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Master's Dissertation 2016

Architecture of Attitude Determination and Control Subsystem in Consideration of Mode Sequences for Micro Dragon Satellite by Using SysML

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Graduate School of System Design and Management
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SUMMARY OF MASTER'S DISSERTATION

Student Identification Number	81434724	Name	Le The Soat
Title Architecture of Attitude Determination and Control Subsystem in Consideration of Mode Sequences for Micro Dragon Satellite by Using SysML			
Abstract Attitude Determination and Control Subsystem (ADCS) plays an important role in attitude control of a satellite to achieve the missions in all modes after separation from the rocket launched, such as De-tumbling mode, Sun pointing mode, and Earth pointing mode. Therefore, the architecture of the ADCS which has different roles in each mode in the mode sequences of Micro Dragon Satellite (MDG) is defined to meet the functions of subsystem such as attitude guidance, attitude determination and attitude control. Moreover, the verification of ADCS designed is planned based on its architecture. In the verification process, the ADCS's design is tested by using a simulation models derived from system models. System Modeling Language (SysML) is a standardized language to enable MBSE. There are a lot of design systems by using SysML because it provides logicality and consistency. This point is very important to decompose a complicated system like a satellite. The architecture definition of ADCS for MDG satellite is very difficult, because the ADCS should correspond to each mode sequence. This thesis uses SysML as a useful tool to analyze the behavior of ADCS in mode sequences to define the architecture of ADCS. From the strong points of SysML, it is expected to bring a good architecture for the ADCS of MDG satellite as well as a highly valuable document for satellite developers.			
Key Words (5 words) The architecture of ADCS, Mode sequences of MDG, SysML, logicality, consistency.			

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Chapter 1 Introduction

1.1 Micro Dragon (MDG) Satellite Background and Challenges

In the framework of cooperation between the Viet Nam and Japan governments in the field of the space technology, Vietnam National Satellite Centre (VNSC) has sent 36 students to universities in Japan. Parallel to the study at the universities, Vietnam's students participating satellite manufacturing, the Micro Dragon (MDG) satellite project was started from October 2014 and expected to finish in October 2017, under the guidance of Professors from five universities, including Keio University, Tokyo University, Tohoku University, Hokkaido University and Kyushu Institute and Technology. The MDG project has a typical meaning and an important role for Vietnam's students because it is not only for education but also the first micro satellite made by Vietnamese.

Micro Dragon satellite is such kind of micro satellite in 50 cm cubic shape and about 50 kg total mass. The satellite is planned to be launched in 2018 as one of piggyback payloads in HII-A vehicle. According to the planning, the satellite will be located in Sun-synchronous orbit with the altitude about 550 km, the life span of the satellite will be within two years.

Outer view of MDG satellite is shown in Figure 1.1-1. In term of system design, the satellite includes seven subsystems, among of them, there is an important and complex subsystem called ADCS (Attitude Determination and Control System). The main functions of this subsystem are to determine the orientation of the satellite and re-orient the satellite to the target direction.

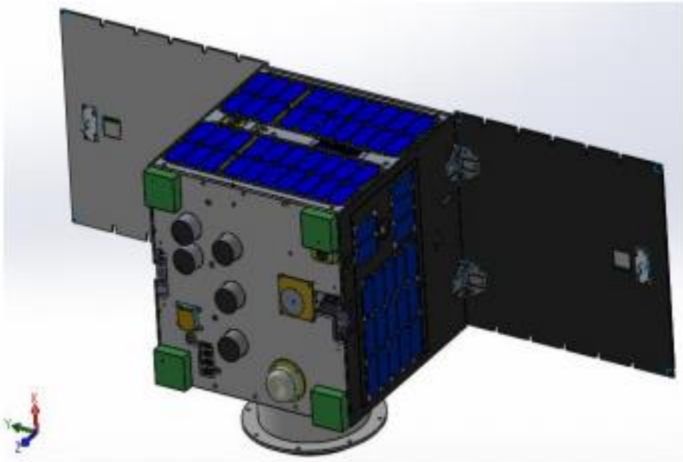

Figure 1.1-1: Micro Dragon satellite in 3D model

(From structure team in MDG development team)

As in every satellites, the ADCS plays a very important role in ensuring the success of the mission in MDG satellite. In this satellite, cameras are required to always point to the Earth to take pictures, solar panels are also needed to point to the Sun to secure power generation and distribute to all satellite's components. The antenna should be oriented toward the Ground station for a high performance for communication. They are all controlled by the ADCS. Without the successful operation of the ADCS, satellite mission cannot be achieved.

The operation of the ADCS is based on its architecture definition. From system requirements, a scenario is made to meet the operation of the satellite as well as missions delivered. According to the scenario of the MDG, there are four phases. The first phase, after separation from the rocket, the EPS (Electric Power Subsystem) will activate some necessary components for communication. The parameters of the satellite are transmitted to the Ground in the first communication. And then, the Ground uplink command to the satellite to open the SAP. This is the most important thing in this phase, it need to consider carefully before doing that. The second phase, the satellite will move on De-tumbling mode to go down its angular rate which causes from separation. The third phase, to secure power generation, the ADCS will control the satellite somehow to the SAP towards the Sun. The fourth phase, to perform the missions delivered, the ADCS will control the satellite to the camera point to a target pointing on the Earth to take a picture. All of these say that the ADCS's design has to guarantee the requirement of modes. In which, the architecture definition is really important, it show the functionalities, the functional allocation to components, and internal interface of components. In this thesis, the architecture of the ADCS of the MDG satellite will be shown clearly and verified by a simulation model on Simulink.

1.2 Overview about the Subsystems of MDG Satellite

As the same other satellites, the MDG satellite is a combination of many subsystems such as, Payload subsystem, Structure subsystem, Thermal subsystem, Electric Power subsystem (EPS), Communication subsystem, Command and Data Handling subsystem (C&DH) and Attitude Determination and Control subsystem (ADCS). Each subsystem is responsible different functions to meet requirements of launch, working conditions in the space environment and to perform the mission. The subsystems interact with each other and support together in order to the satellite can work successfully. Figure 1.2-1 shows the subsystems of the MDG satellite.

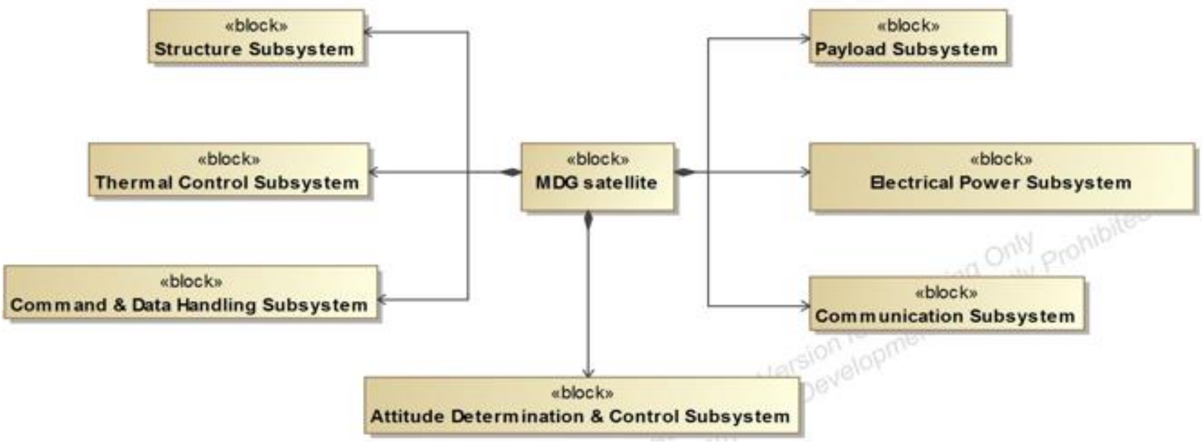

Figure 1.2-1: Subsystems of MDG satellite

The first, Payload subsystem is responsible for performing the missions delivered. The main mission of MDG satellite is to access the coastal water quality of Vietnam's coastline. This is very important mission since Viet Nam is a country with a long coastline of over three thousand kilometers and marine products are one of the country's main exporting goods. Whereby, the satellite will provide images data which can be used by researchers and scientists in fishery and oceanography fields to analyze then distribute necessary information to fishermen and environment managers. Figure 1.2-2 illustrates for the main mission of MDG satellite.

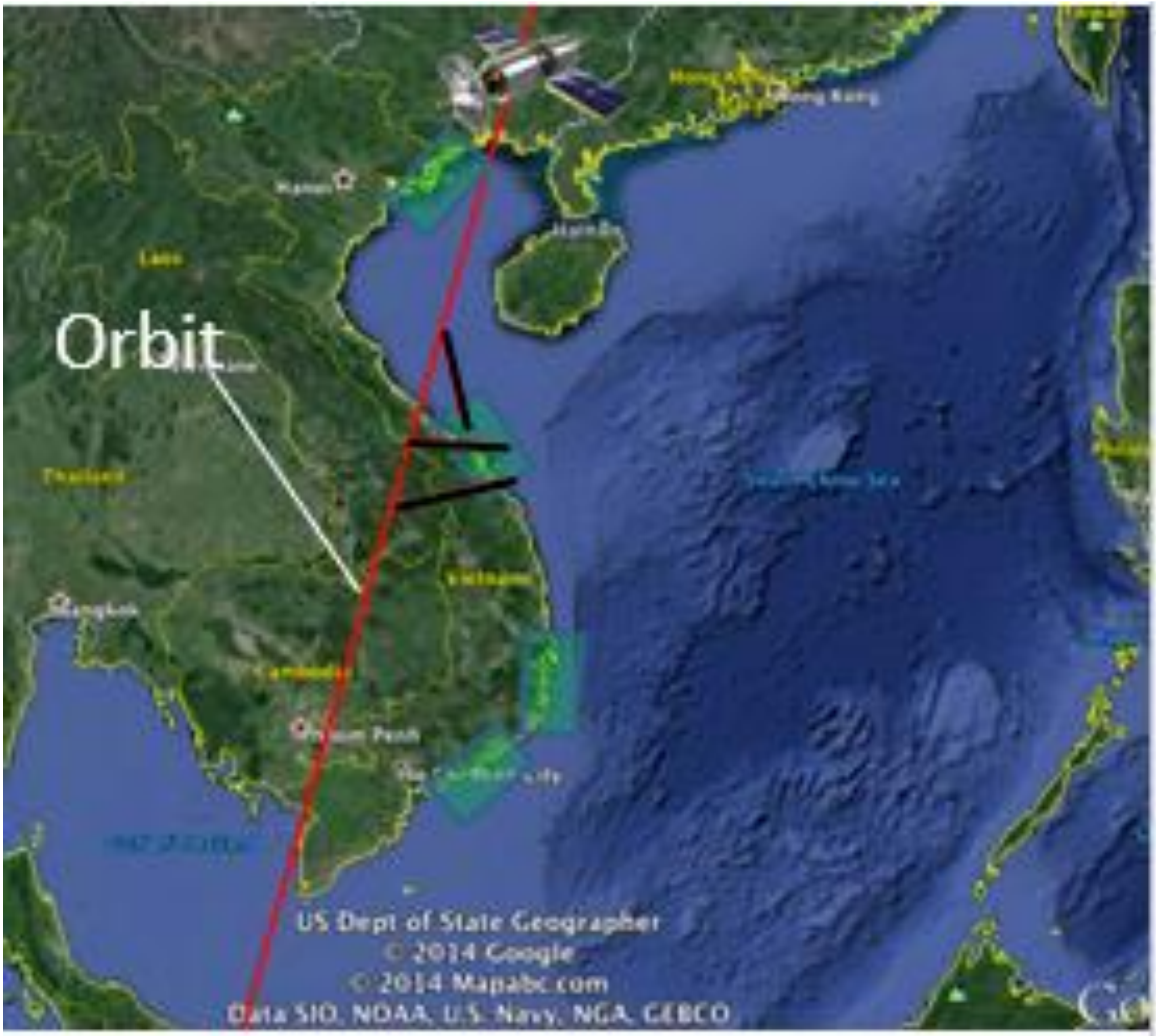

Figure 1.2-2: Main mission of MDG satellite
(From payload team in MDG development team)

In order to achieve that goal, MDG satellite employs two types of camera Space-borne multispectral Imager (SMI) and Triple Polarization Imager (TPI). SMI is used for ocean color observation and atmospheric correction. TPI is designed to observe the polarized and solar radiance reflected from the predefined targets in Vietnam's coastal area. MDG satellite is also equipped with a Science Handling Unit (SHU) is a device to control payloads: SMI, TPI, DPD (Data Packet Decoder – component for Store & Forward mission), save data temporarily, combine image data with time, orbit and altitude data and send data to XTx. The figure below illustrates the architecture of SHU and its interface with the payloads and other subsystem.

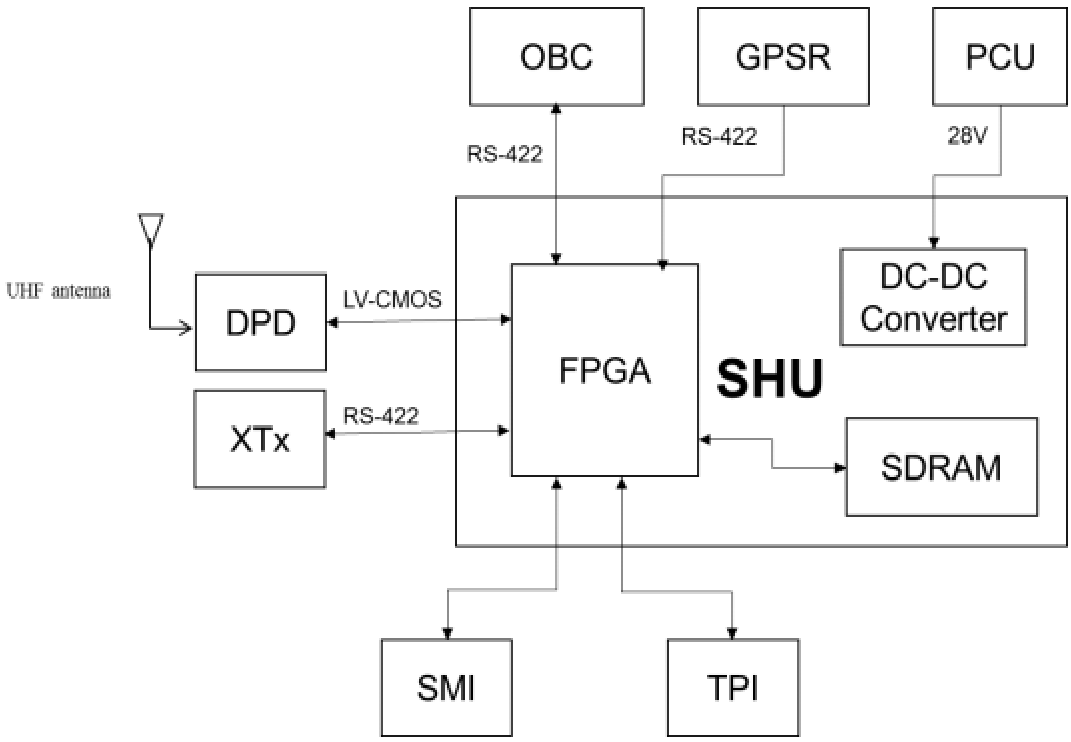

Figure 1.2-3: SHU's architecture and interface with payloads
(From payload team in MDG development team)

The secondary missions: *Store and forward (S&F)*: Components for this mission include the Data Packet Decoder (DPD) installed in MDG satellite and sensor FluoreProbe connected with an UHF transmitter on the sea. FluoreProbe is a highly sensitive measuring instrument for the analysis of chlorophyll with algae class determination. It will get the information from coastal water and send it to the satellite via UHF frequency when the satellite is passing through. The information will be stored in the satellite and when the satellite passes over the Ground station, the data will be forwarded to users via X-band frequency.

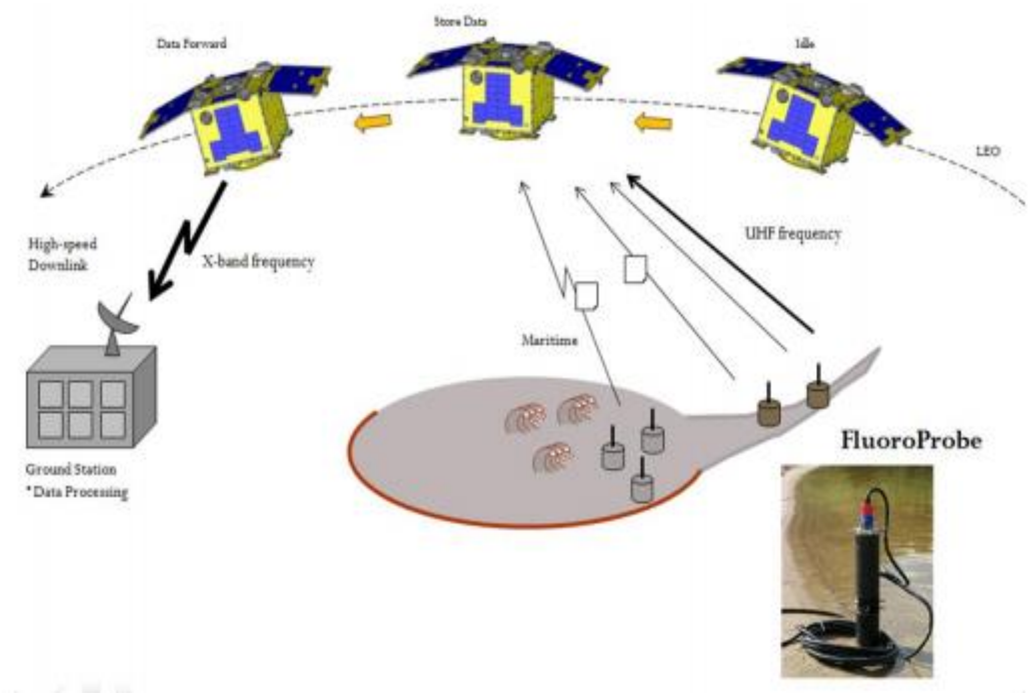

Figure 1.2-4: S&F process
(From payload team in MDG development team)

Antimony Tin Oxide Coating Solar Cell (ATOCSC): Basically, it is a measuring circuit, used to verify the charging mitigation capability of Antimony Tin Oxide. By using the measuring circuit once every 30days, current and voltage generated by this solar cell shall be used to assess the reduction in efficiency of coating solar cell. Finally, *Atomic Oxygen Sample (AOS)*: A satellite moves through the atomic oxygen at a velocity of about 7.5 km/sec at orbital altitudes. Although the density of atomic oxygen is relatively low but the flux of atomic oxygen is high. The large flux of atomic oxygen can produce serious erosion of surfaces through oxidation. Besides, it can alter the conductive or insulating of material. AOS is used to assess damages on orbit.

The second, Structure subsystem is responsible for organization the position of components and holding components. The rocket will be like a vehicle to transport the satellite into the space. The structural satellite have to obligate launch conditions of the rocket and is able to suffer effects from launch environment. Therefore, the structure of the satellite is undergone three test phases strictly before launching. The first phase, Structural Thermal Model (STM), the purpose of STM is to confirm mechanical and thermal characteristic to actual satellite, such as, mechanical characteristic is mass and center of mass, thermal characteristic is heat generation of components, insulation, and surface treatment. Dummy mass of components are made from block of metal but they are not mounted. The designer will carry out vibration test and thermal vacuum test to verify that the design is valid. The second phase, Engineering Model (EM), most actual components are mounted in EM. The goal of EM is to confirm the functions and the performance of electricity, structure and thermal. The test condition is harder than real flight. The third phase, Flight Model (FM), the flight model which is launched, is final model of structure satellite, the test condition is the same with flight. Another, the satellite uses a single spin stabilization in orientation to the Sun with spinning Z axis, so the structure team must design to maximum moment of inertia of Z axis among of moment of inertia of three axis. Another, if the distance between Center of Mass (CM) and geometric center of the satellite is minimum, the disturbance torque will be also minimum.

The third, Thermal Subsystem is responsible for maintaining satellite component temperatures within operational range. The temperature of the satellite as well as the components always change follow satellite's position in the orbit. When the satellite fly on sunlight area, its temperature will go up, contrary to the eclipse, its temperature will decrease significantly. Passive thermal control is method that utilize the characteristic of material, it is mainly used to all satellites. For example use Multi-layer Insulation (MLI), heat insulation material, and surface treatment. The active thermal control is efficient method for parts which is large thermal variation or which allowable temperature range is narrow. It is mainly used to large satellites, for example use heater, heat pipe, heat louver. After analysis heat on thermal models, the design will make a decision which method is suitable for the satellite.

The fourth, Electric Power subsystem (EPS) is responsible for providing power to components. The EPS consists of solar array panels (SAP) attached on two swings and some the surfaces of the satellite with the function is to transfer sunlight energy into electric power as voltage and current, Power Control Unit (PCU) to convert voltage to level voltage of component, the battery for storing power generation, Power Distribution Unit (PDU) like a conduction device to connect power to components. Moreover, a kill switch is also put on PCU, it is activated immediately when the satellite separates from the rocket. The design of the EPS must assure the number of power generation more than the number of power consumption of all components in the system. For solar cells, people try to put the number of maximum them on all plane of the satellite excepting plane +Z, which does not expect to direct to the Sun.

The fifth, Communication subsystem is responsible for the communication between the satellite and Ground station. There are two type of antennas in Communication subsystem, the one part is a S-band antenna including a transmitter antenna for telemetry (or Housekeeping data), which talks about state of components and a receiver antenna for signal from the Ground, the other part is a X-band antenna for transmitter mission data. Antenna receiver is always turned on through a period time to receive signals from Ground station. The signals are demodulated, and then sent to Onboard Computer (OBC). In contrary, the data from OBC going to the antenna is modulated and transmitted to the Ground. The time for communication between Ground and the satellite depends on some factors such as altitude orbit, filed of view of antenna.

The sixth, Command and Data Handling subsystem is responsible for carrying information. In there, C&DH gathers components states and payloads science data (mission data), and send them to Communication subsystem for downlink. C&DH receives commands from the Ground through Communication subsystem and distributes them to designated components/subsystems and mission payloads. In MDG satellite case, the software of C&DH and ADCS is embedded in the same OBC hardware.

The seventh, Attitude Determination and Control Subsystem (ADCS) is responsible for stabilizes satellite motion, changes and maintains its orientation. The attitude control aims to support for other subsystems implementation their missions. Basically, there are four purposes of an attitude control in a satellite. Figure 1.2-5 shows four purposes of the ADCS.

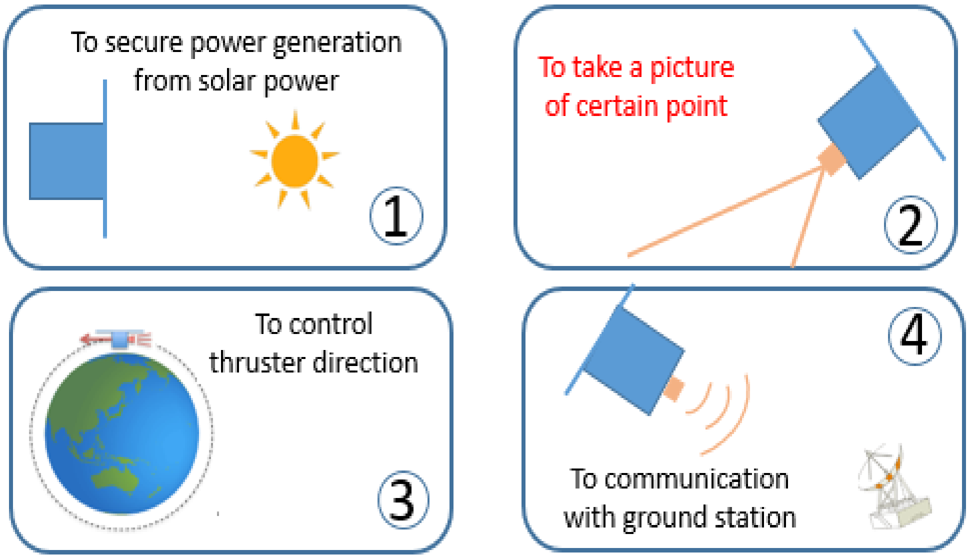

Figure 1.2-5: The purposes of ADCS

Firstly, the purpose of the satellite attitude of ADCS is to support for EPS to secure power generation to all components of system. That attitude control also corresponds with the Sun pointing mode in the MDG's mode sequences, the attitude control in this mode is very important for survivability satellite in the orbit. The ADCS will control the satellite attitude to the SAP perpendicular to the sunlight, it is the best attitude to receive energy from the Sun.

Secondly, the purpose of ADCS is to support for performing the mission of Payload delivered. For instance, the ADCS will change the satellite attitude to camera point to a certain place on the Earth to take a photograph in the Earth pointing mode. The accuracy and stable requirement in this mode are the highest in order to achieve good quality pictures and to access objective precisely. Another, satellites for global positioning system (GPS) are always maintained to point toward the Earth, or satellites observing planets in the solar system and stars. To do that all satellites need to have an ADCS.

Thirdly, thruster is the name of a device, which contains burning fuels, is used to move the satellite to a higher orbit or a lower orbit. The ADCS controls thruster direction by intentionally to help the satellite to transfer orbit. Sometimes, thruster is also used for unloading angular momentum of Reaction Wheel (RW) instead of Magnetic Torque (MTQ) for satellites in deep space where it does not get magnetic of the Earth. Using thruster or not, it depends on kind of satellite and user goal. For MDG case, we don’t use the thruster.

Fourthly, to get a high performance for communication with the Ground, the ADCS controls the attitude to direct the antenna toward the Ground. The time which the satellite pass over the Ground can estimate from the parameters of two-line element set (TLE). “A two-line element set (TLE) is a data format encoding a list of orbital elements of an Earth-orbiting object for a given point in time, the epoch. Using suitable prediction formula, the state (position and velocity) at any point in the past or future can be estimated to some accuracy” [1].

In conclusion, in case of the MDG, the ADCS is designed to control the satellite direct to the Sun and the Earth for different purposes. In addition, it is also used to decease the angular rate of satellite after separation from the rocket. This will discuss in part of the De-tumbling mode in the next chapter.

1.3 Literature Review about Design of Attitude Determination and Control Subsystem (ADCS)

Before designing an ADCS, it needs to know the physical properties of satellite as kinematic and dynamics, the satellite's environment. What environments affect the satellite and how the satellite behaves to its environment? The elements in satellite domain decomposed in Figure 1.3-1. The space environment is a harsh environment and so different with the ground, with factors such as magnetic field, micro gravity, radiations, air drag, vacuum, high temperature, low temperature and oxidation.

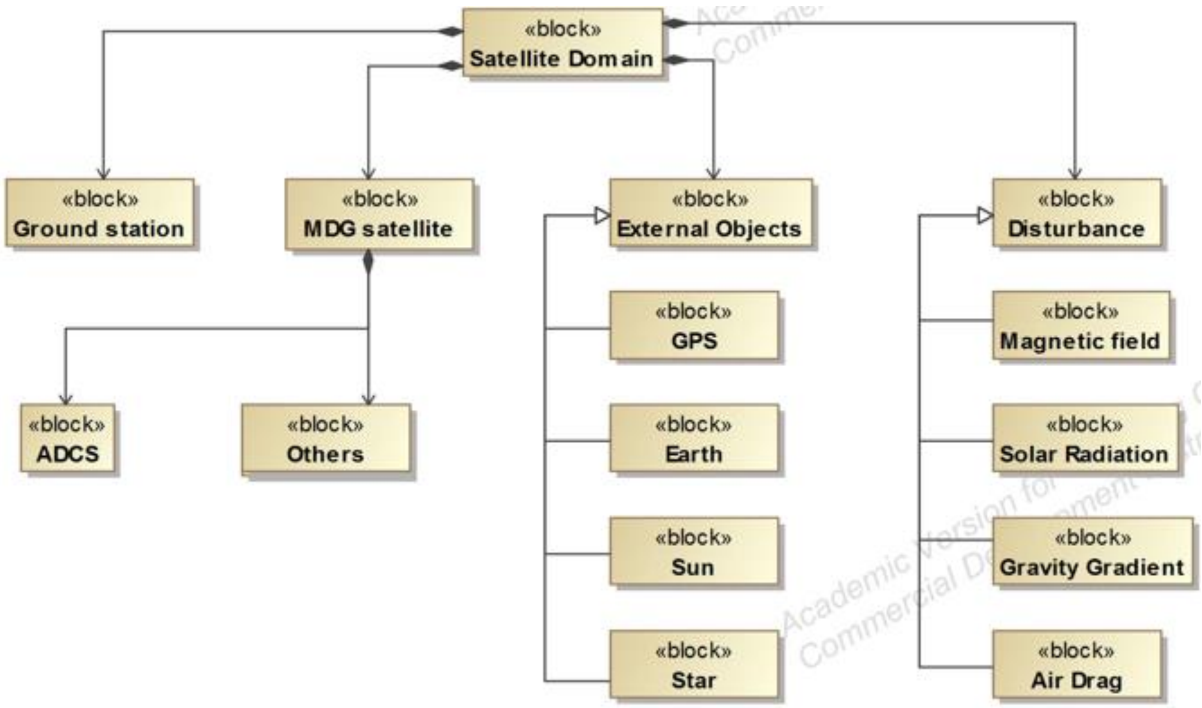

Figure 1.3-1: Elements in satellite domain

The objects have effects to the satellite such as GPS (global positioning system), the Earth, the Sun, the Stars. The GPS (global positioning system) is a satellite constellation in higher to locate for all objects under them. A sensor is called star tracker which can take a picture the position of stars and then compare with a star map installed and give a current attitude of satellite. The Earth and Sun are two objects having the most effect to the satellite, they affect in two different directions, both positive and negative. For example, the magnetic field of the Earth supports for magnetorquer (MTQ) to generate torque to adjust satellite attitude but it also makes noise to devices with permanent magnetic and produces torque disturbance to the satellite. The gravity gradient can support for the satellite with using passive control law but it produces disturbance torque in case of active control law. The sunlight provides energy for the solar cells but also the pressure of solar radiation produces an external torque to the satellite.

In order to understand more clearly the effects of environment to the spacecraft, Figure 1.3-2 [2] illustrates the effects of external objects to the attitude control.

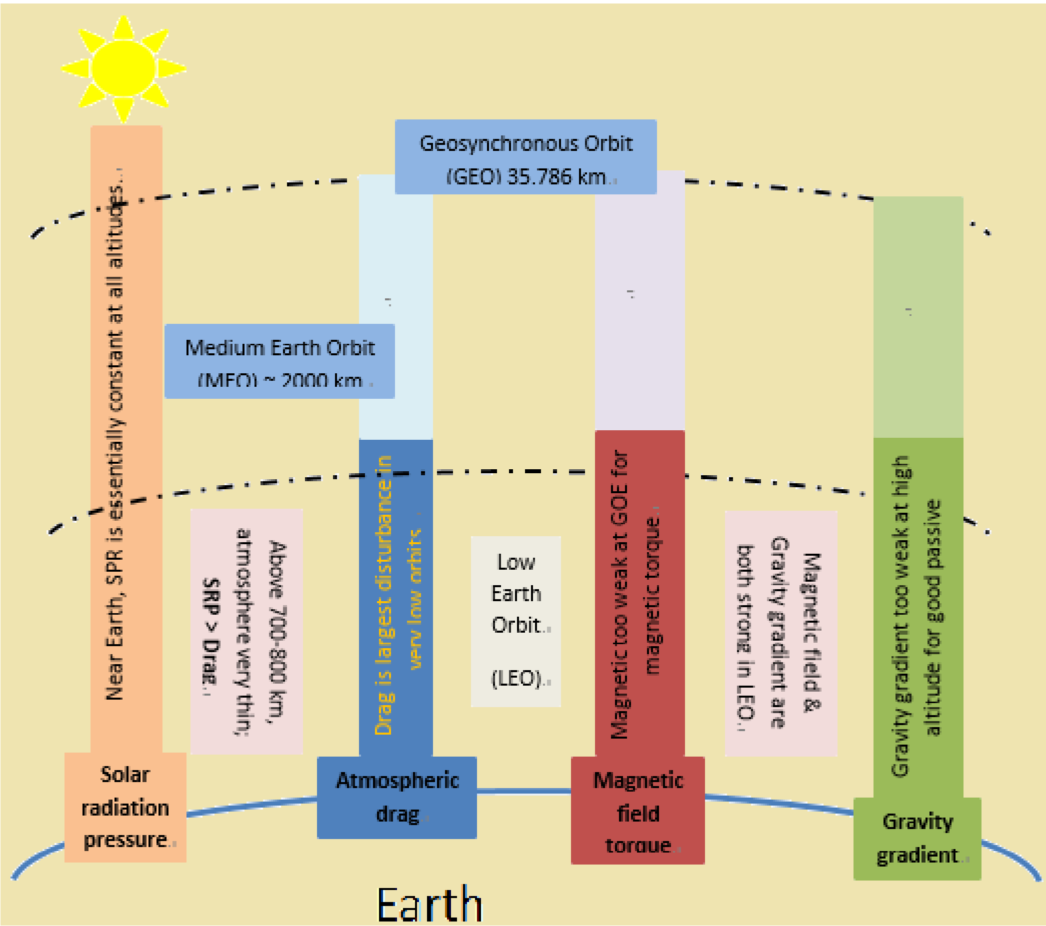

Figure 1.3-2: Effects of major environmental disturbances on spacecraft attitude system design [2]

"The environment in which the spacecraft will operate constrains what types of control methods will be effective" [2]. "For example, the relatively strong magnetic fields that occur in low Earth orbit (LEO), due to using magnetorquers (MTQ) is feasible, a means of attitude control not available at higher altitudes like geosynchronous (GEO)"[2]. Some attitude sensors, such as star imaging, may be highly sensitive to the radiation of Earth's magnetosphere, they can underperform even get no information. Similar to the magnetic field, in high orbit, the gravity become too weak, it can't use passive control. When the altitude is get higher and higher, the atmospheric also becomes thinner that means the air drag decreases. To sum up, the design of ADCS need to analyze the effects of space environment. Steps in attitude system design is described in Table 1.3-1. [2].

Table 1.3-1: Steps in attitude system design [2]

Step	Inputs	Outputs
1a) Define control modes 1b) Define or derive system-level requirements by control	Mission requirements, mission profile, type of insertion for launch vehicle	List of different control modes during mission. Requirements and constraints
2) Quantify disturbance environment	Spacecraft geometry, orbit, solar/magnetic models, mission profile	Values for torques from external and internal sources
3) Select type of spacecraft control by attitude control mode	Payload, thermal & power needs Orbit, pointing direction Disturbance environment Accuracy requirement	Method for stabilization & control: three-axis, spinning, gravity gradient, ect.

Step	Inputs	Outputs
4) Select and size ADCS hardware	Spacecraft geometry and mass properties, required accuracy, orbit geometry, mission lifetime, space environment, pointing direction, slew rates.	Sensor suite: Earth, Sun, inertial, or other sensing devices. Control actuators: reaction wheels, thruster, magnetic torquers, ect. Data processing avionics, if any, or processing requirements for other subsystem or ground computer.
5) Define determination and control algorithms	Performance considerations (stabilization methods, attitude knowledge & control accuracy, slew rates) balanced against system-level limitations (power and thermal needs, lifetime, jitter sensitivity, spacecraft processor capability)	Algorithms and parameters for each determination and control mode, and logic for changing from one mode to another.
6) Iterate and document	All of above	Refined mission and subsystem requirements. More detailed ADCS design Subsystem and component specification.

The ADCS is the most complex subsystem in a satellite because it integrates many fields. "Attitude systems include the sensors, actuators, avionics, algorithms, software, and ground support equipment used to determine and control the attitude of a vehicle" [2]. In the scope of thesis concentrates on the architecture definition of ADCS. Normally, there are three units as well as three main functions of the ADCS including Attitude Guidance (AG), Attitude Determination (AD), Attitude Control (AC). The block definition diagram of Figure 1.3-3 shows three units in an ADCS.

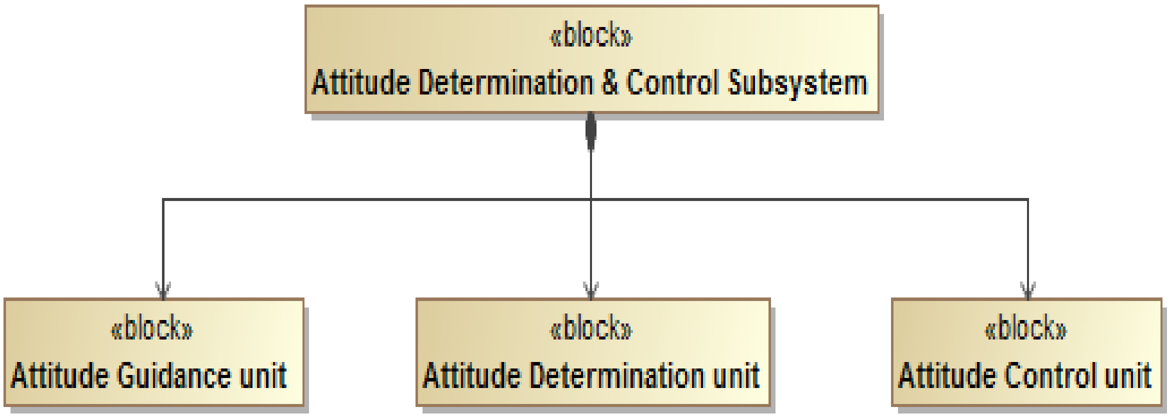

Figure 1.3-3 Three units of ADCS

The ADCS is still called (GNC) guidance, navigation and control. The attitude guidance unit has the function to define desired attitude. The attitude determination unit has the function to estimate current attitude from sensor output. The attitude control unit has the function to calculate control signal for an actuator. The feedback control loop of ADCS is shown in Figure 1.3-4.

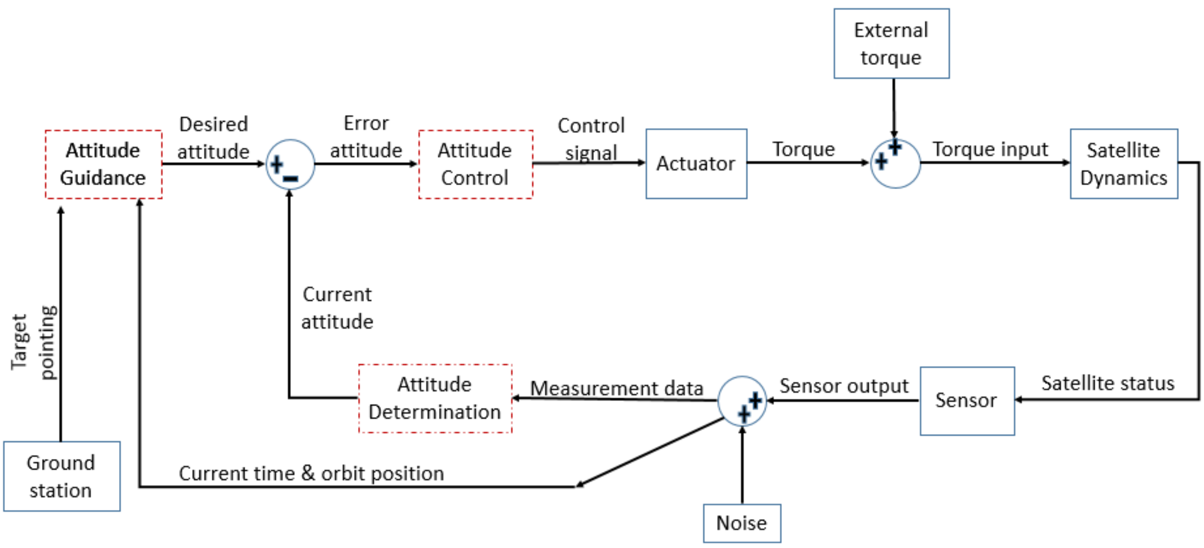

Figure 1.3-4: The feedback control loop of ADCS [2]

First of all, the Ground station sends a command to the satellite to carry out a mission, For example as in the target pointing mode, the attitude guidance will calculate the desired attitude based on the target pointing, current position and time of satellite. The information about satellite attitude is determined by sensor output but it is not really correct because of the effect of noise from outside. The quality of attitude control will be better if the information of attitude determination is more precisely. The Kalman filter is a popular algorithm used for a spacecraft to estimate current attitude. By comparing desired attitude and current attitude, the attitude error is defined and makes input for the attitude control. The controller will calculate requirement torque by the formula of algorithm chosen, it transfers to an actuator. The actuator generates torque to change the satellite attitude. As a result, the satellite dynamics also changes and the sensor continues measuring attitude. The process is repeated until the attitude error approaches to zero. The satellite achieves target attitude.

For the verification, there are four steps to develop as well as ways to assess an ADCS, it is shown in Figure 1.3-5. Firstly, the Model-in-the loop simulation (MILS) is based on kinematic and dynamics equations and environment of satellite to build models to simulator, the simulator models of sensors and actuators can be also added. This step is very important because these models will be used for the next steps. Then, the designer implements the algorithm of ADCS to the simulator model of satellite and sees results.

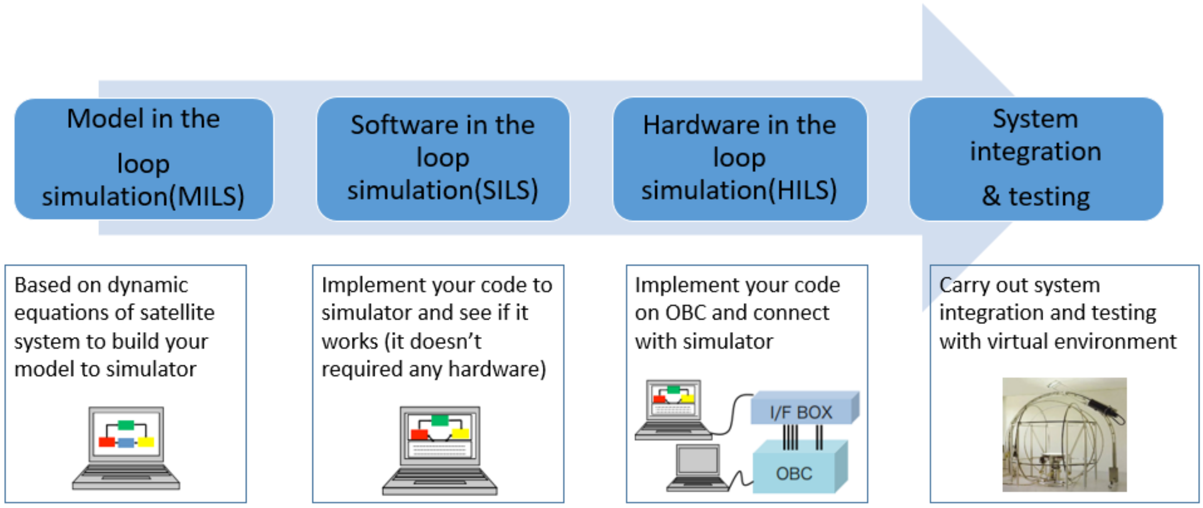

Figure 1.3-5: The verifications of ADCS

The second step, software-in-the loop simulation (SILS), the simulation models still keep on a personal computer (PC), not appear any hardware. The algorithm will be written by a C language. The purpose is to verify the algorithm in C code.

In the third step, a real controller will connect with the virtual environment on PC, the ADCS's algorithm will be embedded on onboard computer (OBC) hardware. It is called Hardware-in-the loop simulation (HILS).

The final step is a system integration, components is assembled to make a satellite. People create a virtual environment, not on PC, which can generate magnetic field, sunlight like some conditions of the space environment and a table to simulator the gravity environment in the space. The satellite will be finally tested by this table, its name is called testbed. Actually, some steps can ignore, it depends on experiences of designer and schedule of system development.

Overall, in a satellite mission, the ADCS plays an important role as it provides the attitude information of the satellite and stabilizes the satellite. The design of the ADCS is typically divided into several steps, including the decomposition of working environment of the satellite, choice method control and hardware, application algorithm, verification by software. As a result, there are a lot of information and data of the ADCS development process. Traditionally, designers have employed a document-based systems engineering to carry out the systems engineering activities. The architecture definition of ADCS for MDG satellite is very difficult, because the ADCS should correspond to each mode sequence. To define the architecture of ADCS, this thesis uses SysML as a useful tool to analyze the behavior of ADCS in mode sequences. The system model built on the SysML will also support for system requirements, design, analysis, verification, and validation activities in the conceptual design phase and continuing throughout development. Normally, if we know the amount of components of a system, functional components and the interactions between components, they are enough to define for the architecture of that system. However, in this thesis, the program in onboard computer such as software and control law is also decomposed in each mode to see the operation whole of the system as well as the interactions of ADCS with other subsystems. In addition, the analysis of the control law also supports for verification the requirement of ADCS. The size and mass of a satellite have strongly effect to satellite's movement. For example, the characteristics of a micro satellites movements like MDG satellite, which have a small Moment of Inertial (MOI), are sensitive, and are greatly affected by changes in attitude. In addition, the orbit of MDG satellite will be low hence the effects of space environment are significant. Thus, the ADCS design for micro satellites is difficult. The originality in this thesis is consideration of mode sequences to define the architecture of ADCS for MDG satellite.

1.4 Fundamental Approach of MBSE using SysML

The system engineering emphasis is placed on controlling the documentation and ensuring the documents and drawings are valid, complete, and consistent, and that the developed system complies with the documentation. Document-based systems engineering typically relies on a concept of operation document to define how the system is used to support the required mission or objective. Functional analysis is performed to decompose the system functions, and allocate them to the components of the system.

The document-based approach can be rigorous but has some fundamental limitations. The completeness, consistency, and relationship between requirements, design, engineering analysis, and test information are difficult to assess since this information spread across several documents. "Model-Based Systems Engineering (MBSE) applies systems modeling as part of the system engineering process to support analysis, specification, design, and verification of the developed system" [4].

System Modeling Language (SysML) is a standardized language in the MBSE. SysML is an extension of the Unified Modeling Language (UML) version 2, which has become the standard software modeling language. SysML supports the specification, design, analysis, and verification of systems which may include not only software but also data, hardware, etc.

"SysML is graphical modeling language for representing requirements, behaviors, structure, and properties of the system and its components" [4]. SysML has capability to model complex systems from a board range of domain such as satellites. By using SysML, the architecture of attitude determination and control subsystem is consistent with the other subsystems of satellite.

The type of diagrams of SysML is showed in Figure 1.4-1. The requirement diagram and parametric diagram are the new diagrams compare to UML. One benefit of SysML is allowing traceability between requirements and design model.

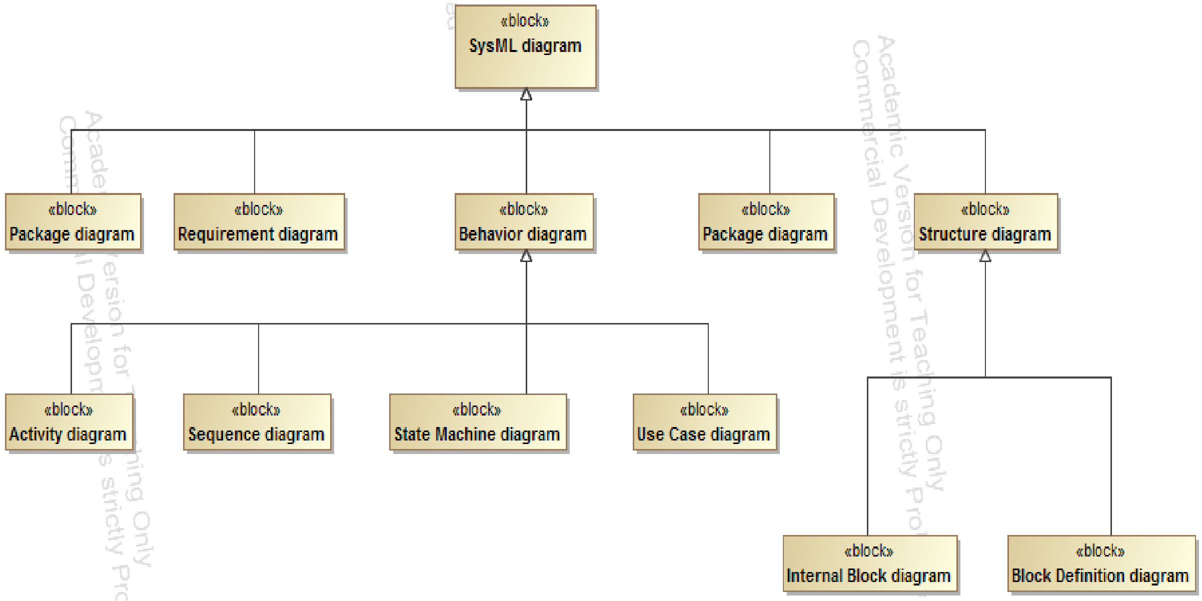

Figure 1.4-1: SysML diagram taxonomy

1.5 Research Objective and Approach

The objective of this research is the architecture definition of the ADCS of the MDG satellite. The purpose of using SysML to describe the architecture of the ADCS is to support for the design of ADCS. From the system requirement, having a few modes needs an attitude control system. According to the scenario, the MDG has three important modes such as De-tumbling mode, Sun pointing mode, Earth pointing mode.

After separation from the rocket, the satellite may get a high angular rate, therefore it needs to reduce this speed. And to secure power generation, the satellite needs to control attitude somehow to the solar panel towards the Sun. For performing missions, the satellite needs to control attitude so that the camera can point to a target on the Earth. Therefore, the number of components used and algorithms applied in a mode will change to meet functions of the ADCS to achieve different goals, and the requirements of each mode will be also different as criteria about stability and pointing accuracy. As a result, the architecture of the ADCS in each mode is not the same, it needs to do clearly requirements, functionalities and the physical interface to define the architecture for that mode.

For instance, in De-tumbling mode, the goal is to decrease the angular rate of the satellite after separation from the rocket, it means that the ADCS only care how the angular rate go down, but not need to control attitude, only two components is used in this mode. Thus, the architecture is also the simplest in among all modes. Another, in the Sun pointing mode, to ensure the satellite survives in an orbit, the solar cells need to direct to the Sun to take energy. Hence, the ADCS must has the function for sun detection, sun sensors are chosen to determine the position of the Sun, and the reaction wheels are also use as a main actuator in Fine sun mode of Sun pointing mode to increase pointing accuracy. The architecture of the ADCS will become more complex when the amount of components in a mode increases to meet the functions of system. The Earth pointing mode needs to have more functions such as attitude guidance to determine target attitude, and attitude navigation to determine current attitude.

The behavior of the ADCS for each mode will be described by using SysML to draw diagrams such as the requirement diagram for description requirements of the ADCS, the use case diagram for description functionalities, the sequence diagram for description behavior in terms of a sequence of messages exchanged between subsystems, the activity diagram and the internal block diagram for description allocation of functions to physical components of the ADCS. For the verification, a simulation model on Simulink software including dynamic & environment satellite model, sensor models and actuator models and connecting with the ADCS’s algorithms applied are to simulate to take the results as well as verifying for the above architecture.

1.6 Dissertation Outline

Chapter 1, all subsystems are introduced to see an overview of the MDG, the role of the subsystems and typical emphasis about the attitude control system. In brief, the design of the ADCS is also told as a literature review to understand the development process as well as its important role with respect to a satellite system. The reason of using SysML for description the architecture of the ADCS is explained clearly in the fundamental approach of MBSE using SysML.

Chapter 2, a mode sequence scenario is given to do clearly the operation of the satellite. In which, the mode transition and the purpose of using each mode are explained in condition constraint, for modes without the ADCS are also described by diagrams as use case, sequence and activity to catch all system operation as well as logical thinking.

Chapter 3 describes the architecture of the ADCS for De-tumbling, Sun pointing and Earth pointing mode. The difference about the purpose and function in three modes causes the different architecture, the functions are allocated to the components in their physical interface, and finally, it generates an ADCS's architecture for MDG satellite.

Chapter 4, by using a simulation model on Simulink with full elements including the environment and dynamics satellite model, sensors and actuators model to verify the architecture of the ADCS defined in above. To run the simulation model, the algorithms application on each mode are implemented and explained in this chapter.

Chapter 5 is the conclusion to summarize the results of this research and discussions about the future works including the necessary of applying SysML for designing satellites.

Chapter 2 Mode Sequences of MDG Satellite

2.1 Mode Sequences Scenario through Satellite Whole Operation

According to the scenario of MDG's mode sequences, there are four phases including after separation phase, de-tumbling phase, sun pointing phase and earth pointing phase, each phase consists of a lot of different modes. The purpose of using modes will be explained in description detail about the modes. Figure 2.1-1 describes the operation phases of MDG satellite in the space.

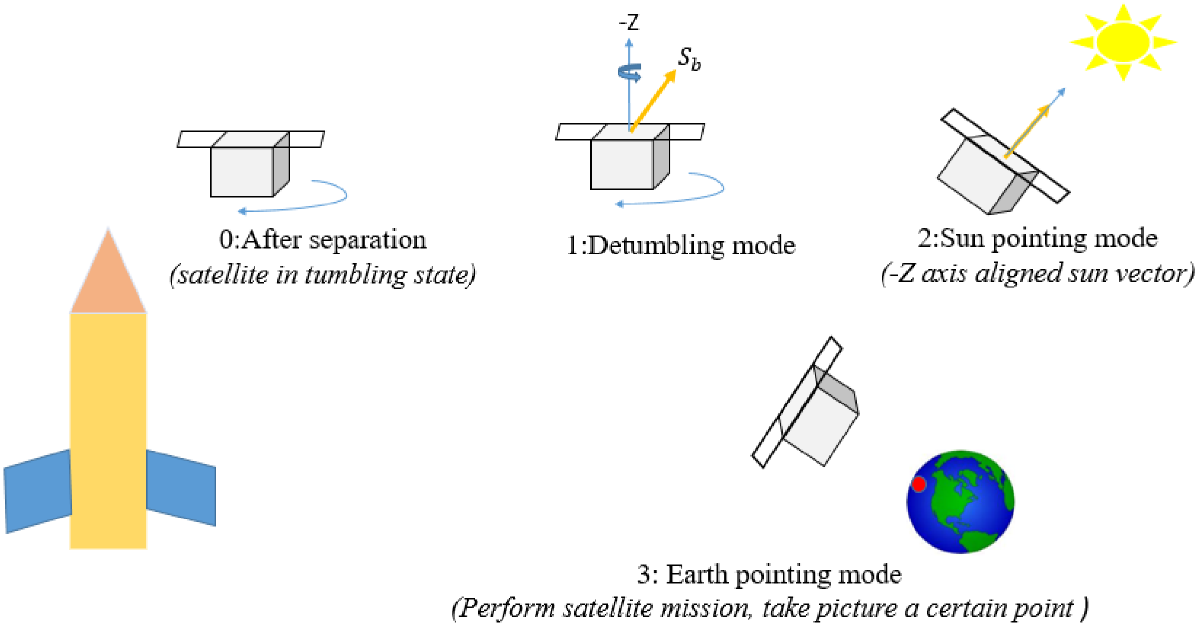

Figure 2.1-1: Operation phases of MDG satellite in the space

The scenario of MDG's mode sequences is drew by using the state machine diagram of the SysML as Figure 2.1-1. Beginning from the recovery mode, some vital components are activated to communicate with the Ground. The satellite will stay the Safe mode when the successful deployment of the SAP. By the command from the Ground, the satellite moves on the Attitude log mode to check some components to prepare for the next mode. In the Sun pointing phase is divided into two modes, the Spin sun mode and Fine sun mode. The transition from the De-tumbling to the Spin sun mode will be automatically in the condition of the angular rate of the satellite. After the Fine sun mode, the satellite enter to the Earth phase for doing the missions delivered. This phase consist of four modes, they can transfer to others by the command from the Ground or the command block which is set up before.

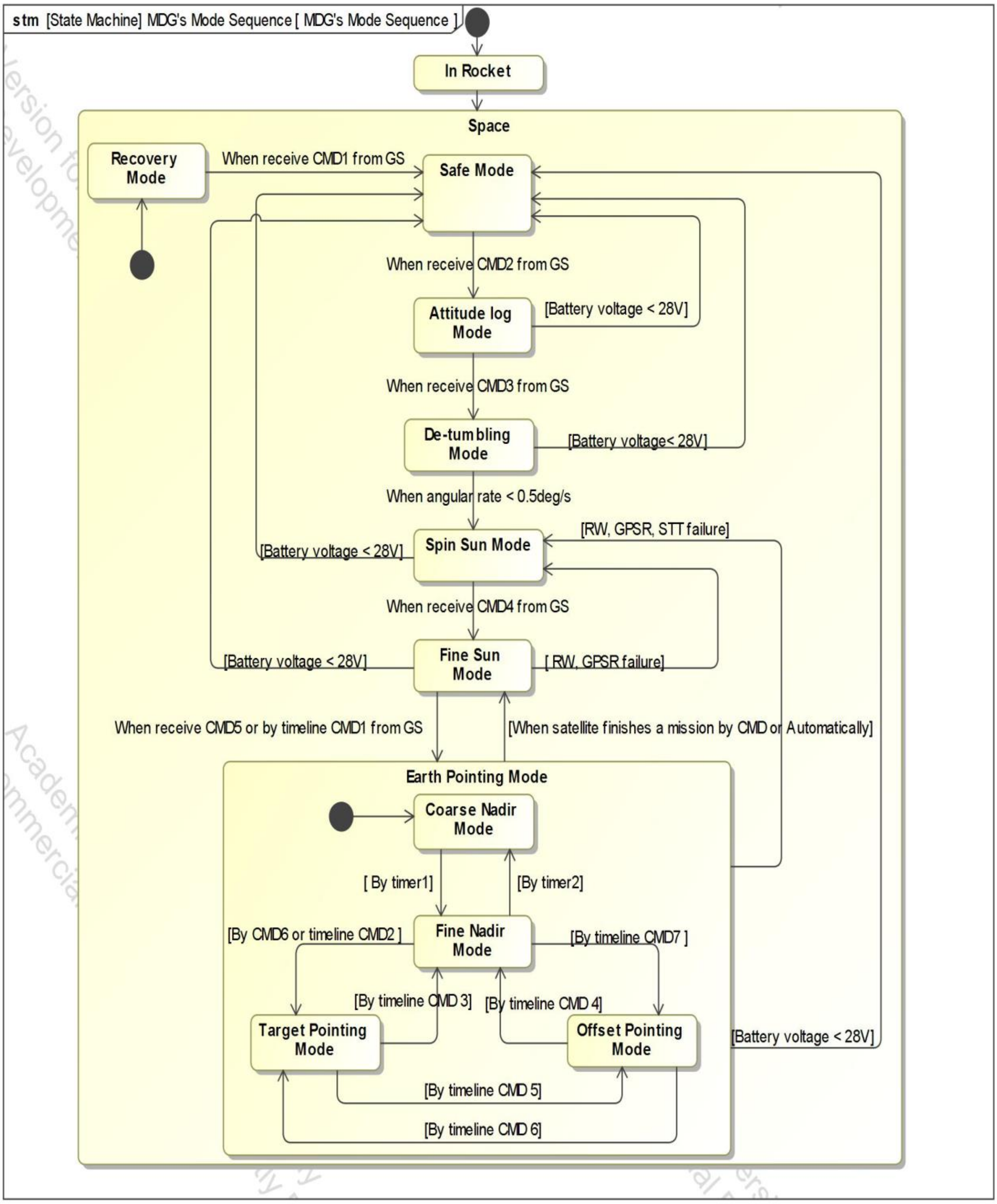

Figure 2.1-2: The scenario of MDG's mode sequences

Almost the mode transition is carried out by the commands from the Ground to supervise the satellite operation. However, in some cases emergency, the transition is automatic when the satellite meets bad problems. For example, the satellite will go back the Safe mode when battery voltage is less than 28 voltage to guarantee the safety of battery. Another, the satellite will go back Coarse Sun mode when some components are failure such as Reaction Wheel, GPS, Star tracker.

2.2 Each Mode Sequence of MDG Satellite

In order to study on the modes, it starts decomposing the components of the satellite as Figure 2.2-1 to capture their functions. Normally, the component of the communication subsystem is called STRX, it contains three small devices. The antenna receiver in S-band frequency (SRX) (2 to 4 GHz) is responsible for reception signal from the Ground, the antenna transmitter (STX) is responsible for transmit telemetry which is the data of satellite status or called housekeeping data, the antenna transmitter in X-band frequency (XTX) (7 to 11.2 GHz) is responsible for transmitting mission data) to the Ground.

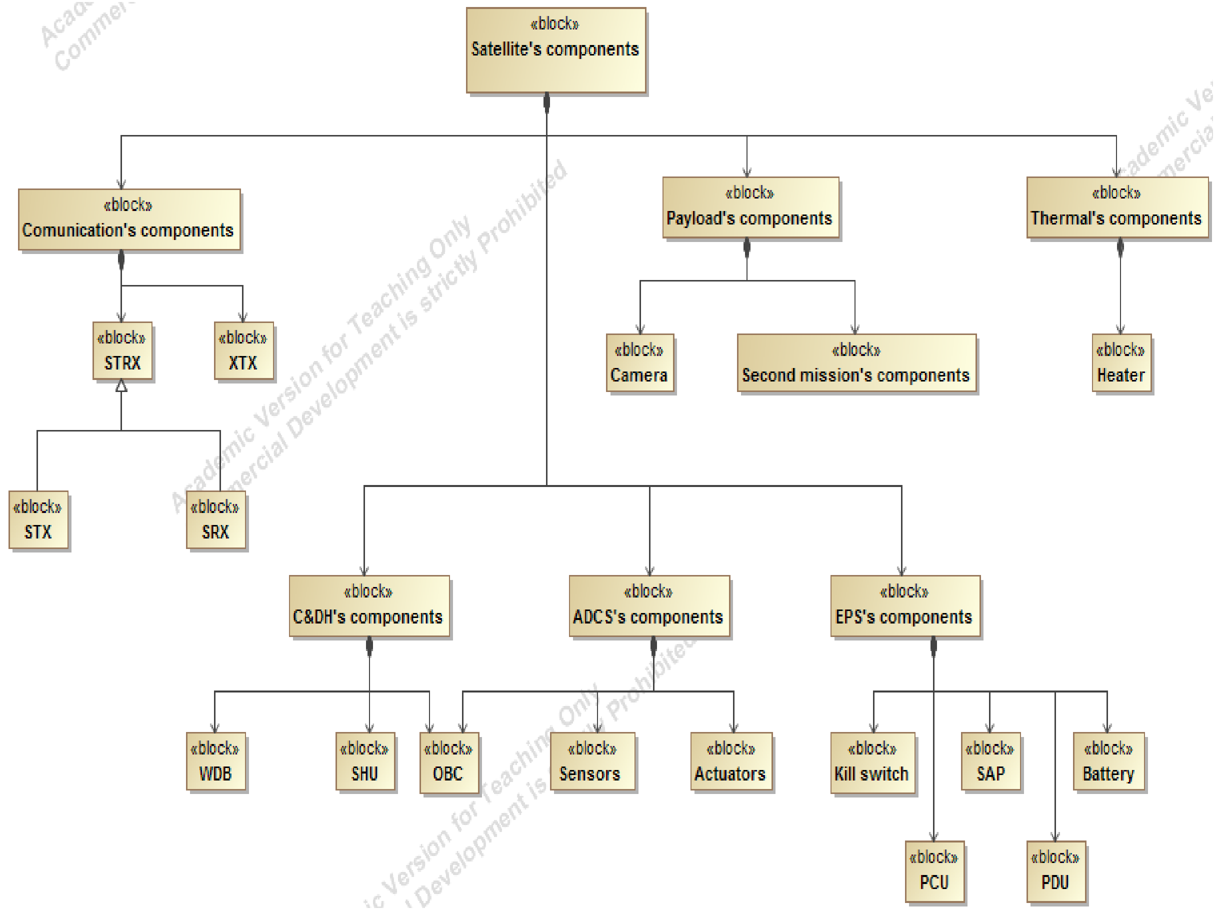

Figure 2.2-1: The components of MDG satellite

The components of C&DH, ADCS and EPS have a strong impaction together. The OBC is a common hardware for both C&DH and ADCS. The EPS distributes power to components under control of OBC. In there, Kill switch is used only one time after separation from the rocket. The solar panel (SAP) transfers sunlight energy into electric power. The power control unit (PCU) is to regulate voltage and current from the solar panel. The power distribute unit (PDU) is to conduct voltage and current to devices.

The process of separation from the rocket is represented in Figure 3.3. The rocket push the satellite go to the space, at the same time, the Kill switch is also activated by the mechanism. Everything begins from at that time. And now, the satellite stays in Recovery mode.

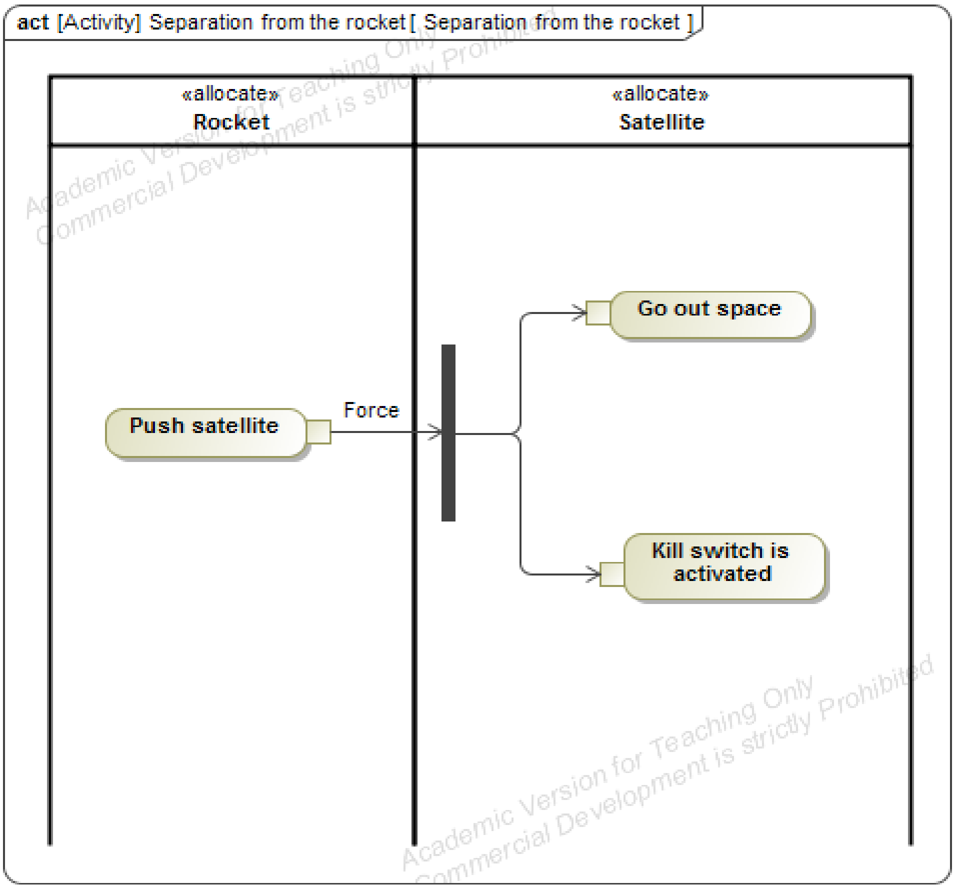

Figure 2.2-2: Activity diagram of separation from the rocket

2.2.1 Recovery Mode

After separation from the rocket, the satellite stays in emergency situation, and has a lot of disadvantages coming to it. As the SAP has not been opened and directed to the Sun yet. Hence, to save power source, only some vital components is turned on such as PCU to provide power to devices, OBC for acquisition parameters of satellite and sending commands to subsystems by C&DH subsystem and receiver antenna in STRX for communication with the Ground.

Figure 2.2-3 illustrates for functionalities of the EPS. In this mode, its main function is to activate other components.

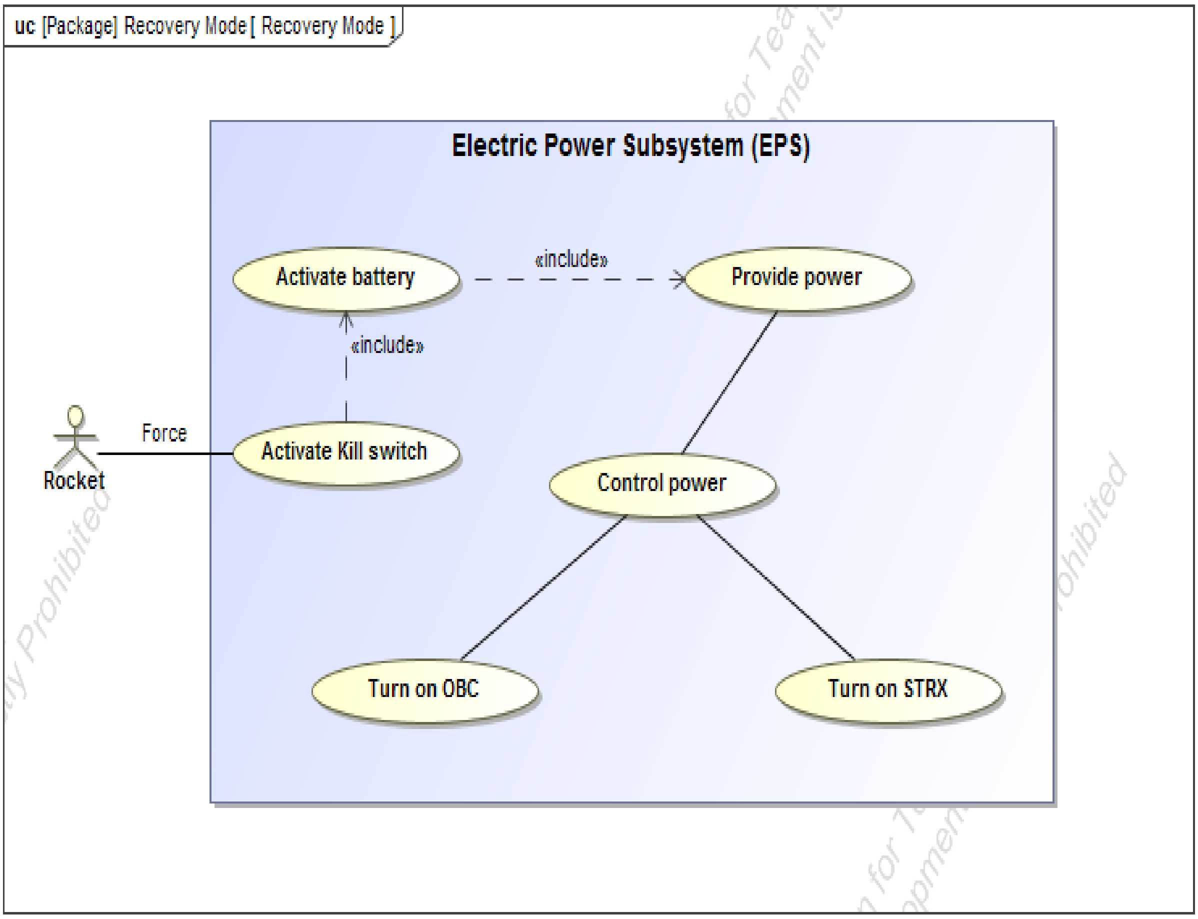

Figure 2.2-3: Use case diagram of EPS in Recovery mode

The behavior of the EPS is described in Figure 2.2-4. Therein, C&DH and STRX are turned on by timers which are set up in the programming of PCU.

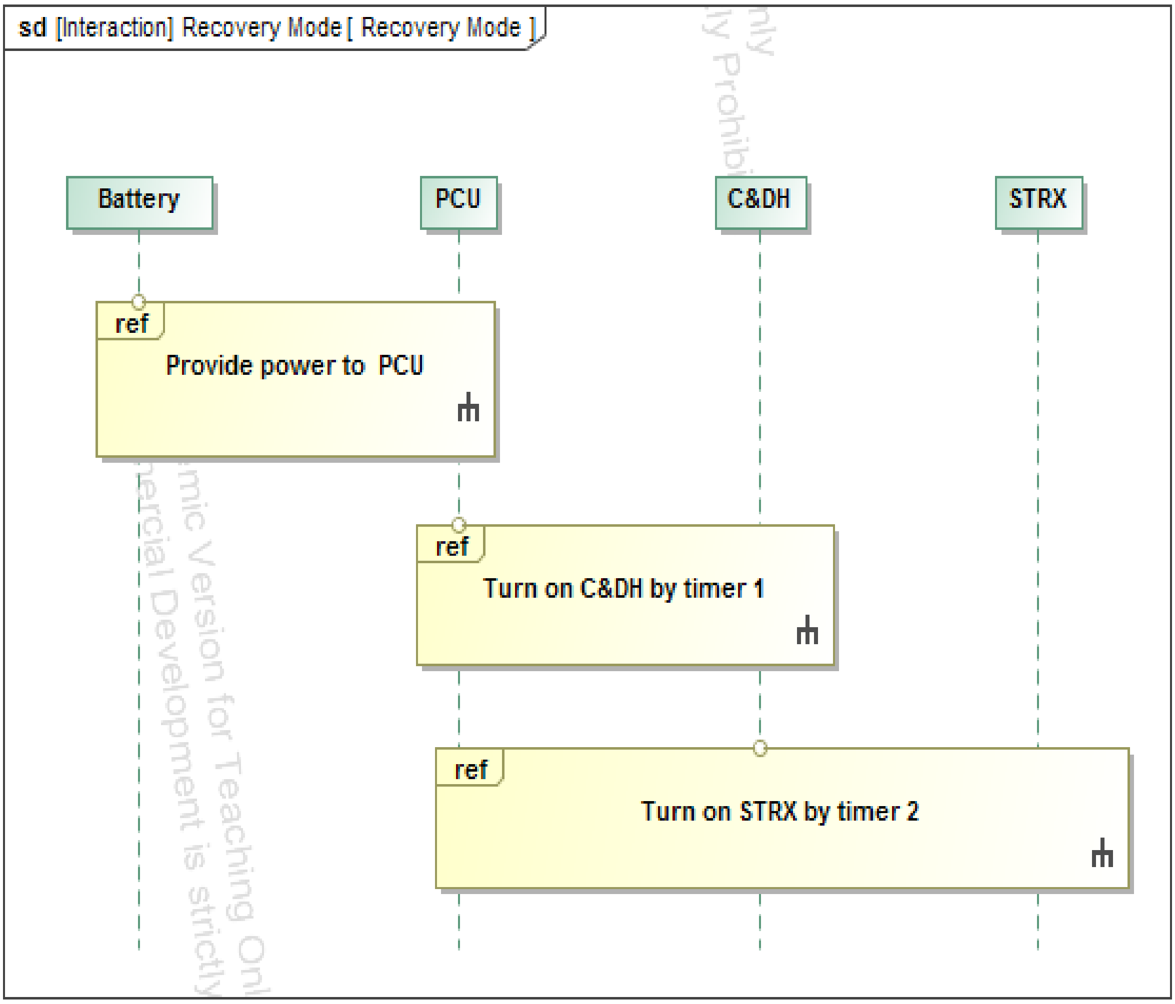

Figure 2.2-4: Sequence diagram of Recovery mode

Figure 2.2-5 is the activity diagram of Recovery mode, in this time, C&DH updates telemetry (housekeeping data), parameters such as battery voltage and temperature, onboard computer temperature, ect to transmit to the Ground. Note that, the telemetry includes two kinds of data. The one is of the parameters data about the satellite status, it is called housekeeping data. The other is of the mission data.

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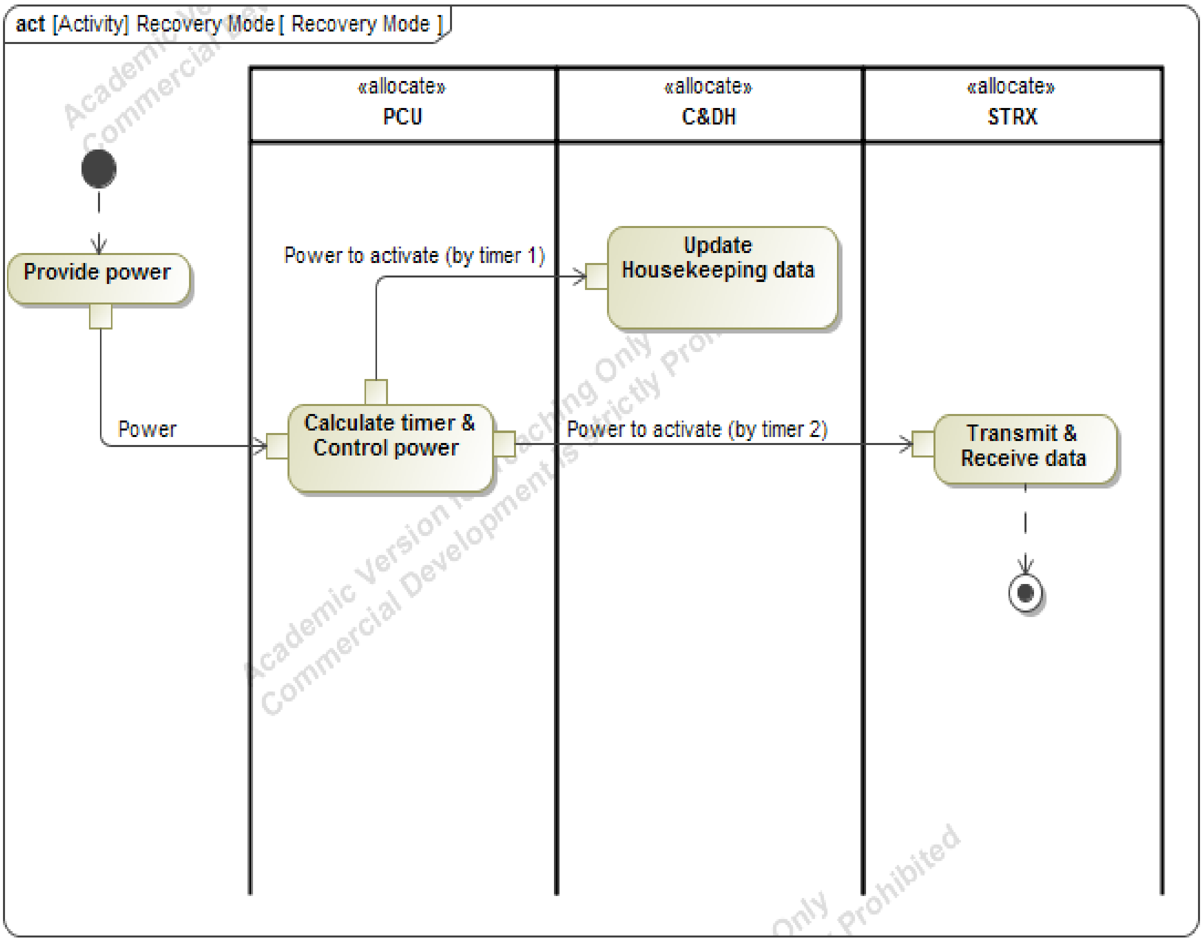

Figure 2.2-5: Activity diagram of Recovery mode

In the first voice of the satellite, the housekeeping data will be transmitted to the Ground station. The operator considers the parameters status of the satellite and then sends command feedback the satellite.

To understand the communicative process between the Ground station and the satellite, we go to the activity diagram of Ground station in Figure 2.2-6.

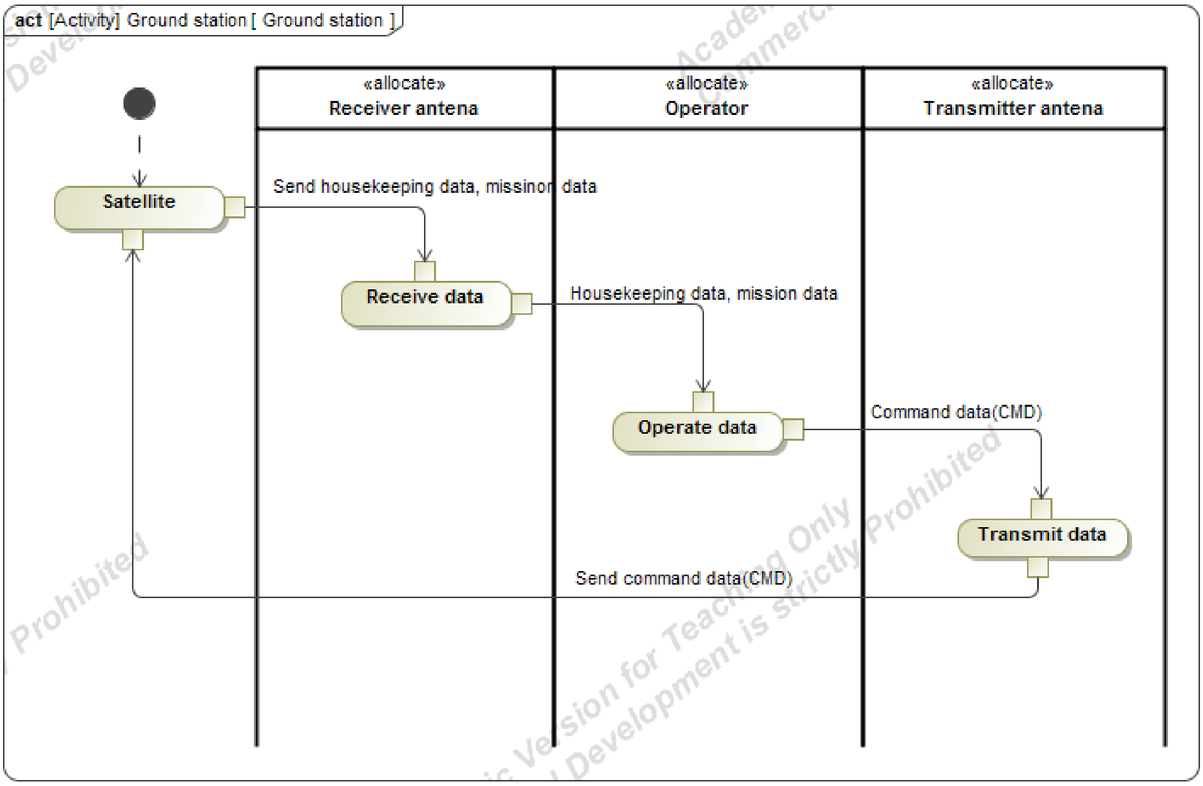

Figure 2.2-6: Activity diagram of the Ground station

There are three parts in the Ground station including receiver antenna, operator and transmitter antenna. The satellite sends the housekeeping data or mission data to the Ground. The Ground receives the data via receiver antenna after that the operator considers the data and makes a command to the satellite through transmitter antenna.

The battery voltage is an important parameter to decide whether the SAP can deploy or not. It needs to have enough the power to provide for burning the wire nicrom circuit which ties the SAP. The SAP deployment operation is described in Figure 2.2-7.

The Ground will uplink the first command data for the SAP deployment, the STRX of the satellite receives and demodulates this command, the C&DH understands the purpose of the command and requires the EPS provide power for the circuit. The wire nicrom of the circuit is burned by the electric current. As a result, the SAP is opened.

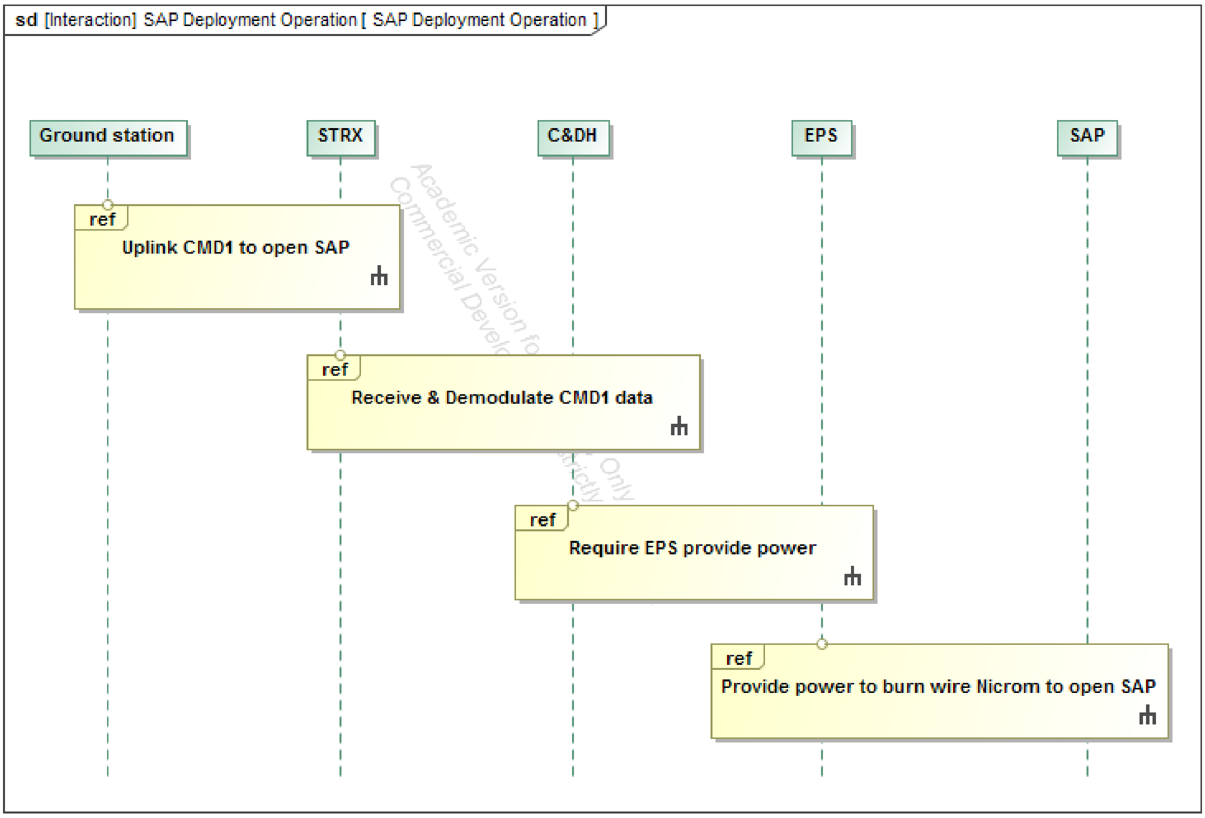

Figure 2.2-7: Sequence diagram of SAP deployment operation

In a bad case, the capacity of battery is not enough for burning the wire nicrom. We have to wait to increase the battery voltage until it is likely to burn the circuit. After waiting a long time, if the voltage battery can't go up, it is really dangerous for the satellite. However, we should still uplink a command to open the SAP to take an opportunity.

The behavior of the SAP deployment is shown in Figure 2.2-8. The functions are allocated to the subsystems as well as their components. The commands signal in the waveform data from the Ground transmit to the STRX. Then the STRX demodulates into the digital data and delivers to the C&DH.

In the second communication with the satellite, people can know the successful deployment SAP through the values such as the raising of the battery voltage and the power generation.

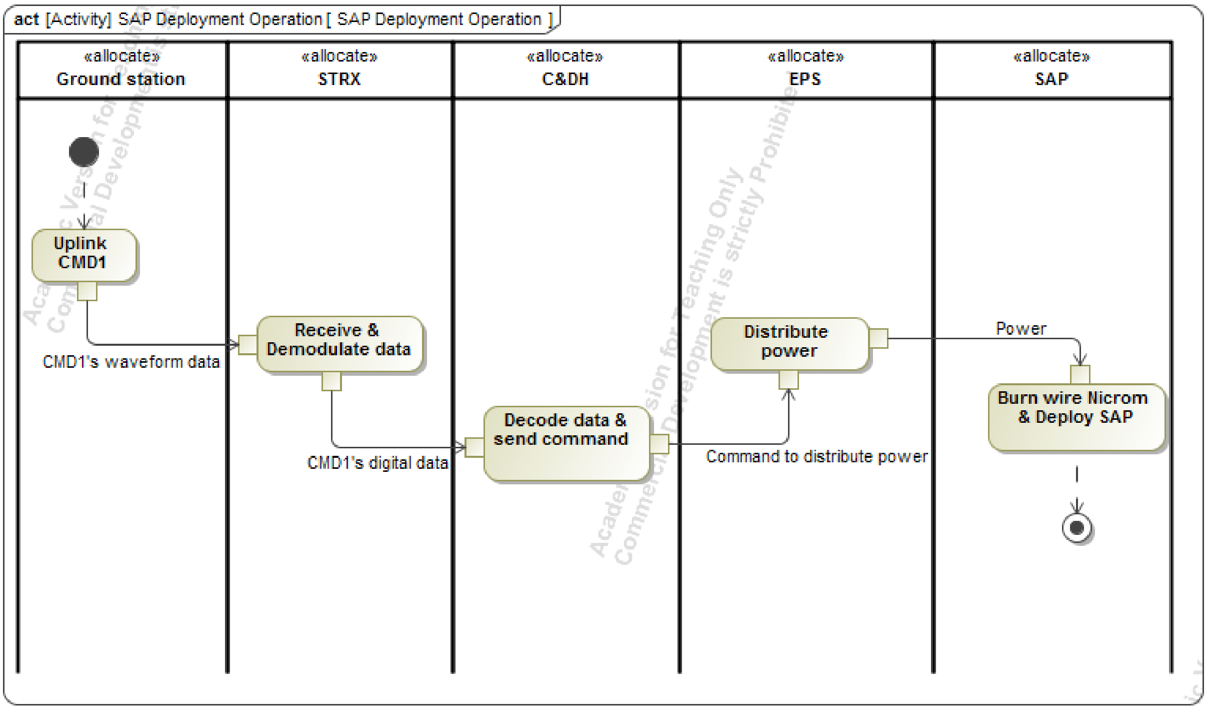

Figure 2.2-8: Activity diagram of SAP deployment operation

2.2.2 Safe Mode

Now, the satellite deployed successfully the SAP and can receive more energy from the Sun. With the same number of devices activated like the Recovery mode, Safe mode is minimum power consumption mode, it is appropriate for the satellite to relax when it falls on case of emergency as drop in battery voltage. Therefore, according to the MDG's scenario, the satellite will go back to this mode when the battery voltage is lower than 28V. In this mode, the satellite will gather telemetry and transmit them to the Ground.

The use case diagram of the Safe mode is described as Figure 2.2-9. There are three functions in the C&DH subsystem.

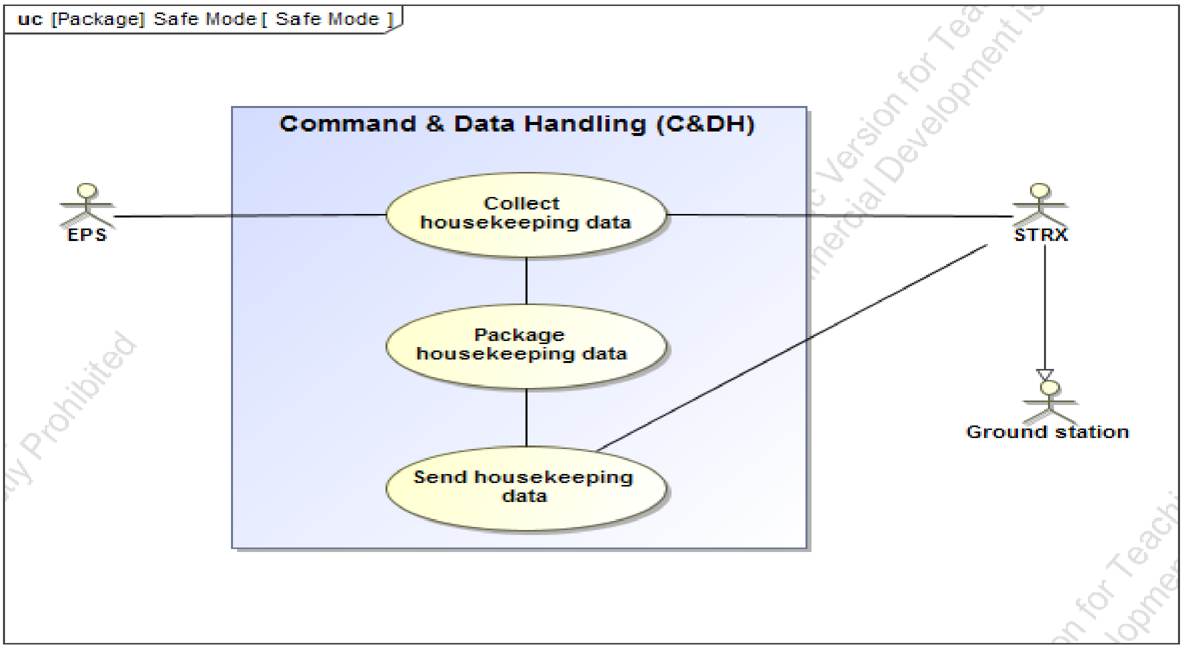

Figure 2.2-9: Use case diagram of C&DH

The C&DH collects the housekeeping data from other subsystem such as the EPS, STRX and itself. The data is coded into the package data by the programmer to send them to STRX for transmitting to the Ground.

Figure 2.2-10 is the sequence diagram of Safe mode.

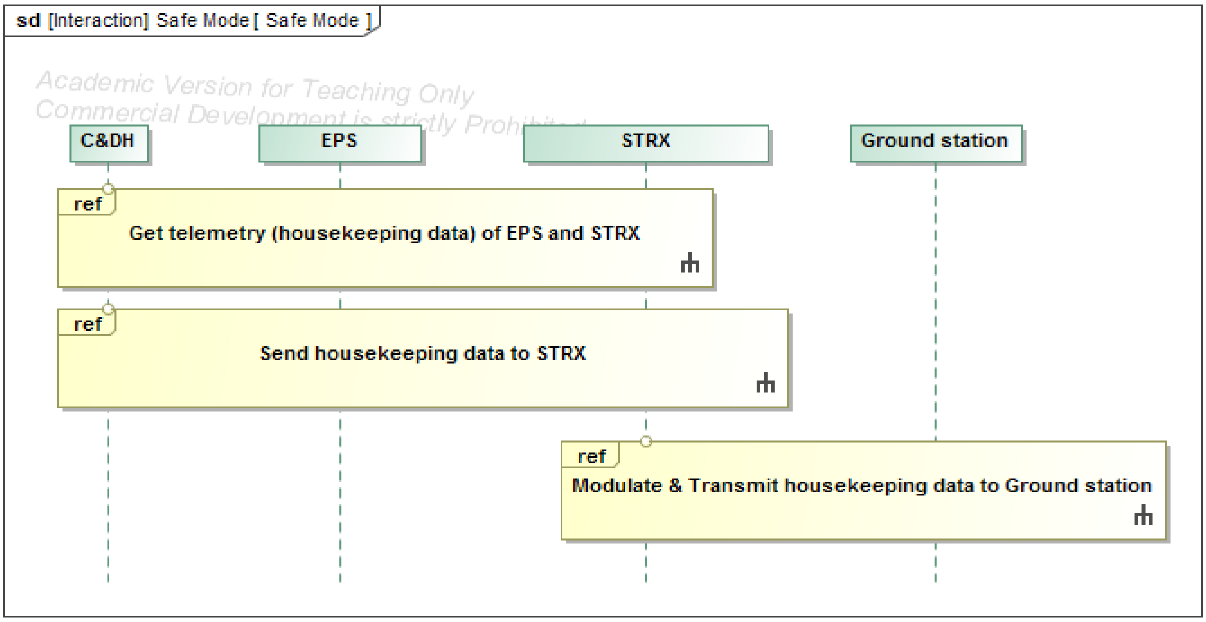

Figure 2.2-10: Sequence diagram of Safe mode

The functions is allocated to the subsystems as well as the components in Figure 2.2-11.

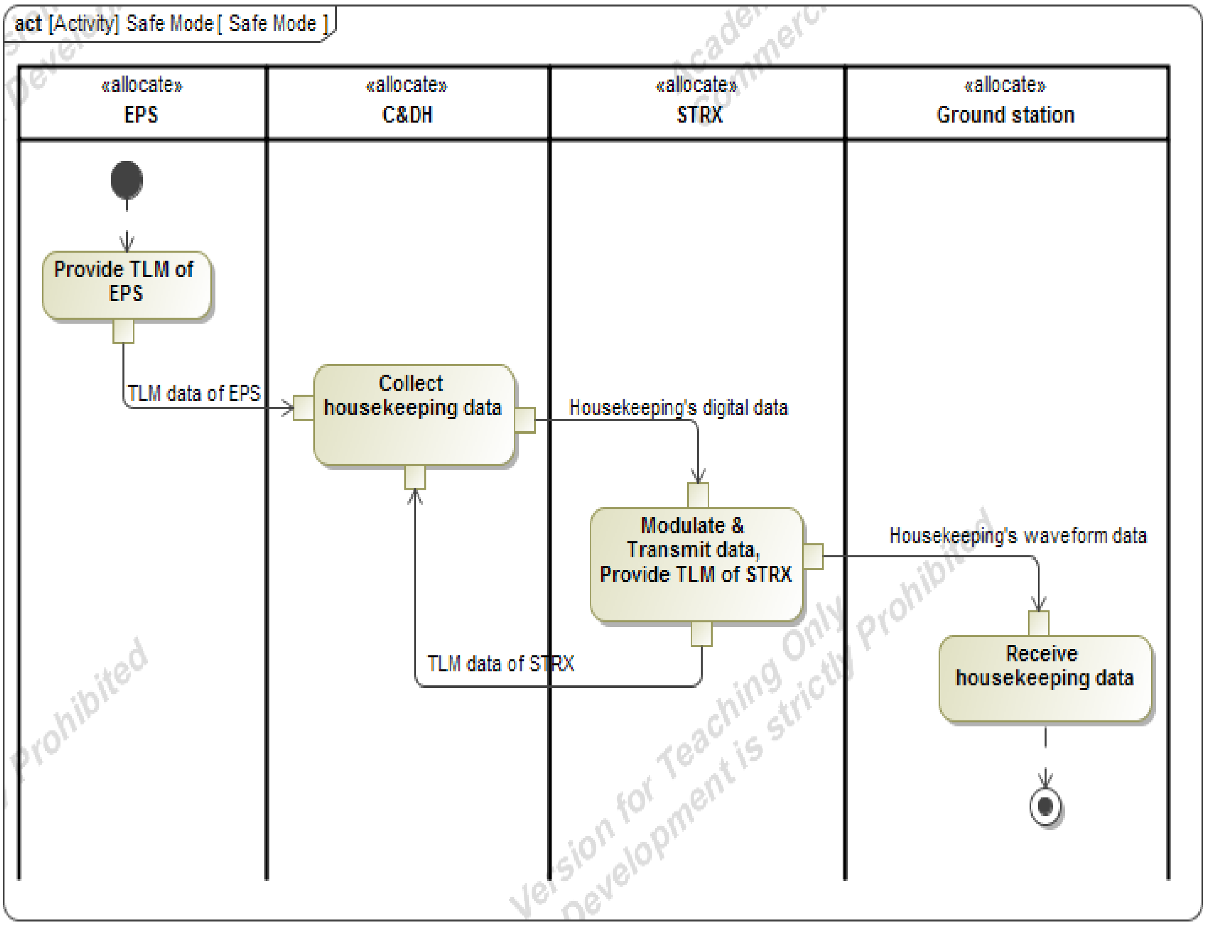

Figure 2.2-11: Activity diagram of Safe mode

The housekeeping data packed is in form of digital data. For the STRX, it always keeps two functions. The one is to provide its telemetry, the other is to communicate with the Ground. Therein, the STRX will modulate the housekeeping's digital data from the C&DH into the waveform data to transmit to the Ground, on the contrary, the Ground station uplinks the information of a command in the waveform data, the STRX receives and demodulates it into the digital data and send to the C&DH. The C&DH decodes the data and understands the content of command data, and commands to the subsystems.

2.2.3 Attitude Log Mode

This mode is used to check some components such as Geomagnetic Aspect Sensor (GAS), Nonspin Solar Aspect Sensor (NSAS), Fiber Optic Gyroscope (FOG), Magnetorquer (MTQ), they will be used for De-tumbling mode and Coarse Sun mode.

The C&DH subsystem plays with a role as a central control, it is illustrated in Figure 2.2-12. There are three functions for the C&DH, the data decoding, the command to the EPS and acquisition data from the components checked.

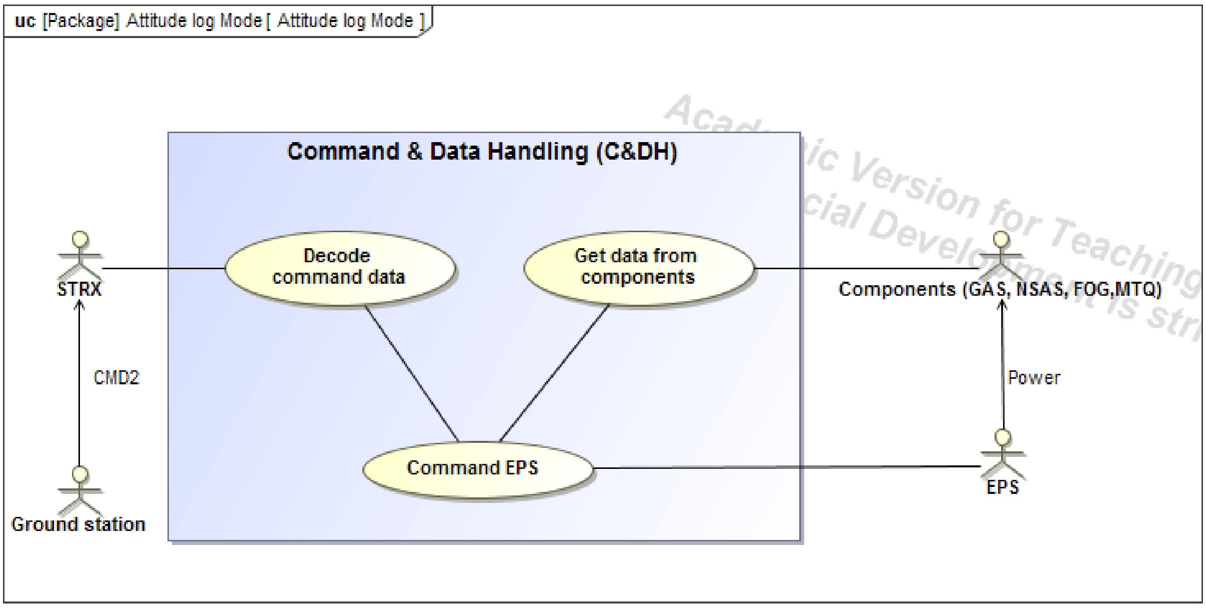

Figure 2.2-12: Use case diagram of Attitude Log mode

According to the sequence diagram of Attitude log mode in Figure 2.2-13, the Ground station shall uplink the command to the satellite to checkout components. After that, the sensors are turned on. As a result, they can measure values such as the magnetic field of the Earth from GAS, the sun vector from NSAS, the angular rate of satellite from FOG. For MTQ, it is tested two statuses, + MTQ and – MTQ, these values is reflected by the direction of the electric current and voltage in the output of the power distribute unit (PDU).

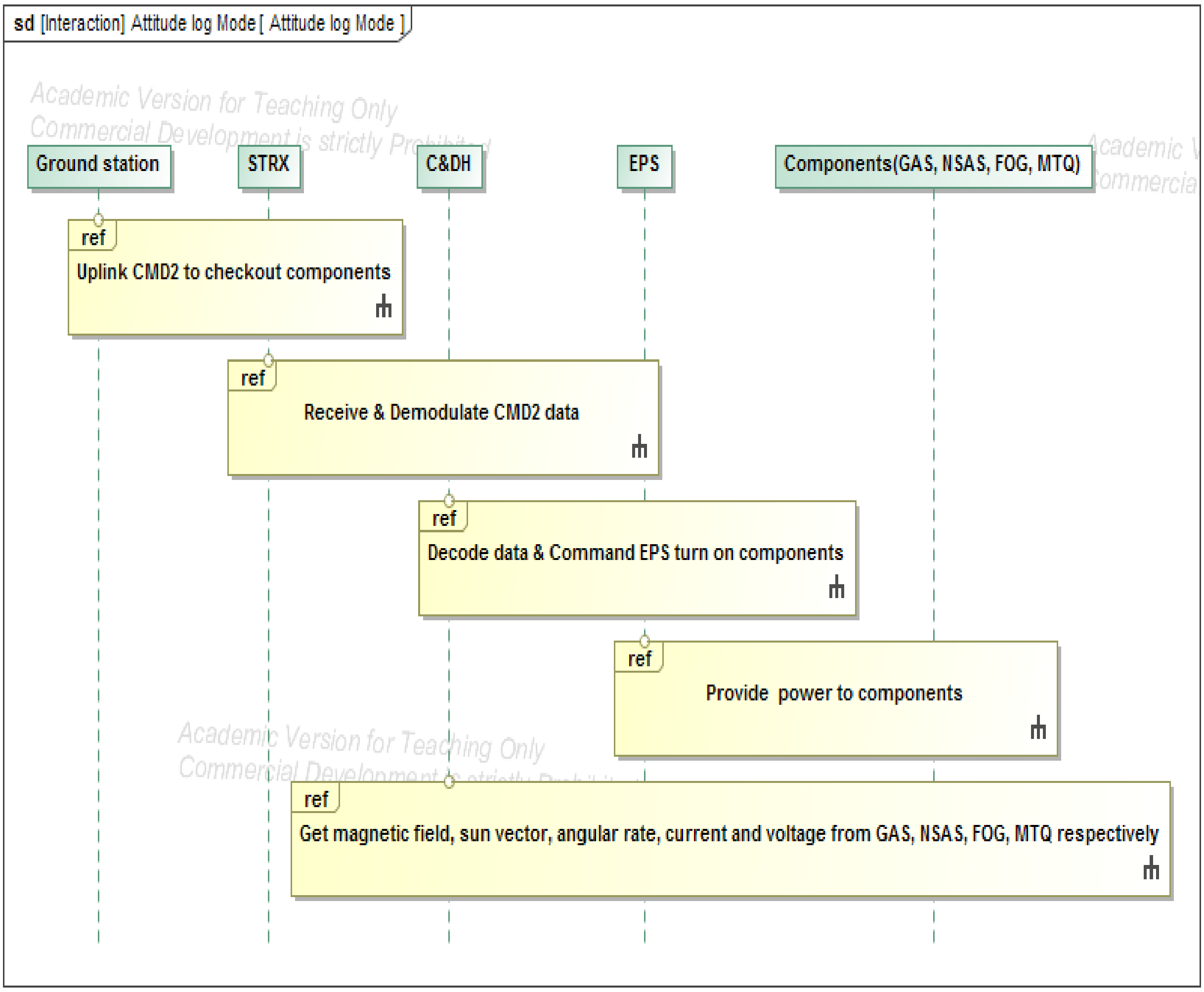

Figure 2.2-13: Sequence diagram of Attitude log mode

The activity diagram of Attitude log mode is described in Figure 2.2-14.

The time for components testing will last a certain time, not too long because it needs to save power, on the other hand, the MTQ is an actuator which can generate torque and affect the satellite dynamics as a disturbance. Therefore, after checking, the components are turned off, and now the satellite status is similar to the Safe mode. The data from the components is accumulated to send the Ground in the next communication. If everything is normal, the satellite will be transferred to the next mode by the command.

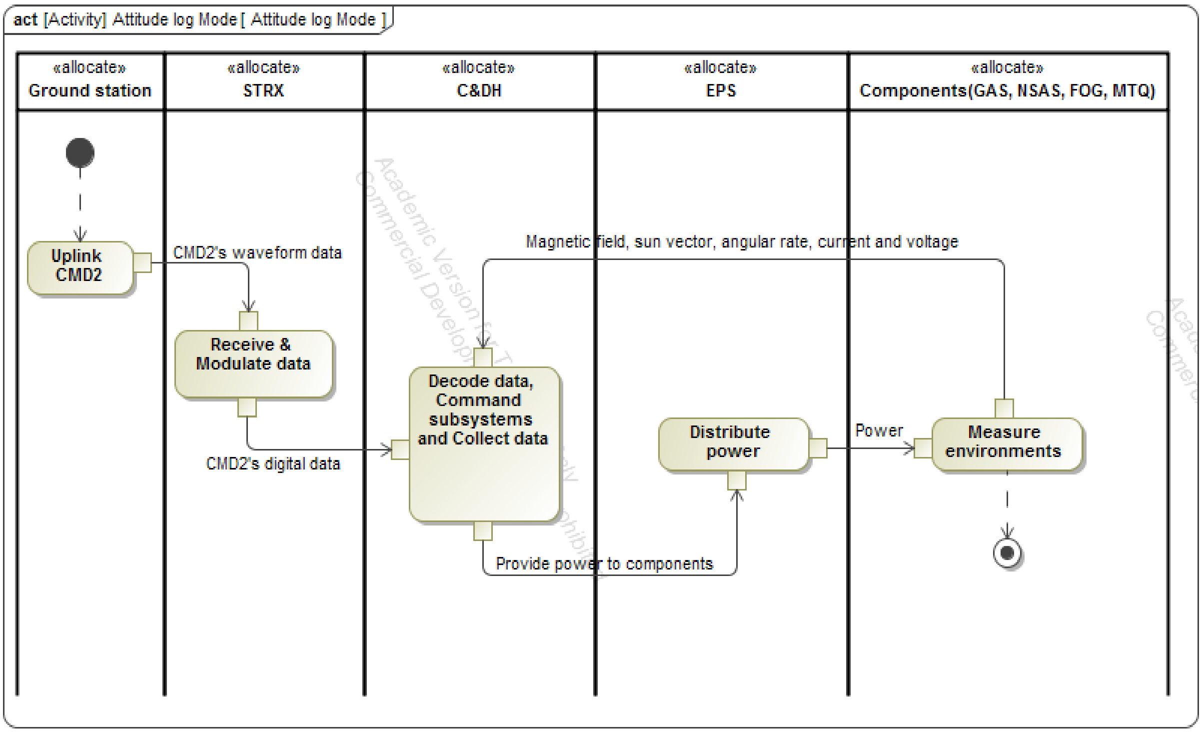

Figure 2.2-14: Activity diagram of Attitude log mode

2.2.4 De-tumbling Mode

This mode is used to reduce the satellite's angular rate after it is separated from the rocket. Using only one sensor (GAS) and one actuator (MTQ), the controller de-spins the satellite relative to the geomagnetic field vector. Figure 2.2-15 images for the satellite in the De-tumbling.

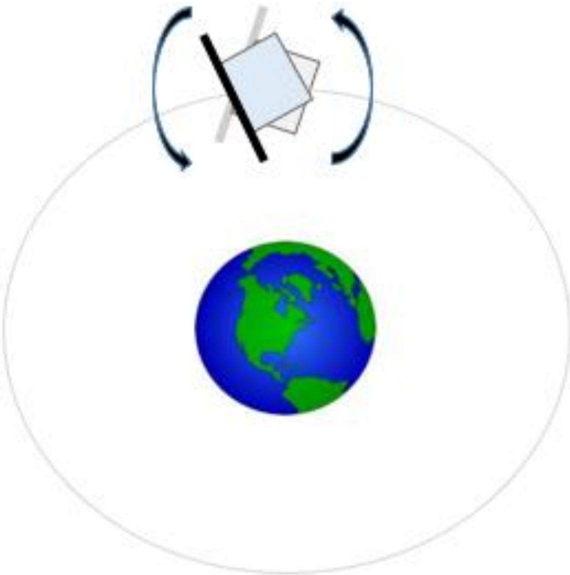

Figure 2.2-15: Satellite in De-tumbling mode

2.2.5 Sun Pointing Mode

The sun pointing mode is one of important mode to secure power generation for the satellite. According to the scenario, in this phase is divided into two modes including the Spin sun mode and the Fine sun mode.

Figure 2.2-16 images for the satellite in Spin sun mode. In this mode, the satellite is controlled to rotate around –Z axis with an angular rate intentionally by the designer, then rotating axis is moved so that solar panels are faced to the Sun. Sensor to be used in this mode are NSAS, FOG and GAS, MTQ is only actuator. Although the pointing accuracy is low but it has been still a good mode for the survivability of satellite. Hence, the Spin sun mode is designed as a safe mode when the satellite occurs emergency situation. It will go back this mode when having some components broken such as GPSR, STT and RW and stay there until the next command transmitted to recover the failure.

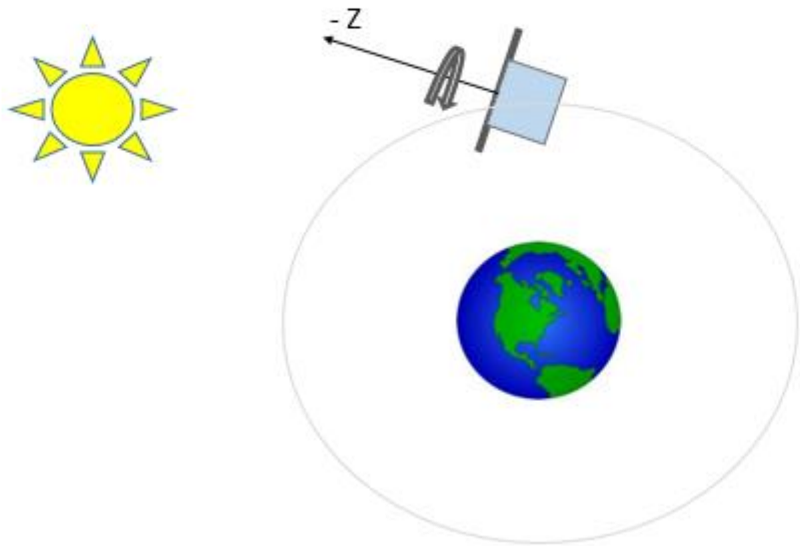

Figure 2.2-16: Satellite in Spin sun mode

Figure 2.2-17 images for the satellite in Fine sun mode. Similar to the Spin sun mode, the satellite also needs to face solar panels to direction of the Sun. However, 3-axis controlled algorithms is used to increase pointing accuracy so that the solar cells can generate maximum power as designed from Sun light. This mode is helpful when the satellite requires a large amount of electrical power generation in very short time period. List of components to be turned on are GAS, NSAS, FOG, RW and MTQ. In which, MTQ is used for unloading the angular momentum of the RW.

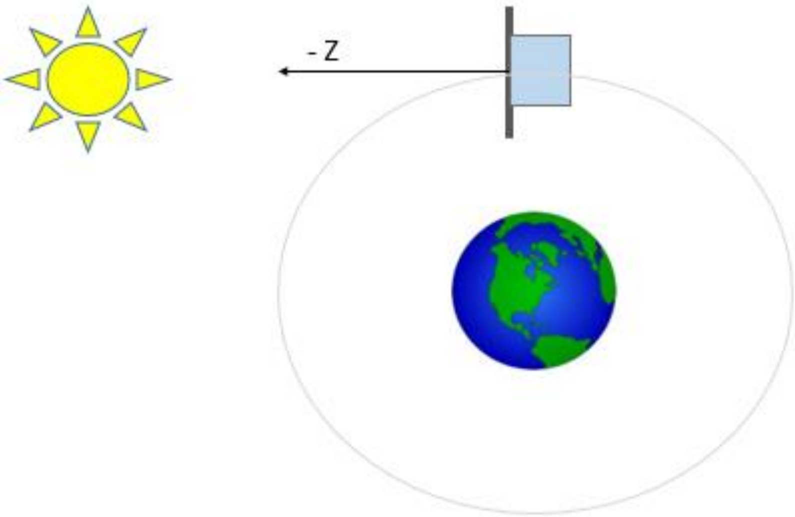

Figure 2.2-17: Satellite in Fine sun mode

2.2.6 Earth Pointing Mode

In Earth pointing mode, the cameras will be pointed towards the Earth to perform the mission, that means the +Z axis is controlled to direct to the Earth. According to the MDG's scenario, the Earth pointing mode is divided into four specific modes, including Coarse nadir mode, Fine nadir mode, Offset pointing mode and Target pointing mode.

Coarse nadir is the mode which the satellite can't use star tracker sensor (STT) for determination current attitude to avoid the sunlight shines directly on the sensor and cause damage to the device. In case of noon orbit, it means local time with 12 pm is the most effect. In the lucky case, the satellite gets the local time of orbit away the noon orbit, the STT can be turned on throughout orbit period. Therefore, this mode does not exist, exception STT broken. It is based on field of view of STT and the position of orbit to calculate the amount of time the sun shines on the sensor as well as the amount of time to turn off the STT. List of components to be turned on are GAS, NSAS, FOG, RW and MTQ. The information from GAS and NSAS is used to determine the current attitude.

Figure 2.2-18 images for the satellite in Fine nadir mode. After during time of Coarse nadir mode, the satellite will transfer automatically to Fine nadir mode by turning on the STT to determine the current attitude. The transition between Coarse nadir and Fine nadir mode is set up by timer in the programing. The Fine nadir mode is chosen as a nominal operation mode. It is very typical for Earth observation satellite like MDG because in this mode, cameras can always take pictures of the Earth. Another reason for choosing this mode as nominal operation mode is that, when the mission data is required for specific area on the Earth, the ADCS can quickly respond to the command and change the direction of camera to the target. By doing that, efficiency of the satellite is increased, while the time that satellite is passing above target area is very limited and satellite is traveling with very high speed in the orbit. List of components to be used for the mode are GAS, FOG, STT, GPSR, RW and MTQ.

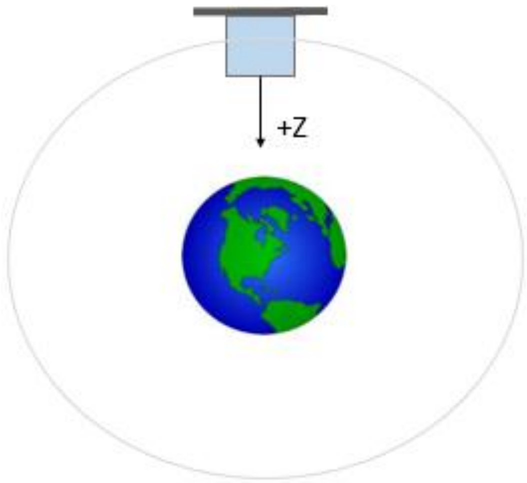

Figure 2.2-18: Satellite in Fine nadir mode

Figure 2.2-19 images for the satellite in Target pointing mode. This mode in which the highest pointing accuracy is required. The satellite is controlled to tilt to the target direction on the Earth. The transition to this mode is carried out by the command or timeline command from Ground station.

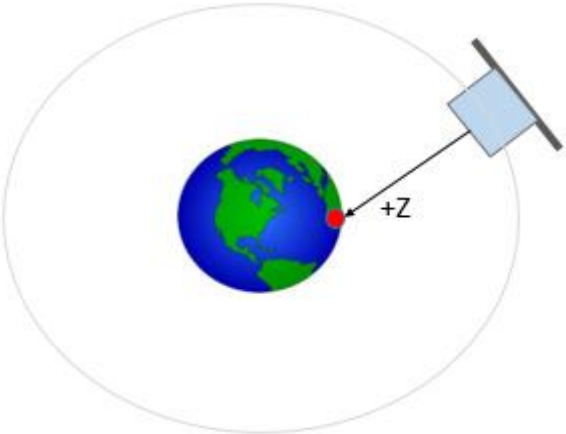

Figure 2.2-19: Satellite in Target pointing mode

The target direction is a certain point on the Earth where people want to the satellite take a picture. By uplink the command with the information of latitude and longitude of target direction and the information of GPSR sending to the satellite, it can define target attitude and then control the camera towards the target.

Moreover, the MDG satellite still has another mode, it is similar to Target pointing mode, only different about time of take a photograph. Offset pointing is a mode in which the camera scans, the satellite will tilt a constant angle with nadir direction.

A summary of list components activated for modes with ADCS is shown in table 2.2-1, green squares for on and red squares for off.

	GAS	NSAS	FOG	GPSR	STT	MTQ	RW	OBC
De-tumbling mode	O	X	X	X	X	O	X	O
Spin sun mode	O	O	O	X	X	O	X	O
Fine sun mode	O	O	O	X	X	O	O	O
Coarse nadir mode	O	O	O	O	X	O	O	O
Fine nadir mode	O	X	O	O	O	O	O	O
Offset pointing mode	O	X	O	O	O	O	O	O
Target pointing mode	O	X	O	O	O	O	O	O

Table 2.2-1: List of components of modes with ADCS

Chapter 3 Architecture of ADCS for Mode Sequence

3.1 Functional Architecture of ADCS for De-tumbling, Sun Pointing and Earth Pointing Modes

As mentioned above, the attitude determination and control subsystem is designed to control the satellite for de-tumbling, Sun direction and Earth direction. To satisfy the requirements delivered, the ADCS must have the corresponding functions for each mode to meet that requirement. By using two diagrams in SysML are Use case and Sequence diagram to describe the functionalities of the ADCS and how they interact with external objects to accomplish a set of goal, the Sequence diagram helps to represent behavior between subsystems in terms of sequence of messages exchanged.

Firstly, in the De-tumbling mode, the ADCS has to control the satellite to reduce the angular rate for the separation from the rocket. To achieve that, the ADCS gets the functions as description in Figure 3.1-1.

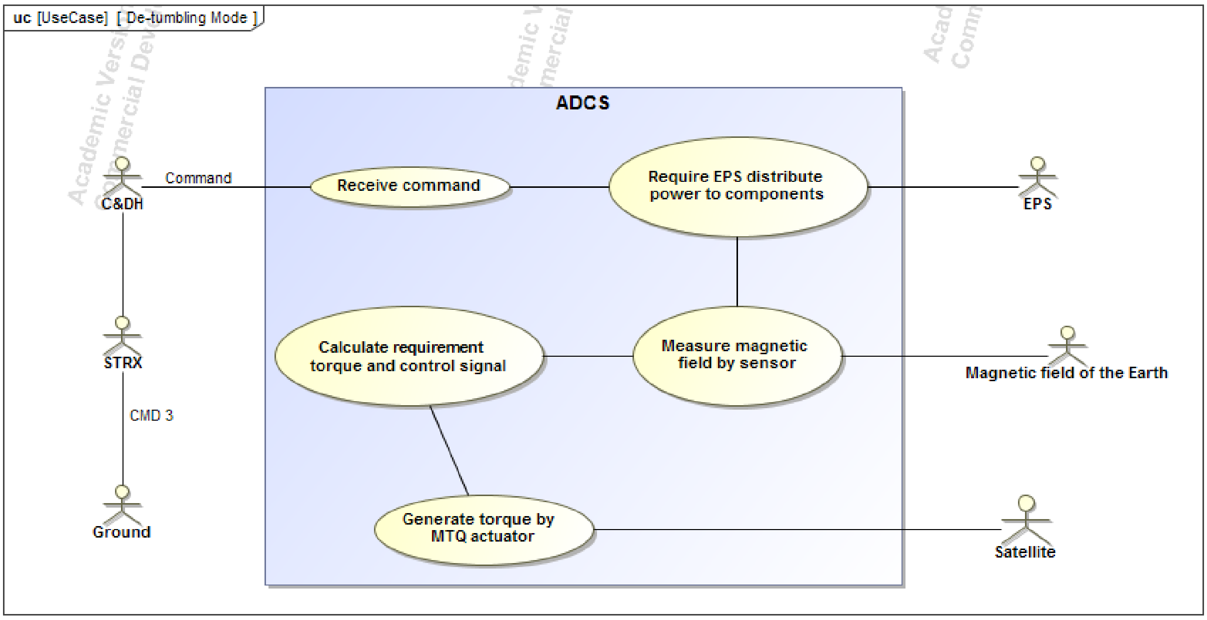

Figure 3.1-1: Use case diagram of De-tumbling mode

It needs functional communication with subsystems. For example, the ADCS is able to receive the command from the C&DH and require the EPS to distribute power to components so that they can work. The first thing which the attitude control has to do is measurement values of environment, this information reflects the change of satellite dynamics. In this mode, the value of magnetic field of Earth which is measured by a sensor is used for input information of the controller to calculate requirement torque and control signal. And MTQ actuator generates torque by leading of control signal to reduce the angular rate of satellite.

In order to understand exchange between the subsystems, Figure 3.1-2 describes the sequence of De-tumbling mode.

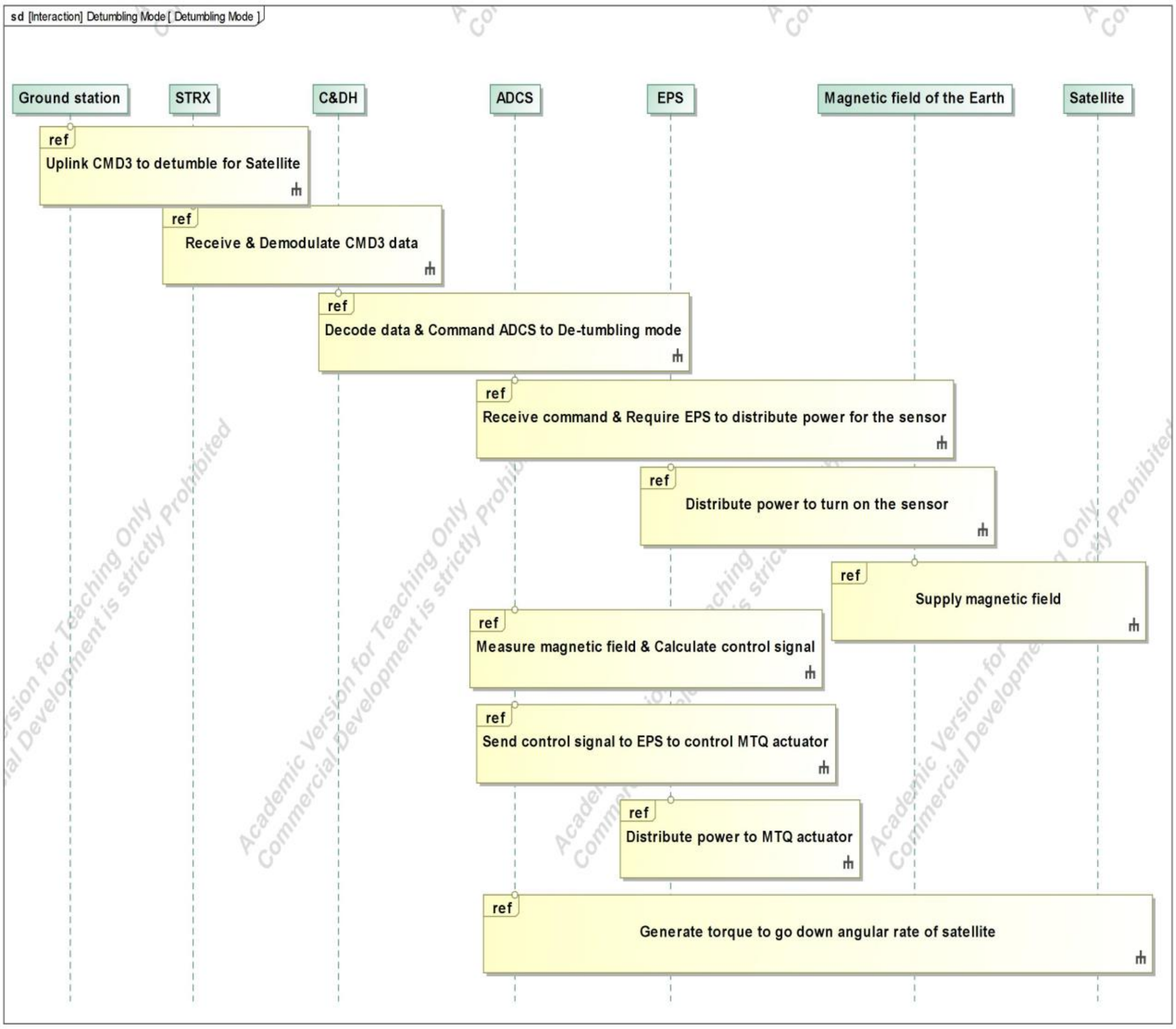

Figure 3.1-2: Sequence diagram of De-tumbling mode

According to the scenario, the ground station will send a command to the satellite to take De-tumbling mode. In the satellite, the STRX is responsible for receiving and demodulation the command, the C&DH is responsible for decoding the command and deliver to the ADCS to carry out the mode, the EPS supports for components under ADCS's requirements, the magnetic field of the Earth has a role as a supply source.

Secondly, after de-tumbling is the Sun pointing mode, the satellite will transfer automatically to the Spin sun mode. With the purpose is to direct the solar cells towards the Sun as soon as possible. The ADCS's functions in this mode is represented in Figure 3.1-3.

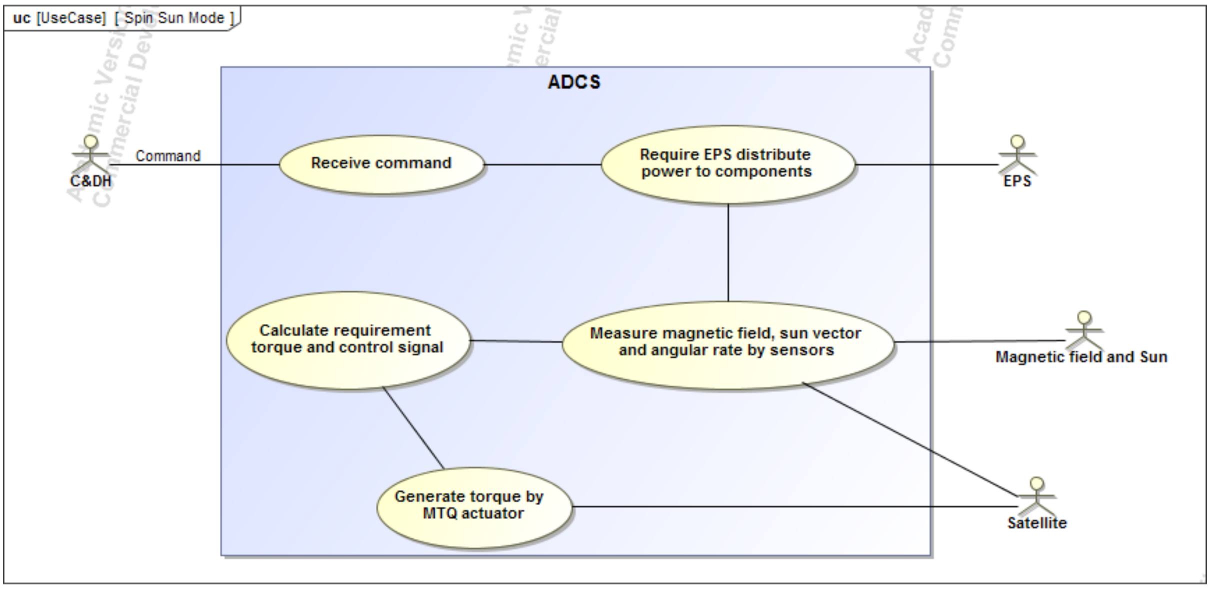

Figure 3.1-3: Use case diagram of Spin sun mode

Almost the functions is similar to the De-tumbling mode. However, to do the mission in this mode, two actions are added more on the function of measurement of ADCS. One is to get the information of Sun position, the other is to get the information of angular rate to control the satellite spinning around –Z axis as required.

Figure 3.1-4 shows the sequence diagram of Spin sun mode.

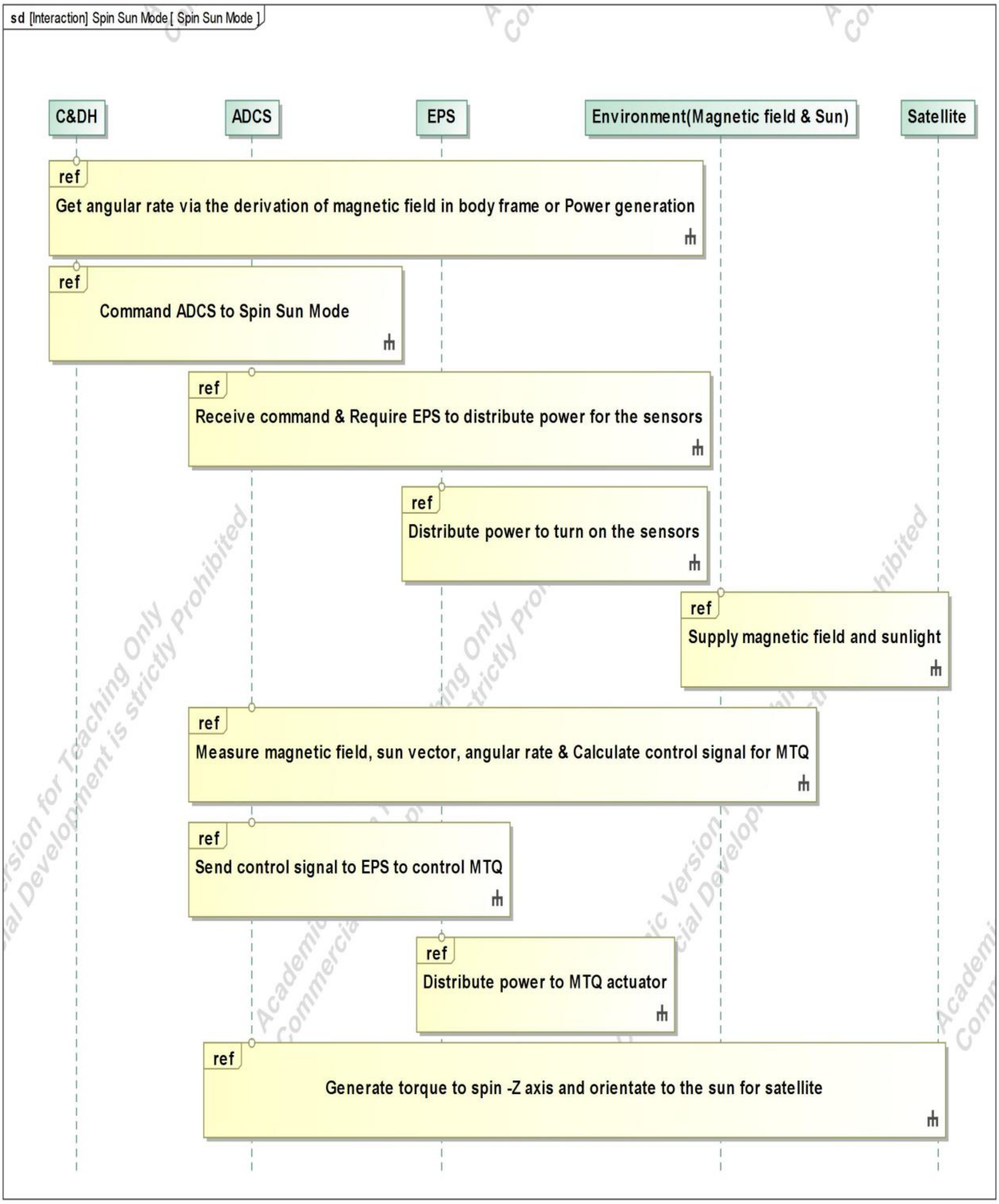

Figure 3.1-4: Sequence diagram of Spin sun mode

The C&DH subsystem is always responsible for acquisition data. Hence, it knows parameters of satellite and then compares with the condition installed in before to implement the next mode. In which, the angular rate is assess via the derivation of magnetic field in body frame or power generation approximately. Because the change of angular rate causes also the change of the value of magnetic field in the body frame. Actually, the change of magnetic field also causes from travelling of satellite in the orbit. However, the angular velocity of orbit is very small compared to the angular rate so an approximate estimation of the derivation of magnetic field in the body frame is used. For the assessment through the number of power generation, people can simulate a model with the initial value of angular rate which was known from checkout component of gyroscope sensor in Attitude log mode. The result of power generation in the simulation may estimate the angular rate and also predict the end of time of De-tumbling mode. When the satellite moves on this mode, we can be confident on its survivability.

In order to receive maximum energy from the Sun, the satellite will transfer to Fine sun mode in which the ADCS uses RW actuator to bring high accuracy. Figure 3.1-5 is the Use case diagram of Fine sun mode.

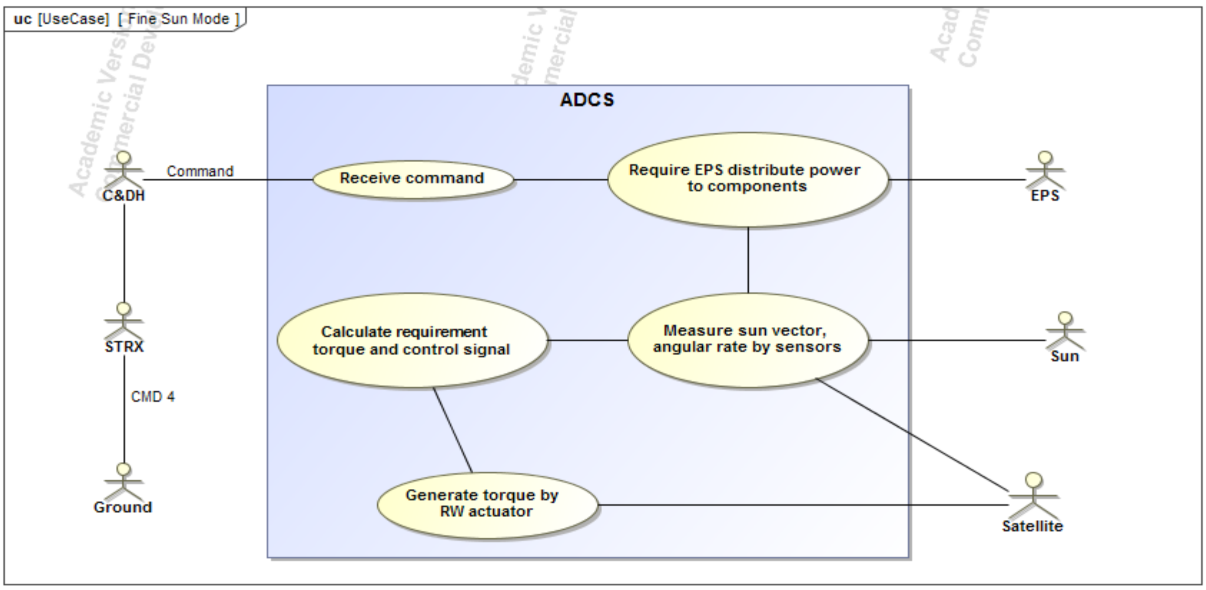

Figure 3.1-5: Use case of Fine sun mode

The mode transition will be performed by the command data from the Ground station. The Sequence diagram of Fine sun mode is illustrated in Figure 3.1-6.

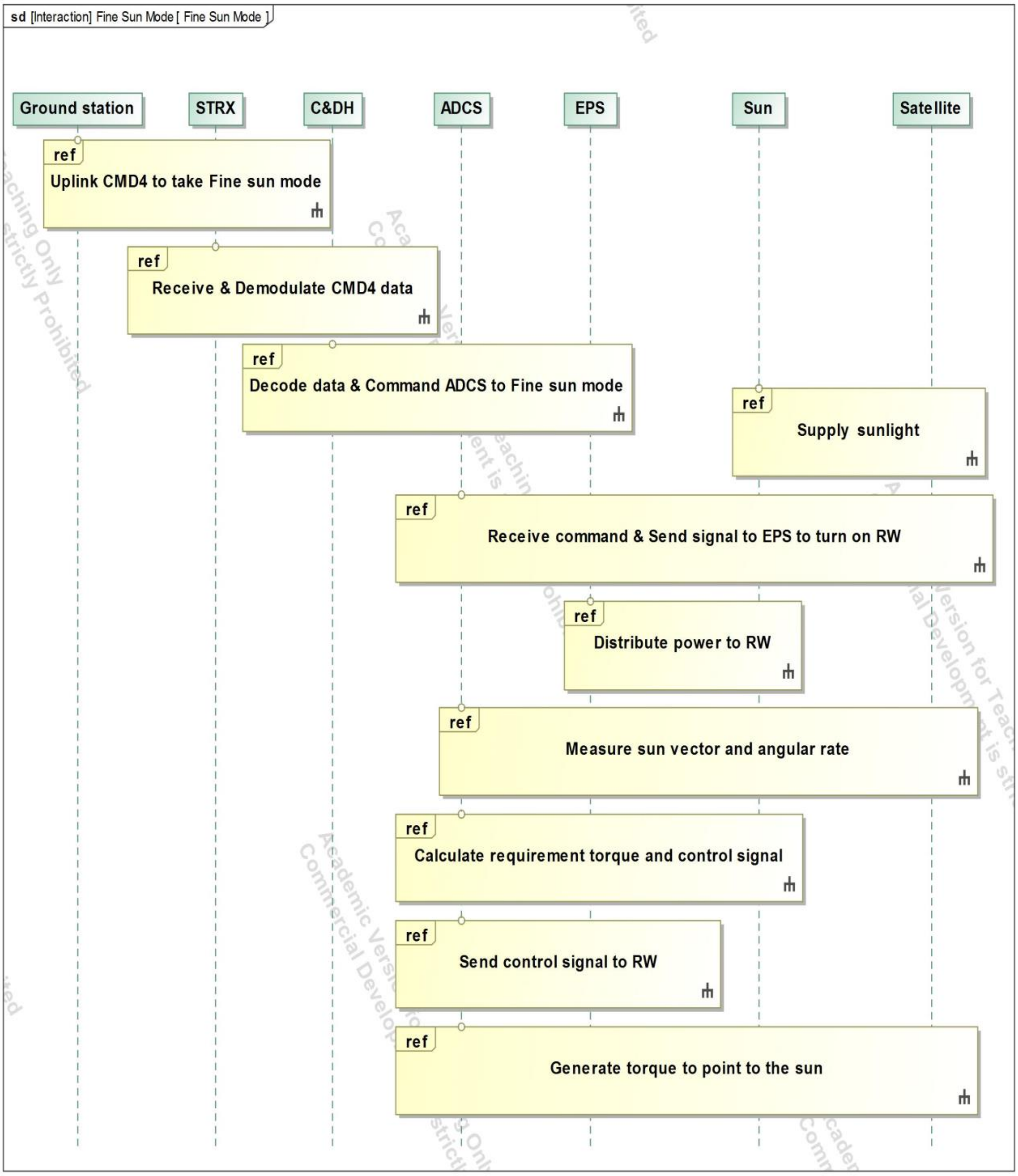

Figure 3.1-6: Sequence diagram of Fine sun mode

Thirdly, Earth pointing mode, in order to work in this mode, the ADCS needs to add the functions for determination target attitude and current attitude. As a result, some parts in the functional measurement also change to support for determination target and current attitude. The functionality of the ADCS is shown in Figure 3.1-7.

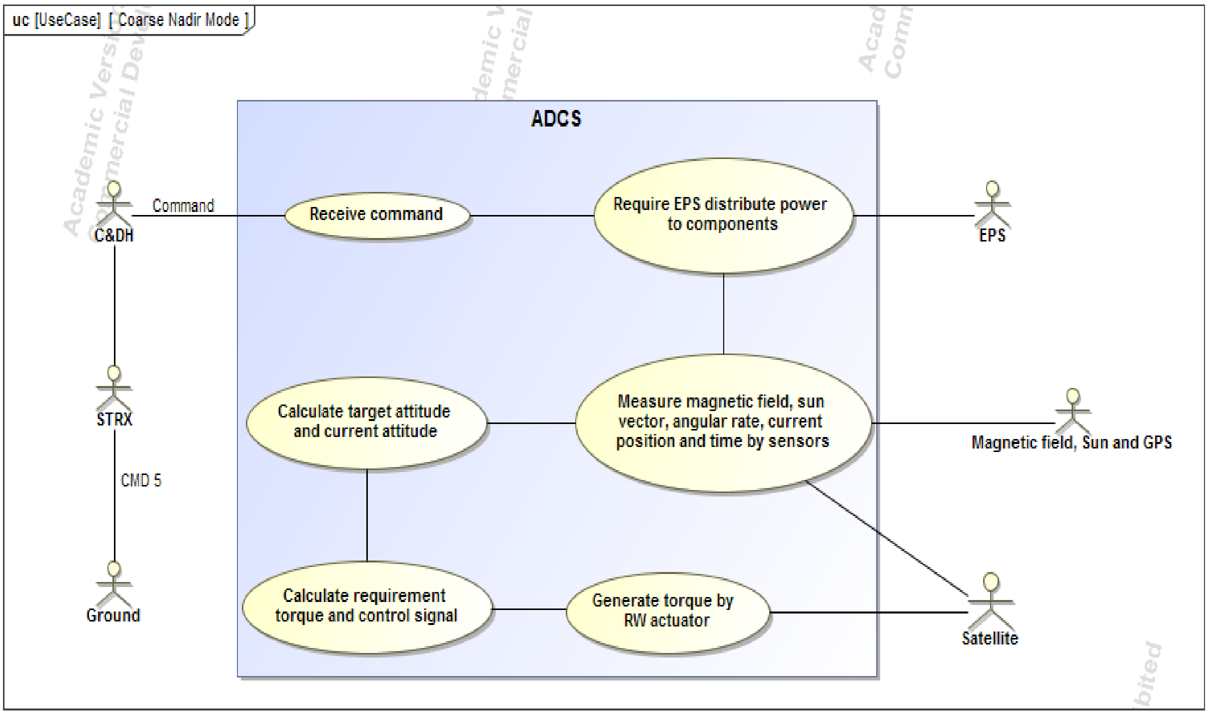

Figure 3.1-7: Use case diagram of Coarse nadir mode

Figure 3.1-8 is the Sequence diagram of Coarse nadir mode in which GPSR sensor is turned on to get the data of position and time.

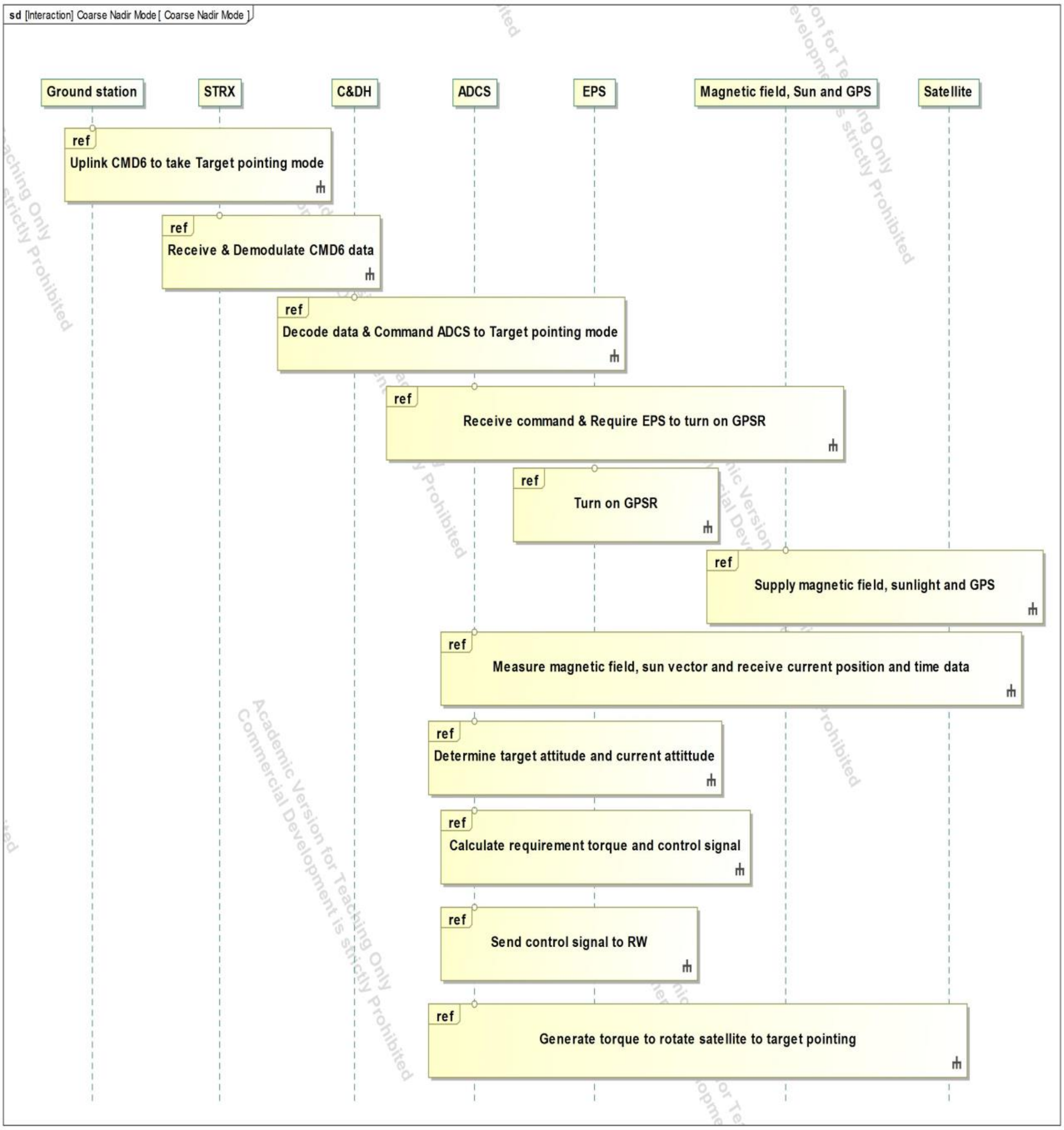

Figure 3.1-8: Sequence diagram of Coarse nadir mode

Basically, the architecture of the ADCS for the modes in Earth pointing mode is same only different in determination attitude method. For Fine nadir mode, Offset pointing mode and Target pointing mode, they have the same the number of sensors used. Therefore, the architecture of other modes and control algorithm are similar to the Target pointing mode. Figure 3.1.9 is the Use case diagram of Target pointing mode.

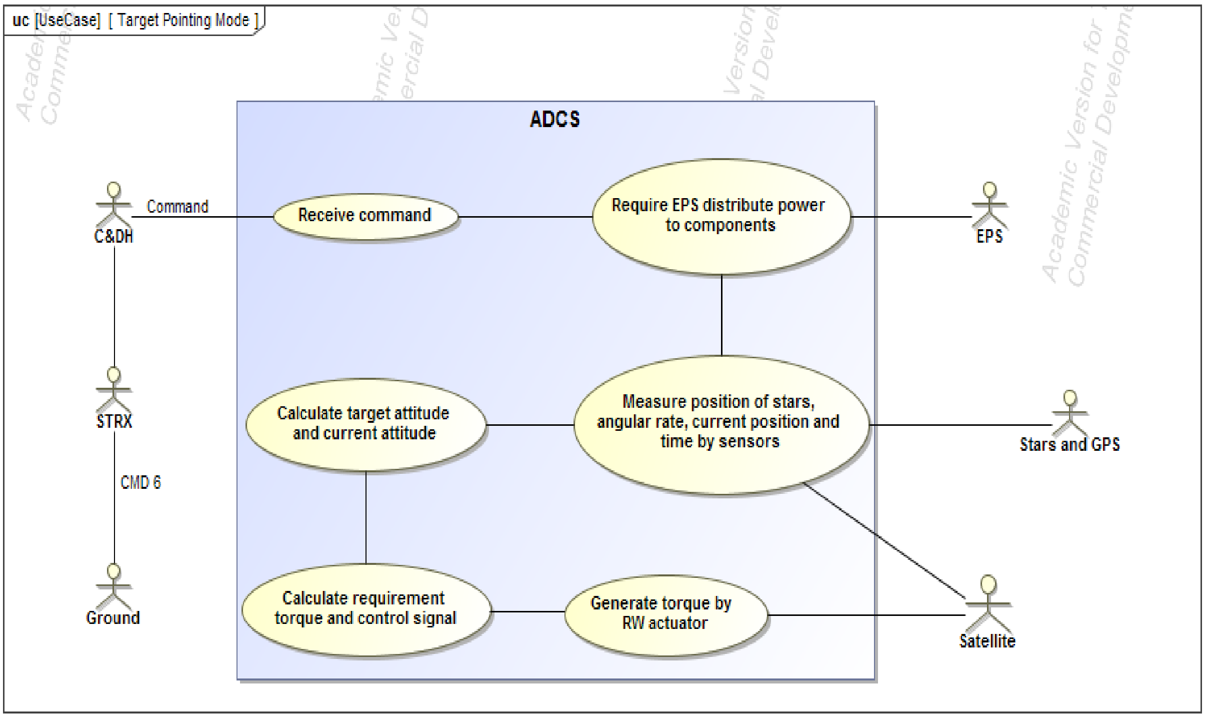

Figure 3.1-9: Use case diagram of Target pointing mode

In this mode, the attitude determination is based on position of stars, this function is allocated to a star tracker sensor. We will explain in the next part.

Figure 3.1-10 is the Sequence diagram of Target pointing mode. The content of command from the Ground is an address of a certain place in on the Earth. Actually, these command are often called timeline commands because it spends time on processing data and control, another reason, the place to take a picture can be far the Ground so it has to uplink timeline command before. In this mode, Star tracker sensor (STT) is turned on instead of sun sensor (NSAS) in attitude determination.

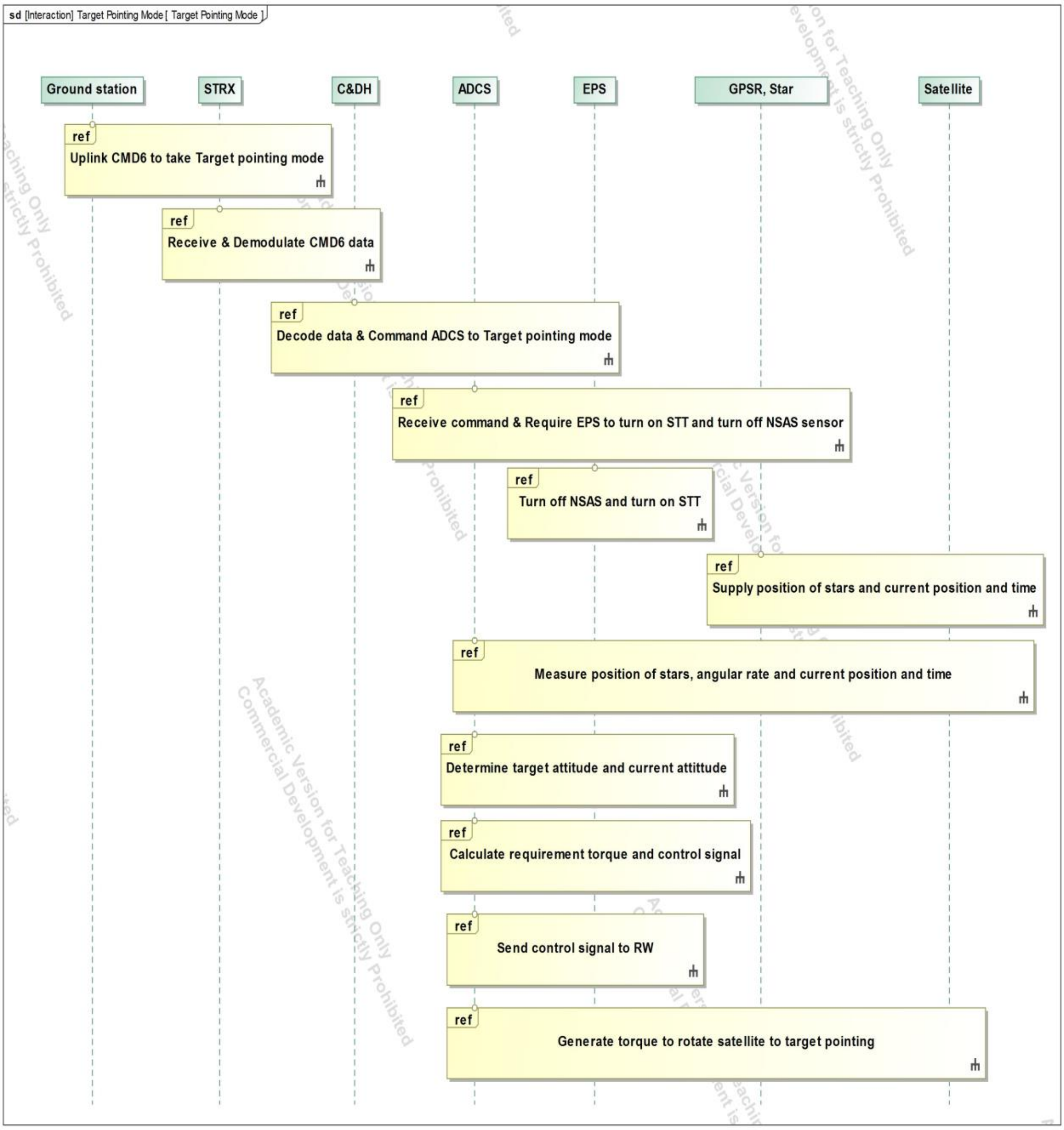

Figure 3.1-10: Sequence diagram of Target pointing mode

3.2 Allocation of Function to Physical Components of ADCS

The architecture of ADCS is described clearly by two diagrams in SysML. The first is the Activity diagram to allocate functions to components and to represent the availability of inputs, outputs and control. The second is the Internal block diagram to represent interconnection and interfaces between the components. To connect between the parts, we continue to decompose behavior of subsystem by the Activity diagram.

Figure 3.2-1 is the Activity diagram of De-tumbling mode. In which, the functions are allocated to the subsystems, the ADCS will send requirement to the EPS to turn on the sensor. After calculation, the ADCS also sends control signal to the EPS to distribute power for actuator. In fact, the C&DH subsystem can assume the role to manage devices on and off like the modes without ADCS. However, it is not important to distinguish that role because both subsystem use a common onboard computer.

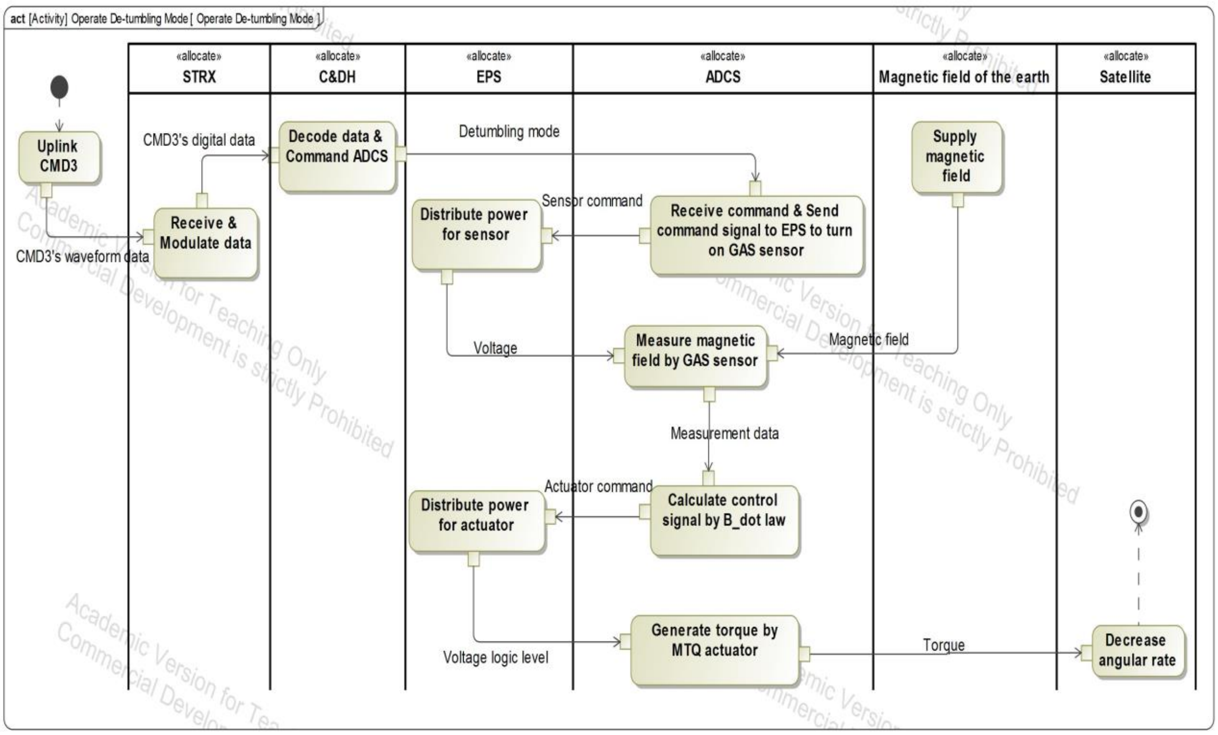

Figure 3.2-1: Activity diagram of operate De-tumbling mode

We continue analyzing to the behavior of ADCS in which the functions are allocated to components detail in Figure 3.2-2. The function of geomagnetic aspect sensor (GAS) is to measure magnetic field value of the Earth. But this value is represented in component frame. Thereby, the attitude control system needs to transfer into the value represented in body frame by a rotation matrix which represents the correlation of the two coordinate systems. The controller applies $\dot{B}_b$ algorithm which means the derivation of magnetic field value in body frame to calculate the requirement moment magnetic and sends control signal to the EPS to distribute power for the actuator.

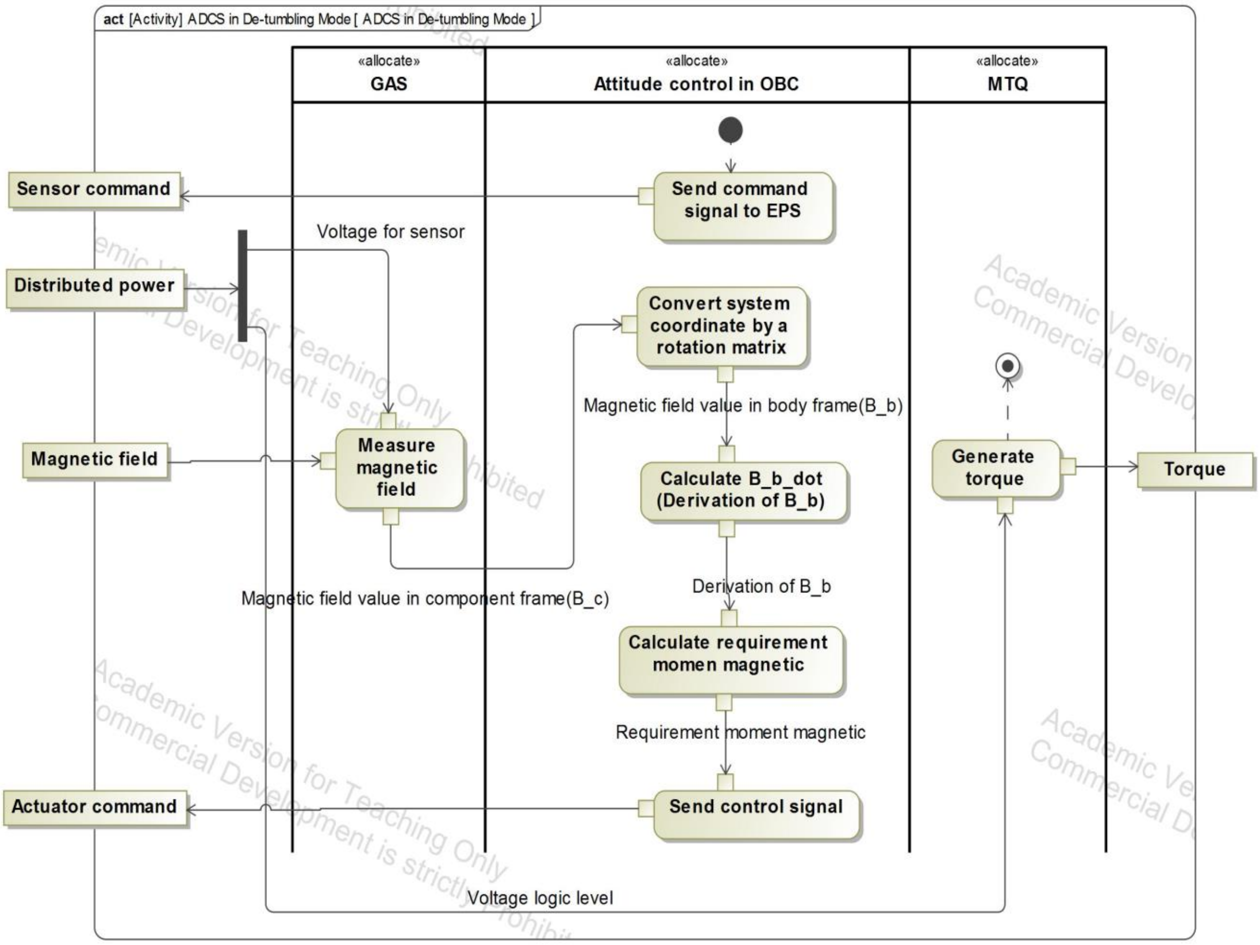

Figure 3.2-2: Activity diagram of ADCS in De-tumbling mode

The interconnection and interface between the components is shown in Figure 3.2-3. In case of MDG satellite, the amplitude of electric current running through the magnetorquers' coil is constant and only the direction of the electric current is controlled. The reason for this decision is because controlling the electric current needs more time to process the command than switch control. Thereby, the values of voltage logic level are respective with +1, 0 and -1.

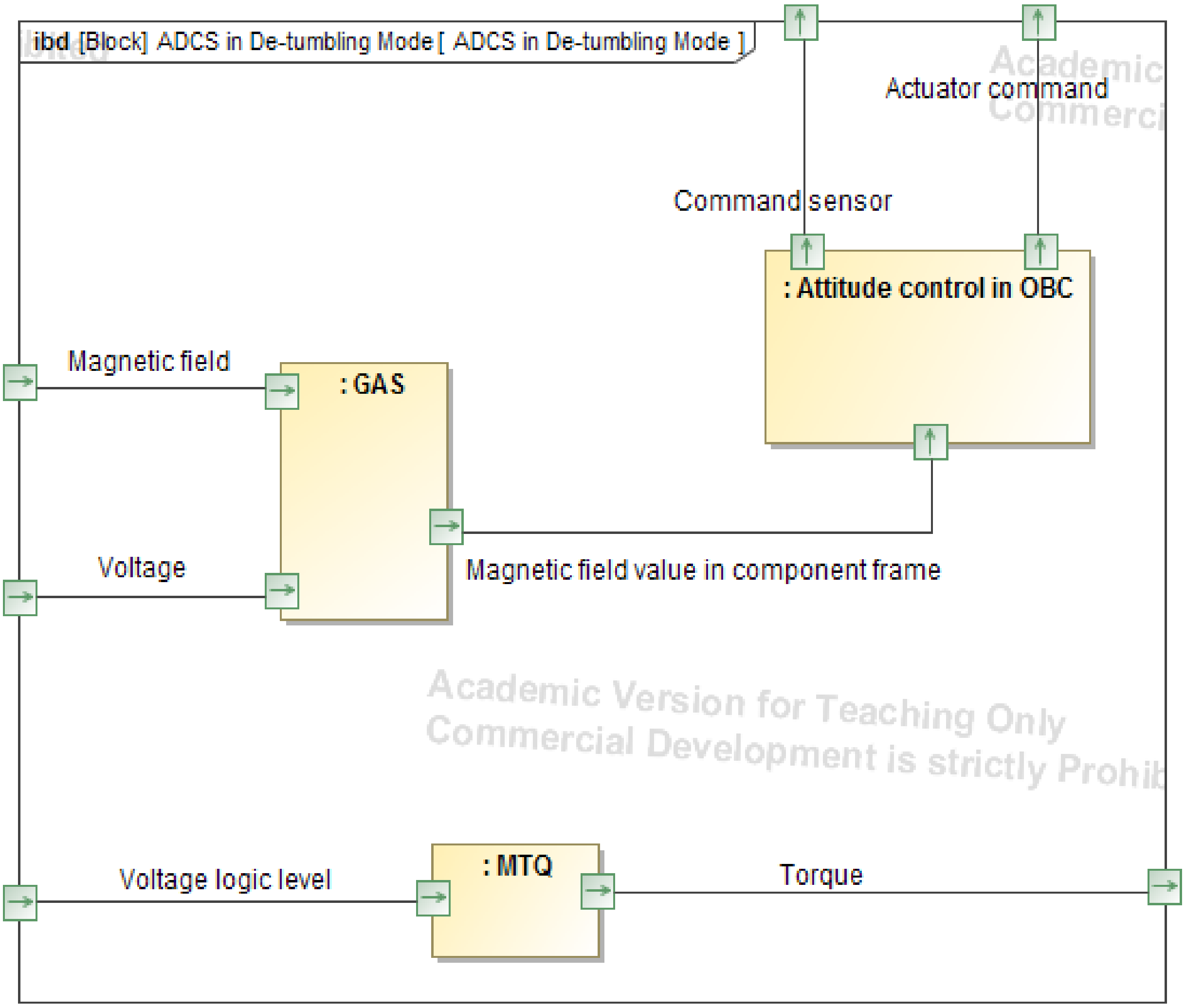

Figure 3.2-3: Internal block diagram of ADCS in De-tumbling mode

The block definition diagram represents structural elements of ADCS in this mode as Figure 3.2-4.

The magnetorquer actuator (MTQ) is an electric coil that develops a magnetic field which interfaces with the magnetic field of the Earth, generating a torque that can be used for attitude control.

To control MTQ, the Onboard computer (OBC) will send control signal to power distribute unit (PDU) of EPS to change voltage direction.

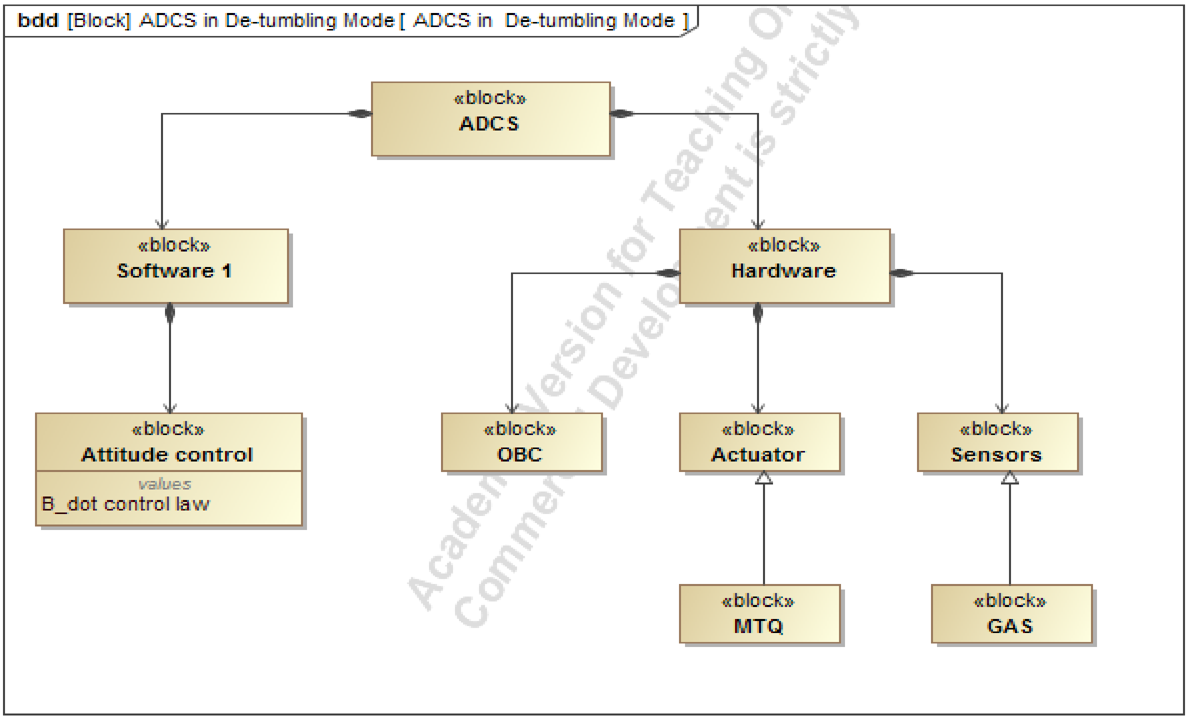

Figure 3.2-4: Definition block diagram of ADCS in De-tumbling mode

As explained above, the angular rate value can estimate from the derivation of magnetic field value in body frame or power generation. When the angular rate of satellite decrease to 0.5deg/s, the satellite will move on the Spin sun mode automatically, the aim is to the solar panel of satellite quickly toward the Sun to receive energy. However, this work has also an enterprise that in case of battery voltage is too low after de-tumbling, it is not enough to maintain voltage for components in the control process of pointing to the Sun. As a result, the satellite shall go back the Safe mode to protect the battery. Therefore, before entering to this mode, it needs to consider the condition of battery voltage.

Activity diagram of Spin sun mode is described in Figure 3.2-5. Noted that the satellite will be controlled in the sunlight area but not in the eclipse area.

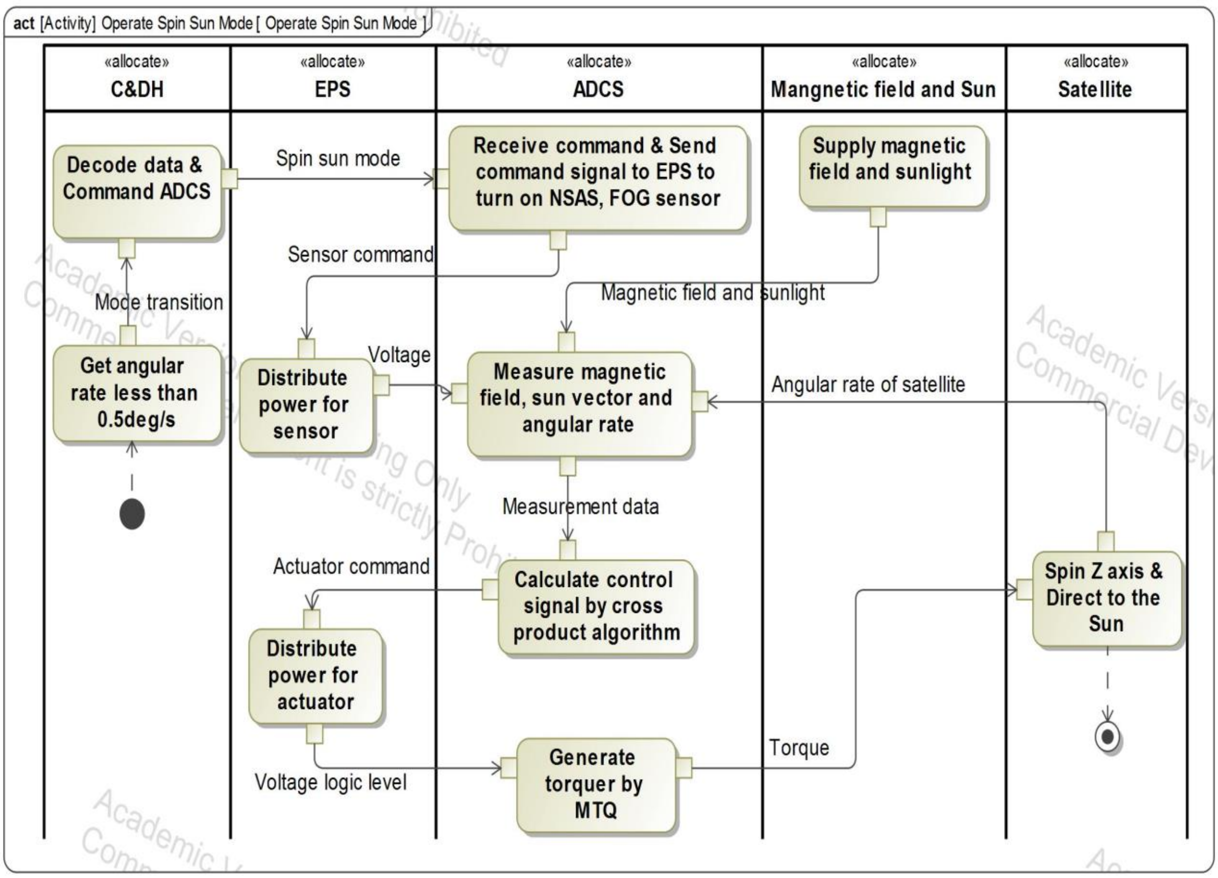

Figure 3.2-5: Activity diagram of operate Spin sun mode

In this mode, the sun sensor (NSAS) is turned on to measure sun vector value and the gyroscope sensor (FOG) is also turned on to define angular rate value. These value will be inputs for the controller.

Not same as the algorithm in De-tumbling, the requirement moment magnetic for MTQ is calculated from the requirement torque of cross product algorithm. This algorithm aims to reduce the angle between sun vector S_b and the –Z axis, orienting the surface with the solar panels toward the Sun. Figure 3.2-6 represents the Activity of ADCS in Spin sun mode.

When the satellite transfers to a new mode, it shall send command signal to the EPS to turn on more new components for that mode. The devices have already turned on in a previous mode, the satellite doesn't need to send the command signal to turn on them when they are still used.

This diagram does not represent distribution power to the GAS sensor.

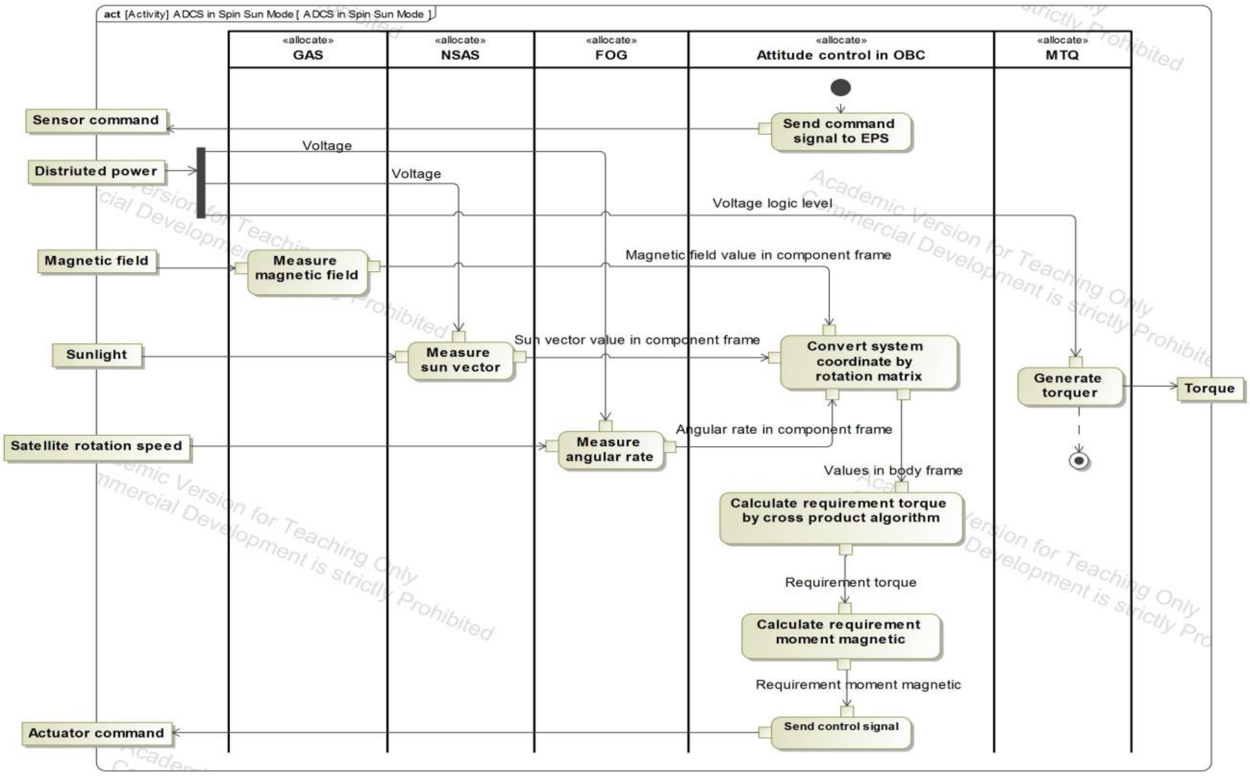

Figure 3.2-6: Activity diagram of ADCS in Spin sun mode

Figure 3.2-7 is the Internal block diagram of ADCS in Spin sun mode.

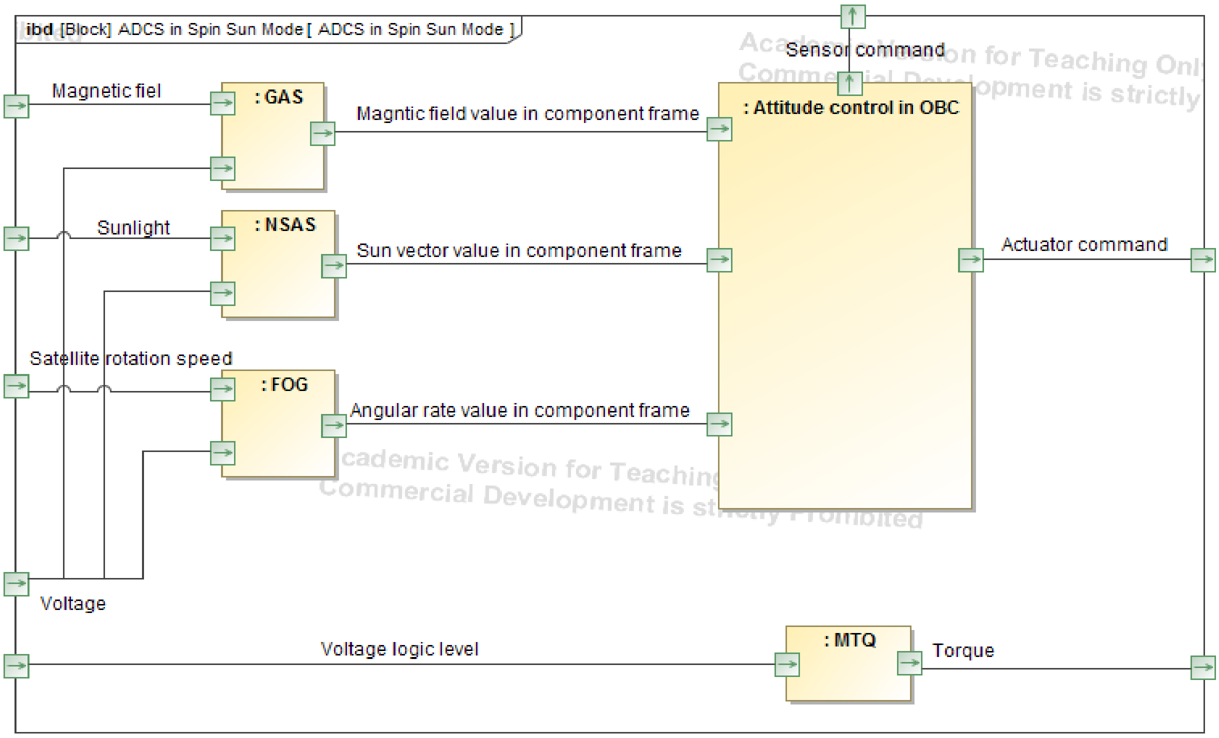

Figure 3.2-7: Internal block diagram of ADCS in Spin sun mode

The block definition diagram of Spin sun mode is shown in Figure 3.2-8.

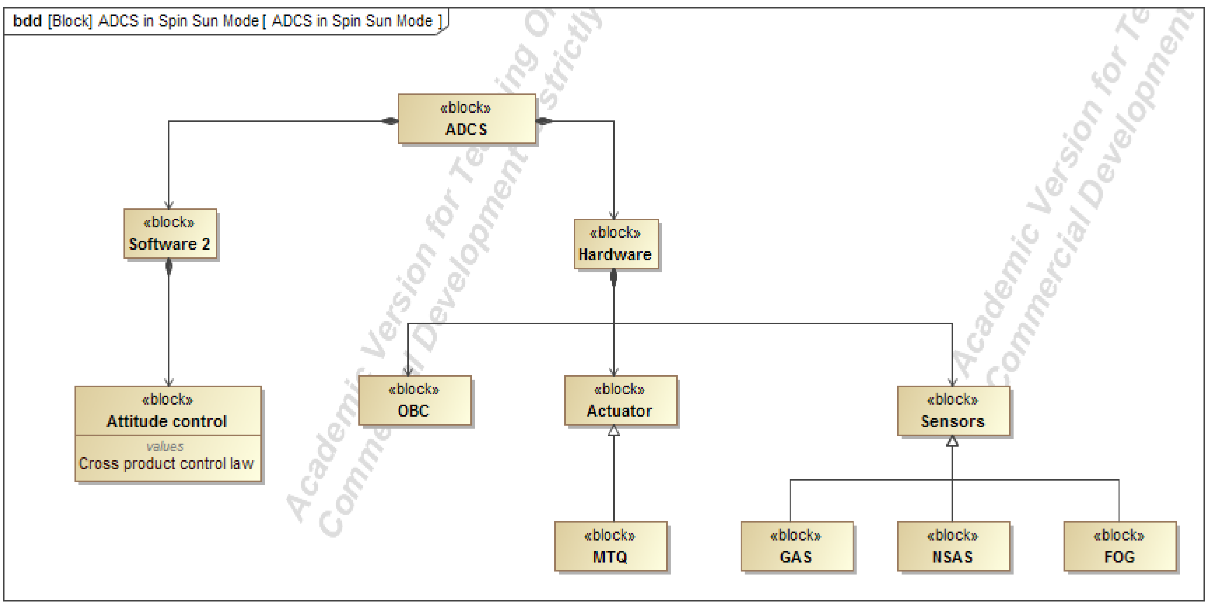

Figure 3.2-8: Block definition diagram of ADCS in Spin sun mode

The transition to Fine sun mode will be performed by the command from the Ground as Figure 3.2-9. In this mode, the number of sensors used is the same with the previous mode.

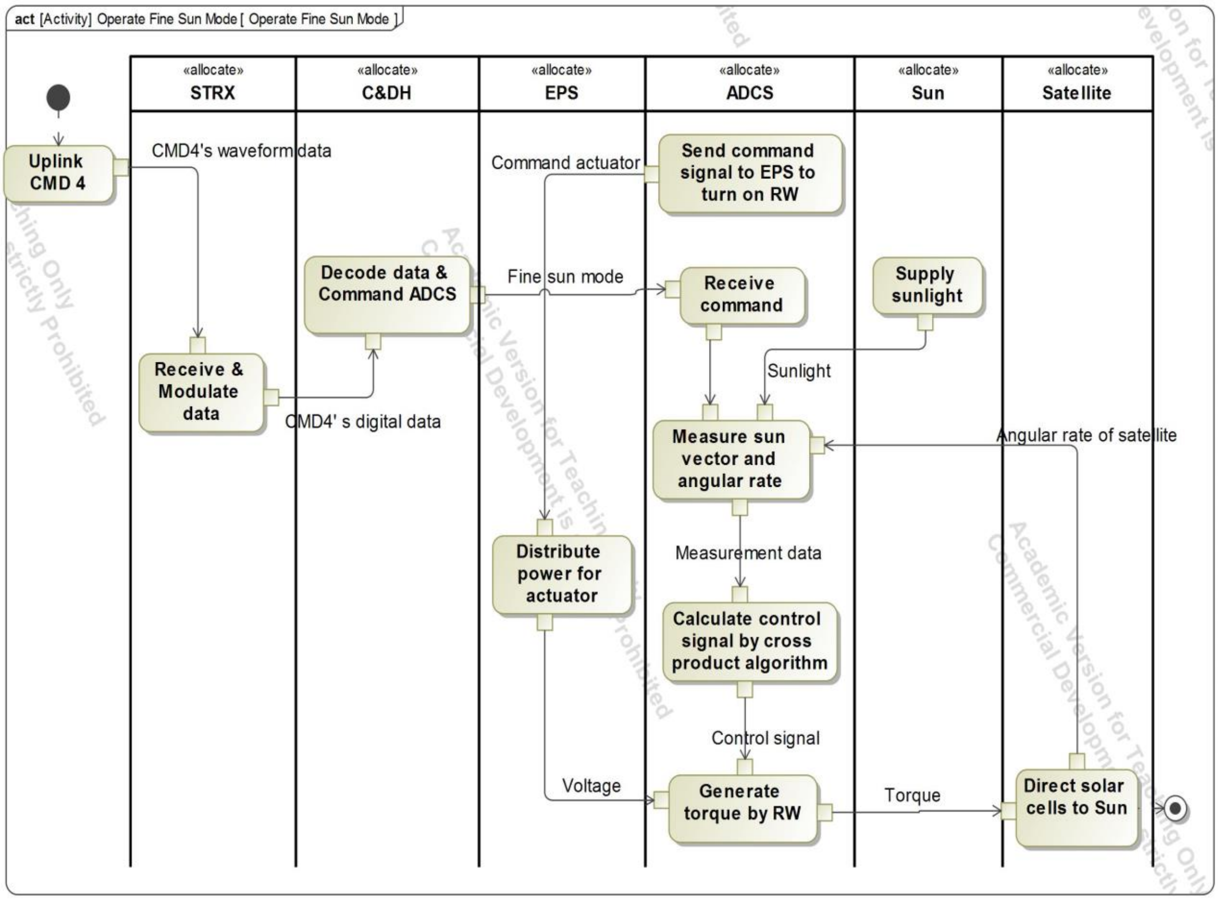

Figure 3.2-9: Activity diagram of operate Fine sun mode

The ADCS will send command signal to the EPS to distribute power for the RW. However, there is a difference in controlling a reaction wheel (RW) and a MTQ that the rotation speed of wheel is controlled by a microprocessor in this actuator. Hence, the OBC will communicate with this microprocessor in sending control signal.

The functions of ADCS are allocated to the components as Figure 3.2-10. The utilization of the reaction wheels (RWs) is based on the conservation of angular momentum. When the reaction wheels' rotation speed changed, it will make the satellite rotate in the opposite direction. Reaction wheels are actuators that can control the satellite's attitude rapidly with high accuracy and high torque, therefore they will be used as the main actuator in the higher accurate pointing mode such as Fine sun and Earth pointing mode.

There is a small difference between the elements of the cross product algorithm in Spin sun mode and Fine sun mode. It will be explained in the verification.

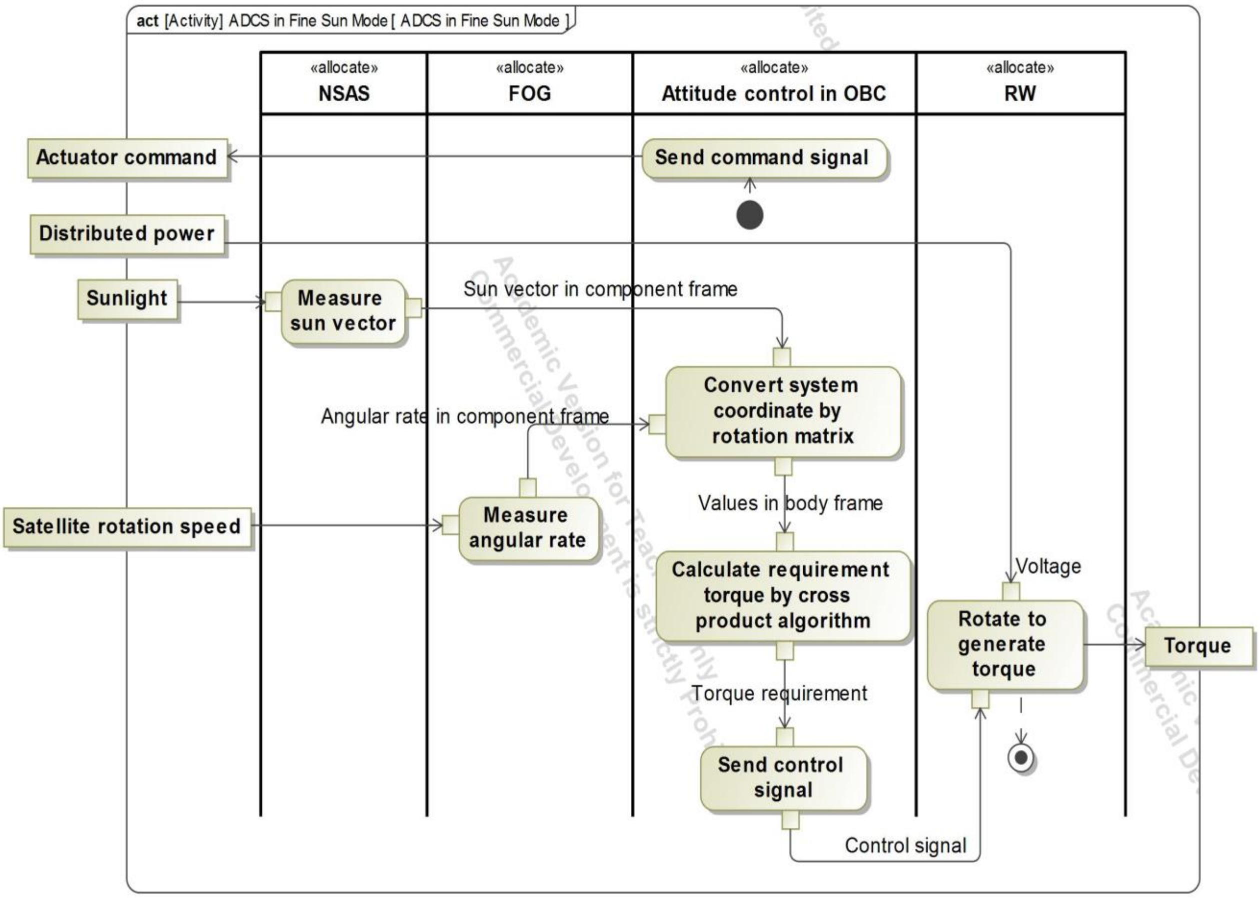

Figure 3.2-10: Activity diagram of ADCS in Fine sun mode

The interface of components of ADCS in Fine sun mode is represented in Figure 3.2-11.

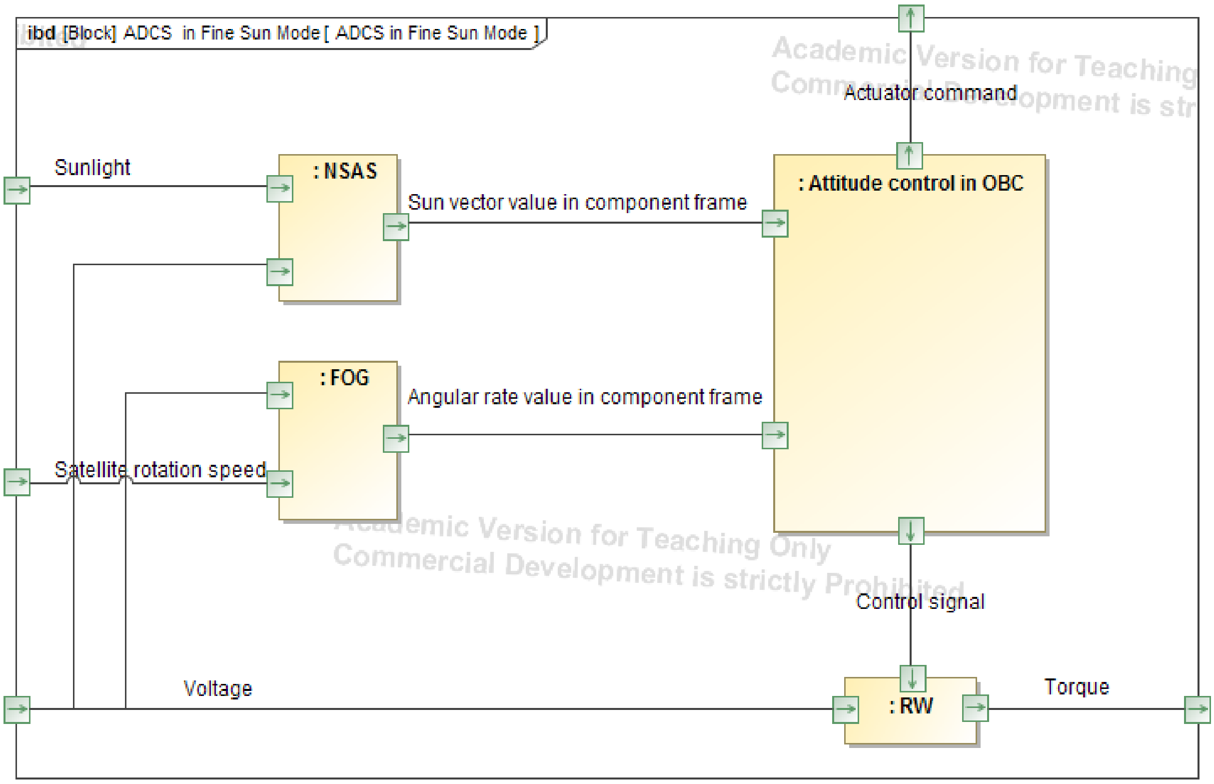

Figure 3.2-11: Internal block diagram of ADCS in Fine sun mode

List of components to be used in this mode is shown in Figure 3.2-12.

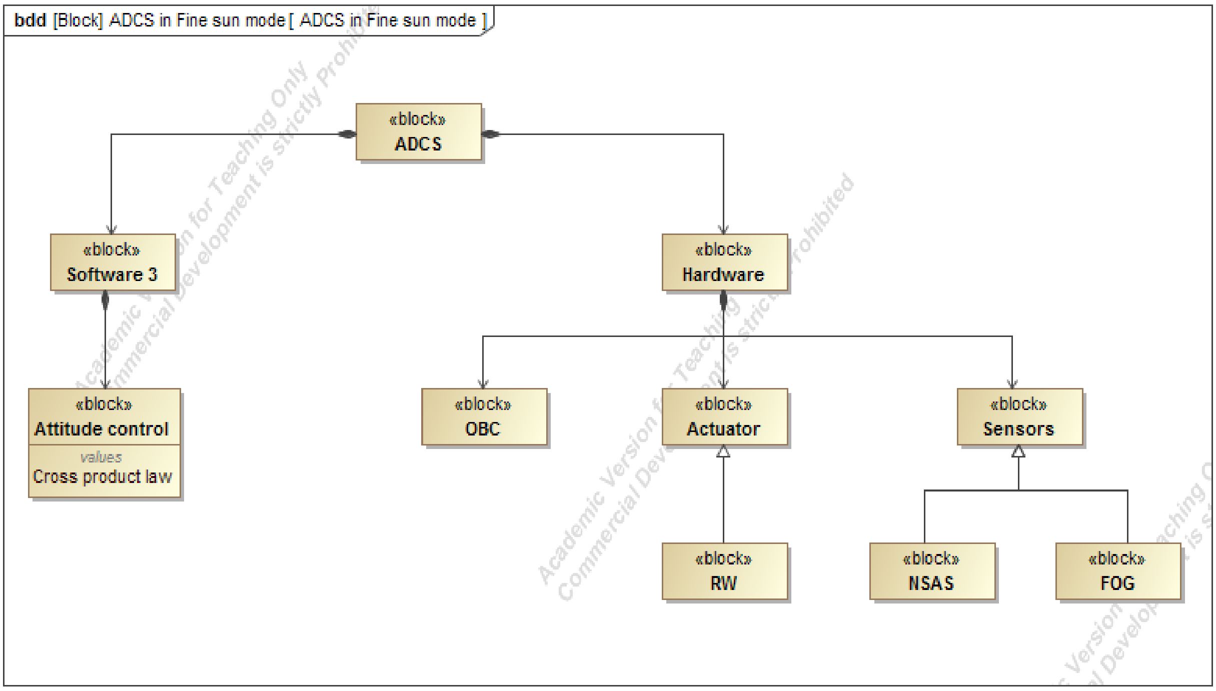

Figure 3.2-12: Block definition diagram of ADCS in Fine sun mode

In fact, the GAS sensor and MTQ actuator are used always for the modes with the reaction wheels to unload the angular momentum. However, it is not mentioned in the diagram of this thesis.

The unloading angular momentum of reaction wheels is explained as follow. In the working process of the reaction wheel, it can rotate to over velocity limit to generate torque like the calculation of the controller. By using MTQ or thruster actuator to make a torque as a disturbance torque affects the satellite, as a result, the satellite leaves the equilibrium position as well as its target attitude. At the moment, the controller will command the reaction wheel to decrease its velocity to generate a torque balance with the disturbance torque. As a result, the velocity of the reaction wheel is decreased to under the velocity limit. The goal of this work is to secure safety for the actuator.

There are two methods to choose for unloading the angular momentum. The first method, the RW's velocity will be decreased to under the allowable velocity and keep it in that velocity, it is called the bias momentum. This way is easy but not high stability for the satellite. The second method, the RW's velocity will be decreased to zero, it is called the zero momentum. This method requires a sophisticated controller but it brings a high stability for the satellite.

Figure 3.2-13 is the Activity diagram of Coarse nadir mode. The PD control is one of the simple control method and high performance, it often sees in the ADCS of satellite. There are two parts in the PD control including the proportion and the derivation. The proportion element has the function to reduce attitude error. That means it helps for adjusting attitude of satellite. The derivation element has the function to counteract the change of attitude. The change of attitude represents in the value of angular rate.

In order to use the PD control, the ADCS has to know the attitude error which is calculated from target attitude and current attitude. Thus, a full ADCS software consists of three main elements as attitude guidance to determine the target attitude, attitude navigation to determine the current attitude and attitude control. They are called guidance, navigation and control (GNC).

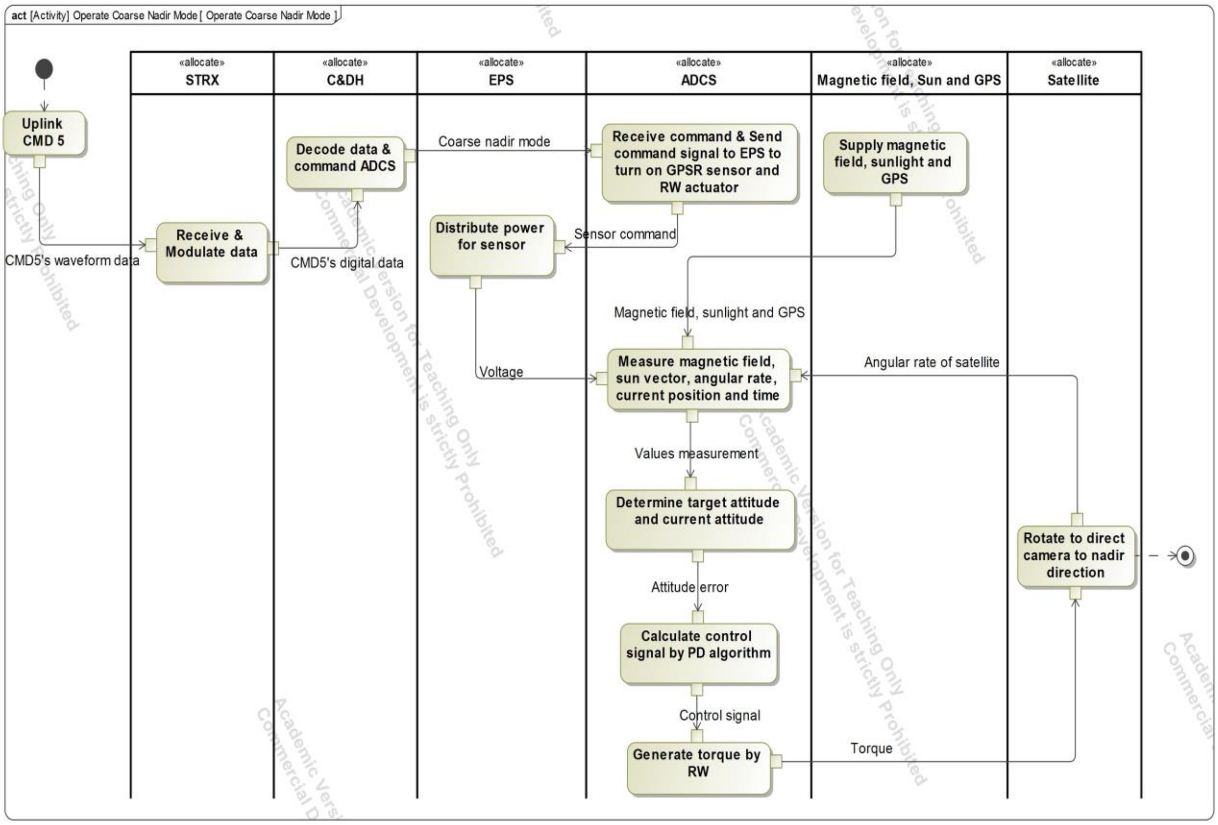

Figure 3.2-13: Activity diagram of operate Coarse nadir mode

In this mode, the GPSR sensor will be used to provide information about current position and time of satellite in the orbit. This information is very typical for a satellite. For example, from the current time will know Julian day which will be also an input for all computational models installed in the satellite such as the Sun model for determination Sun's position, the magnetic field model for definition magnetic vector and the Earth model (Rotation model, Precession and Nutation model) for calculation matrix rotation to transform a value of the earth-centered inertial (ECI) coordinate frames into a value of the earth-centered earth-fixed (ECEF) and inversely. From the current position of a satellite will calculate the nadir direction to get target attitude. When GPSR sensor is failure, the satellite will use the orbital model to replace.

There are two steps in Kalman algorithm. The first step predicts the attitude value from equation kinematic of system and the angular rate of satellite which is measured by FOG sensor. The second step updates the measurement value of attitude. This value is calculated from the data of GPSR, GAS and NSAS sensor. The algorithm of attitude navigation in this mode is called Coarse Kalman.

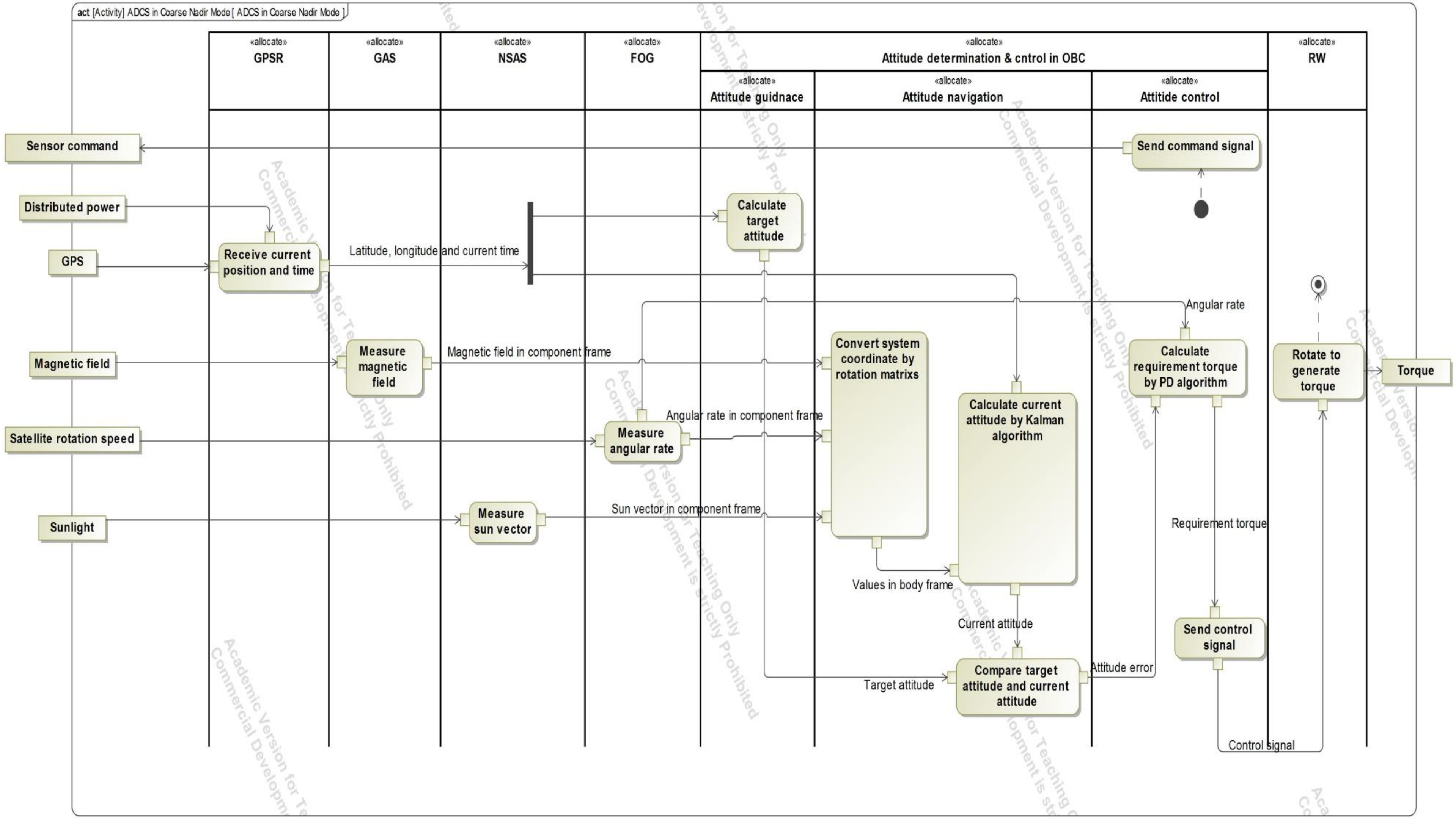

Figure 3.2-14: Activity diagram of ADCS in Coarse nadir mode

The Internal block diagram of ADCS in Coarse nadir mode is described in Figure 3.2-15.

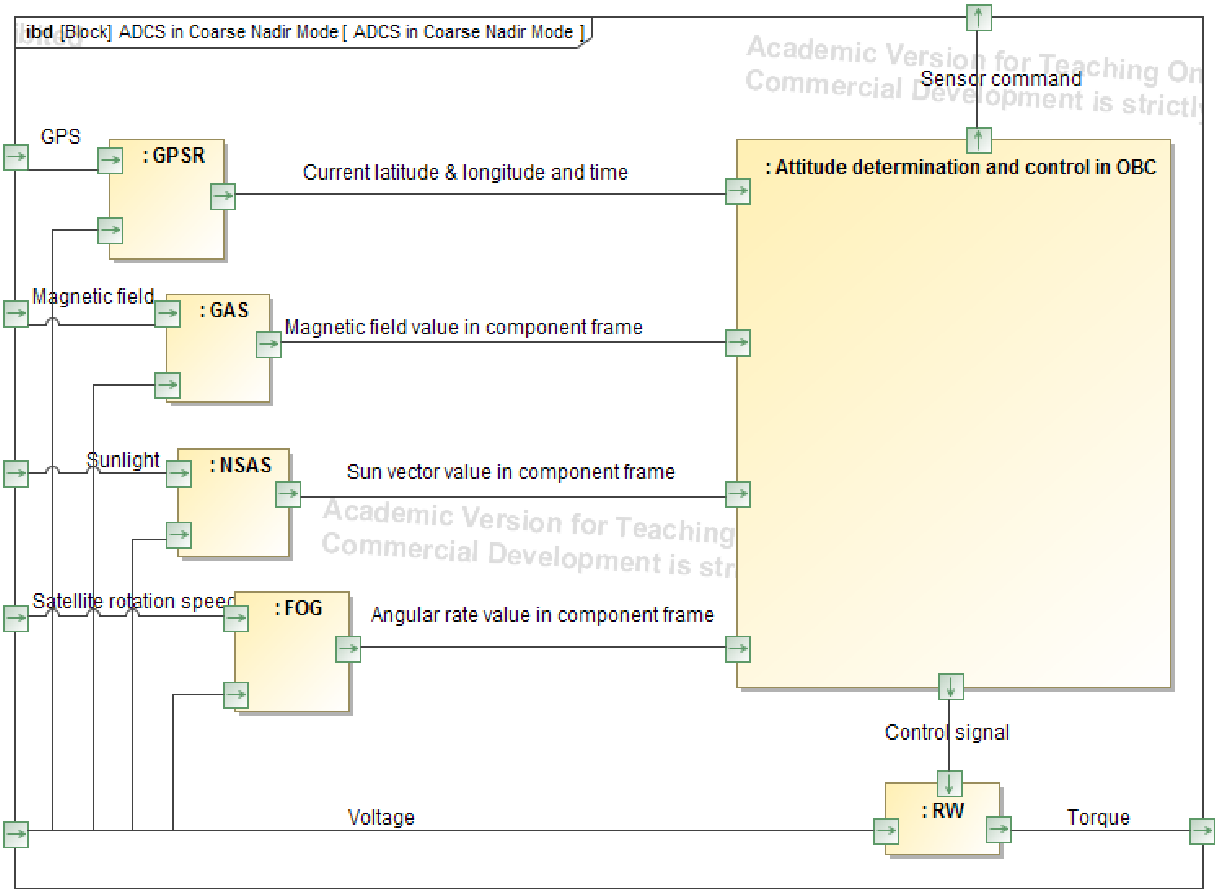

Figure 3.2-15: Internal block diagram of ADCS in Coarse nadir mode

The Block definition diagram of ADCS in Coarse nadir mode is shown as Figure 3.2-16.

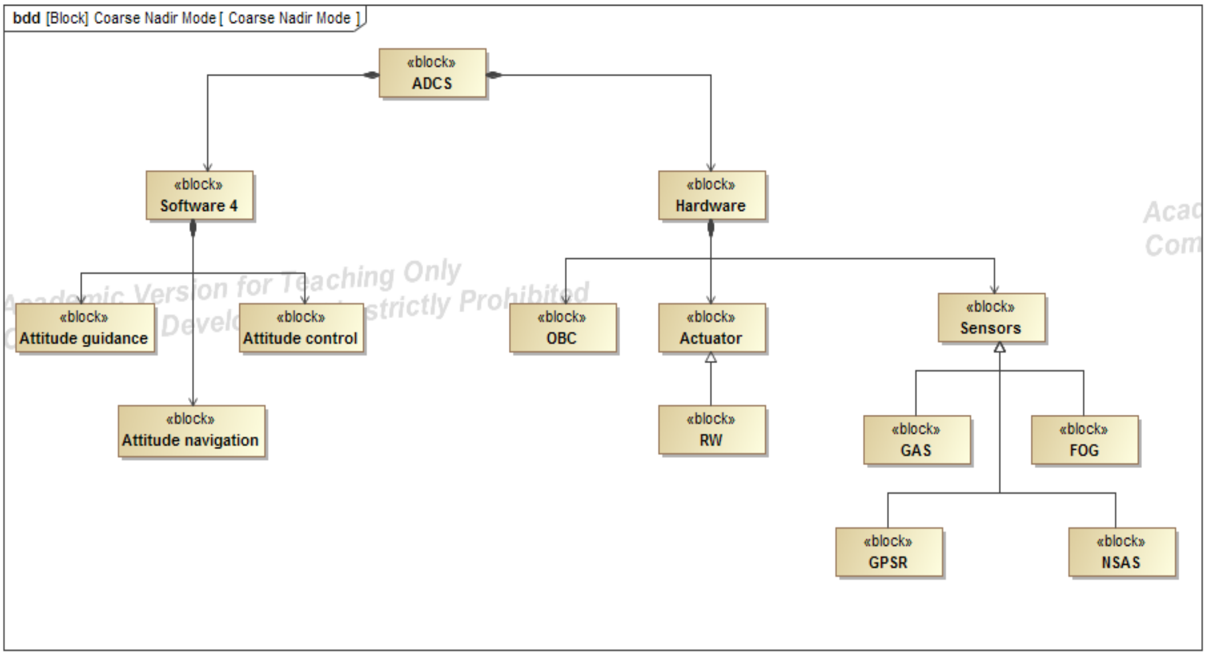

Figure 3.2-16: Block definition diagram of ADCS in Coarse nadir mode

The Activity diagram of ADCS in Target pointing mode is shown as Figure 3.2-17.
The diagram does not represent the activity of EPS in power distribution to the RW because it has already actived from the previous mode as a convention between diagrams. The purpose is to emphasize the sensor command for activation star tracker (STT).

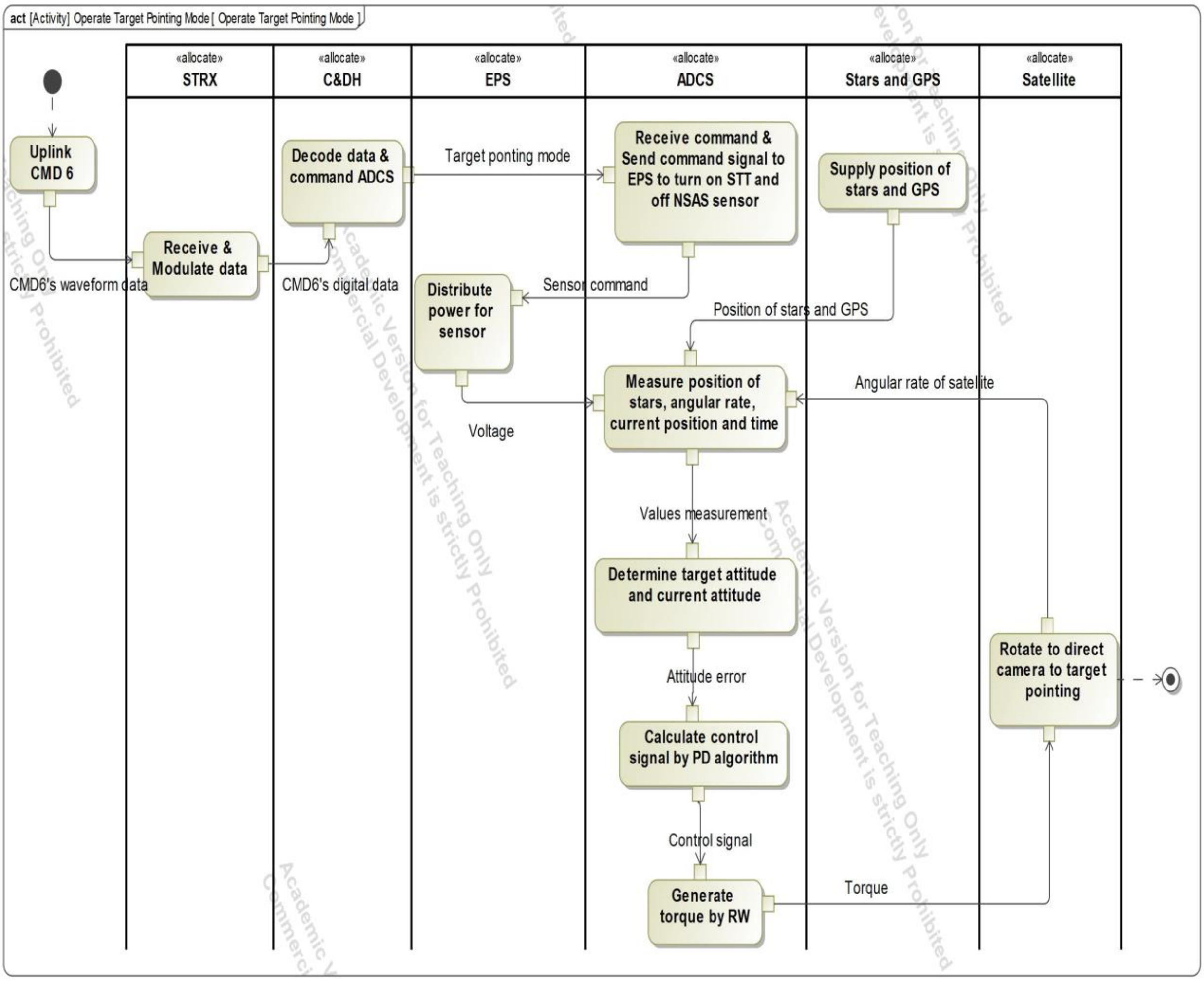

Figure 3.2-17: Activity diagram of operate Target pointing mode

In this mode, the star tracker sensor (STT) is used to determine satellite attitude. It will take picture of position of stars and then compare with a star map to get the information of satellite attitude. The Kalman filter is also applied on attitude estimation but simpler than the Coarse nadir mode. It is shown in Figure 3.2-18.

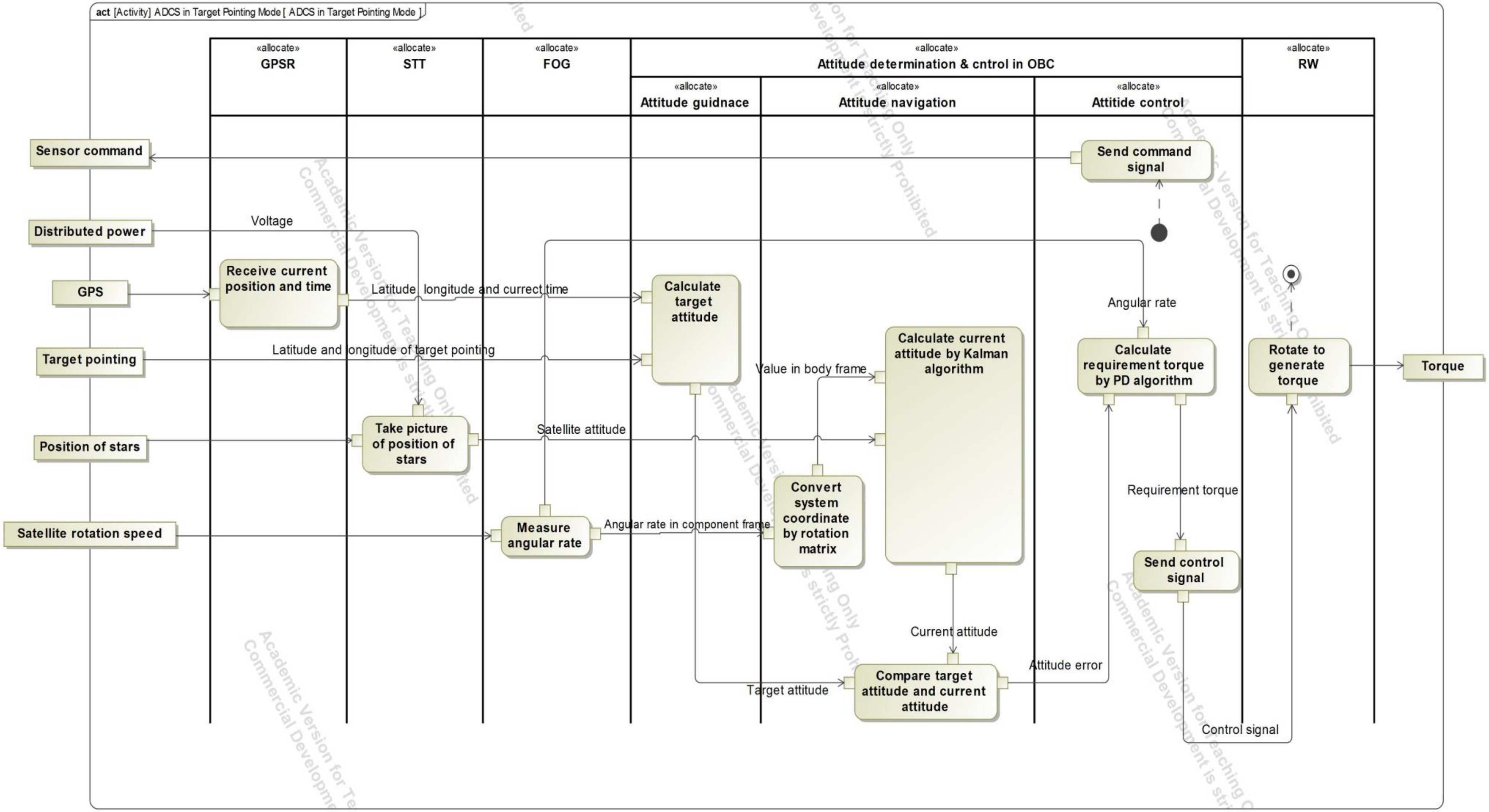

Figure 3.2-18: Activity diagram of ADCS in Target pointing mode

The Internal block diagram of ADCS in Target pointing mode is represented as Figure 3.2-19.

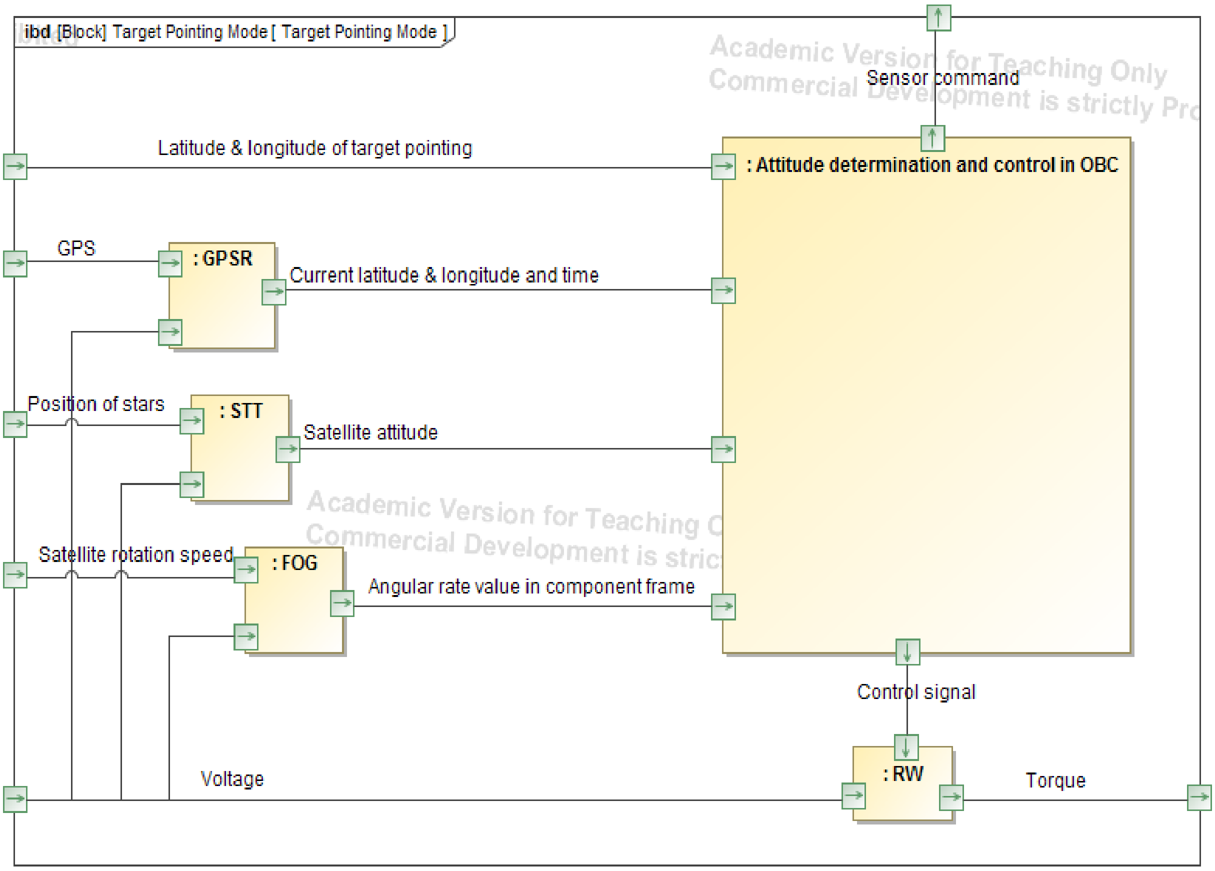

Figure 3.2-19: Internal block diagram of ADCS in Target pointing mode

Figure 3.2-20 is the Block definition diagram of ADCS in Target pointing mode.

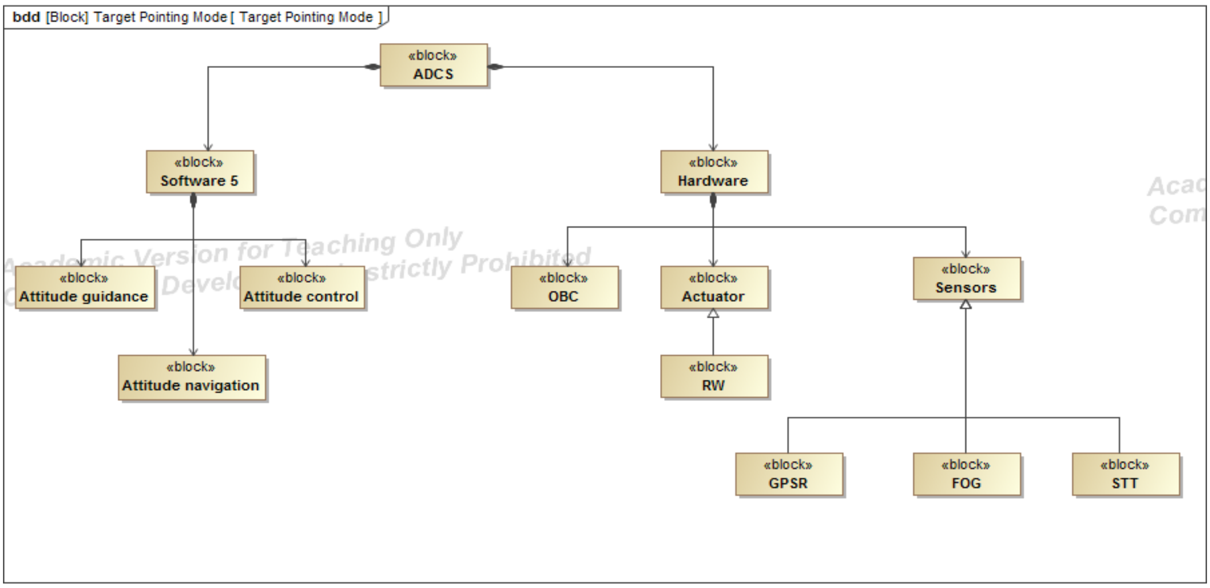

Figure 3.2-20: Block definition diagram of ADCS in Target pointing mode

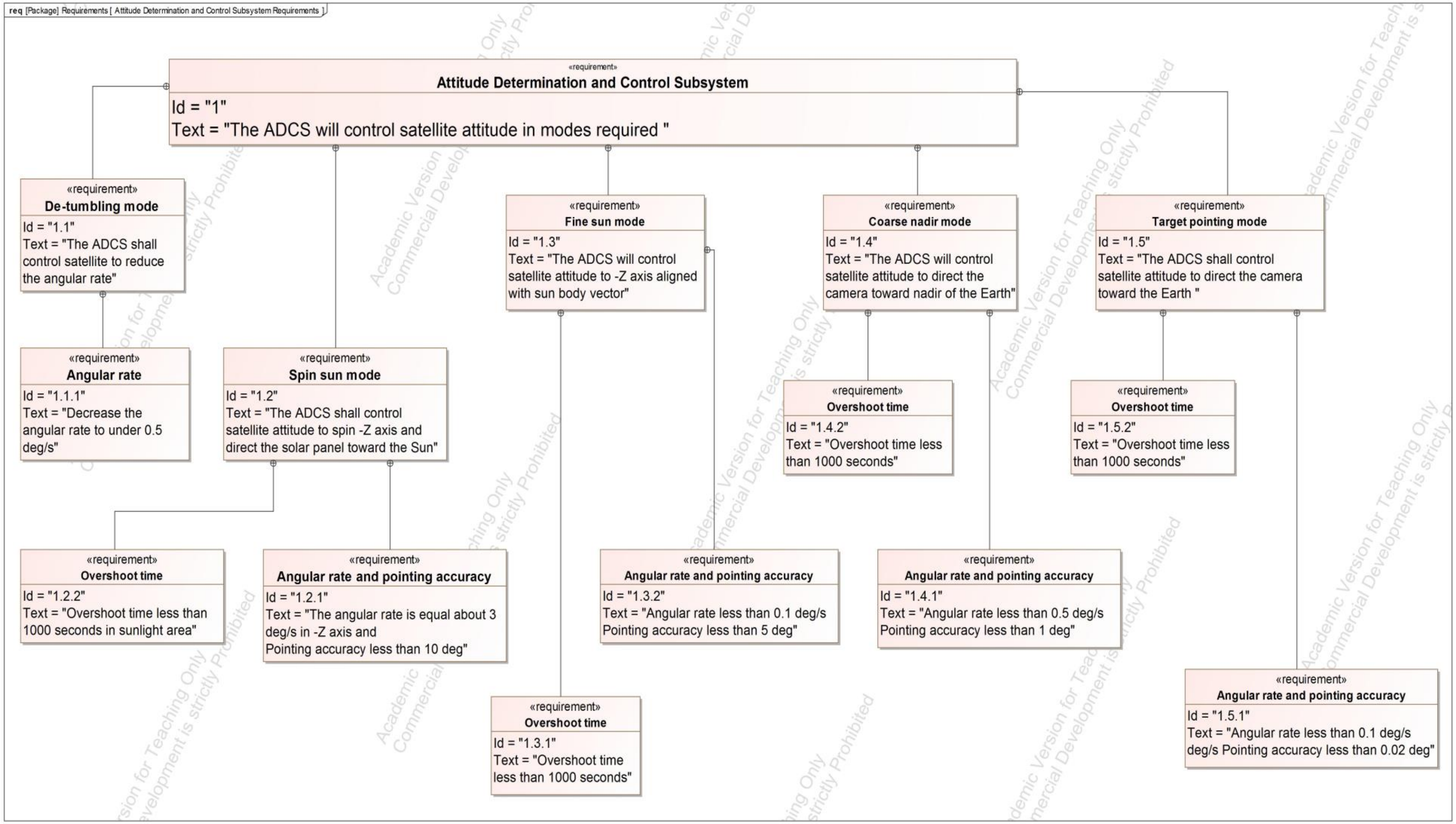

Figure 3.2-21: Requirement diagram of ADCS for MDG satellite

To sum up, the functions, the components and the architecture of ADCS for MDG satellite is depicted in Figure 3.2-22, Figure 3.2-23 and Figure 3.2-24.

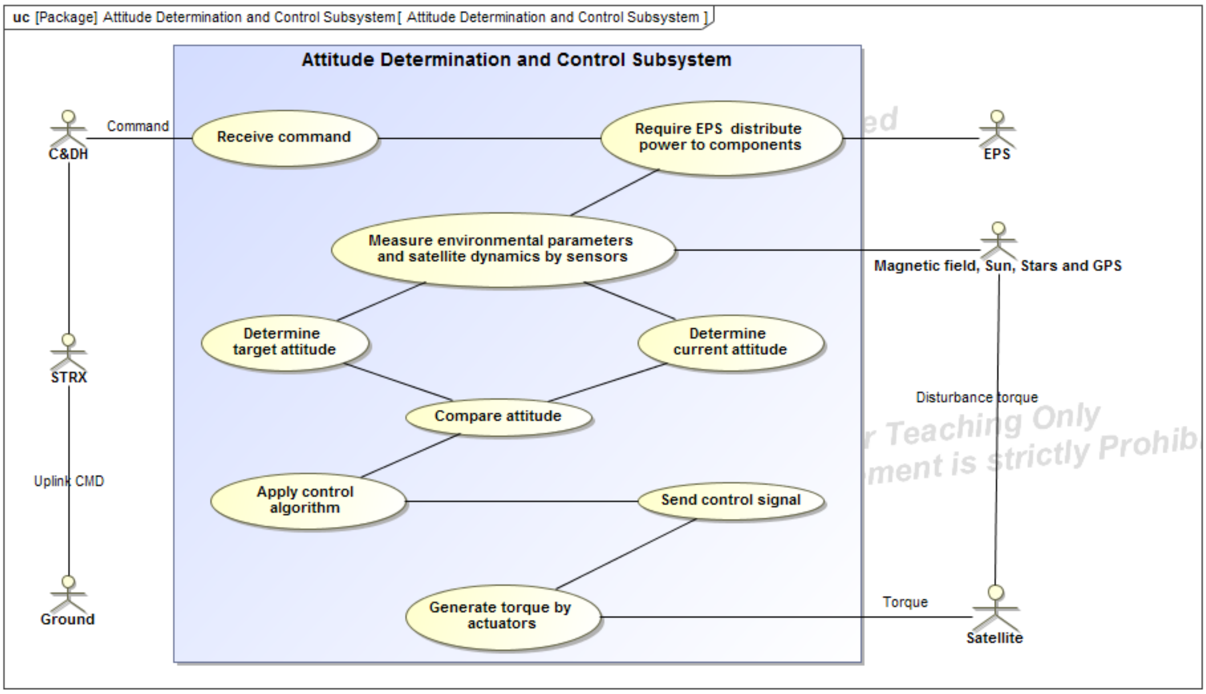

Figure 3.2-22: Use case diagram of ADCS for MDG satellite

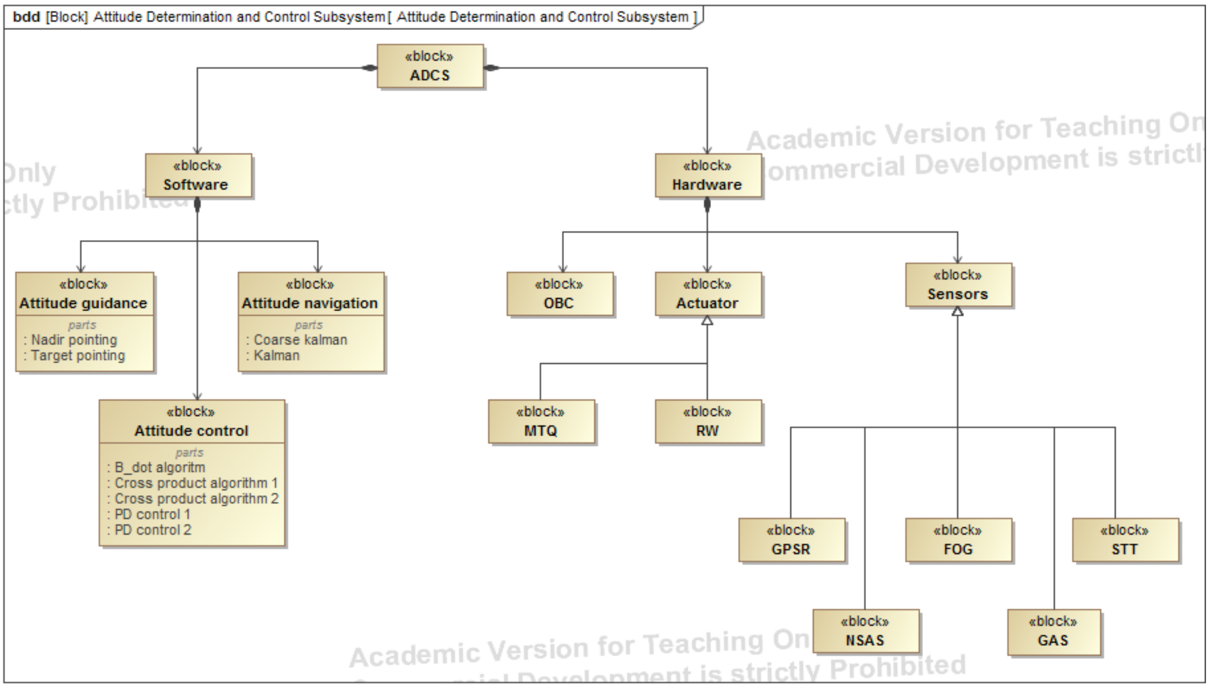

Figure 3.2-23: Block definition diagram of ADCS for MDG satellite

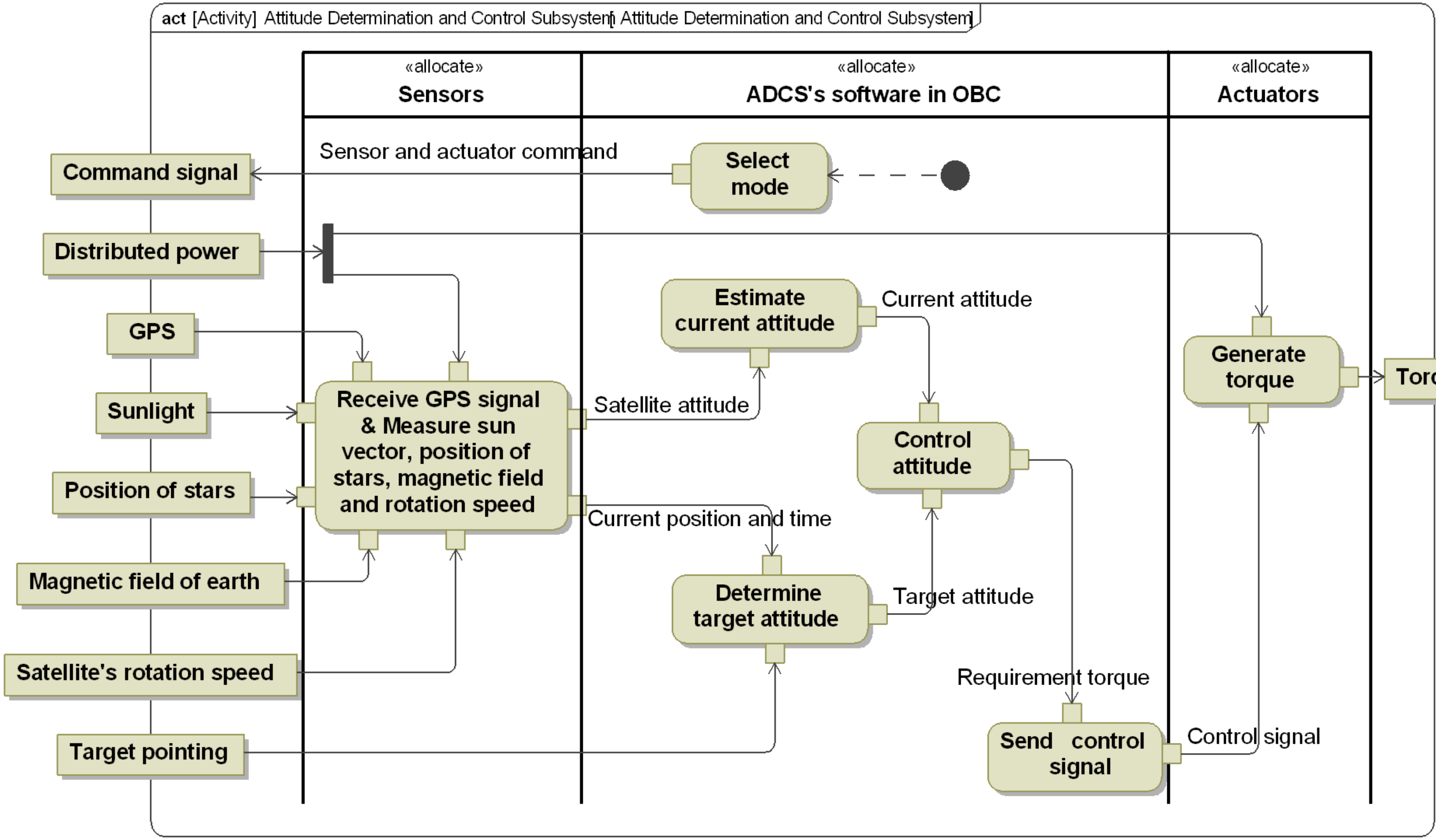

Figure 3.2-24: Activity diagram of ADCS

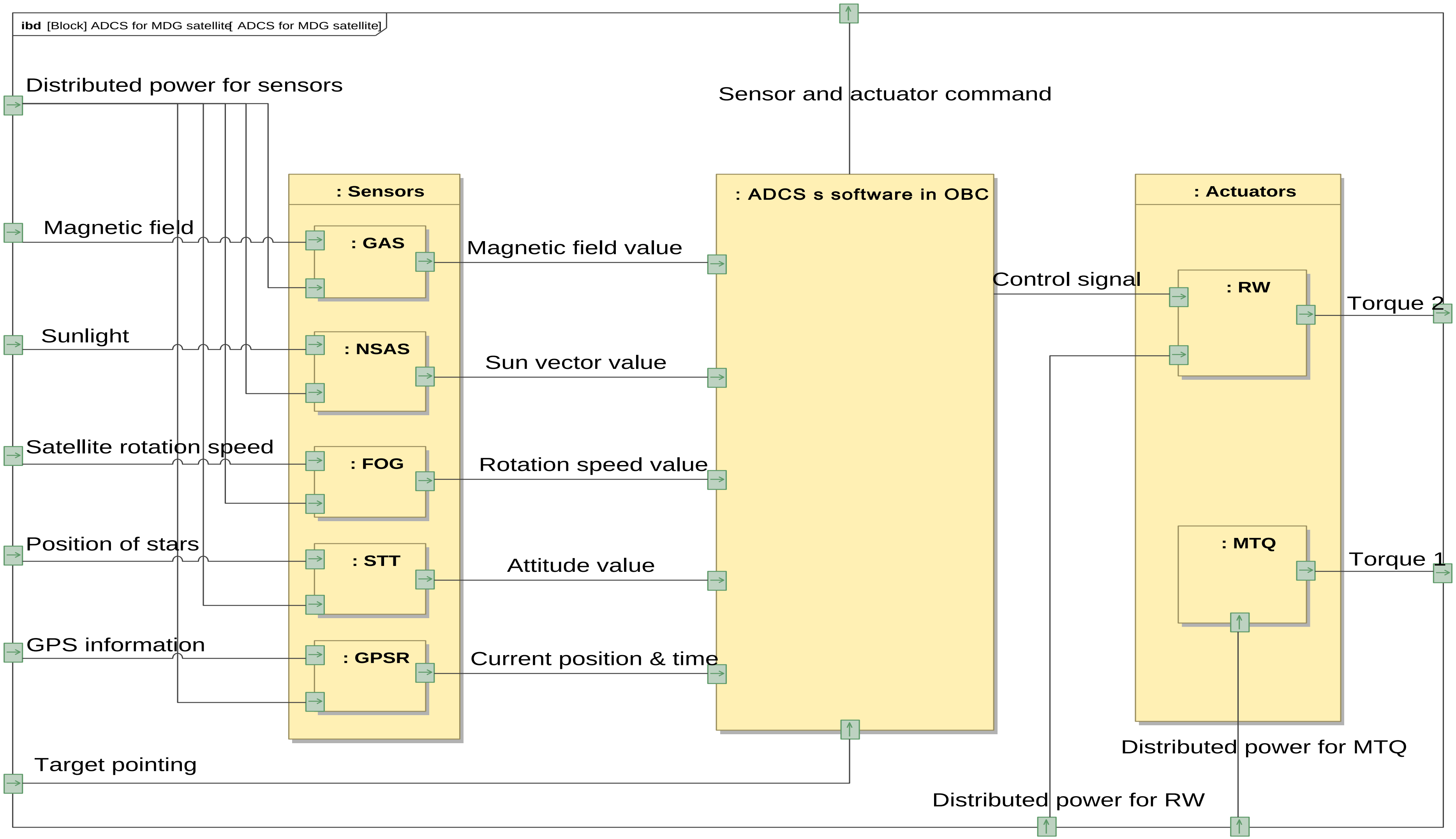

Figure 3.2-25: Internal block diagram of ADCS

Chapter 4 Verification for Architecture of ADCS

In the verification, the system model will be revised by checking consistency of elements such as functional allocation to sensors and actuators, control law and so on. Then, the architecture of ADCS is verified by the synthesized activity diagram and internal block diagram of ADCS for all mode sequences. The final is simulations of ADCS for each mode sequence with the different control law by using the simulation model of Simulink in order to check that the architecture satisfies the requirements delivered.

A simulation model is built on Simulink software to verify for the architecture of attitude determination and control subsystem of MDG satellite. The simulation model is shown as Figure 3.2-24, it includes four main blocks such as the block of satellite environment and dynamics, the block of sensors, the block of controller and the block of actuators.

The sensor and actuator models are represented by the transfer functions which show the relationship between input and output of a device. These models are built from the properties of input and output of components respectively.

The block of controller is the algorithms applied for the modes such as the $\dot{B}_{dot}$ algorithm for De-tumbling mode, the cross product algorithm for Sun pointing mode and the PD algorithm for Earth pointing mode.

The environment models is to describe the space environment such as a geomagnetic model to represent the magnetic field of Earth and a model of Sun. Besides, other models are also considered, for example, a time model to calculate Julian day that talks about the convention time in astronomy, an orbit model to define satellite position, an Earth model to convert a value from a coordinate system fix into a coordinate system rotation and conversely. In addition, the effects to satellite as disturbance torque as well as orbital perturbation such as micro gravity, solar radiation pressure, atmospheric drag and gravitational of Sun and Moon are also added to the simulation model. The simulation results in modes will collate with the requirements of Attitude Determination and Control Subsystem shown in Figure 3.2-21.

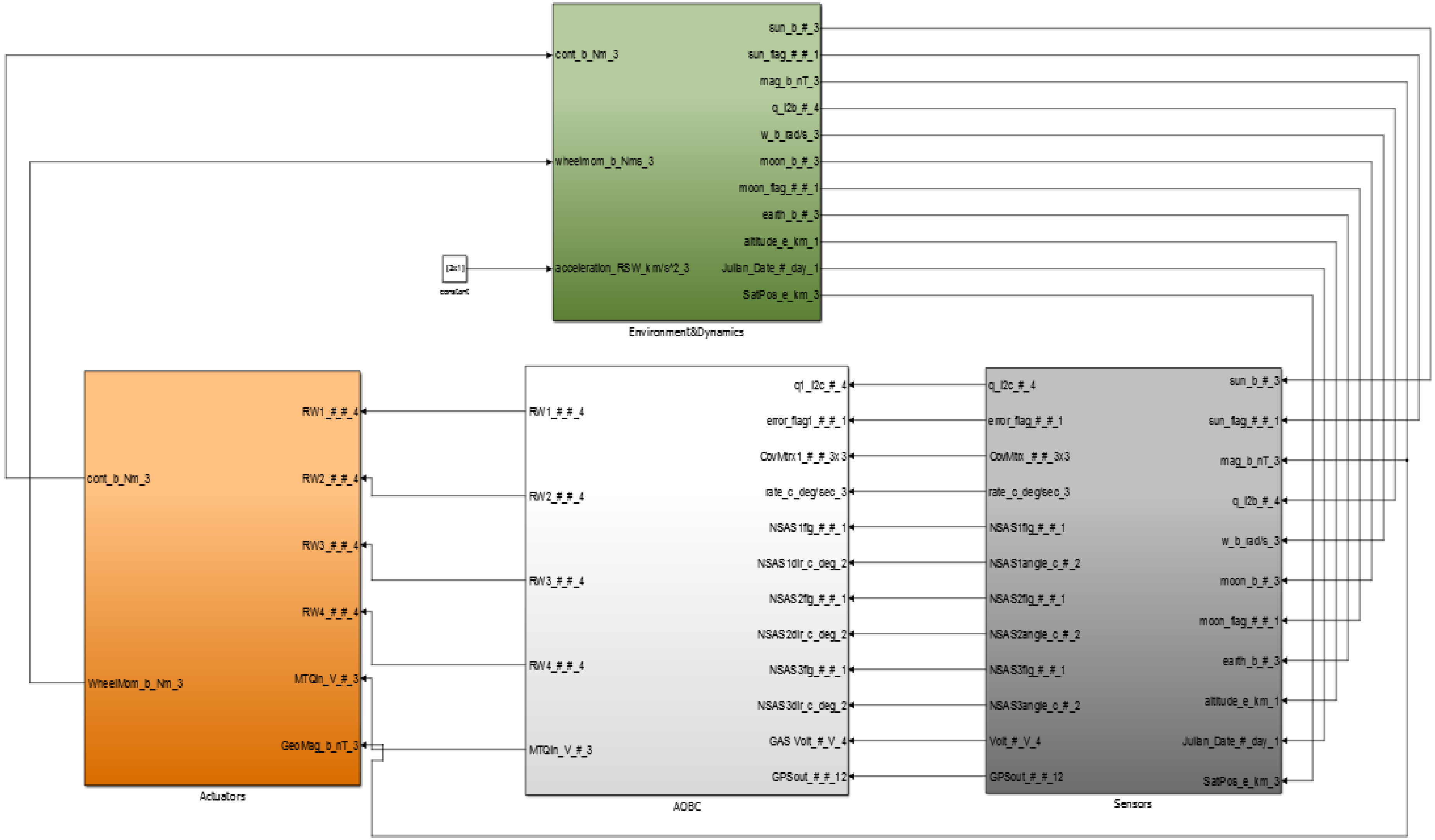

Figure 3.2-26: ADCS model for MDG satellite in Simulink

The satellite dynamic model is built from kinematic and dynamic equations to represent attitude of satellite as well as angular rotational rate.

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix}$$

$$T = I\dot{\omega} + \omega \times (I\omega + h_{rw})$$

Where q is quaternion to represent satellite attitude

ω is angular rotational rate,

I is moment of inertia of satellite,

T is external torque,

h_{rw} is angular momentum of reaction wheel.

The simulations are conducted for the orbit with the following orbital elements:

Eccentricity $e = 0.001$

Semi major axis $a = 7031\ km$

Inclination $i = 97.89\ deg$

Longitude of the ascending node $\Omega = 263.44\ deg$

Argument of periapsis $\omega = 271.6\ deg$

Mean anomaly at epoch $M_0 = 88.44\ deg$

Micro Dragon's moment of inertia is approximated from the CAD model.

$$I = \begin{bmatrix} 1.4423 & 0.0174 & 0.0163 \\ 0.0174 & 1.2540 & 0.0474 \\ 0.0163 & 0.0474 & 1.4668 \end{bmatrix} (kgm^2)$$

4.1 Simulation for De-tumbling Mode

Using only GAS sensor and MTQ actuator, the controller de-spins the satellite relative to the geomagnetic field vector. The only input for this algorithm is the geomagnetic vector written in the body coordinate system frame B_b.

The control algorithm is as

$$M = -k_b \frac{\dot{B}_b}{\|B_b\|}$$

In MDG's case, the amplitude of electric current running through the magnetorquers'coil is constant and only the direction of the electric current is controlled. Therefore, the chosen control law as well as the moment magnetic requirement is

$$M = -M_{max} sign(\dot{B}_b)$$

Where M_{max} is the maximum magnetic moment (= 5.0 Am^2).

In order to verify the de-tumbling control algorithm, a simulation is carried out with the satellite having the initial angular velocity of [5 5 5]deg/s.

The result shows that the satellite can be de-tumbled to an angular rate of less than 0.5deg/s after about 1500 seconds. Thus, the ADCS meet the requirement.

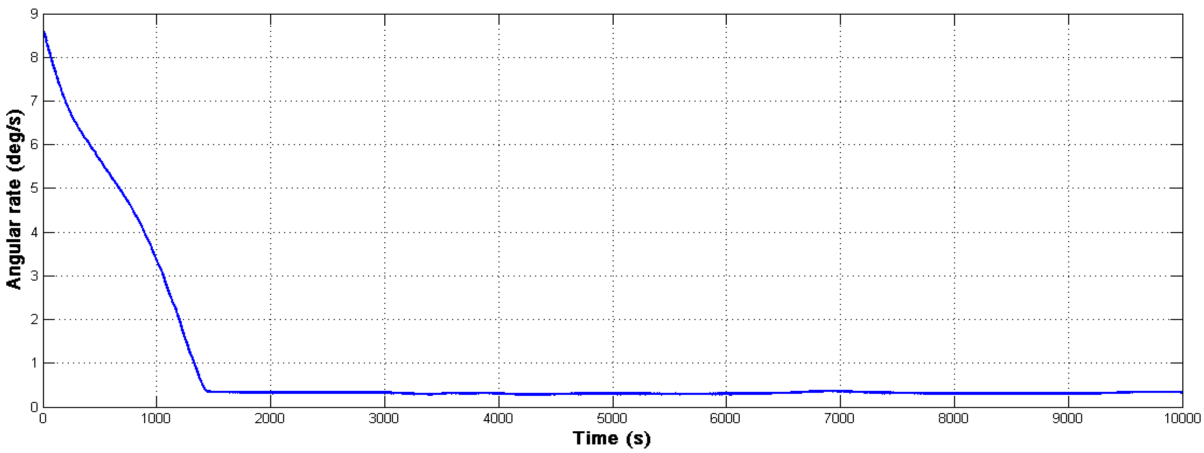

Figure 4.1-1: Angular rate of satellite in De-tumbling mode

4.2 Simulation for Spin Sun Mode

The control algorithm is written as

$$T = K_1(-Z \times S_b) - K_2(\dot{S}_b \times S_b) + K_3(\omega_{ref} - \frac{\dot{B}_b(B_b \times S_b)}{|B_b \times S_b|})S_b$$

Where T is the requirement torque, K_1, K_2 , K_3 are proportional gains, -Z is the negative Z axis (equal to [0 0 -1]), B_b and S_b are the geomagnetic vector and sun vector written in the body coordinate frame, and ω_{ref} is the desired spinning speed.

The first part of the control law $K_1(-Z \times S_b)$ aims to reduce the angle between the sun vector S_b and the –Z axis, orienting the surface with the solar panels toward the Sun. The second part's role is to reduce the angular rate perpendicular to the sun vector, resulting as the satellite can only spin around the axis aligned with the sun vector S_b. The third part is to make this spinning rate to become close to the desired value.

The magnetic moment requirement can be calculated as

$$M = M_{max} sign(B_b \times T)$$

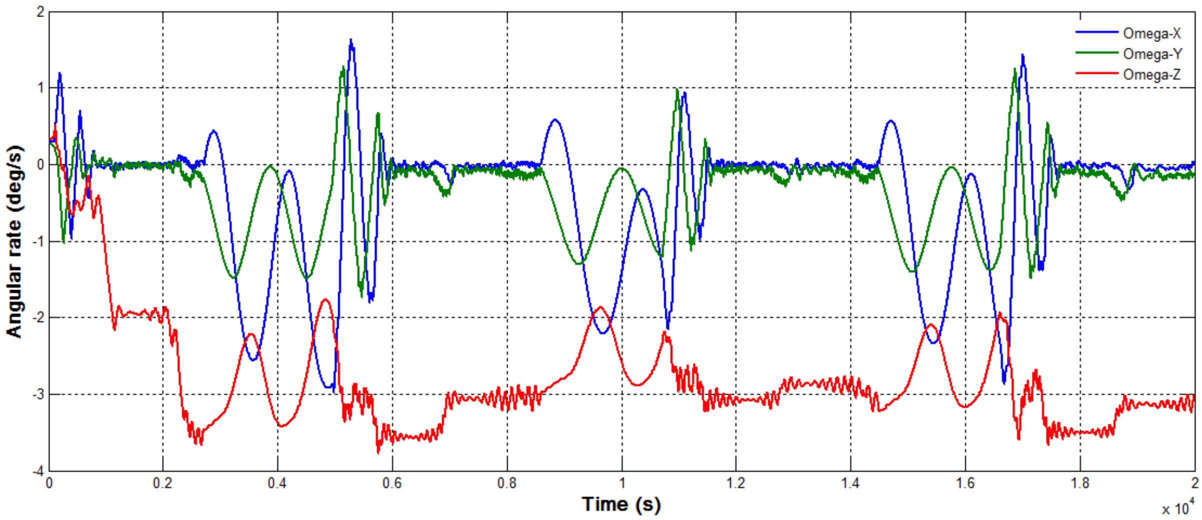

Figure 4.2-1: Angular rate of satellite in Spin sun mode

The desired angular rate $\omega = [0; 0; 3] deg/s$ set up in the simulation. With the result in Figure 4.2-2 shows that the omega of X axis and Y axis has been asymptotically to zero, the omega of -Z axis has also been asymptotically to zero.

The sun flag is shown in Figure 4.2-2 with the sunlight area for value 1 and the eclipse area for value 0. The simulation result in Figure 4.2-3 also shows that the sun angle is less than 10 degree in the sunlight area. To sum up, the simulation results prove that the ADCS can control the satellite toward the Sun and satisfy the requirement.

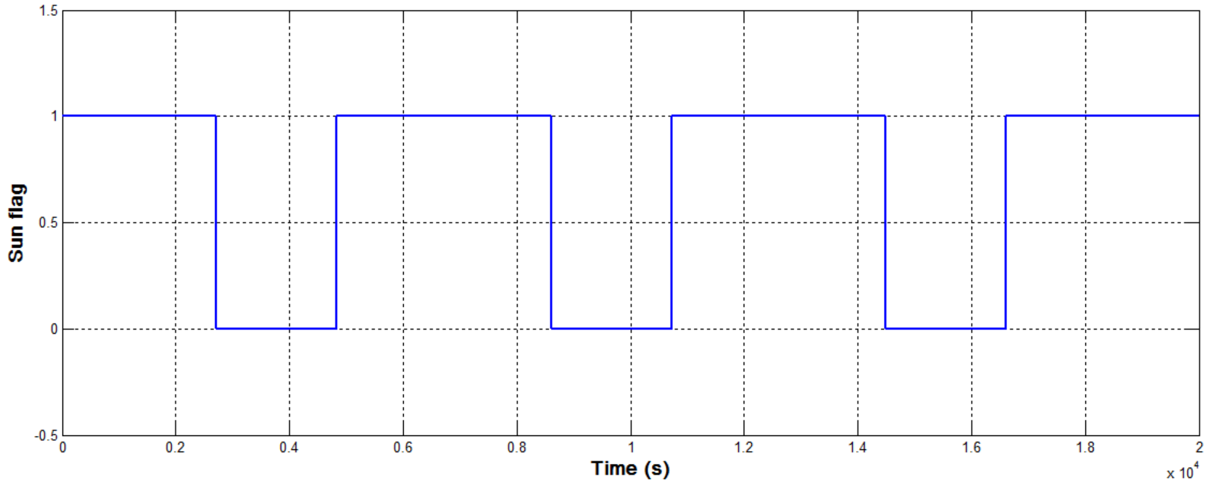

Figure 4.2-2: Sun flag in Spin sun mode

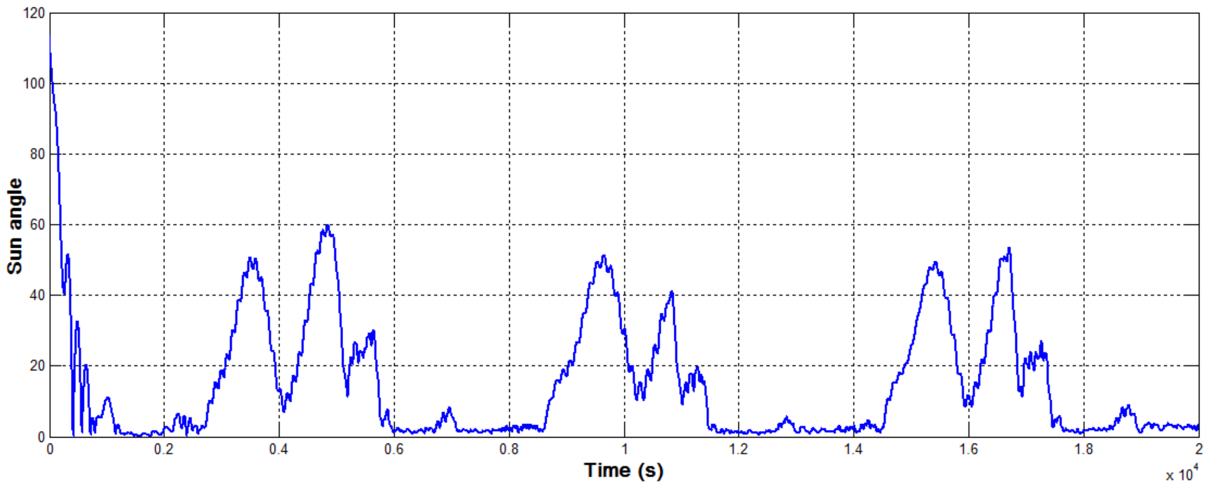

Figure 4.2-3: Sun angle in Spin sun mode

4.3 Simulation for Fine Sun Mode

The control algorithm is proposed as

$$T = K_1(-Z \times S_b) - K_2\omega_e$$

Where K_1 and K_2 are control gains, ω_e is the angular velocity error. We can see that the first part of this control law is the same as the first part of the control law of Spin sun mode. The second part aims to reduce the difference between the satellite's angular velocity and the reference with [0 0 0]deg/s then $\omega_e = -\omega_b$ is the angular rate of satellite in body frame measured by FOG sensor.

The simulation result in Figure 4.3-1 shows that the angular rate increases in sunlight area but it is very small, under 0.1deg/s, and satisfies the requirement in this mode.

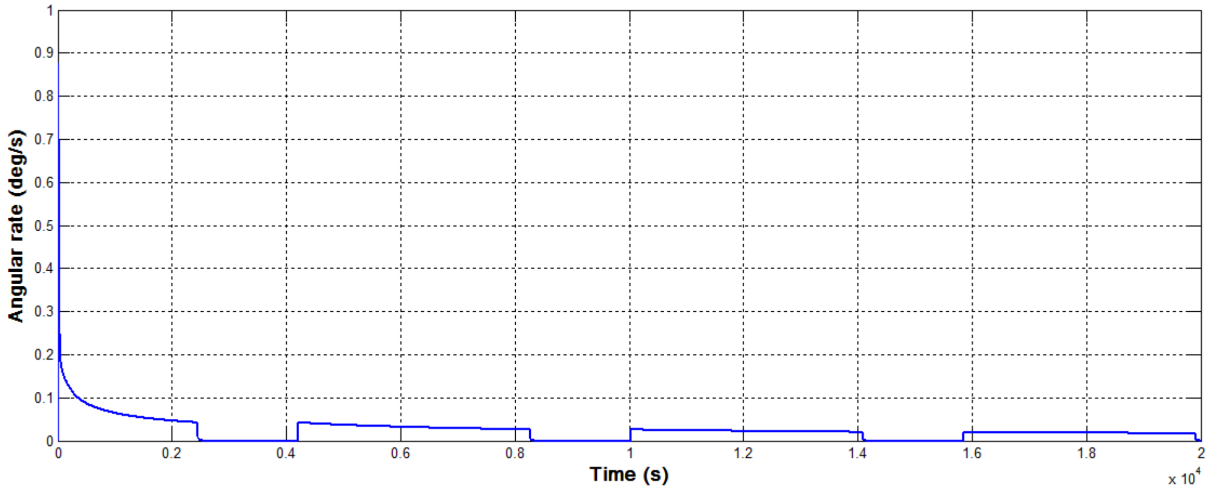

Figure 4.3-1: Angular rate in Fine sun mode

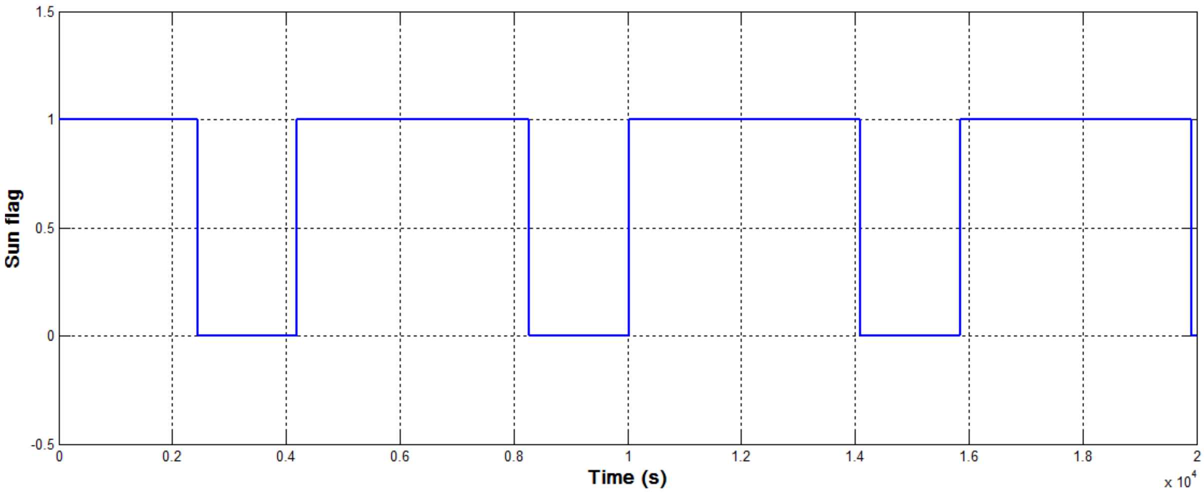

Figure 4.3-2: Sun flag in Fine sun mode

The sun angle in Figure 4.3-3 goes down quickly and keeps under 5deg in during time of simulation.

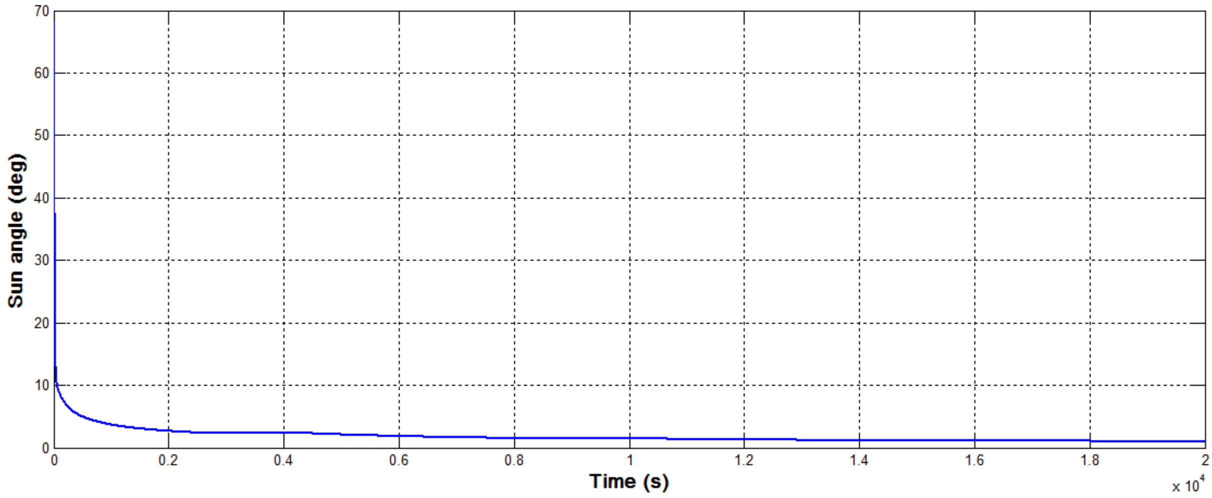

Figure 4.3-3: Sun angle in Fine sun mode

4.4 Simulation for Coarse Nadir Mode

The control algorithm is proposed as

$$T = K_p q_e + K_d \omega_e$$

Where K_p and K_d are control gains, q_e is quaternion error, ω_e is the angular velocity error.

The K_p part aims to reduce attitude error, to achieve the desired attitude and the K_d part is to keep stable attitude.

The initial attitude is $q_{ini} = [0\ 0\ 0\ 1]$, the initial angular rate is $\omega_{initial} = [1\ 1\ 1] deg/s$. From two under figures, they show that the angular rate and Euler angle error decreased to about 0deg/s, that of meaning, the satellite achieved the target attitude through assessment of Euler angle error and kept that attitude as well as its stabilization through assessment of angular rate error. In this mode, the pointing accuracy doesn't need a high requirement because the satellite will not perform the mission.

From results in under Figures, they illustrates that the satellite can point toward nadir direction under the requirement.

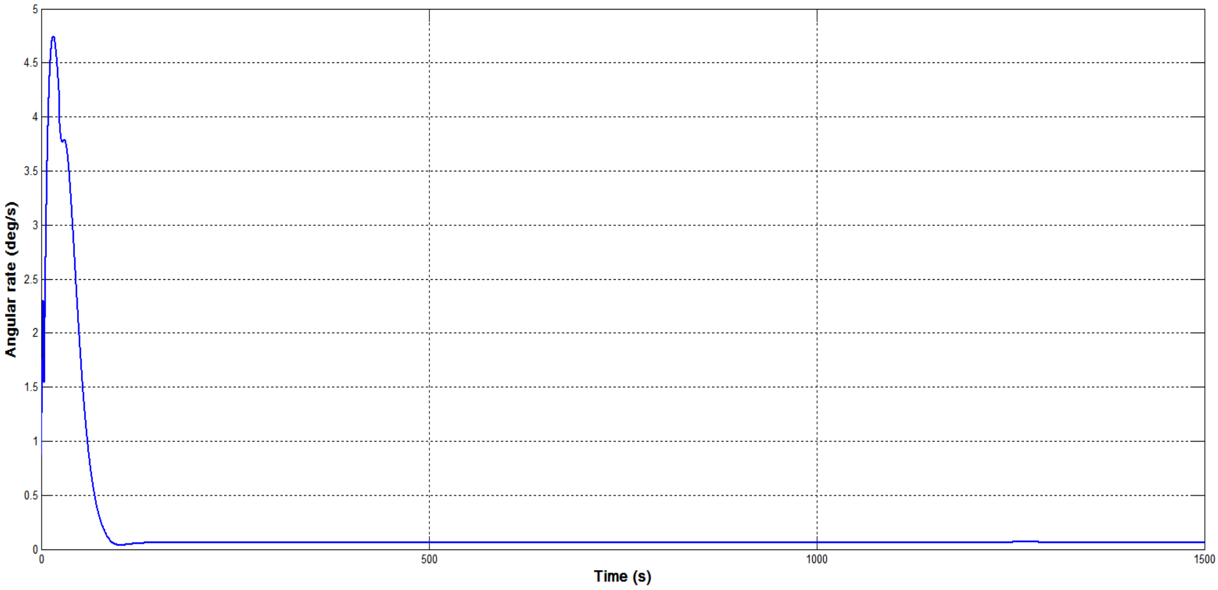

Figure 4.4-1: Angular rate in Coarse nadir mode

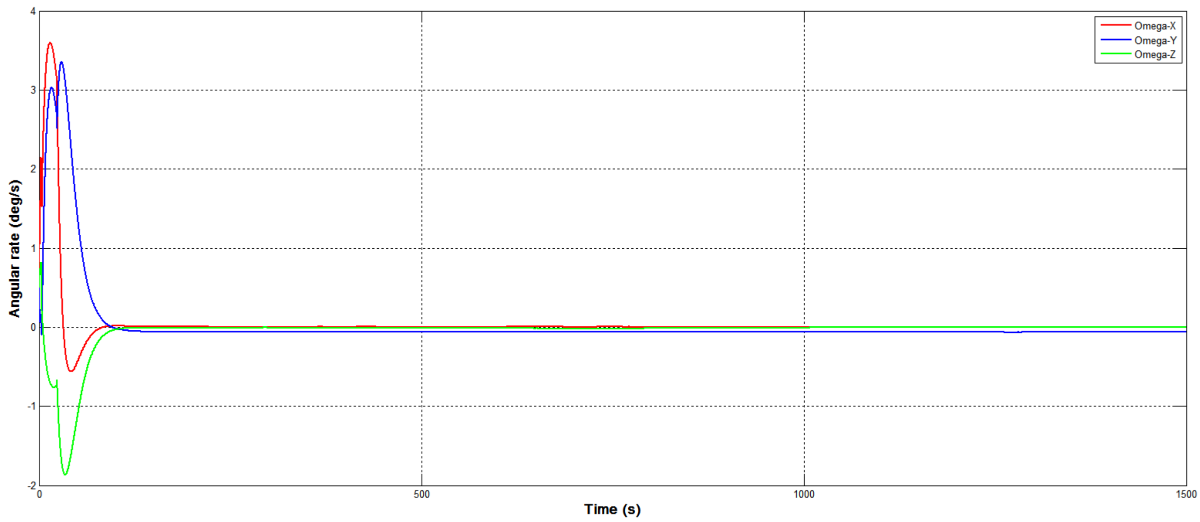

Figure 4.4-2: Angular rate of each axis in Coarse nadir mode

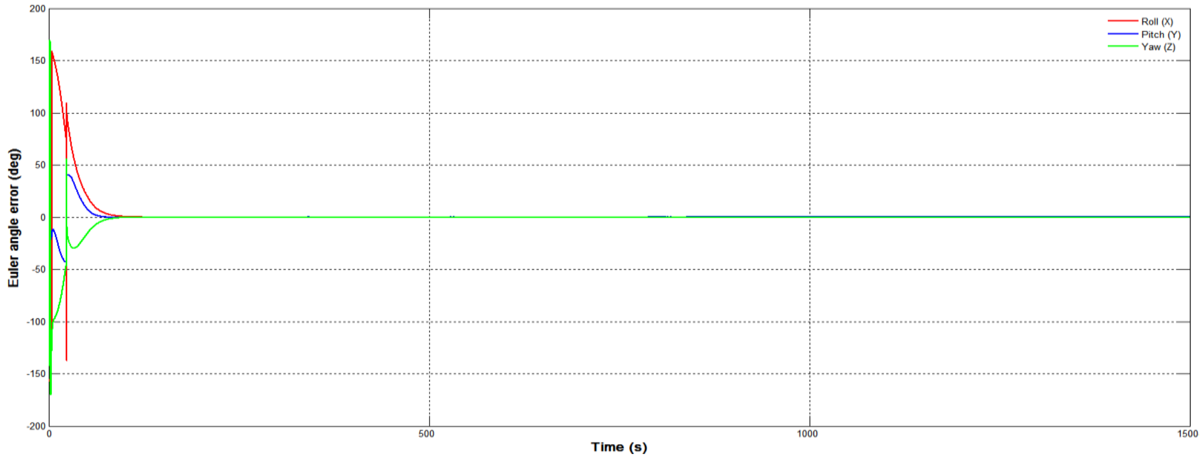

Figure 4.4-3: Euler angle error in Coarse nadir mode

4.5 Simulation for Target Pointing Mode

The control algorithm used is the same as the control algorithm in Coarse nadir mode. The initial attitude is $q_{ini} = [0\ 0\ 0\ 1]$, the initial angular rate is $\omega_{initial} = [0\ 0\ 0] deg/s$, w = [0 0 0]*deg/s* and the target pointing is assumed by the latitude and longitude of the position [12.5 107.5] degree on the Earth.

As said that, in this mode, the accuracy and stability should be the most highest, the STT sensor is used for attitude determination. From the simulation results, we can see that the angular rate error and the Euler angle error are very small. That means the stability are better than that of previous mode and meets the requirement.

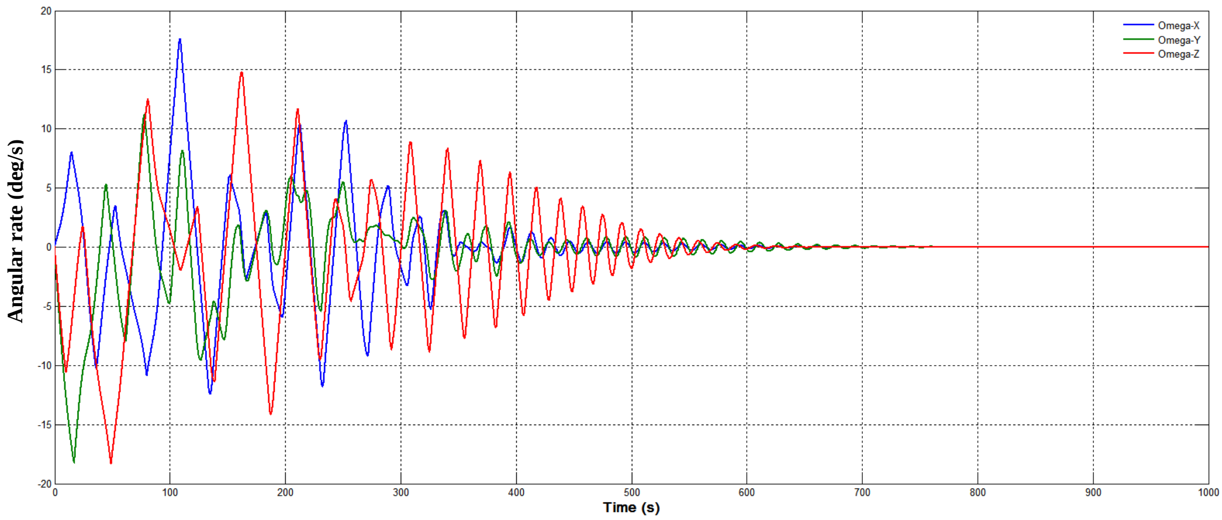

Figure 4.5-1: Angular rate of each axis in Target pointing mode

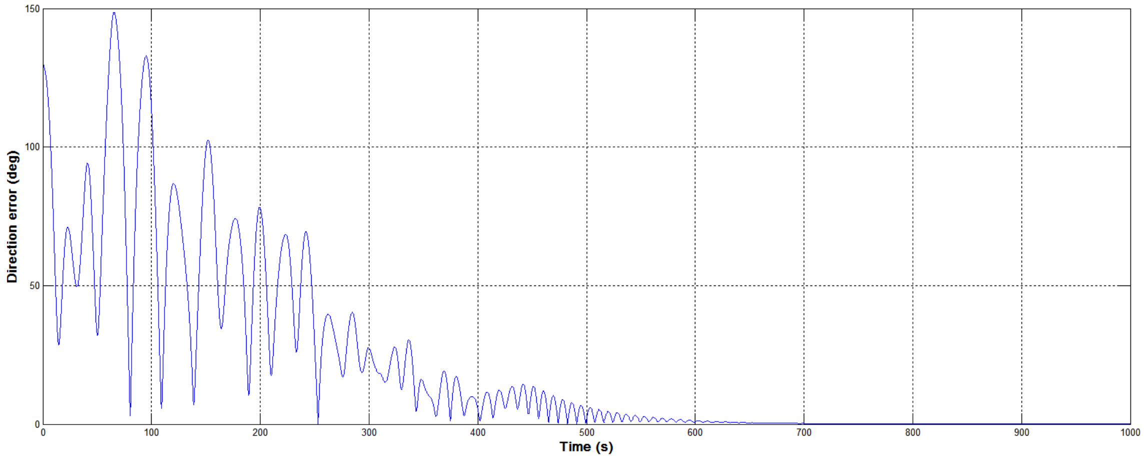

Figure 4.5-2: Pointing accuracy (Direction error) in Target pointing mode

The pointing accuracy is shown as Figure 4.5-3. That means it satisfies the requirement.

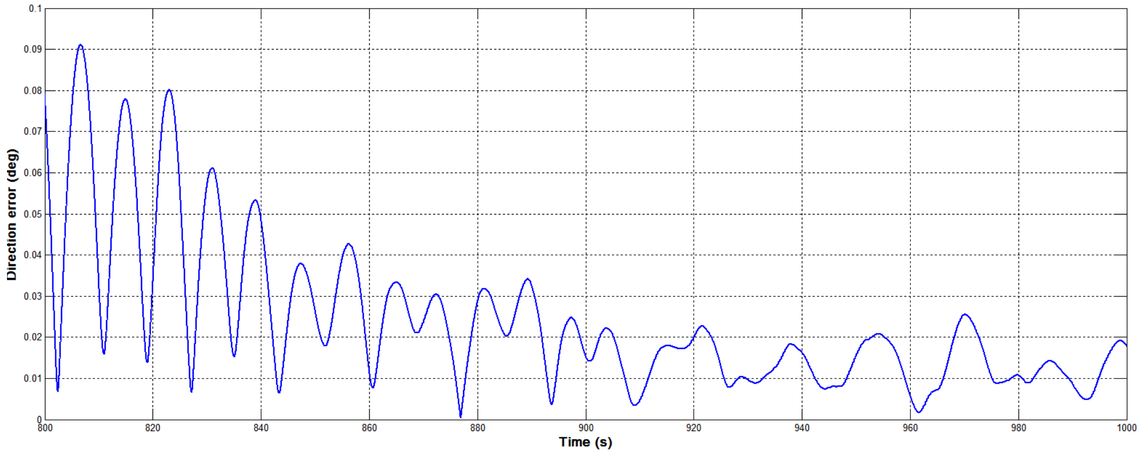

Figure 4.5-3: Pointing accuracy (zoomed in) in Target pointing mode

In conclusion, by using the simulations on Simulink software and the control algorithm applied, they illustrated that the architecture of the ADCS can satisfy the requirements of this subsystem. For instance, the ADCS reduced the angular rate of satellite in De-tumbling mode, controlled the solar panels of satellite toward the Sun in Sun pointing mode and directed the camera toward nadir direction and target pointing in Earth pointing mode.

Chapter 5 Conclusion and Future Works

5.1 Overall Summary

Beginning the requirements of attitude determination and control subsystem (ADCS) of Micro Dragon (MDG) satellite consist of the de-tumbling of satellite after separation from the rocket, the attitude control of satellite to the solar panel towards the Sun to secure power generation and to control the satellite towards the Earth to do the missions delivered such as take a picture of a place, communication with the Ground. In order to understand logically the whole operation of satellite, a scenario of mode sequence is designed to describe modes detail as well as behavior of ADCS in each mode in which some modes in the first phase of satellite are also described to see relationship between modes.

To describe the architecture of ADCS in the mode sequences is very complicated because in each mode the control algorithm is different. For example, in the De-tumbling mode, the $\dot{B}_{dot}$ (the derivation of magnetic field value) law is chosen to de-spin for the satellite. In the Sun pointing mode uses the cross product algorithm $(-Z \times S_b)$ to –Z axis which is perpendicular to the solar panel aligned with sun body vector. And finally, in the Earth pointing mode applies the PD algorithm to control satellite attitude so that the camera and antenna can point to a certain place on the Earth for take picture and the communication with the Ground station respectively.

By using SysML as a professional tool to decompose a system, the architecture of ADCS in modes are defined clearly in logically and consistency. In there, the ADCS's requirements are represented by the requirement diagram to support requirements traceability, the functions are described by the Use case diagram and Sequence diagram, and the allocation of functions to components are illustrated by the Activity diagram and Internal block diagram.

Finally, a simulation model which is built on Simulink software derives from the system model to verify for the architecture of ADCS. The simulation results satisfied the requirements of the ADCS. It also sees the effective of using SysML

5.2 Future Works

In the future works, the ADCS algorithm will be performed on real hardware by implementation in form of C language on onboard computer (OBC), this hardware will connect with a virtual environment on a PC. Then, the OBC shall connect with other PC which contains the software of commands and telemetries to verify mode transition like the mode sequences scenario.

Another, the fault detection isolation recovery (FDIR) needs to develop to support for the ADCS when having sensors or actuators occur fault. The decomposition of the system models will be also continued by using the SysML.

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