this simulator, the example of the ground point tracking mode is shown below. In this analysis, the target satellite is QSAT-EOS. The direction of yaw axis in the coordinate system of the satellite body coincides with the direction of the optical axis of the observation camera, and the satellite dynamics is treated as first-order rigid-body mode.

Configuration parameters

Tables 1 through 4 show the parameters determined by the result of the simulation and control system design. Fig.4 shows the flight path of the satellite calculated by applying the parameters in Table 1. In the case of orbital parameters in Table 1, it takes approximately 800 seconds for the satellite to reach to the closest position to pointing target on the ground from initial attitude which is oriented to the center of the Earth. In the simulation, north latitude and east longitude are treated as positive value, and target attitude is calculated.

Table 1: Simulation parameters (orbit)

Satellite orbit	Sun-synchronous orbit
Semi-major axis [km]	6,900
Eccentricity	0
Inclination [deg]	97
Longitude of ascending node [deg]	-45
Argument of perigee [deg]	160
Mean anomaly [deg]	-60

Table 2: Simulation parameters (target)

Pointing target	Latitude	Longitude
Fukuoka City	33 degrees North	130 degrees East

Table 3: Simulation parameters (satellite)

Item	Set value
Initial attitude of satellite [deg]	[5 5 5]
Inertia moment of satellite [kg]	$\begin{bmatrix} 1.98 & 0 & 0 \\ 0 & 2.03 & 0 \\ 0 & 0 & 1.91 \end{bmatrix}$

Table 4: Parameters by the result of the control system design

controlled parameter (each diagonal element)	value
proportional gain	(0.2,0.2,0.2)
differential gain	(0.6,0.6,0.6)
integration gain	(0.008,0.01,0.008)

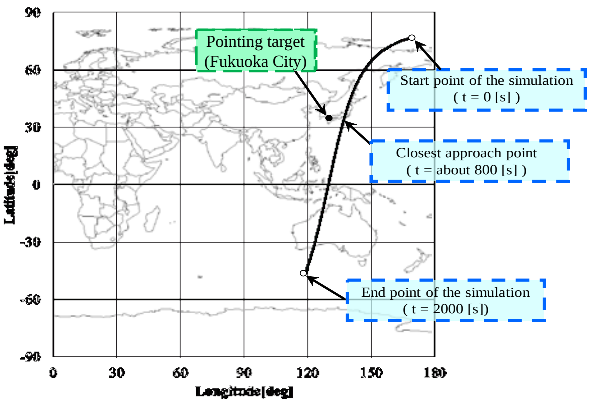


Figure 4: *Flight path of the satellite*

Simulation results

Figure 5 through 8 show the time history of target attitude angles, actual attitude angles, attitude angle errors (differences between the target attitude angles and the actual attitude angles), and angular velocity errors, respectively. Attitude angles are expressed as in the orbital coordinate system.

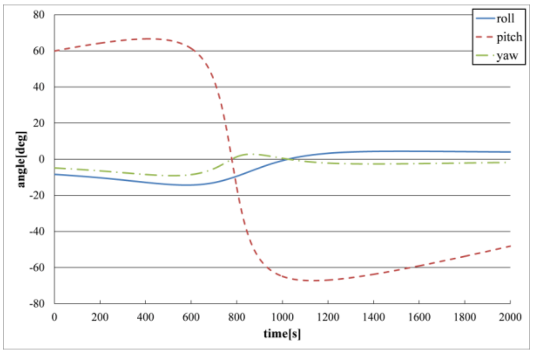


Figure 5: Time history of the target attitude angles

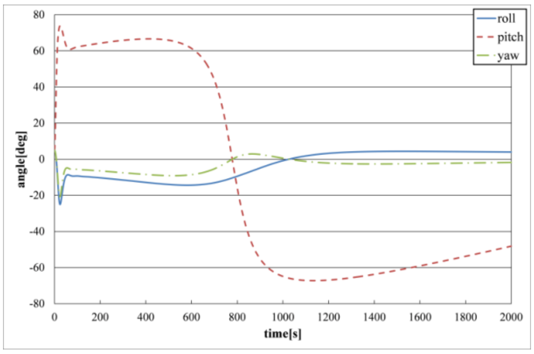


Figure 6: Time history of the actual attitude angles

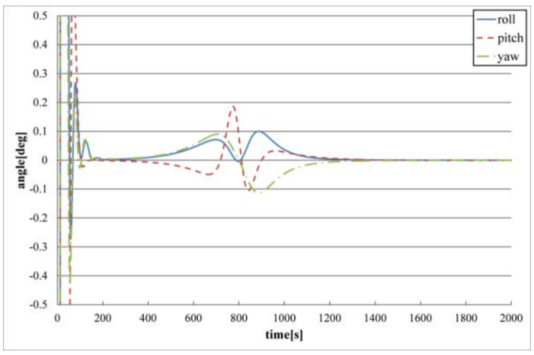


Figure 7: Time history of the attitude angle errors

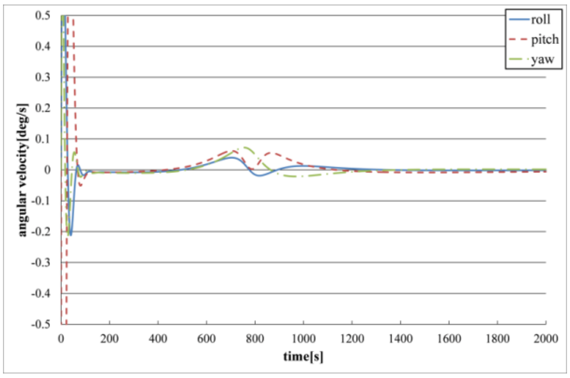


Figure 8: Time history of the angular velocity errors

CONSIDERATION TO THE SIMULATION

By Fig.5 and Fig.6, it is confirmed that the satellite attitude is controlled within the allowable tolerance of ±0.2 deg. In this simulation, it is found that the attitude angle errors are about ±0.1 deg in roll and yaw axes, about ±0.2 deg in pitch axis as shown in Fig.7, respectively. Note that the attitude angle errors in roll axis and pitch axis show the performance of the ground point tracking mode because the optical axis of the observation camera coincides with the yaw axis of the satellite. The error in roll axis or pitch axis is ±0.2 deg for the simulated altitude corresponds to the distance error of about 2 km on the ground. And, it is confirmed that the angular velocity also follows up the target angular velocity, because Fig.8 shows the angular velocity errors in all axes become less than ±0.1 deg/s.

As the simulation examples show, it is confirmed that this simulator is applicable to the study of satellite attitude control using arbitrary orbital elements, pointing targets on the ground surface, and satellite parameters.

CONCLUSION

This simulator was used for the design and the analysis of QSAT-EOS attitude control. At the present stage, accuracy of each model shown in section 3.1 is not optimized. The modeling of sensors and actuators will be sophisticated with the development progress of QSAT-EOS. Furthermore, we plan to evaluate the designed attitude control system and accuracy of this simulator, then we improve the performance of this simulator by correlation with QSAT-EOS on-orbit data.

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Keywords: Attitude control, Simulator, Earth observation, Academic project

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