

Initial Design of EQUULEUS Attitude Determination and Control System: How to Design an ADCS with High Reliability for a Deep Space CubeSat

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This paper presents the initial design of the Attitude Determination and Control System of EQUULEUS, a deep space CubeSat expecting its launch in 2018. Since we adopted a commercial off-the-shelf (COTS) ADCS component and have limited access to its software, it is difficult to assure the reliability of the ADCS. We designed a layered FDIR and the safe mode to effectively integrate the COTS ADCS component and our onboard software into a reliable ADCS, and presented a verification plan with three types of simulators.

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

Nomenclature

$\mathbf{h}$: total angular momentum
 T : rotational kinetic energy
 $\boldsymbol{\omega}$: angular rate
 $\tilde{I}$: tumbling mode parameter

1. Introduction

1.1. Designing an ADCS for deep-space micro spacecraft

Many deep-space CubeSats are planned or proposed to launch in the coming years. In May of 2018, MarCO, the world's first deep-space CubeSats, will be launched to help receive and transmit data during the entry, descent and landing operations of InSight, which will be launched by the same rocket as MarCo.¹⁾ In late 2018, 13 CubeSats, including EQUULEUS, are planned to be launched by NASA's Space Launch System Exploration Mission 1 (SLS EM-1).²⁾ Furthermore, CubeSats are proposed as companions for missions such as ESA's Asteroid Impact Mission³⁾ and NASA JPL's Europa Clipper.⁴⁾

CubeSats usually have limited resources regarding volume, mass, power, and development time. Therefore building a reliable attitude determination and control system (ADCS) in deep space within these constraints requires a new way of thinking while taking advantage of already existing resources at the same time.

1.2. Designing the ADCS for EQUULEUS

EQUULEUS (EQUilibrium Lunar-Earth point 6U Spacecraft) is a deep space CubeSat being developed by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA), expecting its launch in 2018 by NASA's SLS EM-1. To its destination, the Earth-Moon Libration point 2, it will execute multiple lunar gravity assists (LGAs) maneuvers. Before the first LGA is executed a few days after the separation from the rocket, the first trajectory control

maneuver (DV1) needs to be executed over more than 10 hours.

The maneuver will require a reliable ADCS because a) the thrust direction needs to be precise, b) contact with a ground station is not secured for the entire maneuver, and c) it is so time-critical that an ADCS failure may cost a long time for the recovery and lead to the failure of the maneuver.

Like many CubeSat missions, EQUULEUS will adopt a commercial off-the-shelf (COTS) ADCS component – XACT-50 developed by Blue Canyon Technologies (BCT). One of the difficulties in designing an ADCS with a COTS unit such as an XACT-50 is that users do not have much knowledge of or control over the algorithm including attitude determination, attitude control, and FDIR (Fault Detection, Isolation, and Recovery).

However, by taking advantage of “layered FDIR,” it is possible to design a reliable ADCS with a COTS unit. “Layered FDIR,” initially proposed by Shirasaka et al.⁵⁾, is an FDIR system where faults are handled differently according to their levels of abstraction. For example, the FDIR at the lower level (level 1) deals with component-based faults such as a failure in star pattern matching of the STT and a motor drive failure of an RW, while the higher-level (level 2) FDIR deals with sequence-based faults such as attitude control failure and unloading failure. The concept of the layered FDIR was introduced and implemented in PROCYON, the world's first deep-space micro spacecraft, where the basic ADCS functions were designed by its project members.⁶⁾

We designed a layered FDIR system as well as a safe mode for EQUULEUS ADCS with a COTS component.

2. EQUULEUS ADCS overview

2.1. Attitude accuracy requirements

EQUULEUS has two main scientific observation instruments: PHOENIX (Plasmaspheric Helium ion

Observation by Enhanced New Imager in eXtreme ultraviolet), which will observe the Earth's plasmasphere and DELPHINUS (DEtection camera for LUNar impact PHenomena IN 6U Spacecraft), which will observe lunar impact flashes (LIFs) and near-Earth objects (NEOs). Also, during the DV maneuvers, the attitude should be accurate to reduce the DV execution error. Each operation requires the attitude of the spacecraft to be accurate as shown in Table 1.

Let us define the error angle as the angle between the target attitude and the realized attitude. Then the absolute attitude accuracy is defined as the average of the error angle over the observation or the maneuver period. The absolute attitude accuracy is required so that the observation target is at the center of the FoV, or that the delta-V execution error is small.

The relative attitude, on the other hand, is defined as the standard deviation of the error angle over the observation or the maneuver period. The relative attitude accuracy is required so that the observation target does not move largely during the exposure time.

Table 1 Attitude accuracy requirements

	Required attitude accuracy (absolute, 3σ)	Required attitude accuracy (relative, 3σ)
PHOENIX	5 deg	0.085 deg for 10 min 0.085 deg for 60 min
DELPHINUS (LIFs)	On a best-effort basis	0.042 deg for 1/60 sec
DELPHINUS (NEOs)	5 deg	0.042 deg for 15 sec
DV maneuvers	1.7 deg	N/A

2.2. Components

EQUULEUS ADCS consists of the components listed below. See Fig. 1 for the coordinates and component locations.

- A BCT XACT-50 which includes:
 - One star tracker (STT)
 - Three reaction wheels (RWs)
 - One 3-axis MEMS gyroscope (IMU)
- Four sun sensors (SSs)
- A Reaction Control System (RCS) which consists of
 - Four water resistojet thrusters

Also, EQUULEUS has solar array paddles (SAPs) gimbaling system that can rotate the SAPs around the x-axis.

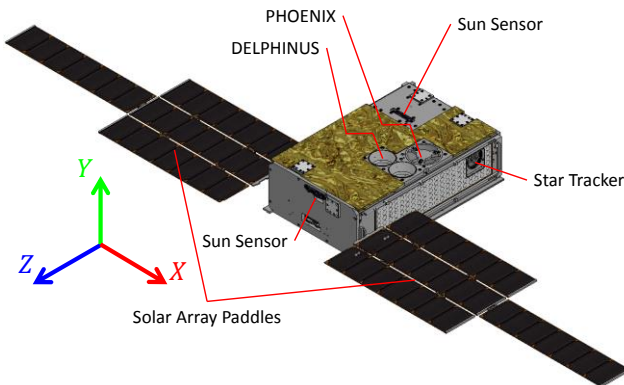


Fig. 1 EQUULEUS overview

2.3. ADCS diagram

In EQUULEUS, the XACT determines and controls the attitude using its sensors and actuators. EQUULEUS flight software (FSW) is in charge of generating targeting values to command to the XACT and monitoring the telemetries from the XACT. The ADCS diagram is shown in Fig. 2.

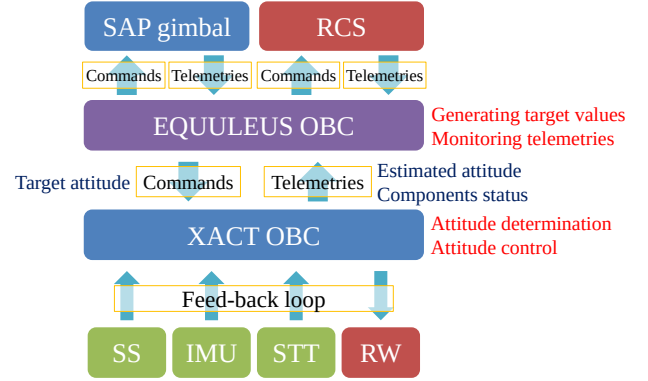


Fig. 2. ADCS diagram

2.4. Angular momentum management

The total angular momentum vector is maintained to be aligned with the sun direction vector so that the SAPs can generate power even in the uncontrolled safe mode. The details are explained in clause 4.2.

2.5. Operation modes

EQUULEUS has seven ADCS modes shown in Table 2.

Table 2 ADCS modes and used components

Mode	Sensors	Actuators
Sun point (safe) mode	SS, IMU	RW
Three-axis stabilization mode	IMU, STT	RW
Trajectory control mode	IMU, STT	RW, RCS
PHOENIX observation mode	IMU, STT	RW
DELPHINUS LIFs observation mode	IMU, STT	RW
DELPHINUS NEOs observation mode	IMU, STT	RW
Unloading mode	IMU, STT	RW, RCS
Uncontrolled safe mode	SS, IMU	None

2.5.1. Sun point (safe) mode

Sun point (safe) mode is a mode where EQUULEUS tries to orient its solar array paddles towards the sun. The used sensors are the sun sensors measuring the sun direction in the body frame and the IMU measuring the angular rate. Attitude is controlled using the reaction wheels.

This functions as the initial mode when the spacecraft is separated from the rocket, and also as the safe mode.

2.5.2. Three-axis stabilization mode

This mode functions as the hub for the other ADCS modes. The spacecraft is three-axis stabilized in the inertial frame using the RWs as the actuators and the STT and the IMU as the sensors.

2.5.3. Trajectory control mode

When EQUULEUS executes a trajectory control maneuver, it transits to the trajectory control mode where the spacecraft is three-axis stabilized in the inertial frame. One difference from three-axis stabilization mode is that the delta-V thrust nominally generates external torque. Therefore feedback

torque is added to the RW control torque so that it cancels out the external torque. Another is that unloading maneuvers are automatically executed because the angular momentum accumulates too fast to execute the maneuvers by commands from the ground before the RWs are saturated.

2.5.4. PHOENIX observation mode

PHOENIX's optical axis needs to be directed towards the Earth during the 1-hour observation. Because the Earth direction changes more than 0.085 degrees during a 1-hour observation, the required accuracy is not satisfied if the spacecraft is three-axis stabilized.

There are two kinds of observation operations to satisfy the requirement. One is that the spacecraft controls its attitude so that PHOENIX's optical axis always points towards the Earth during a 60-minute observation. The other is that the spacecraft is three-axis stabilized in the inertial frame and takes one picture with the exposure time of 10 minutes, and then changes its attitude and takes another picture, and repeats it until it takes six pictures in total. The required accuracy is satisfied because the Earth direction does not change more than 0.085 degrees over 10 minutes during the most of the mission. Compared to the first operation, the attitude accuracy needs to be sustained only for 10 minutes, but 6 times larger data need to be downlinked.

Also, we need to assure that the sun angle – the angle between the sun direction and the PHOENIX's optical axis – is always below the threshold, otherwise the filter will be permanently damaged.

2.5.5. DELPHINUS LIFs observation mode

During the LIF observation, the spacecraft changes its attitude so that DELPHINUS's FoV captures only the dark side of the Moon. To assure that, DELPHINUS constantly monitors whether the bright side is in its FoV as part of FDIR.

2.5.6. DELPHINUS NEOs observation mode

This mode is the same as the three-axis stabilization mode. The spacecraft is three-axis stabilized in the inertial frame so that DELPHINUS's optical axis is in the direction of the observation target.

2.5.7. Unloading mode

When the angular momentum is accumulated by external torque such as the solar radiation pressure torque, EQUULEUS executes unloading maneuver with the RCS to avoid saturation of the RWs. The maneuver can be either automatic or manual (by ground station command) because the accumulation of the angular momentum is slow enough.

2.5.8. Uncontrolled safe mode

If a failure is too critical to execute sun acquisition maneuver, EQUULEUS will transit to the uncontrolled safe mode. Such failures include low battery voltage, an RW fault. The ADCS is turned off, and the SAPs are oriented towards such direction that they generate as much power as possible.

3. FDIR design

3.1. General principle

To integrate the FDIR system with that of XACT, we adopt "layered FDIR," where FDIR system is composed of several layers, each of which handles faults at a different level of

abstraction. The level-1 FDIR handles component-based faults, whereas the level-2 FDIR handles sequence-based faults.

3.2. Level-1: component-based FDIR

3.2.1. Level-1 fault detection

We set three basic criteria to identify a sensor fault: the sensor is considered to be faulty if

1. it outputs nothing or the default value over a certain period of time of time, or
2. the output value does not change over a certain period of time, or
3. the time change rate of the output value exceeds the threshold.

Apart from these basic criteria, some components have health-indicating telemetry that can be used to determine a fault.

We are currently considering not enabling the level-1 fault detection during the DV1 operation because a single false fault detection might lead to a failure of the maneuver.

3.2.2. Level-1 fault isolation and recovery

There are three phases in the level-1 fault isolation and recovery (I&R). In I&R 1, other components function as a complement not to interrupt the mission. If the fault continues so long that the other components can no longer function as a complement, then it will move on to I&R 2, where the XACT-50 is rebooted in the hope that failed component comes to perform normally. In the case of a RCS valve fault, all the valves are closed as I&R 2. If the fault continues after I&R 2, it will finally move on to I&R 3, where EQUULEUS will transit to the safe mode.

Let us explain I&R 1 in detail. As for the IMU and STT, they can complement each other if the spacecraft is stabilized. The angular rate can be estimated by differentiating the quaternions from the STT if the IMU fails; while the quaternion can be estimated by integrating the angular rate from the IMU if the STT fails. This way the mission is not interrupted even the IMU or the STT temporarily fails until the attitude accuracy is too degraded.

On the contrary, the RWs cannot be easily compensated by the RCS, which are not as reliable as the other components because they are not nominally used for attitude control. For the same reason, attitude control with only two wheels cannot be considered to be reliable, either. Therefore if one of the RWs fails, it will directly transit to I&R 2.

Table 3. Level-1 fault isolation and recovery.

Failed component	I&R 1	I&R 2	I&R 3
IMU	STT as complement	XACT-50 reboot	Safe mode
STT	IMU as complement	XACT-50 reboot	Safe mode
RW	N/A	XACT-50 reboot	Safe mode
SS	Another SS as complement	XACT-50 reboot	Safe mode
RCS valve (open)	N/A	All valves closed	Safe mode
RCS valve (close)	N/A	All valves closed	Safe mode

3.3. Level-2: Sequence-based FDIR

3.3.1. Level-2 fault detection

The level-2 fault detection observes errors in the results of maneuvers. It constantly checks telemetries from the XACT (and DELPHINUS when necessary) and regards it as a fault if they are out of the expected ranges during the mode. Table 1 shows the criteria of level-2 fault detections in each mode.

Table 4 Level-2 fault detection

Mode	Fault	Detection
Sun point mode	Detumbling not completed	Timer
	Sun acquisition not completed	Timer
	Sun pointing not completed	Timer
Three-axis stabilization mode	Attitude error too large	XACT telemetry
	Attitude rate too large	XACT telemetry
Trajectory control mode	Thrust not fired	Angular momentum change
Unloading mode	Unloading not performed properly	Angular momentum change
	Unloading not performed properly	Angular momentum change
PHOENIX observation mode	Attitude error too large	XACT telemetry
	Attitude rate error too large	XACT telemetry
	Sun angle too small	XACT telemetry
DELPHINUS (LIF/NEO) observation mode	Attitude error too large	XACT telemetry
	Attitude rate error too large	XACT telemetry
	Moonlight in FoV (LIF only)	DELPHINUS telemetry

3.3.2. Level-2 fault isolation and recovery

No level-1 fault is detected when the level-2 fault detection observes a fault, which is the reason it is difficult to determine the cause of the fault. Therefore the level-2 fault isolation and recovery is mainly a mode transition to the safe mode.

Table 5. Level-2 fault isolation and recovery.

Mode	I & R
Sun point mode	Transit to safe mode
Three-axis stabilization mode	Transit to safe mode
Trajectory control mode	Close the thruster valves and transit to safe mode
Unloading mode	Close the thruster valves and transit to safe mode
PHOENIX observation mode	Close the PHOENIX aperture and transit to safe mode
DELPHINUS (LIF/NEO) observation mode	Transit to safe mode

4. Safe mode design

EQUULEUS has two types of safe modes: sun point safe mode and uncontrolled safe mode.

4.1. Sun point safe mode

The sun point safe mode, shown in Fig. 3, is essentially the same as the initial sun acquisition mode, where EQUULEUS orients the SAPs towards the +Z direction, turn on the XACT, and the XACT controls the attitude so that the SAPs are

oriented towards the sun. If the SAPs cannot be oriented towards the +Z direction or the sun acquisition in the +Z direction failed, EQUULEUS will attempt a sun acquisition again with a different direction as the desired sun direction.

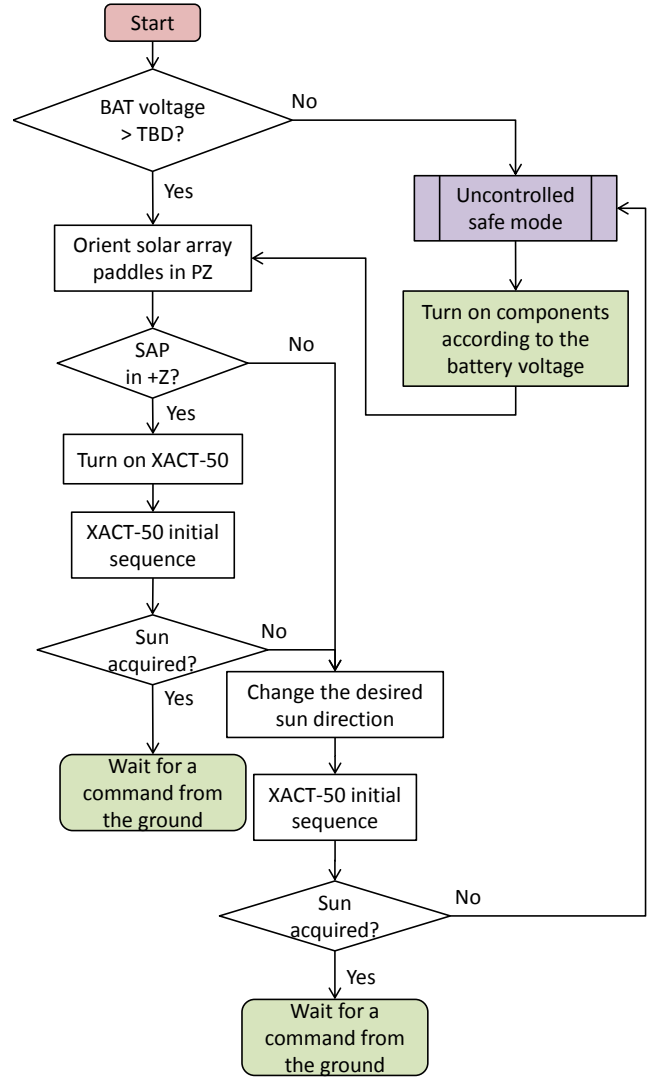


Fig. 3. Sun point safe mode diagram

4.2. Uncontrolled safe mode

If the second sun acquisition in the sun point safe mode failed, EQUULEUS will transit to the uncontrolled safe mode, shown in Fig. 4, where the RWs are turned off, orient the SAPs in the optimal direction to generate as much power as possible, turn off the onboard computer and the XACT, and wait until the battery is charged to the extent where the sun acquisition maneuver can be executed.

Let us briefly explain how to obtain the optimal direction of the SAPs. Let $\mathbf{h}$ be the total angular momentum in the body frame. Then the rotational kinetic energy can be written as

$$\begin{aligned}
 T &= \frac{1}{2} \boldsymbol{\omega}^T \mathbf{I} \boldsymbol{\omega} \\
 &= \frac{1}{2} (\mathbf{I}^{-1} \mathbf{h})^T \mathbf{I} (\mathbf{I}^{-1} \mathbf{h})
 \end{aligned} \tag{1}$$

Then let us define the tumbling mode parameter $\tilde{I}$ as

$$\tilde{I} \equiv \frac{\|\mathbf{h}\|^2}{2T} \quad (2)$$

Figure 5 shows the contour of $\tilde{I}$ against the direction of $\mathbf{h}$ in the case of EQUULEUS. When the spacecraft is not controlled and tumbling, $\tilde{I}$ is constant if the energy dissipation is ignored. Therefore the direction of $\mathbf{h}$, which is also the sun direction, moves on a line in the contour. The optimal direction of the SAP is the center of the line on which the sun direction moves. In the case of EQUULEUS, it is either +Z, -Z, +Y, or -Y direction.

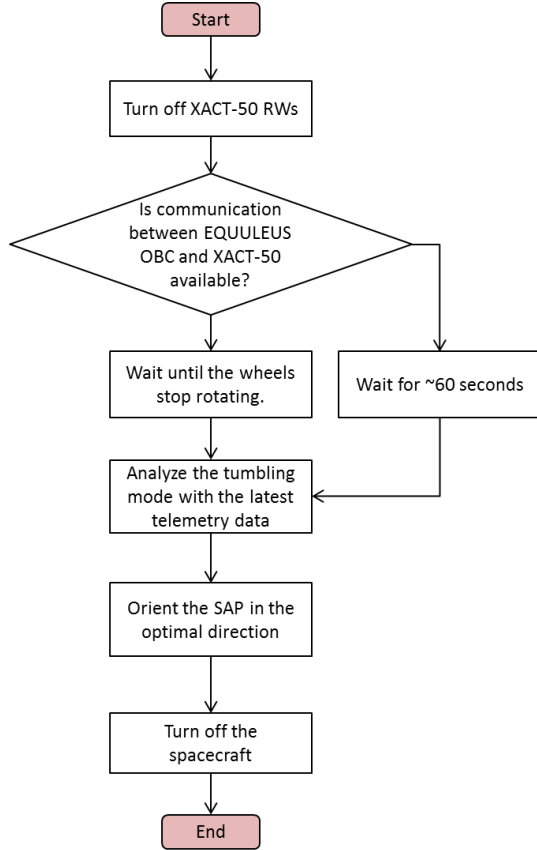


Fig. 4. Uncontrolled safe mode diagram

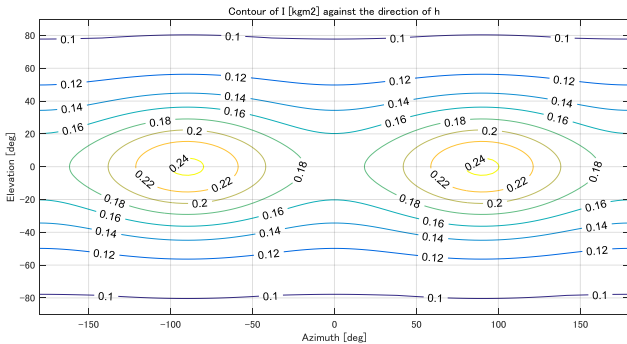


Fig. 5. Contour of $\tilde{I}$ against the direction of $\mathbf{h}$.

5. Verification plan

5.1. Simulators overview

There are three 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 6, the simulators have different characteristics and therefore are used for various purposes.

Table 6. Differences between the simulators

	Simulates XACT FSW	Simulates EQUULEUS FSW	Simulates dynamics	Faster than real-time (runs on PC)
BCT SWSim	Yes	No	Yes	Yes
SILS	No	Yes	Yes	Yes
HILS	Yes	Yes	Yes	No

5.2. BCT software simulator (BCT SWSim)

BCT develops BCT software simulator (BCT SWSim), which simulates XACT FSW and satellite 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 EQUULEUS ADCS software. Therefore this simulator is used only for observing the behavior of XACT FSW.

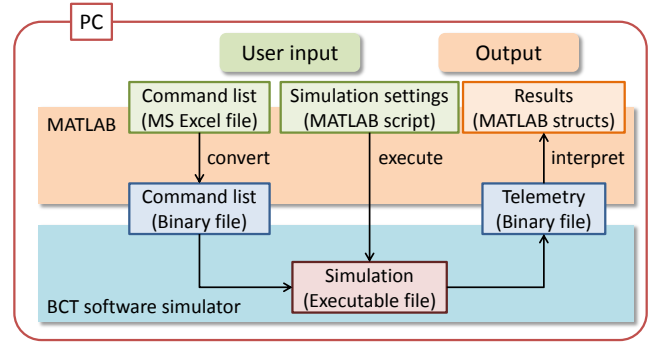


Fig. 6 BCT software simulator diagram.

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

Software-In-the-Loop Simulator (SILS), developed at the Intelligent Space Systems Laboratory, is a simulator that runs on computers and simulates the dynamics and spacecraft's onboard software. This simulator consists of component modules so that it can be used as ADCS simulator for various spacecraft missions. This runs faster than real time, and unlike BCT SWSim, it can simulate more integrated system including the closed-loop of the spacecraft attitude and the RCS. Therefore we can conduct Monte-Carlo simulations to verify the EQUULEUS FSW against uncertain conditions, especially during the DV1 maneuver.

However, since it is not a duplicate of the actual XACT FSW, it cannot simulate the XACT's reaction towards component failures or the attitude control algorithm implemented on the XACT.

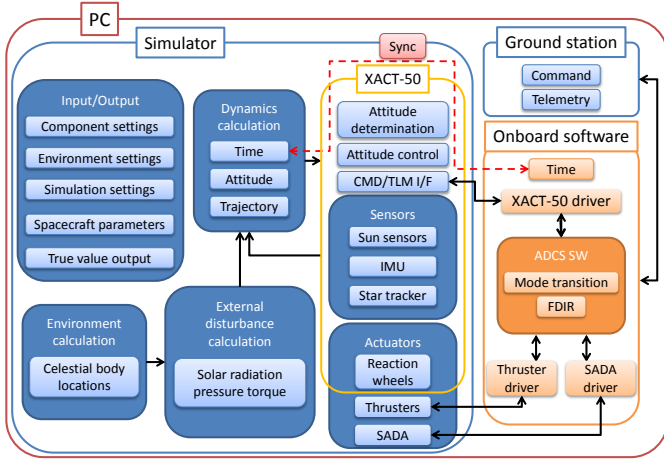


Fig. 7. Software-in-the-loop simulator diagram.

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

Hardware-in-the-loop simulator is an integration of simulators running on four devices: a personal computer, the EQUULEUS onboard computer, the XACT, and the RDP. Unlike the other two simulators, this simulates both XACT FSW and EQUULEUS FSW. Not only that, both run on the same hardware as they will after the spacecraft is launched. 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 for a certain period of time.

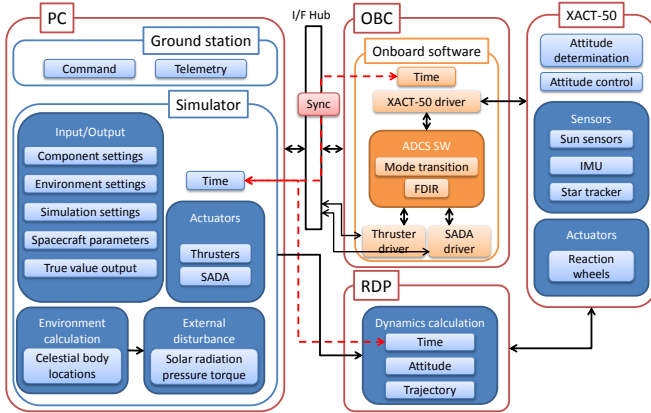


Fig. 8. Hardware-in-the-loop simulator diagram.

5.5. Software verification matrix

is the verification matrix of basic 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 7. 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	X
Level-1 FDIR	X		X
Level-2 FDIR		X	X
Mode transition		X	X
Ground station operation		X	X

6. Conclusion

We designed a reliable ADCS for EQUULEUS, a deep-space CubeSat with a COTS ADCS component and presented a verification plan with three types of simulators.

One problem in adopting a COTS ADCS component is that we do not have full access to its details because of the proprietary information. Due to the limited accessibility to the XACT FSW, we use two types of software simulator to verify ADCS functions: BCT SWSim and SILS.

Another problem is that designing FDIR might be difficult because the component might already have its own FDIR, which is the case in EQUULEUS. We adopt the layered FDIR to integrate the component's low-level FDIR and our high-level FDIR.

We will verify the EQUULEUS ADCS with the simulators and make it robust to realize a successful DV1 operation.

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