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Analysis and Simulation of Attitude Determination and Control Subsystem of a 3U CubeSat: AlainSat-1

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Abstract

This paper presents the analysis and simulation of the Attitude Determination and Control Subsystem (ADCS) of AlainSat-1, to validate the satellite performance during different operational modes. AlainSat-1 is a collaborative project between the IEEE Geoscience and Remote Sensing Society (GRSS) and the National Space Science and Technology Center (NSSTC) at United Arab Emirates University (UAEU). Its mission is to measure soil moisture, ice thickness, vegetation, and monitor cloud coverage. The aim of this work is to conceptually design the ADCS that satisfies the mission requirement and specifications of AlainSat-1. This can be obtained through a sequence of operational modes which required different determination and control algorithms depending on the available power budget and the required pointing accuracy of each mode. The ADCS hardware module from CubeSpace© is utilized for implementing the algorithms. The CubeSat enters the Detumbling mode after being deployed in-orbit and the objective is to decrease the spin rate from 5 deg/s to 1 deg/s by using B-Dot and Y-Thomson control algorithm. Next, the functionality of the ADCS modules is tested in the commission modes. In addition, the sun-pointing mode is designed to recharge the batteries using solar panels in case of low power generation. The Nadir-pointing is the main operational mode that provides a minimum pointing accuracy of less than 1 deg. It uses the Extended Kalman Filter and the Three-wheel algorithm to determine and control the attitude respectively. Determining and controlling the attitude in Nadir-pointing mode rely on Coarse sun, Fine sun, nadir, and rate sensors; magnetometers; and star trackers. Finally, ground contact mode is designed for the communication between the satellite and the ground station in which the satellite sends the collected data and measurement to the ground station. The aforementioned operational modes are validated via numerical simulation using EOS© that is provided with the CubeSpace© module. The numerical result is presented, and the Key Performance Indicators are measured to prove that the result satisfies the satellite mission requirements.

Keywords: Attitude determination, Attitude control, CubeSat, ADCS operational modes.

Nomenclature

The nomenclature for symbols used in this paper are as follows:

$\mathbf{q}$	The unit quaternion of the CubeSat that represents its orientation with respect to the inertial frame.
$\boldsymbol{\omega}_B^I$	The relative angular velocity of the CubeSat with respect to the inertial frame.
$\mathbf{I}$	The moment of inertia matrix of the CubeSat.
$\mathbf{N}_{GG}$	The gravity gradient disturbance torque.
$\mathbf{h}_w$	The reaction wheel angular momentum vector.

Acronyms/Abbreviations

All used acronyms and abbreviations in this paper are as follows:

ADCS	Attitude Determination and Control Subsystem
AURAK	American University of Ras Al-Khaimah
AUS	American University of Sharjah
COTS	commercial off-the-shelf
CuSP	CubeSat for Solar Particles
ECI	Earth-Centered Inertial
ELaNa	Educational Launch of Nanosatellites
GRSS	Geoscience and Remote Sensing Society
KUST	Khalifa University of Science and Technology
LEO	Low Earth Orbit
LQR	Linear Quadratic Regulator

MEO	Medium Earth orbit
MPC	Model Predictive Control
NSSA	National Space Science Agency
NSSTC	National Space Science and Technology Center
PID	Proportional-Integral-Derivative.
SWIR	Shortwave Infrared
UAE-SA	United Arab Emirates Space Agency
UAEU	United Arab Emirates University

1. Introduction

CubeSats are small satellites that have become increasingly popular in recent years for various applications such as remote sensing, communication, and scientific research. They are typically cube-shaped and measure $10 \times 10 \times 10$ cm for a unit and are often constructed using commercial off-the-shelf (COTS) components. They typically weigh less than 1.33 kg [1]. They can be quickly developed and deployed, making them suitable for short-term missions or for testing new technologies. Due to their small size, CubeSats are typically launched as secondary payloads on larger rockets and can be deployed in low Earth orbit (LEO), medium Earth orbit (MEO), or even beyond [2]. They can be used for various applications such as earth observation, atmospheric research, technology demonstrations, and even interplanetary missions [3]. However, the small size and limited resources of CubeSats also pose challenges for their design and operation. These challenges include limited power, communications, and propulsion capabilities, as well as the need for miniaturized and low-cost subsystems such as the Attitude Determination and Control Subsystem (ADCS), power systems, and communication systems [4]. Despite these challenges, the capabilities of CubeSats are continuously growing, with new technologies and solutions being developed to improve their performance and capabilities.

There have been numerous CubeSats that have been successfully launched and operated in recent years such as: 1) MeznSat: This CubeSat is a collaborative project between Khalifa University of Science and Technology (KUST) and the American University of Ras Al-Khaimah (AURAK) with a fund from the United Arab Emirates Space Agency (UAE-SA). It is a 3U CubeSat that carries a shortwave infrared (SWIR) micro-spectrometer as its primary payload, with the aim of deriving greenhouse gas concentrations in the atmosphere by making observations in the 1000–1650 nm wavelength region [5]. 2) Light-1: It is a 3U CubeSat that carries two payloads to monitor and study terrestrial gamma-ray flashes (TGFs) from thunderstorms and lightning. The two payloads were developed and build by a group of student from Khalifa University and New York University in Abu Dhabi with a fund from the United Arab Emirates Space Agency (UAE-SA) and Bahrain National Space Science Agency (NSSA) with the use of two different photo sensor technologies and scintillating crystals [6]. 3) Nayif-1: It was launched by MBRSC in collaboration with educational institutions, primarily the American University of Sharjah (AUS), as part of the sustainable space science knowledge transfer program. The project helped to develop the space technology industry skills of Emirati engineering students and provided them with hands-on experience in the design, manufacture, integration, installation and operation of small satellites [7].

This paper discusses the ADCS development and testing of AlainSat-1. AlainSat-1 is a collaborative endeavor between the IEEE Geoscience and Remote Sensing Society (GRSS) and the National Space Science and Technology Center (NSSTC) at United Arab Emirates University (UAEU). Its main earth observation payloads are developed by three separate international universities which are Universitat Politechnica De Catalunya in Spain, Telkom University in Indonesia and Kyutech Institute of Technology in Japan [8].

The ADCS is a crucial subsystem of a satellite that is responsible for determining and controlling the orientation of the satellite in space. It is a complex subsystem that involves various hardware and software components, including sensors, actuators, and control algorithms [9]. The main objective of the ADCS is to maintain the satellite in the desired attitude throughout its mission. One of the key aspects of the ADCS is its ability to operate in different operational modes. These operational modes are designed to perform different tasks and to satisfy specific mission requirements [10]. Some examples of operational modes include detumbling, sun-pointing, nadir-pointing, and ground contact mode.

The aim of this research is to develop efficient and reliable ADCS that can satisfy the mission requirements of AlainSat-1. A variety of sensors, actuators, and control algorithms have been proposed and implemented in the literature. One of the key sensors used in the ADCS of CubeSats is the magnetometer. This sensor is used to measure the Earth'' magnetic field and to determine the attitude of the CubeSat. A number of studies have proposed the use of magnetometers in the ADCS of CubeSats and have shown that they can provide accurate attitude information [11]. In addition to magnetometers, other sensors such as sun sensors, star trackers, and nadir sensor have been used to determine the attitude of CubeSats [12]. Sun sensors are used to track the sun and to orient the CubeSat towards it.

Star trackers are used to determine the attitude of the CubeSat by identifying the position of stars in the sky. Nadir sensor have been used to take images of the Earth and to determine the attitude of the CubeSat using the images [13].

Actuators used in the ADCS of CubeSats include reaction wheels, magnetorquers, and thrusters. Reaction wheels are used to control the angular momentum of the CubeSat and to change its attitude. Magnetorquers are used to generate torque on the CubeSat using the Earth's magnetic field. Thrusters are used to provide propulsion and to change the attitude of the CubeSat [14]. Control algorithms are a crucial part of the ADCS of CubeSats. The most commonly used control algorithm is the Proportional-Integral-Derivative (PID) controller. PID controllers have been shown to be effective in controlling the attitude of CubeSats. Other control algorithms such as the Linear Quadratic Regulator (LQR) and Model Predictive Control (MPC) have also been proposed in the literature and have been shown to provide good performance for CubeSats. Overall, recent research in the field of ADCS for CubeSats has focused on developing efficient and reliable systems that can satisfy the mission requirements of CubeSats. A variety of sensors, actuators, and control algorithms have been proposed and implemented in the literature, and they have been shown to provide good performance [15].

The aim of this study is to create a conceptual design of the ADCS that meets the specific requirements and specifications of AlainSat-1. This will be achieved by implementing a series of operational modes, each of which utilizes different algorithms for determining and controlling the attitude, based on the available power budget and the required pointing accuracy for that mode. The Structure of the paper is organized as follows: Section 2 presents the kinematic and dynamic models of the CubeSat in presence of the input torque, Section 3 discuss the main operational modes of the ADCS, Section 4 states the mission requirements and specifications that have to be achieved by the ADCS, Section 5 and 6 presents numerical simulation examples of some ADCS operations modes and discuss the results according to the mission requirements, Section 7 concludes the work.

2. Mathematical modelling

The mathematical model of the satellite consists of kinematic and dynamic models. In the kinematic model, the attitude of the satellite is represented by a unit quaternion, which is a four-dimensional vector. The quaternion has three components that represent the rotation axis and one component that represents the rotation angle. The time derivative of the quaternion, also known as the quaternion rate, is used to describe the angular velocity of the satellite. It is worth mentioning that this is a kinematic model. To model the dynamics of the satellite, the equations of motion need to be derived and integrated along with the kinematic model. In the dynamic model, the satellite's motion is represented, considering the forces and torques acting on it. This type of model is used to predict the satellite's attitude over time, as well as to design and analyze the satellite's control systems [16].

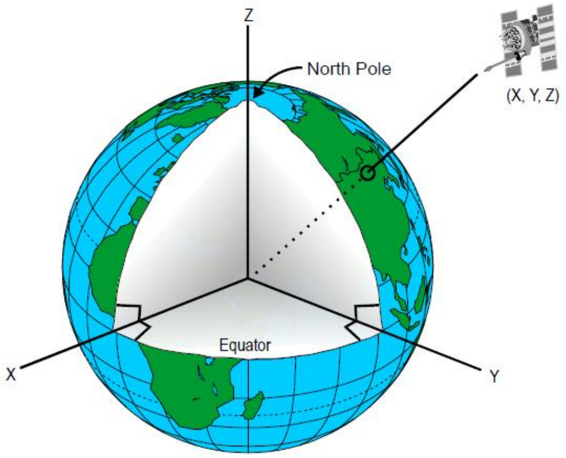

Fig. 1 Earth-Centered Inertial (ECI) frame [17].

2.1. Kinematic model

A kinematic model of a satellite using quaternions is a mathematical representation of the satellite's attitude in space. Quaternions are a mathematical construct that can be used to represent rotations in three-dimensional space. They have several advantages over other methods of representing attitude, such as Euler angles or rotation matrices, including being singularity-free and being more computationally efficient. The quaternion rate can be obtained as in Equation (1):

$$\dot{\mathbf{q}} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & \omega_{zo} & -\omega_{yo} & \omega_{xo} \\ -\omega_{zo} & 0 & \omega_{xo} & \omega_{yo} \\ \omega_{yo} & -\omega_{xo} & 0 & \omega_{zo} \\ -\omega_{xo} & -\omega_{yo} & -\omega_{zo} & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \tag{1}$$

Where $\omega_{xo}, \omega_{yo}, \omega_{zo}$ are the components if the angular velocity of the CubeSat expressed in the orbit frame.

2.2. Dynamic Model

The dynamic model of a satellite typically consists of nonlinear coupled differential equations of motion, which describe the time evolution of the satellite's attitude. These equations are derived from the principles of Newtonian mechanics and are based on the satellite's properties, such as its mass, center of mass, and moment of inertia, as well as the torques acting on it. For satellite dynamics, the most common approach is to model the satellite as a rigid body, which means that the satellite's shape and size are assumed to be constant during its motion. The equations of motion for a rigid body can be expressed using Euler's equations, which describe the time evolution of the angular velocity and angular momentum of a rigid body as presented in Equation (2):

$$\mathbf{I}\dot{\boldsymbol{\omega}}_B^I = \mathbf{N}_{GG} + \mathbf{N}_{MT} - \dot{\mathbf{h}}_w - \boldsymbol{\omega}_B^I \times (\mathbf{I}\boldsymbol{\omega}_B^I + \mathbf{h}_w) \tag{2}$$

Where $\mathbf{I}$ is the moment of inertia matrix of the CubeSat, $\boldsymbol{\omega}_B^I$ is the angular velocity of the CubeSat expressed in inertial frame, $\mathbf{N}_{GG}$ is the gravity gradient disturbance torque, $\mathbf{N}_{MT}$ is the control torque produced by the magnetic torquer rods, and $\mathbf{h}_w$ is the reaction wheel angular momentum vector.

3. Modes of operation

The modes of operation that are implemented in the ADCS of AlainSat-1 include detumbling, sun-pointing, nadir-pointing, and ground contact mode. This section will give an overview of every implemented mode of operation [18].

3.1. Detumbling mode

Detumbling mode is the first operational mode that is activated after the CubeSat is deployed in orbit. The main objective of this mode is to decrease the spin rate from a high initial value to a low value that is suitable for the next operational modes. Different control algorithms, such as B-Dot and Y-Thomson, have been proposed in the literature to achieve this objective. These algorithms have been shown to be effective in reducing the spin rate to a low value within a short time after deployment.

3.2. Sun-pointing mode

Sun-pointing mode is designed to recharge the CubeSat batteries using solar panels in case of low power generation. This mode utilizes solar sensors and algorithms to track the sun and to orient the CubeSat towards it. This mode has been widely used in CubeSat missions to increase the lifetime of the satellite by prolonging the battery life.

3.3. Nadir-pointing mode

Nadir-pointing mode is the main operational mode that provides a minimum pointing accuracy of less than 1 deg. This mode utilizes sensors such as coarse sun, fine sun, nadir, and rate sensors; magnetometers; and star trackers to determine the attitude of the CubeSat. Then, control algorithms such as the Extended Kalman Filter and the Three-wheel algorithm are used to control the attitude of the CubeSat. Nadir-pointing mode has been widely used in CubeSat missions to perform tasks such as imaging and remote sensing.

3.4. Ground contact

Ground contact mode is designed for the communication between the CubeSat and the ground station. This mode enables the CubeSat to send the collected data and measurements to the ground station for further analysis. Ground contact mode has been widely used in CubeSat missions to enable data transmission and to ensure the continuity of the mission.

4. Mission requirements of the ADCS

ADCS is a critical subsystem of a satellite. It is responsible for determining the satellite's attitude and providing the needed stability during the mission. Fig. 2 shows the components of the ADCS that are employed to achieve the mission requirements.

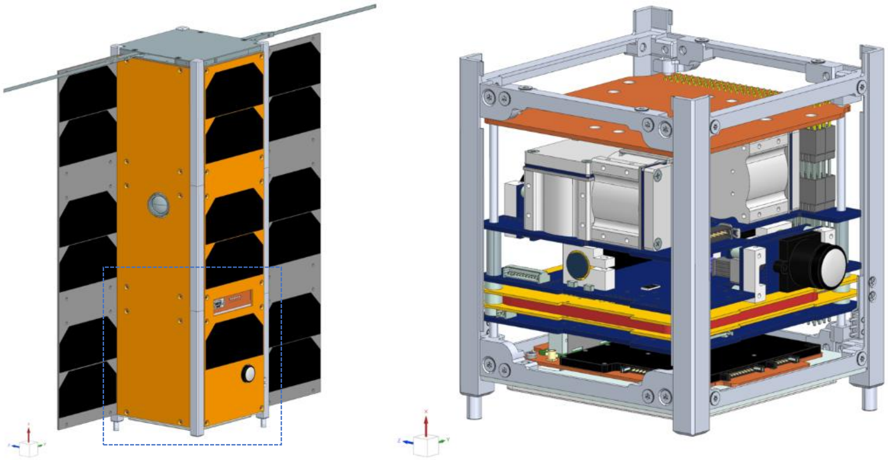

Fig. 2 CAD image of AlainSat-1 and its ADCS

The mission requirements for the ADCS of a CubeSat will depend on the specific goals and objectives of the mission, but in general, they can include the following:

1) Attitude determination: The ADCS must be able to accurately determine the satellite's attitude in real-time, typically using sensors such as magnetometers, star trackers, and sun sensors.
2) Attitude stabilization: The ADCS must be able to stabilize the satellite's attitude and maintain it within a certain tolerance range, typically using control inputs such as reaction wheels, magnetic torquers, and thrusters.
3) Pointing: The ADCS must be able to point the satellite's instruments or antennae towards a specific target, such as a planet or a specific location on Earth.
4) Robustness: The ADCS must be able to handle disturbances and unexpected events, such as solar flares, and be able to recover the satellite's attitude.
5) Low power consumption: The ADCS must consume low power, as CubeSat's have limited power resources.
6) Compactness: The ADCS must be compact and lightweight, as CubeSat's have limited size and weight resources.
7) Reliability: The ADCS must be reliable, as CubeSats are often flown in a swarm or constellations and the failure of one satellite can affect the overall mission.
8) Cost-effective: The ADCS must be cost-effective, as CubeSats missions are usually low budget.
9) Scalability: The ADCS must be scalable, as CubeSats come in different sizes and shapes, and the ADCS must be able to adapt to different mission requirements and constraints.

Table 1 summarize the requirement of the ADCS of AlainSat-1.

Table 1 The technical requirements of the ADCS

Stabilization	The satellite shall be three axes stabilized
Accuracy	The satellite shall have a pointing accuracy of < 0.1 deg
	The satellite shall have a pointing stability of < 1 RMS deg/s
Pointing Vector	The satellite shall be able to point to a specific target on execution of a command from the ground
	The satellite shall be able to determine its own pointing vector in the 3D space

	The ADCS shall be able to stabilize the Satellite from the initial spin rate of 5 deg/s within 1 day
	The ADCS shall be able to determine the position of the Sun
Operating Temperature	The ADCS optical component shall survive in the temperature range of -30 °C to +70 °C
Interface	The ADCS should follow the PC104 standard pin configurations
	The ADCS shall communicate with I2C interface
Power Requirement	The input voltage for the ADCS shall be 3.3 V, 5 V and Battery voltage
Flight Control Software	FCS shall be implemented in the ADCS computer

5. Numerical simulations

In order to achieve the desired performance of the ADCS, it is necessary to numerically verify the different modes of operation of the ADCS. In this section, we present the numerical simulation results of three different ADCS modes of operation, which are detumbling, nadir-pointing, and ground contact mode. These numerical simulations are performed on EOS using *xml* script as shown in Fig. 3.

```
<?xml version="1.0" encoding="utf-8"?>
<SchedulerScript xmlns:xsi="http://www.w3.org/2001/XMLSchema-
instance"
xmlns:xsd="http://www.w3.org/2001/XMLSchema">
<UpdateVisual>true</UpdateVisual>

<ScheduledSettings>

<ScheduledPropertySet Time="0" ObjectId="CubeACP"
Property="EstimationMode" Value="MemsRate" />
<ScheduledPropertySet Time="0" ObjectId="CubeACP"
Property="ControlMode" Value="BDot" />

<ScheduledPropertySet Time="3480" ObjectId="CubeACP"
Property="EstimationMode" Value="Triad" />
<ScheduledPropertySet Time="3480" ObjectId="CubeACP"
Property="ControlMode" Value="YWheel" />
```

Fig. 3 A sample of the xml script that is used to generate the simulation results.

Table 2 shows the used control and estimation algorithms, and the desired accuracy of each operational mode that are utilized in the numerical simulations.

Table 2 The desired pointing accuracy, and control and estimation algorithms of the operational modes

	1st Detumbling Mode	2nd Detumbling Mode	Nadir Mode	Ground contact
Desired state (angular velocity)	< 3 deg/s	< 1 deg/s	< 0.1 deg/s	< 0.1 deg/s
Control algorithm	BDot	Y-Wheel	XYZ-Wheel	XYZ-Wheel
Estimation algorithm	MEMS Rate	Triad	True State	EKF Full State

5.1. Detumbling mode

The first mode of operation is the detumbling mode, which is used to stabilize the satellite's angular velocity after deployment from the launch vehicle. The detumbling mode is activated immediately after deployment. The main objective of the detumbling mode is to reduce the angular velocity of the satellite to a low value. This is traditionally done in two modes as follows:

1) B-dot: during this mode, the satellite's angular velocity is reduced from 10 deg/s (the estimated initial angular rate after deployment) to 3 deg/s by using one actuator, which is Y-magnetorquer and X, Y, Z-axis rate sensor.
2) Y-Thomson: during this mode, the satellite's angular velocity is reduced from 3 deg/s to 1 deg/s by using three actuators they are X, Y, Z-magnetorquer and magnetometer as a sensor.

The simulation results in Fig. 4 and Fig. 5 show that the satellite's angular velocity in both detumbling modes is reduced to the desired values.

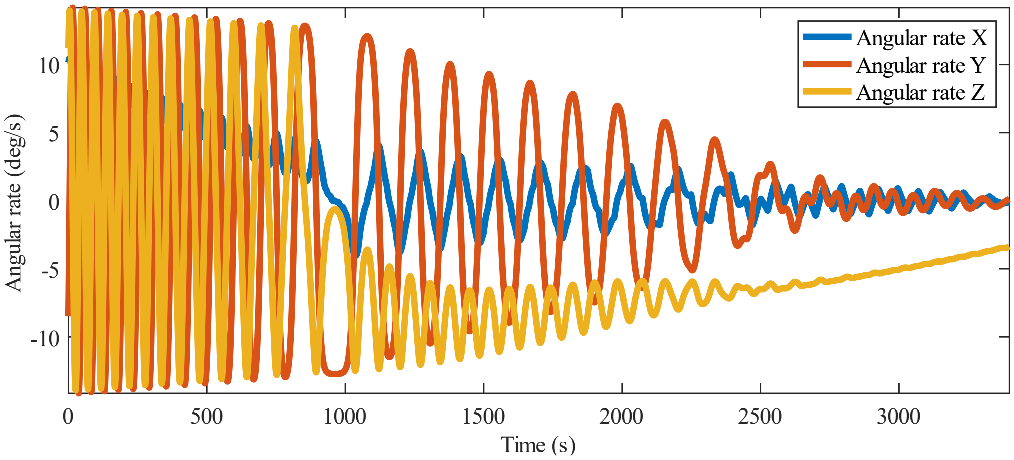

Fig. 4. Detumbling Mode from 10 deg/s to 3 deg/s

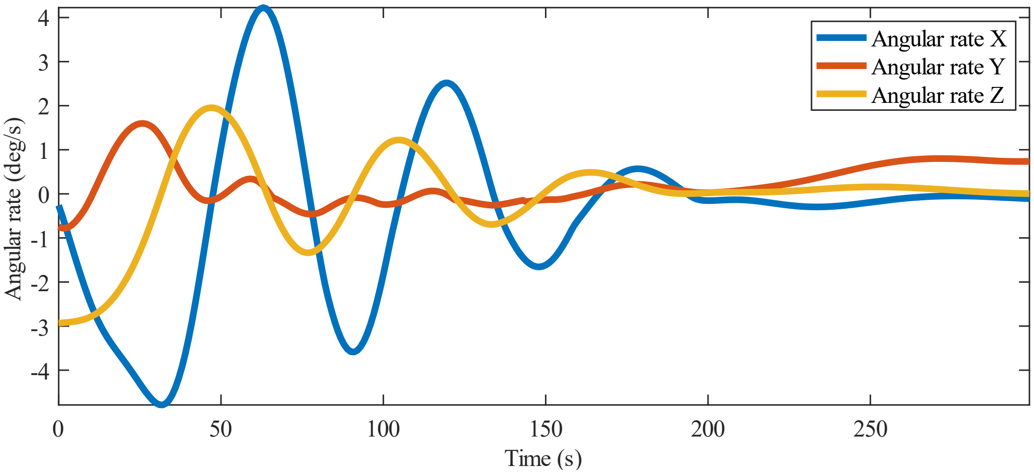

Fig. 5 . Detumbling Mode from 3 deg/s to 1 deg/s

5.2. Nadir-pointing mode:

The second mode of operation is the nadir-pointing mode, which is used to maintain the antennae of the satellite pointing towards the Earth. This mode is activated after the sun-pointing mode and uses the star trackers, Magnetometer, Sun Sensor and Nadir Sensor and reaction wheels and Magnetorquers to maintain the antennae pointing towards the Earth. The simulation results in Fig. 6 shows that the antennae can maintain a pointing accuracy of better than 0.1 degrees towards the Earth.

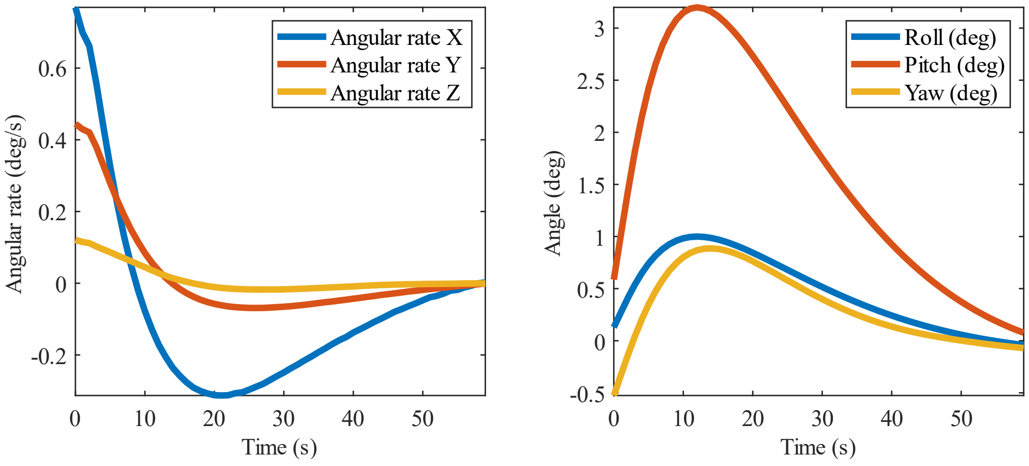

Fig. 6. Nadir Pointing Mode from 1 deg/s to 0.1 deg/s

5.3. *Ground contact mode:*

The third mode of operation is the ground contact mode, which is used to establish communication with ground stations. This mode is activated during the pass of the satellite over a ground station and uses the antennae and the radio frequency communication systems to establish communication. The simulation results in Fig. 7 shows that the satellite is able to establish communication with the ground station within a few minutes with 0.1 deg as required.

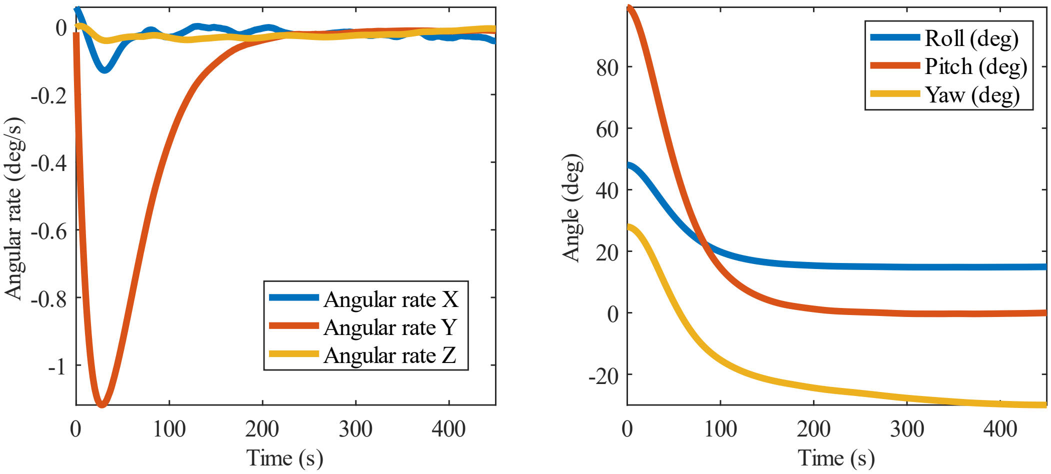

Fig. 7. Ground contact mode

5. Discussion

The numerical simulation results presented in the previous section demonstrate the performance of the ADCS of AlainSat-1 in different modes of operation. The results show that the ADCS is able to effectively stabilize the angular velocity of the satellite in the detumbling mode, maintain the antennae pointing towards the Earth in the nadir-pointing mode, and establish communication with ground stations in the ground contact mode.

The performance of the ADCS in the detumbling mode is particularly important, as it is the first mode of operation after deployment from the launch vehicle. The results show that the satellite's angular velocity is reduced to the desired level within an hour after deployment, which indicates that the ADCS is able to effectively stabilize the satellite's angular velocity.

The performance of the ADCS in the nadir-pointing mode is important for the communication with the ground station, as it ensures that the antennae are able to point towards the Earth. The results show that the antennae are able to maintain a pointing accuracy of better than 0.1 degrees towards the Earth, which indicates that the ADCS is able to effectively maintain the antennae pointing towards the Earth.

The performance of the ADCS in the ground contact mode is also critical for the mission, as it ensures that the satellite is able to establish communication with ground stations. The results show that the satellite is able to establish communication with the ground station within a few minutes, which indicates that the ADCS is able to effectively establish communication with ground stations.

6. Conclusions

In conclusion, In this paper, we presented the numerical simulation results of the ADCS in three different modes of operation: detumbling, nadir-pointing, and ground contact mode. The results demonstrate the ability of the ADCS to effectively stabilize the satellite's angular velocity, maintain the antennae pointing towards the Earth, and establish communication with ground stations. The numerical simulation results provide confidence in the ability of the ADCS to perform its intended functions during the mission. However, it is important to note that these results are based on simulation, and further testing and validation in real-world conditions are required to fully confirm the ADCS performance. The ADCS of a CubeSat plays a critical role in the success of the mission, and its performance must be thoroughly evaluated and tested before launch. The numerical simulation results presented in this paper provide a valuable insight into the performance of the ADCS in different modes of operation and demonstrate the ability of the ADCS to operate and achieve the desired performance effectively. Future work will include hardware testing the validate the proposed ADCS in real-time.

Acknowledgements

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