ISTANBUL TECHNICAL UNIVERSITY ★ FACULTY OF AERONAUTICS AND ASTRONAUTICS

ATTITUDE DETERMINATION AND CONTROL SYSTEMS IN CUBESATS

GRADUATION PROJECT

Mehmet Caner AVCI

Department of Astronautical Engineering

Thesis Advisor: Prof. Dr. Alim Rüstem ASLAN

JANUARY, 2022

ISTANBUL TECHNICAL UNIVERSITY ★ FACULTY OF AERONAUTICS AND ASTRONAUTICS

ATTITUDE DETERMINATION AND CONTROL SYSTEMS IN CUBESATS

GRADUATION PROJECT

Mehmet Caner AVCI
(110170715)

Department of Astronautical Engineering

Thesis Advisor: Prof. Dr. Alim Rüstem ASLAN

JANUARY, 2022

Mehmet Caner AVCI ,student of ITU Faculty of Aeronautics and Astronautics student ID **110170715**, successfully defended the **graduation** entitled "**Attitude Determination and Control Systems in CubeSats**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Alim Rüstem ASLAN** ....
İstanbul Technical University

Jury Members : **Prof. Dr. Name SURNAME** ....
İstanbul Technical University

Prof. Dr. Name SURNAME ....
İstanbul Technical University

Date of Submission : 17 January 2022
Date of Defense : 24 January 2022

To my precious family and dearest friends,

FOREWORD

I have to express my deep appreciation to Prof. Dr. Alim Rüstem ASLAN for all his suppport, patience as well as his opinions, technical commments and personal advices.

I would like to thank Prof. Dr. Cengiz HACIZADE and engineers of Attitude Determination and Control Department of TÜBİTAK Space Technologies Research Institute, who enlightened me with their knowledge about Attitude Determination and Control Systems and increased my excitement for the subject.

I would like to thank everyone there who helped me when I first started to this project, and especially to Ferim AKASLAN and Onur ÖZTEKİN for their help.

Endless thanks to my precious family, who have endured many difficulties to bring me to where I am today, take pride in my every move, whether I have achieved and failed, and who have placed respect and love in my life in the best possible way. Thanks to them who are my greatest chances in life, my dear father Prof. Dr. İsmail Yaşar AVCI and my dear mother Vildan AVCI, who taught me never to give up. I would also like to thank my dearest brother Kadircan AVCI and my sister Canan Nur AVCI.

January 2022 Mehmet Caner AVCI

TABLE OF CONTENTS

ABBREVIATIONS

ACS	**:** Attitude Control System
ADCS	**:** Attitude Determination and Control System
ADC	**:** Attitude Determination and Control
ADS	**:** Attitude Determination System
YBKS	**:** Yönelim Belirleme ve Kontrol Sistemi
YBK	**:** Yönelim Belirleme ve Kontrol
U	**:** Unit
P-POD	**:** Poly Picosatellite Orbital Deployer
GCI	**:** Geocentric Inertial Frame
ECI	**:** Earth-Centered Reference Frame
ECEF	**:** Earth-Fixed Reference Frame
LVLH	**:** Local-Vertical/Local-Horizontal
GPS	**:** Global Positioning System
CCD	**:** Charge-Coupled Device
CMOS	**:** Complementary Metal-Oxide Semiconductor
APS	**:** Active Pixel Sensors
SRP	**:** Solar Radiation Pressure
FOV	**:** Field of View
CSS	**:** Coarse Sun Sensor
DSS	**:** Digital Sun Sensor
FSS	**:** Fine Sun Sensor
MEMS	**:** Micro Electro-Mechanic Systems
IMU	**:** Inertial Measurement Unit
ISS	**:** International Space StationS
RF	**:** Radio-Frequency
RMS	**:** Root Mean Square
RCS	**:** Reaction Control System
RW	**:** Reaction Wheel
LEO	**:** Low Earth Orbit

LIST OF TABLES

LIST OF FIGURES

ATTITUDE DETERMINATION AND CONTROL SYSTEMS IN CUBESAT

SUMMARY

With the developing technology, the shrinking hardware elements have started a new era in space exploration. Small and relatively economical satellites have entered our lives. Access to satellites has increased, more engineers around the world have started working on satellites. The name of this new technology is "CubeSat". Cube satellites are made up of many subsystems. This thesis covers one of the subsystem of CubeSats which is called Attitude Determination and Control Systems.

Spacecraft Attitude Determination and Control covers the entire range of techniques for determining the orientation of a spacecraft and then controlling it so that the spacecraft points in some desired direction. ADC Systems are mainly divided into two as determination and control. Attitude determination refers to memoryless approaches that determine the attitude point by point in time, quite often without taking the statistical properties of the attitude measurements into account. Spacecraft attitude control is essential to meet mission pointing requirements, such as required science modes and thruster pointing requirements for orbital maneuvers. (Markley & Crassidis, 2014, pp. 1–3) The entire ADCS subsystem works in feedback to each other.

Various CubeSat tasks and their Attitude Determination and Control Systems are reviewed in this article. Many ADC Systems are examined which was used in past missions. Different requirements in various missions and the ADCS equipment selected to meet these requirements were observed. The data obtained as a result of the researches were visualized and interpreted in tables.

KÜP UYDULARDA YÖNELİM BELİRLEME VE KONTROL SİSTEMLERİ

ÖZET

Gelişen teknoloji ile birlikte küçülen donanım elemanları uzay araştırmalarında yeni bir dönemi başlatmıştır. Küçük ve nispeten ekonomik uydular hayatımıza girmiştir. Uydulara erişim artmış, dünya çapında daha fazla mühendis uydular üzerinde çalışmaya başlamıştır. Bu yeni teknolojinin adı "Küp Uydu"dur. Küp uydular birçok alt sistemden oluşur. Bu tez, bir alt sistem olan Küp Uyduların Yönelim Belirleme ve Kontrol Sistemleri'ni kapsamaktadır.

Uzay aracı Yönelim Belirleme ve Kontrolü, bir uzay aracının yönünü belirlemek ve daha sonra uzay aracının istenen bir yönü gösterecek şekilde kontrol etmek için kullanılan tüm teknolojiyi kapsar. YBK Sistemleri temel olarak Yönelim Belirleme ve Yönelim Kontrolü olarak ikiye ayrılır. Yönelim belirleme, çoğu zaman yönelim ölçümlerinin istatistiksel özelliklerini hesaba katmadan, yönelim noktalarını zaman içinde belirleyen hafızasız yaklaşımları ifade eder. Uzay aracı konum kontrolü, yörünge manevraları için gerekli yönelim modları ve faydalı yük yöneltme gibi görev gereksinimlerini karşılamak için gereklidir. (Markley & Crassidis, 2014, pp. 1-3) YBK alt sisteminin tamamı birbirine geri bildirimde bulunarak çalışır.

Bu makalede çeşitli Küp Uydu görevleri ve bu görevlerde kullanılan Yönelim Belirleme ve Kontrol Sistemleri gözden geçirilmektedir. Geçmiş görevlerde kullanılan birçok YBK Sistemi incelenmiştir. Çeşitli görevlerde farklı gereksinimler ve bu gereksinimleri karşılamak için seçilen YBKS ekipmanları gözlemlenmiştir. Araştırmalar sonucunda elde edilen veriler tablolarda görselleştirilmiş ve yorumlanmıştır.

1. INTRODUCTION

CubeSats have shown to be incredibly effective to access to space. The payload designer has more freedom with materials and production procedures because of the tiny size and encapsulation. It also permits the launch vehicle to employ existing capabilities with minimum danger to the primary payload. Building on the success of the 1U and 3U, a new family of payloads was developed to provide even greater scientific and military capabilities. (An Advanced Standard for CubeSats)

CubeSat is a standard that is maintained by California Polytechnic State University, and it aims to provide a design standard for picosatellites to reduce cost, and increase frequency of launch. This standard has to be followed in order to have compatibility with Poly Picosatellite Orbital Deployer (P-POD), and in the event of a violation of the standard, developers are expected to fill out Deviation Waiver Approval Request. (The CubeSat Program, “CubeSat Design Specification Rev.13,”)

This paper is about ADC Systems of various CubeSat missions. Reasons of ADCS desing decisions are closely examined. The system requirements of various predetermined CubeSat missions and the ADC systems which are designed to meet these requirements are reviewed. 22 CubeSats from different fields and tasks were selected to embody the work. Each Cubesat's ADCS content and tasks were examined. The reason for choosing the ADCS of CubeSats in 22 different tasks is revealed with a result.

1.1. Purpose of Thesis

This thesis aims to bring together and examine the various CubeSat missions and ADC systems they used. This paper is planned to be a guiding resource for the Attitude Determination and Control System of future CubeSat projects. The main questions answered in this thesis are “What are the tasks of CubeSat projects? What are the ADCS requirements of CubeSat projects? What are the ADC Systems that will meet the requirements for various CubeSat missions?”.

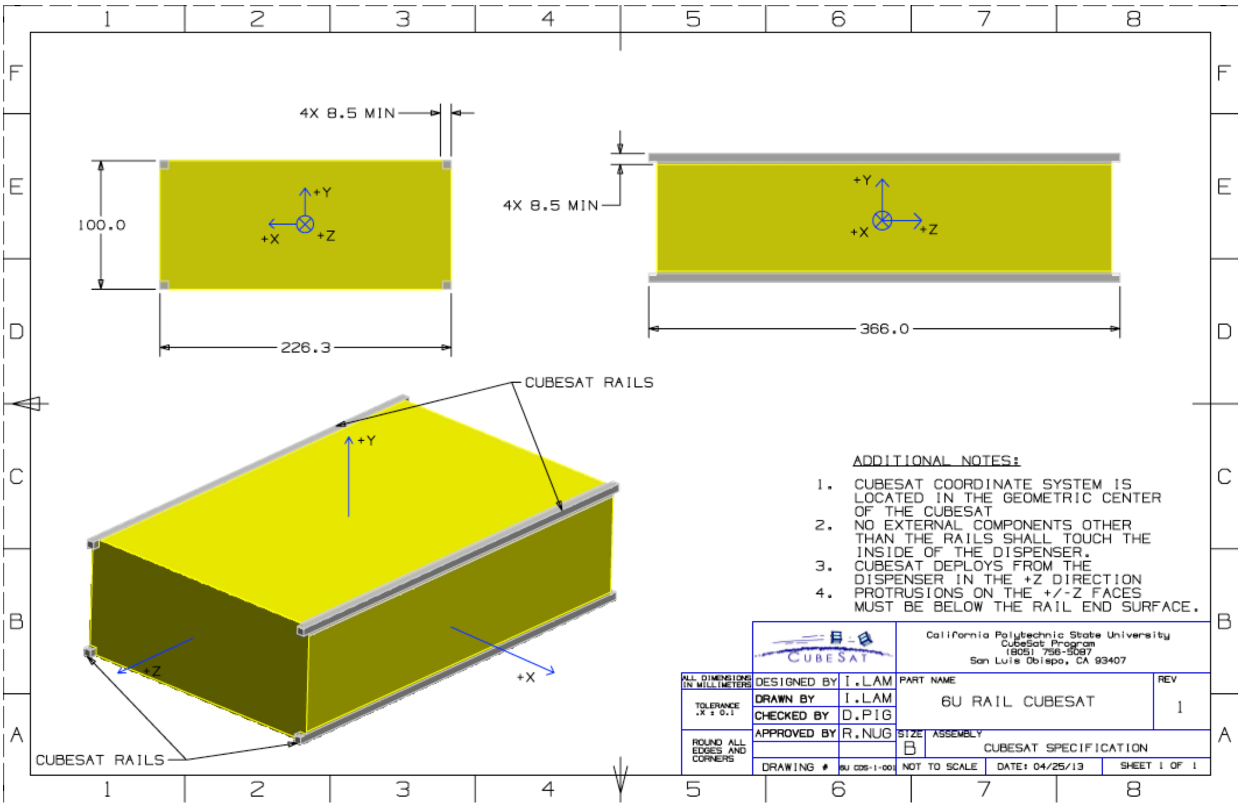


Figure 1 3U CubeSat with Dimensions

2. ATTITUDE DETERMINATION AND CONTROL

The "attitude" of a spacecraft is its orientation in space. Some form of attitude determination and control is required for nearly all spacecraft. For engineering or flight-related functions, attitude determination is required only to provide a reference for control. Attitude control is required to avoid solar or atmospheric damage to sensitive components, to control heat dissipation, to point directional antennas and solar panels (for power generation), and to orient rockets used for orbit maneuvers. (wertz) ADC Systems are mainly divided into two as Determination and Control.

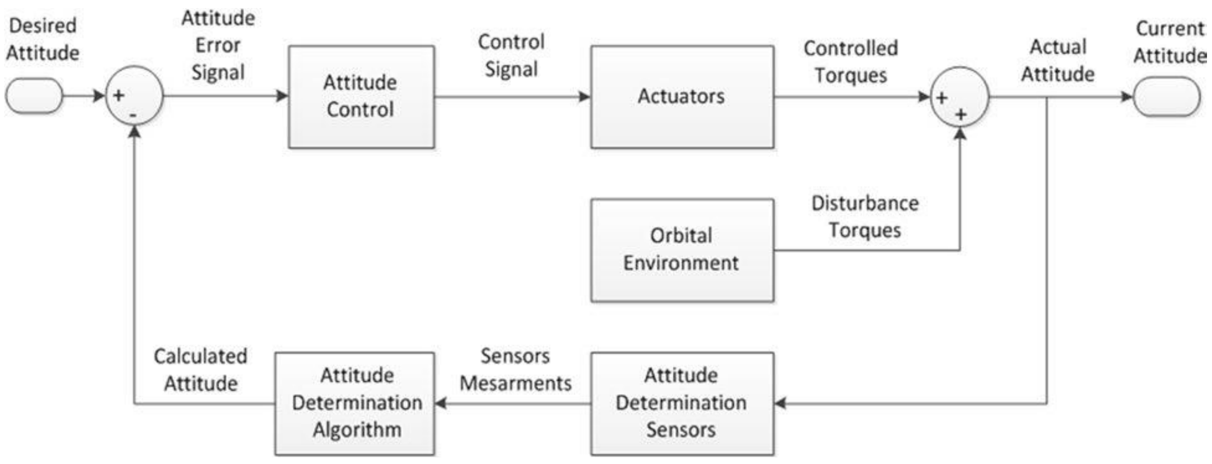


Figure 2 Block Diagram of ADC System

2.1. Reference Frames

In order to describe the position, velocity, and orientation of an object of interest, the object's motion must be compared to a type of standard known as a reference frame. A reference frame is comprised of an origin that defines a position in space and three orthogonal unit vectors or axes that make up a right-handed system. There are numerous reference frames that can be used to measure an object's motion depending on the type of application and desired results, such as Spacecraft Body Frame, Inertial Body Frame, Earth-Centered/Earth-Fixed Frame and Local-Vertical/Local-Horizontal Frame.

2.1.1. Spacecraft Body Frame

A spacecraft body frame is defined by an origin at a specified point in the spacecraft body and three Cartesian axes. A body frame is used to align the various components during spacecraft assembly. Spacecraft body frame is fixed to the satellite's body, with its origin at the centre of mass of the satellite. This frame is used to represent the actual satellite in space. The X, Y and Z axis need to be perpendicular to each other and should be popping out of the different faces of the satellite. An example of Satellite Body frame has been given in figure. Therefore, it is quite common to define the body coordinate system operationally as the orientation of some sufficiently rigid navigation base, which is a subsystem of the spacecraft including the most critical attitude sensors and payload instruments.

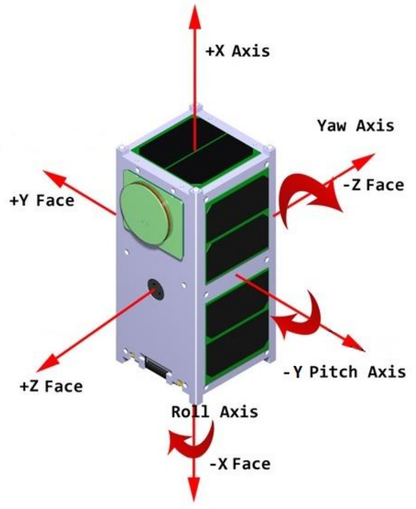


Figure 3 Satellite Body Frame

2.1.2. Inertial Reference Frames

An inertial reference frame is a frame in which Newton's laws of motion are valid. It is a well known fact of classical mechanics that any frame moving at constant velocity and without rotation with respect to an inertial frame is also inertial [crassidis5]. Celestial reference frames with their axes fixed relative to distant "fixed" stars are the best realizations of inertial frames. An approximate inertial frame, known as the Geocentric Inertial Frame (GCI) has its origin at the center of mass of the Earth. This frame has a linear acceleration because of the Earth's circular orbit about the Sun, but this is unimportant for attitude analysis.

2.1.3. Earth-Centered/Earth-Fixed Frame

- **Earth-Centered Reference Frame:**

It is also called “Celestial Coordinates”. The ECI frame is non accelerated (inertial) reference frame in which Newton’s laws are valid. The frame is fixed in space with origin at the Earth’s center and the z-axis pointing towards the North Pole. The x-axis points toward vernal equinox, the point where the plane of the Earth’s orbit about the Sun crosses the Equator going from South to North, and y-axis completes the right hand Cartesian coordinate system. The frame is denoted I. This reference frame, which is very nearly non-rotating, is a suitable approximation to an inertial frame for the analysis of near-earth space vehicle trajectories and for their attitude control.

- **Earth-Fixed Reference Frame:**

This frame has also its origin at the Earth’s center. The coordinate axes are fixed to the earth and rotates relative to the ECI frame with a frequency. Because of Earth’s daily rotation and its yearly rotation around the sun, the ECEF frame is not an inertial reference frame. The z-axis points towards the North Pole, x-axis points towards the intersection between the Greenwich meridian and the Equator, and the y-axis completes the right handed orthogonal system. The frame is denoted E. (ders notları)

2.1.4. Local-Vertical/Local-Horizontal Frame

It is often convenient, especially for Earth-pointing spacecraft, to define a reference frame referenced to the spacecraft’s orbit, which we will identify by the subscript O. The most common case is the Local-Vertical/Local-Horizontal (LVLH) orbit frame. It has its z axis o_3 pointing along the nadir vector, directly toward the center of the Earth from the spacecraft, and its y axis o_2 pointing along the negative orbit normal, in the direction opposite to the spacecraft’s orbital angular velocity. The x axis o_1 completes the right-handed triad. (crassidis)

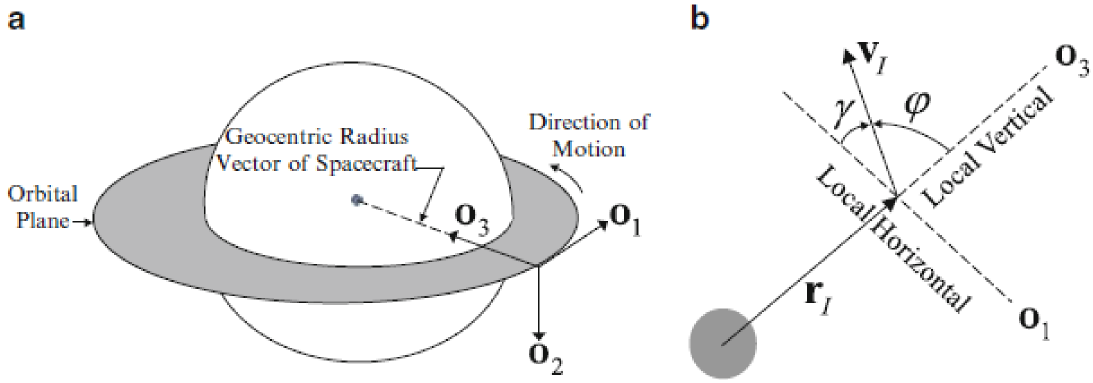


Figure 4 Local-vertical/local-horizontal frame. (a) Frame definition. (b) Flight path angle

2.2. External Torques

External torques involve an interaction with entities external to the spacecraft. As opposed to internal torques, external torques change the overall momentum of the spacecraft. In common with internal torques, external torques include both undesirable disturbance torques and torques deliberately applied for control.

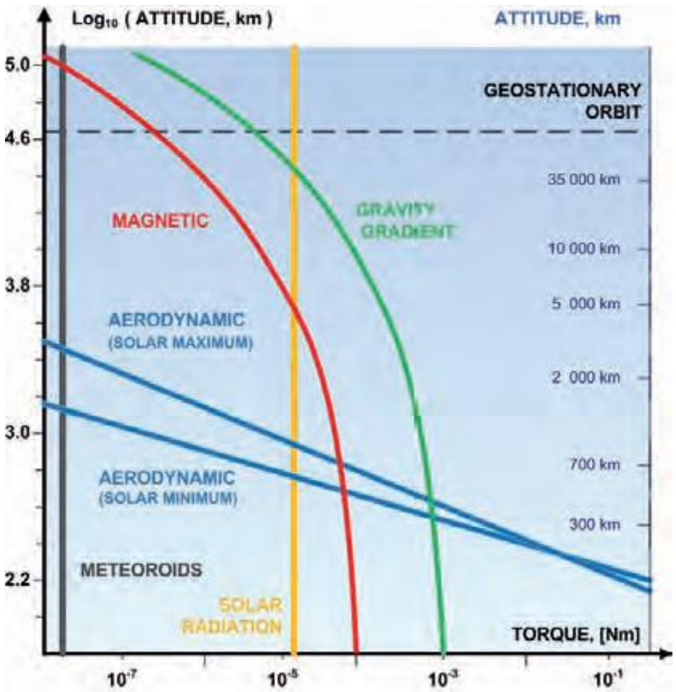


Figure 5 External Torques

2.2.1. Gravity-Gradient Torque

Any nonsymmetrical rigid body in a gravity field is subject to a gravity-gradient torque. We compute this torque by summing the contributions of the gravitational forces on the various point masses constituting the rigid body. It is usually adequate to approximate the gravity field as spherically symmetric for computing gravity-gradient torques.

Gravity-gradient torques are often used for passive stabilization of a spacecraft. A gravity-gradient boom with a mass at the end can be deployed along the positive or negative yaw axis The boom deployment must be carefully timed to avoid an inverted orientation, with the desired nadir-pointing axis pointing in the zenith direction. Pendular motions, known as libration, can be damped out by energy-dissipating libration dampers, which are very similar in design and function to nutation dampers. Finally, we note that the gravity-gradient torque cannot provide stability against rotations around the nadir vector. These are controlled either by active means or by employing a momentum wheel to provide a momentum bias along the pitch axis. (crassisdis)

2.2.2. Magnetic Torque

The most basic source of a magnetic dipole is a current loop. A current of I amperes flowing in a planar loop of area A produces a dipole moment of magnitude m = I x A in the direction normal to the plane of the loop and satisfying a right-hand rule. It follows from this definition that the natural unit for the dipole moment is Am^2. The dipole moment can be significantly increased by wrapping the wire loops around a ferromagnetic core. Magnetic control torques are used almost exclusively in near-Earth orbits, where the magnitude of the Earth's magnetic field is roughly in the range of 20–50 μT. Commercially available torquers can provide dipole moments from 1 to 1,000 Am^2, so the resulting magnetic control torques range from 2×10^{-5} to 0.05 Nm. The magnetic field strength falls off as the inverse cube of the distance from the center of the Earth, so magnetic control has rarely been employed in higher orbits, but it has sometimes been used even in geosynchronous orbits. Undesirable magnetic dipoles can lead to magnetic disturbance torques, which are generally several orders of magnitude smaller than the above estimates of control torques.

One advantage of magnetic torques is that they produce no force, so they do not perturb the spacecraft's orbit. A significant disadvantage is that the torques are constrained to lie in the plane orthogonal to the magnetic field. so only two out of three axes can be controlled at a given time instant. Because magnetic torques cannot provide three-axis control at any instant of time, they are generally employed in conjunction with some other form of attitude control. This can be passive control, such as spin stabilization or gravity-gradient stabilization, but it is more common to employ magnetic control in conjunction with reaction wheels. In this application, the wheels provide the actual pointing and maneuvering torques, and magnetic torques are used to unload the secular angular momentum buildup in the wheels. (crassidis)

2.2.3. Aerodynamic Torque

For objects in low-Earth orbit, atmospheric drag is a significant source of perturbing torque. The torque depends on the velocity of the spacecraft relative to the atmosphere. This is not simply the velocity of the spacecraft in the GCI frame, because the atmosphere is not stationary in that frame. The most common assumption is that the atmosphere co-rotates with the Earth. The drag coefficient is determined empirically, and is usually in the range between 1.5 and 2.5. In principle, aerodynamic torques could be used for attitude control, either for passive control like the feathers on an arrow, or even for active control by providing movable surfaces. Applications of this concept have been exceedingly rare, however. (crassidis)

2.2.4. Solar Radiation Pressure Torque

Solar radiation pressure (SRP) is another source of disturbance torque. In low-Earth orbit, the effect of SRP is dominated by aerodynamics, but SRP torques will generally dominate aerodynamic torques in higher altitude orbits ($\geq$800 km). The SRP torque is zero when the spacecraft is in the shadow of the Earth or any other body, of course. In contrast to the case of aerodynamic torques, movable surfaces have been used on some spacecraft in geosynchronous orbits to balance the SRP torques. In most applications, the surfaces have been moved by daily commands, and not controlled autonomously or in real time by an onboard computer. (crassidis) Solar radiation pressure can be used as a propulsion with solar sails.

3. ATTITUDE DETERMINATION SYSTEMS

Attitude determination is the process of computing the orientation of the spacecraft relative to either an inertial reference or some object of interest, such as the Earth. This typically involves several types of sensors on each spacecraft and sophisticated data processing procedures. The accuracy limit is usually determined by a combination of processing procedures and spacecraft hardware. (wertz)

Attitude determination systems uses a combination of sensors and mathematical models to collect vector components in the body and inertial reference frames. These components are used in one of several different algorithms to determine the attitude, typically in the form of a quaternion, Euler angles, or a rotation matrix. It takes at least two vectors to estimate the attitude. (atte)

3.1. Attitude Determination Sensors

Attitude determination sensors are used to sense or measure the state of a spacecraft. Commonly used attitude determination systems are Star Trackers, Sun Sensors, Horizon Sensors, Magnetometers, Gyroscopes and GPS.

3.1.1. Star Trackers

A star tracker is basically a digital camera with a focal plane populated by either CCD (charge-coupled device) or CMOS (complementary metal-oxide semiconductor) pixels (picture elements). CCDs have lower noise, but CMOS has several advantages. It is the same technology used for microprocessors, so the pixels can include some data processing capabilities on the focal plane itself. Sensors taking advantage of this capability are known as active pixel sensors (APS). CMOS is more resistant to radiation damage than CCDs, and also provides the capability of reading out different pixels at different rates, which is not feasible with CCDs.

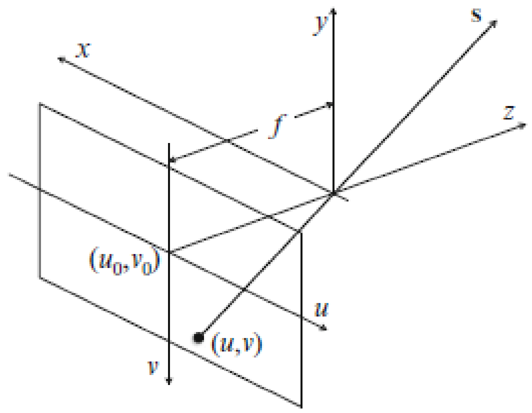


Figure 6 Star Tracker Geometry

Figure 6 shows the geometry of a star tracker, which is basically the geometry of a pinhole camera. A star tracker has two modes of operation: tracking mode and initial attitude acquisition.If a tracked star moves out of the field of view (FOV), the tracker searches for another star, preferably well separated from the other tracked stars. The a priori knowledge of the approximate spacecraft attitude makes this search relatively easy.

The resolution of the star tracker depends on the number of pixels, the size of the FOV, and the accuracy of the centroiding. Higher resolution can be obtained by decreasing the size of the FOV, increasing the number of pixels in the focal plane, or improving the centroiding. If the physical size of a pixel and the field of view are held constant, adding pixels requires a larger focal plane and thus a proportionally larger focal length, increasing the weight of the optics. Pixel sizes have historically decreased, however, allowing more pixels in a smaller focal plane.

Star trackers have several sources of errors. Optical distortions can be reduced by calibration, and temperature-dependent errors can be minimized by controlling the temperature of both the focal plane and the optics. Shot noise results from the random nature of photons, which obey Poisson statistics.

3.1.2. Sun Sensors

One of the most obvious references sources for attitude is the sun. A sun sensor provides a measurement of orientation relative to the sun. Because the orientation about the sun line cannot be measured, the sun sensor provides only two axes of attitude measurement. Sun sensor measurements are not available during portions of

Earth orbits when the spacecraft enters the umbra, or dark side of the orbit. Sun presence detectors are used to detect when the sun enters the field of view (FOV) of an instrument. The sun presence detector output increases sharply when the sun enters its FOV. It does not provide a measure of attitude. (Pittelkau)

Sun sensors fall into two classes, coarse Sun sensors (CSSs) and fine or digital Sun sensors (DSSs). The most common form of a CSS is a photocell (an eye) or an assembly of photocells. To a good approximation, the output of a photocell is an electric current directly proportional to the intensity of the light falling on it. This may include light from Earth albedo or glint off nearby components of the spacecraft, which can pull CSS outputs off the true Sun direction by as much as 20° in extreme cases. (crassidis 5-6)

3.1.2.1. Analog Sun Sensors

The simplest and most reliable, but least accurate attitude sensor, is the coarse sun sensor (CSS). It is used for safe-hold control of a spacecraft, sun presence detection for sensitive instruments, sun acquisition, and solar array pointing. The basic CSS is a photocell whose output current is $I = I_o.\cos\theta$, where θ is the angle of incidence from surface normal, and I_o is the output current when $\theta = 0°$. (Pittelkau)

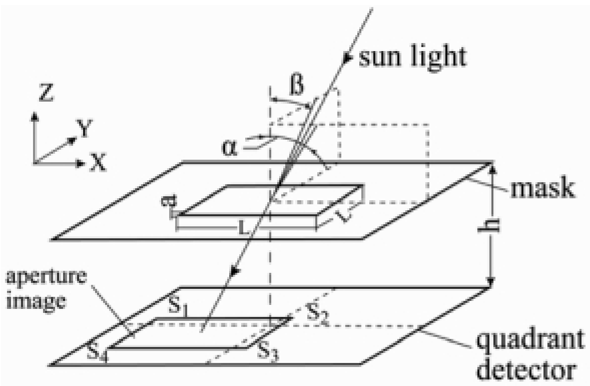


Figure 7 Operational principle of traditional analog sun sensor (Pittelkau)

3.1.2.2. Digital Sun Sensors

Another type of sun sensor is the digital sun sensor (DSS). The sun light passes through a narrow slit onto a mask containing holes that form a binary Gray code

(Wertz, 1991). Below the mask is an array of solar cells. The binary readout indicates the angle of the sun relative to a plane normal to the mask and passing through the slit. The resolution of the DSS is limited because the sun subtends an angle of 0.53° when viewed from Earth. Two or three offset patterns for the least significant bit provide data to an interpolation circuit to yield 0.25° to 0.125° resolution. The FOV of the digital sun sensor is typically 128◦. A pair of DSS arranged orthogonally provides two axes of attitude measurement. Five pairs provide full 4π steradian coverage (full sphere coverage). (Pittelkau)

The Adcole fine sun sensor (FSS) is much more accurate than the DSS. The FSS comprises a number of entrance slits and a reticle that has four rows of slits staggered by 1/4 of the width of the reticle slits (Wertz, 1991).

Another type of sun sensor uses an active pixel detector array. This sun sensor is typically accurate to around 0.02° with resolution down to 0.005°. The sensor typically consumes less than 1 watt of power and is less than 0.5 kg mass. (Pittelkau)

3.1.3. Horizon Sensors

3.1.4. Magnetometers

3.1.5. Gyroscopes

3.1.6. GPS

4. ATTITUDE CONTROL SYSTEMS

Attitude control is the process of orienting the spacecraft in a specified, predetermined direction. It consists of two areas-attitude stabilization, which is the process of maintaining an existing orientation, and attitude maneuver control, which is the process of controlling the reorientation of the spacecraft from one attitude to another. The two areas are not totally distinct, however. For example, we speak of stabilizing a spacecraft with one axis toward the Earth, which implies a continuous change in its inertial orientation. The limiting factor for attitude control is typically the performance of the maneuver hardware and the control electronics, although with autonomous control systems, it may be the accuracy of orbit or attitude information. (wertz)

4.1. Passive Control Systems

4.1.1. Passive Control Actuators and Methods

4.1.1.1. Hysteresis Rods

4.1.1.2. Gravity Gradient Beams

4.1.1.3. Nutation Dampers

4.2. Active Control Systems

4.2.1. Active Control Actuators

4.2.1.1. Reaction Wheels

4.2.1.2. Control Moment Gyros

4.2.1.3. Magnetic Torquers

4.2.1.4. Thrusters

4.3. MATLAB Applicaitons

5. CUBESATS CLASSIFIED BY MISSIONS

22 separate CubeSat projects are classified according to their tasks. The examined CubeSat projects can be listed as 4 Earth Observations, 7 Communications, 6 Scientific, 2 Moon Observations, 1 Technology Demonstration, 1 Space Debris Detection and 1 Deep Space Planetary Observation.

Table 5.1. ADCS of Earth Observation Missions

Attitude Determination and Control Systems of Earth Observation Missions					
CubeSat Name - Size	Brief Purpose of Project	ADCS Accuracy	ADCS Elements		About ADCS Configuration
			Determination	Control	
AENEAS - 3U	To track the location cargo containers on a global scale	Determination: n.d. Control: 2°	Sun Sensor Magnetometer Gyroscope	3 x Reaction Wheels 3 x Torque Coils	To achieve the required surface track, the attitude must be compared with a desired attitude to generate an error signal, the error signal must be fed through a control law to generate torque commands, and the commands must be acted upon with enough authority to maintain pointing accuracy throughout a pass.
POPSAT-HIP - 3U	To demonstrate the functionality of a high-resolution optical payload and attitude control propulsion system	Determination: n.d. Control: 2°	Sun Sensor Magnetometer Gyroscope	3 x Torque Coils 12 x Micro Thrusters	The configuration has been chosen to maximize the arm of the nozzles while occupying the least possible volume. All satellite electronics are arranged to occupy 1U of the satellite while the rest of the 2U are utilized for a pressurized tank containing Argon gas at about 8 bar. The tank is completely customized and integrated in the secondary payload of the satellite for the most efficient use of the available volume. The satellite is equipped with fixed and deployable solar panels and its primary attitude determination and control system is based on magnetorquers, magnetometers, sun sensors and gyroscopes.
STU2A - 3U	Taking pictures of polar with an onboard CMOS color camera	Determination: ≤ 1° Control: ≤ 2° Stabilization: ≤ 0.1°/s	Sun Sensor Magnetometer Rate Gyro Star Tracker	3 x Reaction Wheels 3 x Torque Coils	Camera equipment that is fixed into position, need to be aimed by slewing the satellite; keeping its high gain antenna-oriented toward the earth for sending and receiving data and commands; keeping their solar arrays angled toward the sun to optimize power absorption and reduce the satellite’s reliance on internal power systems; thermal heating and cooling of the craft and its subsystems can also be controlled by the craft’s orientation.
JUGNU - 3U	To provide data for agriculture and disaster monitoring	Determination: n.d. Control: n.d.	Magnetometer Gyroscope	4 x Reaction Wheels 3 x Torque Coils	The spacecraft is 3-axis stabilized. The ADCS is comprised of a 3-axis magnetometer and 3-axis MEMS gyros for attitude sensing; actuation is provided by reaction wheels and magnetorquers. The ADCS orients the satellite in a manner such that maximum solar energy is incident on solar panels. During imaging, the satellite has to point into the target area in order for image capture. From a communication point of view, control of the attitude is necessary so that the antennas, which have narrow beams, are pointed correctly towards the ground station.
STRaND-1 – 3U	To take images of the Earth from space. to demonstrate new technologies - including a mobile phone as a operating system.	Determination: ≤ 0.5° Slew Rate: 2°/s	Sun Sensor Horizon Sensor Magnetometer	3 x Reaction Wheels Magnetorquers	The purpose of the first attitude mode is to limit the angular rotation of the satellite ultimately resulting in a rotation only about the Y-axis. After the solar panels have deployed, the control mode will change to a sun-seeking precession controller.

Table 5.2. ADCS of Communication Missions

Attitude Determination and Control Systems of Communication Missions					
CubeSat Name - Size	Brief Purpose of Project	ADCS Accuracy	ADCS Elements		About ADCS Configuration
			Determination	Control	
MarCO - 6U	Bent pipe communications relay station during the InSight entry, descent, and landing	Control: ≤ 0.007°	IMU Coarse Sun Sensor Gyroscope Stellar Reference Unit (SRU)	3 x Reaction Wheels 8 x Micro Thruster	Reaction wheels were used to reach the desired attitude for necessary sub-systems. Micro thrusters were preferred for trajectory corrections and reaction wheel desaturation.
SMDC ONE I - 3U	To receive data from a ground transmitter and relay that data to a ground station	Determination: - Control: -	-	Passive Magnetic Control	The mission has no precise pointing requirement; hence, the satellite will be controlled passively by onboard magnetic moment production. No onboard attitude estimation is required for the nanosatellite.
RAFT - 1U	Digital communications relay for amateur radio users to transmit their GPS coordinates and messages via the satellites	Determination: - Control: -	-	Passive Magnetic Control	RAFT use a permanent magnet to align itself with the Earth's magnetic field. This allows its attitude to be predictable.
TURKSAT 3USAT - 3U	Voice communication at LEO, to provide radio amateur world a long-awaited opportunity	Determination: - Control: -	Magnetometer Gyroscope	Passive Magnetic Control	The mission has no precise pointing requirement; hence, the satellite will be controlled passively by onboard magnetic moment production. No onboard attitude estimation is required for the passively controlled nanosatellite.
PSAT A - 3U	Two-way communications transponder system that could be used to relay data from remote terminals to a global network of internet linked volunteer ground stations to speed up the return of data from remote environmental sensors	Determination: n.d Control: n.d.	Sun Sensor Magnetometer	3 x Torque Coils	The primary attitude control requirement is to evenly expose the four side panels to the sun so that the Ni-Cd cells are equally charged and to even-out the thermal load on the panels. A very slight spin about the Z axis is maintained by the unbalanced solar radiation pressure on each side. the side solar panels are always within +/- 23 degrees or so of the Sun. This can maintain more than 90% power budget through the seasons.
GOMX-3 - 3U	To demonstrate new capabilities of nanosatellites focusing on attitude control, RF sensing, and high-speed data downlink	Determination: n.d. Control: ≤ 1°	Fine and Coarse Sun Sensors Magnetometer Rate Gyro	3 x Reaction Wheels 3 x Torque Coils	The satellite is capable of periods of 1 degree pointing (1σ), but suffers from worse performance when the orientation vectors (magnetic and sun) are close together or during eclipse, when the sun vector is lost entirely and the magnetometer and gyro are used to propagate the satellite attitude. The stability of the ADCS system is also of note. After proving momentum dumping via the magnetorquers, the GOMX-3 was set to nominally point its 1U face toward the local ram vector, a minimum drag configuration. The consistency of the ADCS in maintaining this attitude has extended the expected orbit lifetime from 6 months to well over 1 year, providing much more utility from the ISS orbit.
FOX 1A - 1U	Amateur radio satellite	Determination: - Control: -	-	Passive Magnetic Control	The mission has no precise pointing requirement; hence, the satellite will be controlled passively by onboard magnetic moment production. No onboard attitude estimation is required for the passively controlled nanosatellite.

Table 5.3. ADCS of Scientic Missions

Attitude Determination and Control Systems of Scientific Missions					
CubeSat Name - Size	Brief Purpose of Project	ADCS Accuracy	ADCS Elements		About ADCS Configuration
			Determination	Control	
AEROCUBE - 0.5U	Measuring radiation in the space environment	Control: ≤ 0.1° Slew Rate: 5°/s	Magnetometer Earth and Sun Sensors	3 x Torque Coils	Magnetic torque rods provide all attitude control. For modest attitude control needs, magnetic systems are adequate.
BISONSAT - 1U	Imagery to study atmospheric aerosols, cloud formation, and various hydrologic processes.	Determination: - Control: -	-	Passive Magnetic Control	BisonSat is passively attitude stabilized by a bar magnet inside, which will line up with Earth's magnetic field. This allows for earth imaging, where the magnetic field has a large downward vertical component. Oblique imaging is possible in equatorial areas. When the satellite is over Montana, the magnetic field will point the camera straight down, making it easier to gather data for Montana. Over much of North America the camera will be pointed to within 10º-30º of nadir. At perigee, the 35 mm optic yields a 8.4º field of view, and a 69 km maximum ground swath width. Best resolution is 43 m ground sampling distance at nadir.
MINXSS - 3U	To measure the solar soft X-ray spectrum	Determination: 0.05° Control: ±0.003º for 2 axes; ±0.007º for 3rd axis Slew Rate: ≥ 10°/s	Nano Star Tracker Sun Sensor Magnetometer IMU	3 x Reaction Wheels 3 x Torque Coils	The MinXSS bus is a 3-axis-controlled nanosatellite to observe the solar SXR spectrum between 0.04 and 3 nm. Use of the XACT (One of the commercially 3-axis ADCSs for CubeSats) unit of BCT (Blue Canyon Technologies) XACT (fleXible ADCS Cubesat Technology) is a standalone 0.5U 3-axis stabilized ADCS unit. The stellar-based attitude determination and control provides accuracy of 0.002º RMS.
O/OREOS - 3U	Real-time analysis of the photo stability of organic sand biomarkers and the collection of data on the survival and metabolic activity for microorganisms	Determination: - Control: -	-	Passive Magnetic Control	The O/OREOS spacecraft is equipped with a passive attitude control system that utilizes multiple permanent magnets to orient its ''patch'' antenna toward ground stations when above the northern hemisphere.
CubeSTAR - 2U	Measuring the electron density is of interest for space weather monitoring over the polar caps	Attitude Determination and Control System: ≤ 10°	Sun Sensor Magnetometer Gyroscope	3 x Torque Coils	The data from the sensor is used in the ADS to compute the satellites present attitude. This information is given to the ACS that rotates the satellite to the wanted attitude. The control torques on CubeSTAR are three magnetic coils mounted perpendicular to each other. The three coils x, y and z are mounted on their respective axis seen in the satellites body frame.
Lunar Impactor - 3U	To perform new measurements of lunar magnetic fields, less than 100 meters above the Moon's surface	Determination: n.d. Control: n.d.	Star Tracker Sun Sensor Magnetometer	3 x Torque Coils 6 x Micro Thrusters	The thrusters must be configured in such a way that they provide full three-axis control, and they must be able to compensate for perturbations. Attitude knowledge and control is a key driver of performance.

Table 5.4. ADCS of Various Missions

Attitude Determination and Control Systems of Various Missions						
Mission	CubeSat Name – Size	Brief Purpose of Project	ADCS Accuracy	ADCS Elements		About ADCS Configuration
				Determination	Control	
Moon Observation	Lunar Ice Cube - 6U	To prospect, locate, and estimate size and composition of water ice deposits on the Moon for future exploitation by robots or humans	Control: 0.14 arcsec at 1σ Slew Rate: 10°/s	3-axis Stellar Attitude Determination (XACT)	3-axis reaction wheel control Ion Thruster	BIT-3 system has a built-in two-axis gimbal and can support active thrust vectoring for spacecraft attitude control, alignment, or reaction wheel desaturation. BCT's XACT ADCS unit has chosen because of the accuracy capability.
	LUMIO - 12U	To observe, quantify, and characterize the impact of meteoroids on the lunar surface	Control: ≤ 0.1° Stabilization: 79.9 arcsec/s	Sun Sensor Star Tracker IMU	3 x reaction wheel 4 x Micro Thruster	One of the major challenges of the mission is the strict pointing budget, which imposes high-precision tracking of a specific attitude that maximizes power generation. This is particularly relevant for the Attitude Determination and Control System (ADCS) due to the limited capacity of the reaction wheels. In addition, the de-tumbling and de-saturation maneuvers are undertaken using only four thrusters, which adds to the complexity of the control design.
	EQUULEUS - 6U	Trajectory control experiment, and its objective is to develop and demonstrate astrodynamics techniques for CubeSat missions	Control: ≤0.02°	Star Tracker Sun Sensor IMU	3 x Torque Coils 4 x Micro Thrusters	The XACT-50, developed by the Blue Canyon Technologies, is an integrated ADCS unit that is equipped with three reaction wheels, an inertial measurement unit, a star tracker, and external sun sensors, and it takes on the role of attitude determination and control of EQUULEUS. The four RCS thrusters in the propulsion system produce torques in any of the three-axis directions, and are used to control or desaturate the angular momentum accumulated by the disturbance torque arising mainly from trajectory control maneuvers and the solar radiation pressure.
Space Debris Detection and Rendezvous	ARAPAIMA - 6U	Debris detection at LEO	Determination: ≤ 6 arcsec Control: ≤ 1 arcmin at 3σ	Star Tracker Sun Sensor Magnetometer IMU	16 x Micro Thrusters	The propulsion system comprises a set of 16 reaction control system (RCS) thrusters, of 25 mN each, installed in pairs that generate torques about each of the satellite body axes and provide up to 100mN of thrust in two directions for orbital maneuvering. Given that the pointing performance of both actuators is comparable and the propellant usage is the same for this combination of thrust and propellant specications, the RWs were removed from the design in order to save mass and volume needed for other components.
Planet Observation	PicSat - 3U	Observation of planet Beta Pictoris	Control: ≤ 30 arcsec	Star Tracker Gyroscope Magnetometer Accelerometer	3 x Reaction Wheels 3 x Torque Coils	The ADCS selected for the PicSat Mission is the iADCS100 provided by Hyperion Technologies. The role of the ADCS will be to point the instrument to Beta Pictoris with accuracy and stability of 30 arcsec. The iADCS100 matches the ST200 star tracer with Hyperion's RW200-series of reaction wheels, as well as the MTQ200 series of magnetorquers. Combined with Berlin Space Technologies' flight-proven control algorithms, it offers an entirely autonomous attitude control system, in the space of two standard CubeSat PCB's. With the help of precisely pointing and slewing 3U CubeSat.

5.1. ADC Analysis of Similar CubeSat Missions

22 CubeSat projects classified according to different requirements are shown in the tables above.

5.1.1. Earth Observation Missions Requirements and ADC Systems

TIROS-1, a US meteorological satellite launched in 1960, was the first satellite to be launched for the purpose of observing the Earth. Since then, hundreds of Earth observation satellites have been launched that provide useful data for Earth. The power of space-based measurements compared to ground-based or air borne measurements lies on their global or regional coverage and their relatively high temporal resolution. These two characteristics have made satellite measurements a key as set for a variety of societal applications including amongst others weather forecasting, disaster monitoring, water management, pollution, and agriculture. (CubeSat Design for LEO-Based Earth Science Missions)

High attitude determination and control system accuracy is key parameter for observing the Earth from space with high resolution. In addition, it is very important to direct the solar panels to the sun to obtain energy. When examining various missions, determination accuracy of 1° and less, pointing control accuracy of 2° and less is sufficient for Earth Observation missions. Earth observation missions use magnetometers, gyroscopes, star trackers and sun sensors to achieve these accuracies for attitude determination. Also, reaction wheels, magnetorquers and micro thrusters are used for high accuracy control capability. Magnetorquers and micro thrusters are preferred for damping reaction wheels that have reached a certain saturation.

5.1.2. Communications Mission Requirements and ADC Systems

Since the early 21st century, many communication cube satellites have been launched into space. At first, cube satellites were sent for relatively low-frequency amateur radio communication, but today, CubeSat projects that provide communication at even higher frequencies are being implemented.

As can be seen in Table 5.2, high accuracy orientation is not considered necessary for low-frequency communication cube satellites. Generally, passive attitude control systems are preferred. Attitude determination systems are not preferred. Thus, both mass budget and cost are reduced.

When it comes to high frequency communication CuebSats, ADC system preferences are changd. As the wavelength gets smaller, the pointing accuracy of the satellite needs to increase. Reaction wheels, gyroscopes and magnetorquers are preferred to meet this requirement. Magnetorquers are preferred for damping reaction wheels that have reached a certain saturation. In order to increase the orientation accuracy of high-frequency communication satellites, the control system must be supported by an adequate detection system. To increase the lifetime of a mission, solar arrays must point to the Sun.

5.1.3. Scientific Missions Requirements and ADC Systems

The system requirements and equipment of cube satellites designed for scientific research purposes vary. For example, passive control equipment is preferred for the biological research spacecrafts' attitude system.

Active control systems are preferred in projects which are aiming to measure radiation and atmosphere electron density. Determination system requirements have been formed to feed the active control systems. While sun sensors, magnetometers and gyroscopes are sufficient for the satellites operating in LEO, a star tracker is also used in the CubeSat designed to go to the Moon.

5.1.4. Moon Observation Missions Requirements and ADC Systems

High-accuracy Attitude systems are preferred for lunar observation missions. The ion propulsion system was used in the Lunar Ice Cube project. Two-axis gimbaled Ion Thruster can support active thrust vectoring for spacecraft attitude control, alignment, or reaction wheel desaturation. For high accuracy orientation determination, a star tracker is often preferred in addition to the sun sensor and IMU in deep space missions such as lunar missions.

5.1.5. Space Debris Detection and Rendezvous Mission Requirements and ADC Systems

The ARAPAIMA mission proposes a reconnaissance approach to perform visible, infrared (IR), and 3D imaging of RSOs without a priori knowledge of their shape or attitude. To perform orbital approach maneuvers, the satellite is equipped with a diuoroethane warm gas propulsion system operated via rapid solenoid valve actuation and miniaturized 2D nozzle sets attached to the satellite body. The system comprises 16 RCS thrusters setup in pairs, each one capable of producing up to 25 mN of thrust.

For this mission ADCS accuracy determination and control requirements was decieded as ≤ 6 arcsec and ≤ 1 arcmin at 3σ respectively. Given that the pointing performance of both actuators is comparable and the propellant usage is the same for this combination of thrust and propellant specications, the RWs were removed from the design in order to save mass and volume needed for other components.

5.1.6. Planet Observation Mission Requirements and ADC Systems

Observing very distant planets requires a highly accurate ADC system. For example, to observe the planet Beta Pictoris, which is 63.4 light-years away, it was determined as 30 arcsec (<<1°) and reaction wheels were used to provide high-accuracy pointing control. Magnetorquers were preferred for reaction wheel desaturation.

For high accuracy determination Star Tracker, 3-Axes MEMS Gyro, Magnetometer and Accelerometer was preffered.

6. CONCLUSION

REFERENCES

Abrahart, R. J., and See, L. (1998). Neural Network vs. ARMA Modelling: Constructing Benchmark Case Studies of River Flow Prediction. In GeoComputation '98. *Proceedings of the Third International Conference on GeoComputation*, University of Bristol, United Kingdom, 17–19 September (CD-ROM).

Abrahart, R. J., and See, L.(2000). Comparing neural network and autoregressive moving average techniques for the provision of continuous river flow forecasts in two contrasting catchments, *Hydrolog. Process.*,***14***, 2157–2172.

Acar, M. H. and Yılmaz, P.(1997). Effect of tetramethylthiuramdisulfide on the cationic poymerization of cylohexeneoxide, *The 2nd International Conferences on* Advanced *Polymers via Macromolecular Engineering*, Orlando, Florida, USA, April 19-23.

Box, G. E. P., and Jenkins, J. M. (1976).*Time Series Analysis: Forecasting and Control*. Holden-Day, San Francisco, CA.

Burger, J., Gochfeld, M., Jeitner, C., Burke, S., Stamm, T., Snigaroff, R.,and Weston, J. (2007). Mercury levels and potential risk from subsistence foods from the Aleutians. *Science of The Total Environment*, ***384***, 93-105 doi:10.1016/j.scitotenv.2007.05.004.

Burke, W.F. and Uğurtaş, G.(1974). Seismic interpretation of Thrace basin, TPAO internal report, Ankara, Turkey.

Burlando, P., Rosso, R., Cadavid, L. G., and Salas, J. D.(1993).Forecasting of Short-term Rainfall Using ARMA Models. *J Hydrol.* Vol. ***144***, no. 1-4, pp. 193-211.

Deci, E. L., and Ryan, R. M. (1991). An motivational approach to self: Integration in personality. In R. Dienstbier (Ed.), *Nebraska Symposium on Motivation:* Vol.38. *Perspectives on motivation* (pp. 237-288). Lincoln: University of Nebraska Press.

IOC-UNESCO. (1981). *International bathymetric chart of the Mediterranean,* Scale 1:1,000,000, 10 sheets, Ministry of Defence, Leningrad.

LePichon, X. (1997).Personal communication.

McCaffrey, R. and Abers, G. (1988). SYN3: A program for inversion of teleseismic body wave forms on microcomputers, *Air Force Geophysics Laboratory Technical* Report, **AFGL-TR-88-0099,** Hanscomb Air Force Base, MA.

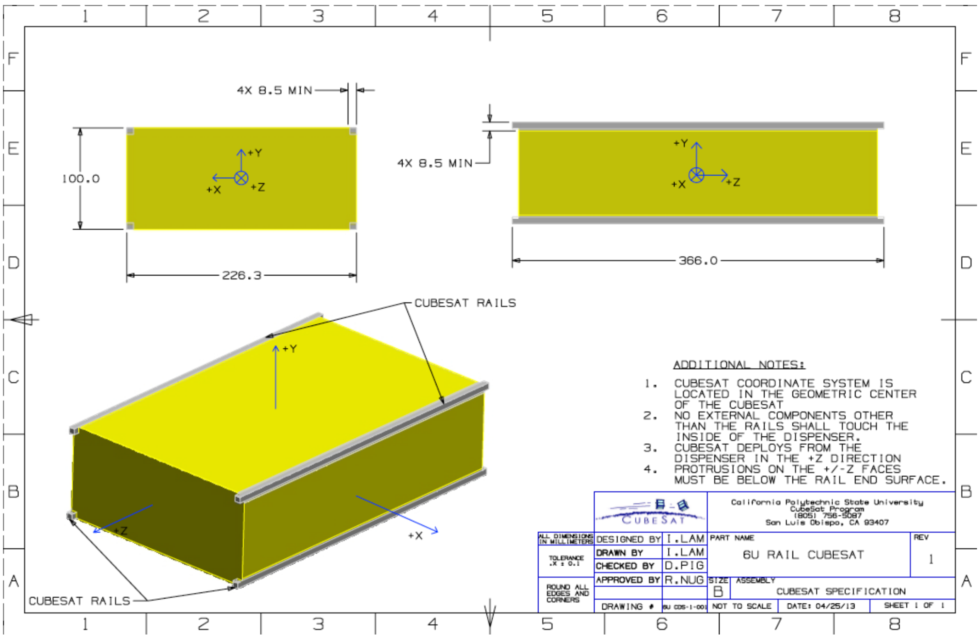
Moore, C. (1991). Mass Spectrometry. In *Encyclopedia of chemical technology* (4th ed.) (Vol. 15, pp. 1071-1094). New York, NY: Wiley.

Nelson, M.R.(1988). Constraints on the seismic velocity structure of the crust and upper mantle beneath the eastern Tien Shan, Central Asia, *PhD Thesis*, MIT, Cambridge, MA.

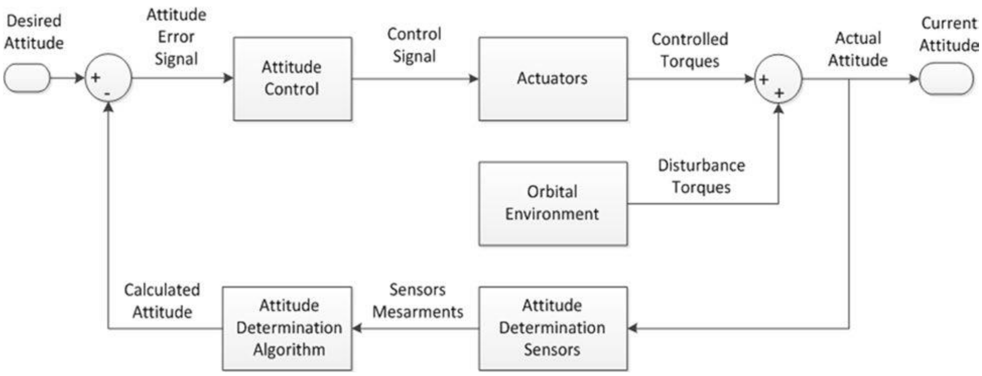
Roberts. S. and Jackson, J.A.(1991). Active normal faulting in central Greece: An overview, in *The Geometry of Normal Faults,* Spec. Publ. Geol. Soc. Lond., **56,** p. 125-142, Eds. Roberts, A.M., Yielding, G. and Freeman,

APPENDICES

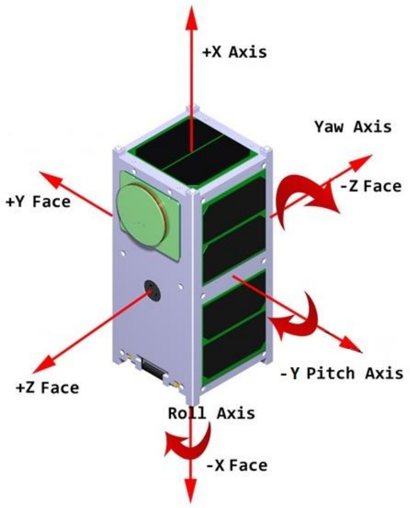
APPENDIX A: 3U CubeSat with Dimensions



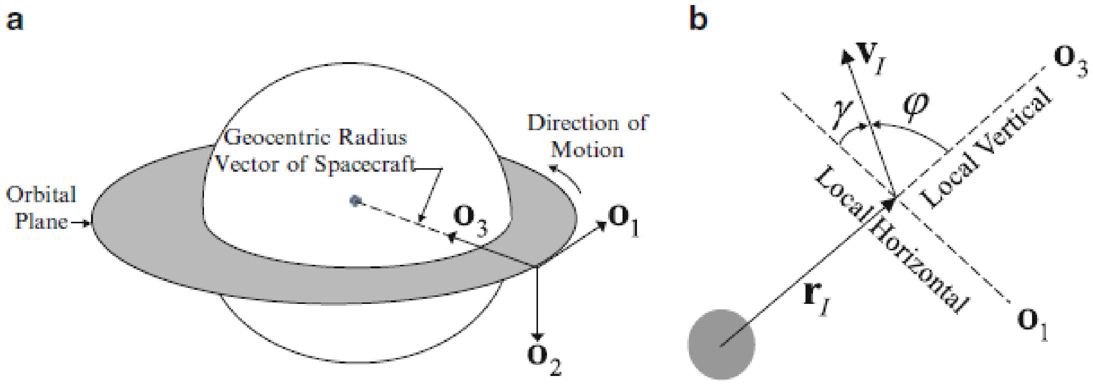
APPENDIX B: Block Diagram of ADC System



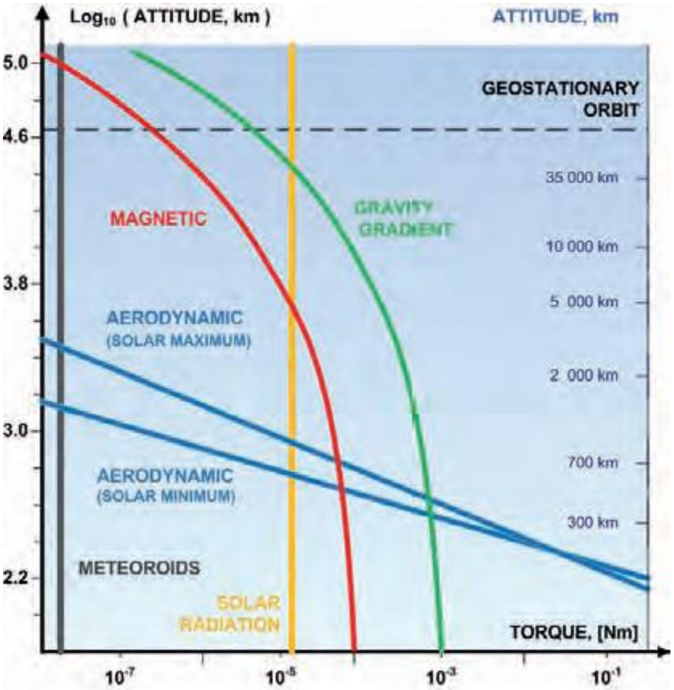
APPENDIX C: Satellite Body Frame



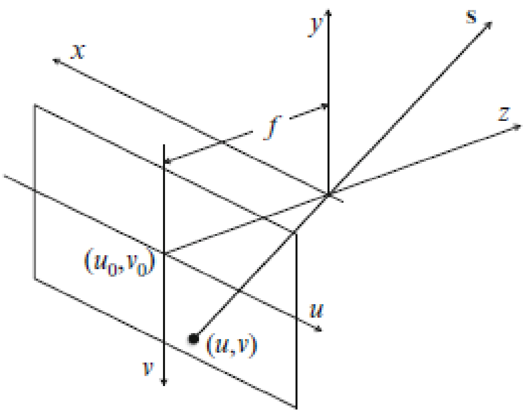
APPENDIX D: Local-vertical/local-horizontal frame.



APPENDIX E: External Torques



APPENDIX F: Star Tracker Geometry



APPENDIX G: Operational principle of traditional analog sun sensor