

Updates on EQUULEUS ADCS: Design of the Critical “DV1” Operation and Initial Results from Hardware-In-the-Loop Simulations

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This paper presents design updates of the attitude determination and control system (ADCS) of EQUULEUS, a deep space CubeSat expecting its launch in 2020. For the spacecraft to be able to achieve the sun pointing state after a sudden unexpected shutdown, we proposed an angular momentum vector control policy. We also proposed a thrusting sequence policy during trajectory control operations including the critical “DV1” operation. Then we presented software validation and verification plan with three types of simulators that can collectively validate and verify the software even in the existence of a commercial off-the-shelf (COTS) ADCS component that we have limited knowledge of.

Key Words: Attitude Determination, Attitude Control, CubeSat, EQUULEUS

Nomenclature

- ϕ : angle between the sun direction and the angular momentum
 θ : angle between the body y-axis and the sun direction
 $\mathbf{e}_s$: sun direction vector
 $\mathbf{h}$: angular momentum vector

Superscripts

- i : inertial frame
b : body frame

demonstration of the trajectory control techniques in the Sun-Earth-Moon region, 2) imaging observation of the Earth’s plasmasphere and 3) observation of lunar impact flash. To meet these goals, EQUULEUS is required to control its attitude with the accuracy of 0.1 degrees and to stabilize its attitude below 0.021 degrees.

Table 1. ADCS components of the 13 CubeSats on SLS EM-1. Note that some of the CubeSats are equipped with a propulsion system as part of their ACS in addition to the components listed here. The manufacturers are presented in brackets. It is listed as “unknown” in case the information is unavailable.

Spacecraft	ADS components	Primary ACS components
Skyfire	Unknown	Unknown
Lunar IceCube ³⁾	XACT (BCT)	XACT (BCT)
NEA Scout ³⁾	Modified XACT (BCT)	Modified XACT (BCT)
BioSentinel ³⁾	XACT (BCT)	XACT (BCT)
Lunar Flashlight ³⁾	XACT-50 (BCT)	XACT-50 (BCT)
CuSP ³⁾	XACT (BCT)	XACT (BCT)
LunaH-Map ³⁾	XB1 (BCT)	XB1 (BCT)
EQUULEUS ³⁾	XACT-50 (BCT)	XACT-50 (BCT)
OMOTENASHI ³⁾	XACT (BCT)	XACT (BCT)
ArgoMoon ³⁾	XACT (BCT)	XACT (BCT)
Cislunar Explores ^{3,4)}	Optical navigation (in-house)	Water propulsion (in-house)
CU-E3 ³⁾	XB1 (BCT)	XB1 (BCT)
Team Miles ⁵⁾	TS Nano Star Tracker (BCT), COTS sun sensors (unknown)	Plasma thruster (in-house)

1. Introduction

1.1. ADCS of Deep-Space CubeSats

While CubeSats (spacecraft composed of multiple cubic “units” with the side length of 10 centimeters) have been utilized in Earth orbits for a variety of purposes, they are also beginning to be used in deep space as well. In 2018, twin 6U CubeSats called Mars Cube One (MarCO) were launched to help receive and transmit data during the entry, descent and landing operations of Mars lander InSight, the primary payload of the launch.¹⁾ In 2020, NASA plans to launch the Space Launch System (SLS) Exploration Mission-1 (EM-1) with 13 CubeSats as secondary payloads.²⁾

Being limited in volume, mass, power and development time, many deep-space CubeSats adopt commercial off-the-shelf (COTS) components. Table 1 lists the ADCS components of the 13 CubeSats on SLS EM-1.

1.2. EQUULEUS ADCS

EQUULEUS is one of the deep-space CubeSats that will be launched by the SLS EM-1 and is being jointly developed by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA). Its mission objectives include 1)

EQUULEUS has one XACT-50 as its attitude determination and control system (ADCS). It is an integrated ADCS unit developed by Blue Canyon Technologies and is equipped with a star tracker, three 50-mNms reaction wheels, a three-axis gyroscope, and four external sun sensors as well as ADCS software that communicates with the main onboard computer and controls the attitude as commanded using its sensors and actuators. The attitude control accuracy in 3-sigma by the specifications is 0.021 degree around the star tracker boresight axis and 0.0092 degrees around the other two axes. Considering other sources of attitude error such as the misalignment between the star tracker and the observation instruments, the thermal strain of the structure, and the spacecraft navigation error, the attitude requirements are satisfied with on-orbit correction of the misalignment between the star tracker and one of the scientific instruments.

Another requirement for the ADCS is that it needs to realize the sun pointing after sudden shutdown of the spacecraft. Therefore, the angular momentum is controlled with the reaction control thrusters (RCTs) so that the solar cells will generate enough power to turn on crucial components and all the components will be in its survival temperature range in the tumbling state after the shutdown.

The detailed design of EQUULEUS ADCS is also presented in Nomura et al⁶⁾.



Fig. 1. External view of EQUULEUS.

1.3. DV1 Operation

The CubeSats on SLS EM-1 will be in heliocentric orbit after the first lunar flyby that occurs 5 to 6 days after the separation unless they execute an adequate thrusting maneuver before the flyby. Therefore, for the CubeSats that aim to stay in cislunar space, it is essential to execute the thrusting maneuver to control the trajectory within the first 5 to 6 days after the separation, which we call “DV1 operation”. This operation is planned in at least six missions – including EQUULEUS – out of the 13 CubeSats on the SLS EM-1.

The DV1 operation of EQUULEUS will begin in 32 hours after the separation and continue for approximately 10 hours. During the DV1 operation, EQUULEUS needs to output the required delta-V within the allowable accuracy without real-time communication with the ground, while controlling its angular momentum in case of a sudden shutdown.

1.4. Validations and Verifications of ADCS

We need to design and test our ADCS software in a way that the ambitious DV1 operation will be successful. This is often achieved by integrating the ADCS software with a simulator and testing whether the software behaves as

designed. However, one of the difficulties in designing and testing our ADCS software is that we have limited knowledge of or control over the XACT-50 software. We have designed three types of simulators to tackle this difficulty, which will be explained in Section 4.

2. Angular momentum management

In case of a sudden shutdown, the reaction wheels will gradually stop rotating due to friction and the spacecraft will start tumbling according to the angular momentum initially stored by the wheels. Therefore, controlling the angular momentum vector is essential to ensure that the spacecraft will generate at least 11W, the power consumption of crucial components, and the spacecraft will be within the allowable temperatures, namely more than -20 degrees Celsius, in the tumbling state.

We simulated the power generation and the temperature of the spacecraft bus in various tumbling cases to analyze the angular momentum requirement. The initial condition was set as shown in Table 2.

Table 2. Initial conditions in tumbling simulations.

Parameters	Initial values
Angular momentum norm	25 mNms
θ : Angle between the body y-axis and the sun direction	$0 \leq \theta \leq 360$ [deg]
ϕ : Angle between the sun direction and the angular momentum	$0 \leq \phi \leq 90$ [deg]

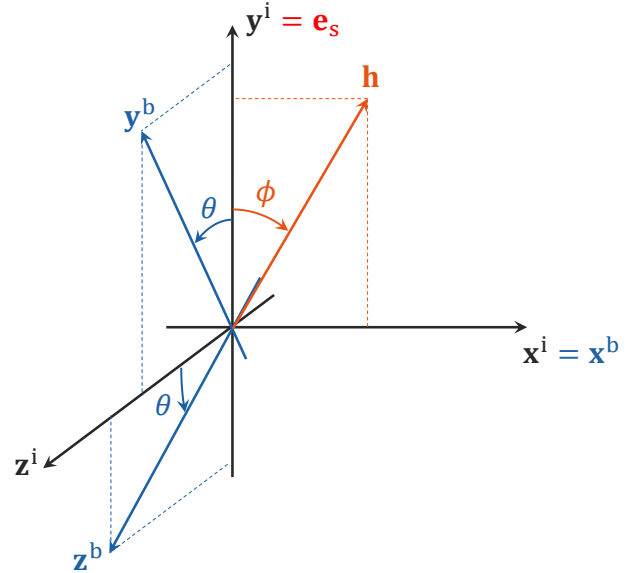


Fig. 2. Coordinate definitions defining the angle ϕ and θ . $\mathbf{h}$ and $\mathbf{e}_s$ represent the angular momentum vector and the sun direction vector respectively. $(\mathbf{x}^b, \mathbf{y}^b, \mathbf{z}^b)$ represents the spacecraft body frame and $(\mathbf{x}^i, \mathbf{y}^i, \mathbf{z}^i)$ the inertial frame. Without loss of generality, we assumed that $\mathbf{x}^i$ is aligned with $\mathbf{x}^b$ and $\mathbf{y}^b$ is aligned with $\mathbf{e}_s$.

The results are shown in Fig. 3. The yellow region indicates that both the power generation and the spacecraft bus temperature satisfy the requirement. Since the angular momentum vector and the sun direction vector is fixed in the

inertial frame in the short term, the angle ϕ is also fixed while the angle θ changes every time the spacecraft changes its attitude. Therefore, by controlling the angle ϕ so that the power generation and the spacecraft bus temperature fulfill the requirements in the tumbling state for any θ , we can ensure that the spacecraft can realize the sun pointing after a sudden shutdown. Currently, we plan to control the angle ϕ from 40 degrees to 70 degrees, based on Fig. 3.

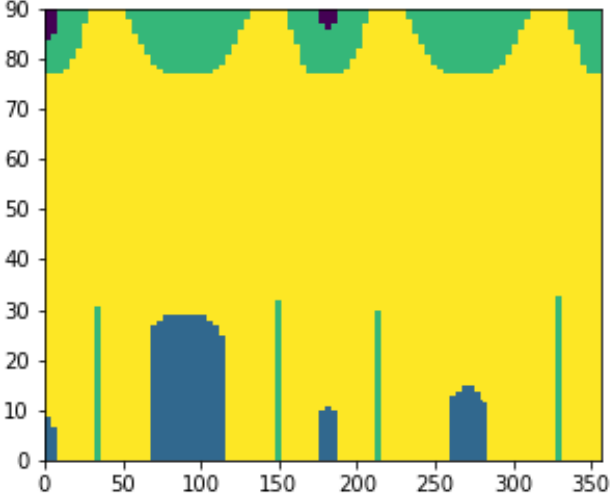


Fig. 3. The results of the tumbling simulations. The horizontal axis shows θ : the angle between the body y-axis and the sun direction; and the vertical axis shows ϕ : the angle between the sun direction and the angular momentum, both in degrees. Blue indicates only the power generation requirement is satisfied; green indicates only the temperature requirement is satisfied; purple indicates neither of them is satisfied; and yellow indicates both of them are satisfied.

3. DV1 Operation

There are two requirements for the DV1 operation: 1) the accurate execution of delta-V and 2) the angular momentum management as described in Section 2.

The spacecraft needs to be able to estimate the executed delta-V autonomously to satisfy the first requirement even without communication with the ground at the end of the thrusting maneuver. For this reason, the thrusting maneuver will be a repetition of the same propellant injection cycle. More concretely, the thrusting maneuver in the DV1 operation will consist of delta-V thruster (DVT) cycles and RCT cycles, as shown in Fig. 5.

Since the DVTs generate torque around the y-axis, the spacecraft decides which DVT to activate based on the current angular momentum vector and controls the angular momentum around the y-axis to satisfy the second requirement. If the angular momentum vector needs to be controlled around x or z-axis, the spacecraft will activate the corresponding RCTs to keep the angular momentum vector under control.

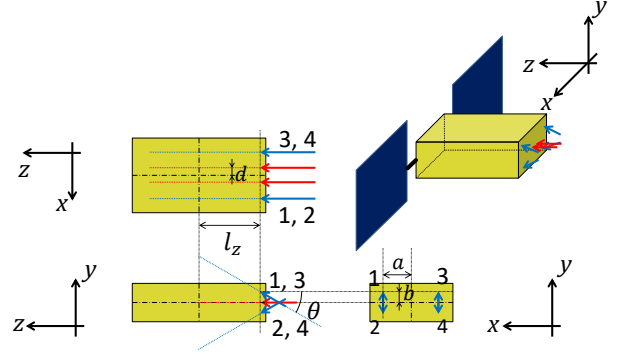


Fig. 4. EQUULEUS thruster configuration. The red arrows represent the two DVTs, and the blue arrows represent the four RCTs.



Fig. 5. Example of thrusting sequence during the DV1 operation.

4. Validation and Verification of ADCS

4.1. Simulators overview

There are four types of simulators for the verification of EQUULEUS ADCS: the BCT software simulator (BCT SWSim), the software-in-the-loop simulator (SILS), and the hardware-in-the-loop simulator (HILS) – all of which will be explained in detail in the following clauses. As shown in Table 3, the simulators have different characteristics and therefore are used for various purposes.

	Simulates XACT SW	Simulates OBC SW	Simulates dynamics	Faster than real-time
BCT SWSim	Yes	No	Yes	Yes
SILS	No	Yes	Yes	Yes
HILS	Yes	Yes	Yes	No

4.2. BCT software simulator (BCT SWSim)

BCT software simulator (BCT SWSim) is provided by BCT and simulates XACT software and spacecraft dynamics. This simulator runs on computers with MATLAB and is faster than real-time. However, it cannot be integrated with other simulators to execute a closed-loop simulation with the software on EQUULEUS onboard computer. Therefore, this simulator can be used to check the behavior of the XACT software.

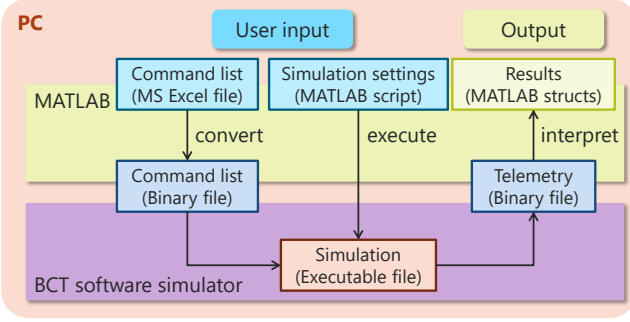


Fig. 6 BCT software simulator diagram.

4.3. Software-In-the-Loop Simulator (SILS)

Software-In-the-Loop Simulator (SILS) is a general spacecraft simulator developed in house. It runs on computers and can be integrated with actual onboard software source codes. Since it is entirely built in the house, it can contain any component necessary by implementing its simulator, and it can run the simulation faster than real time. Therefore, it can be used to run Monte-Carlo simulations to verify the software against uncertainties in operations, especially the critical DV1 operation.

One of the limitations of the SILS is the accuracy of component simulators. Especially in case of EQUULEUS, most of the ADCS is implemented as the XACT software, of which we have limited knowledge. Therefore, the behavior of the XACT-50 implemented in the SILS may be different from that of the original XACT-50 software in details.

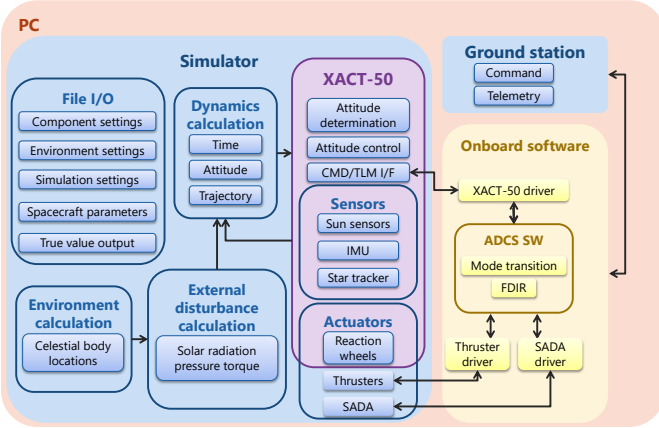


Fig. 7. Software-in-the-loop simulator diagram.

4.4. Hardware-In-the-Loop Simulator (HILS)

Hardware-in-the-loop simulator is an integration of software and simulators running on four devices: a personal computer, the EQUULEUS onboard computer (OBC), the XACT-50, and the Real-time Dynamic Processor (RDP). Unlike the other two simulators, the HILS has the original XACT software and the OBC software running on the actual hardware. In that sense, this simulator is the most accurate of the three.

However, the drawback is that because it only runs real-time on the actual hardware, it can run only when the hardware is available.

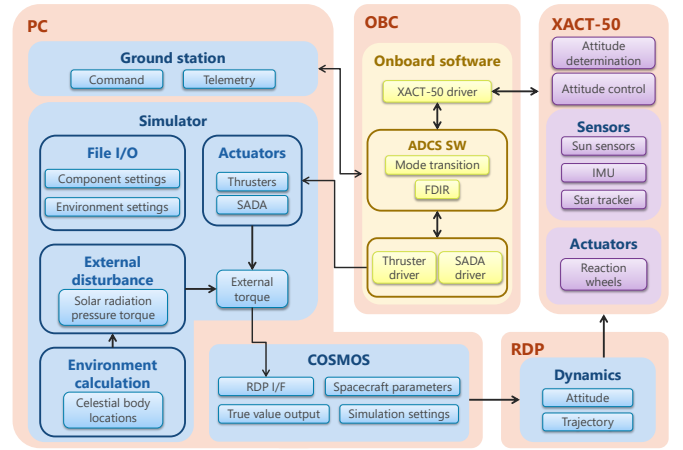


Fig. 8. Hardware-in-the-loop simulator diagram.

4.5. Software verification matrix

Table 4 shows the verification matrix of essential ADCS functions and the simulators with which they are verified. We verify all the functions with either the BCT SWSim or the SILS and run the HILS to see if the whole integrated ADCS works properly on the flight hardware.

Table 4. Software verification matrix with simulators

Function to be verified	BCT SWSim	SILS	HILS
Initial sun acquisition	X		X
Attitude determination	X		X
Attitude control	X		X
Unloading algorithm			X
Thrusting maneuvers			X
FDIR		X	X
Mode transition		X	X
Ground station operation		X	X

5. Initial Results of Hardware-In-the-Loop Simulation

This section presents initial results from simulations of sun pointing maneuvers in extreme separation conditions with HILS.

5.1. Simulation case settings

The specifications state that the tip-off rate is 10 degrees per second per axis at maximum. We tested seven extreme cases shown in Table 5 and checked if the sun pointing could be achieved in 8 minutes as expected. Note that there is a gap between when the “initial angular rate” is set and when the sun pointing maneuver is initiated.

For all cases, the initial attitude quaternion representing the coordinate conversion from ECI to the EQUULEUS body frame is $(0, -\sqrt{2}/2, 0, +\sqrt{2}/2)$. The simulated time started from 2019-12-15 00:00:00UTC.

Table 5. Initial angular rate in each simulation case.

Case	Initial angular rate [deg/s]
1	(+10, +10, +10)
2	(+10, +10, -10)
3	(+10, -10, -10)
4	(-10, +10, +10)
5	(-10, +10, -10)
6	(-10, -10, +10)
7	(-10, -10, -10)

5.2. Results

Fig. 9 presents the sun angle error profile and Fig. 10 and Fig. 11 present the angular rate profile in each case. It can be observed that the sun pointing state is achieved in less than 80 seconds in all cases.

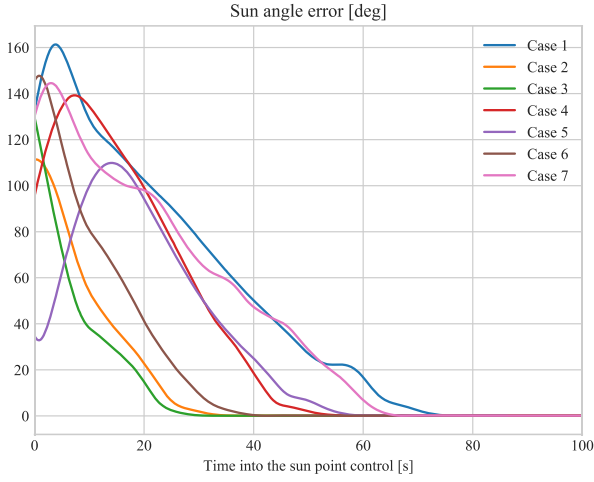


Fig. 9. Sun angle error profile in each simulation case.

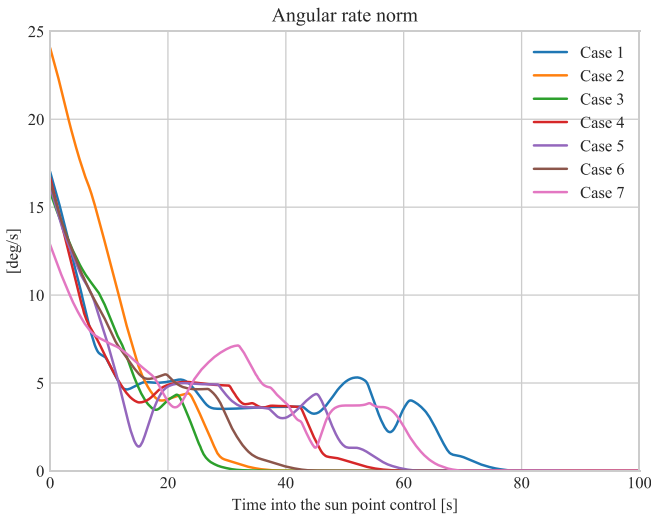


Fig. 10. Angular rate norm profile in each simulation case.

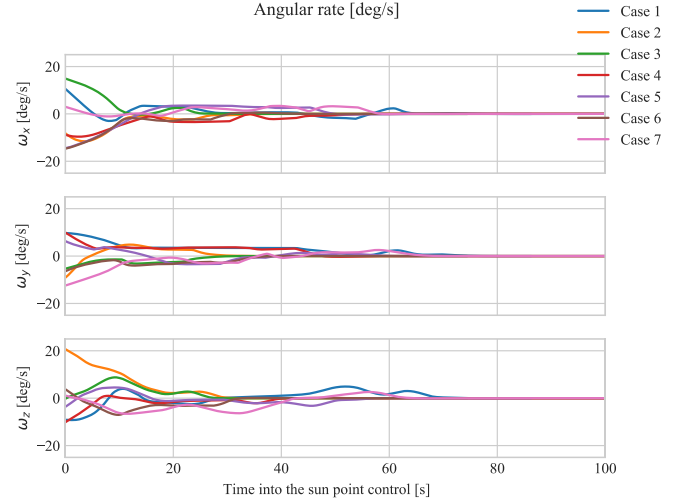


Fig. 11. Angular rate profile in each simulation case. Note that there is a gap between when the “initial angular rate” is set and when the sun pointing maneuver is initiated.

5.3. Discussion

The results confirmed that the initial sun acquisition is possible even in extreme tip-off rates in less than 80 seconds, which is less than the required time of 8 minutes.

To verify the ADCS software, we need further testing with the HILS. For the critical DV1 operation, we will test our angular momentum control software together with propulsion control software and simulated propulsion system in the HILS.

6. Conclusion

We designed the ADCS for EQUULEUS with a COTS ADCS component XACT-50. To achieve the sun pointing after a sudden shutdown, EQUULEUS will manage its angular momentum by controlling the angle ϕ – the angle between the sun direction and the angular momentum. This strategy was tested with tumbling simulations and the results suggest both the power generation and the spacecraft bus temperature satisfy the requirement in the tumbling state.

We also designed the thrusting sequencing algorithm in the critical DV1 operation so that the executed delta-V can be estimated autonomously onboard and that the angular momentum vector is controlled in case of a sudden shutdown.

Although we have limited knowledge of the XACT-50 software, we designed three types of simulators to verify our software. We presented initial results of sun pointing simulations using the HILS and showed the sun pointing maneuvers could be carried out in less than 80 seconds even in the extreme tip-off cases.

We will further test our software with the simulators to make it robust against uncertainties, especially in the critical DV1 operation.

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