Western University
Faculty of Engineering
Mechatronic Systems Engineering Program

CubeSat Attitude Determination and Control System

Design Review I

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1. Introduction

Western Faculty of Engineering has received a grant from the Canadian Space Agency (CSA) to develop a CubeSat[1] over the course of three years, beginning in May 2018. Any spacecraft in orbit will need an attitude determination and control system (ADCS) to effectively orient the spacecraft.

The ADCS will provide accuracy and stability to the spacecraft to ensure mission success. Although there have been other attitude determination and control systems created for other CubeSat projects, the ADCS will be created based on the specifications determined for this specific CubeSat, leading to the following problem statement:

> Design a system to stabilize and control the pose of the CubeSat.

The functional constraints involve an ADCS system which must be able to point and stabilize the CubeSat along three axes. The whole CubeSat must be under 3.6 kg (which is a CSA proposal limitation), and the ADCS team has been allotted a maximum weight of 0.43 kg[2]. All the components of the CubeSat must fit within a 20cmx10cmx10cm volume.

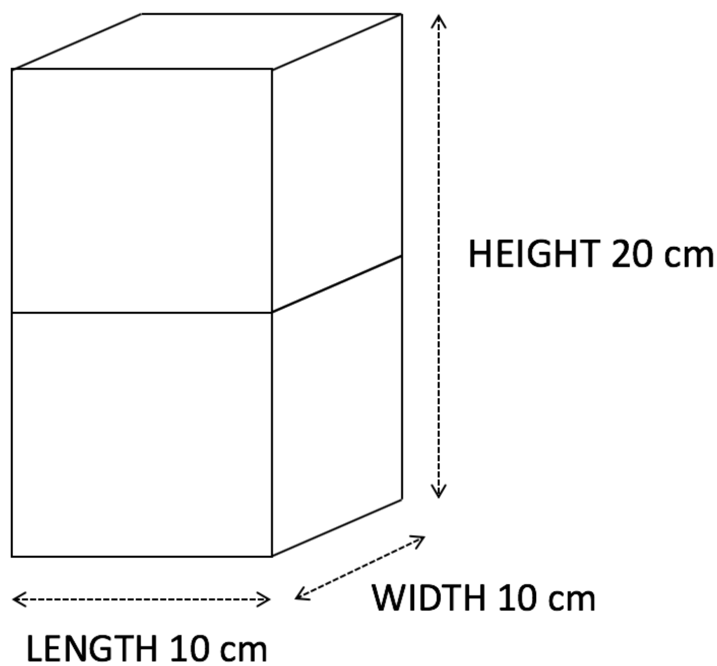

Figure 1: Dimensions of the CubeSat

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[1] A CubeSat is a nano-satellite used commonly in academic research and development.

2. Operational Modes

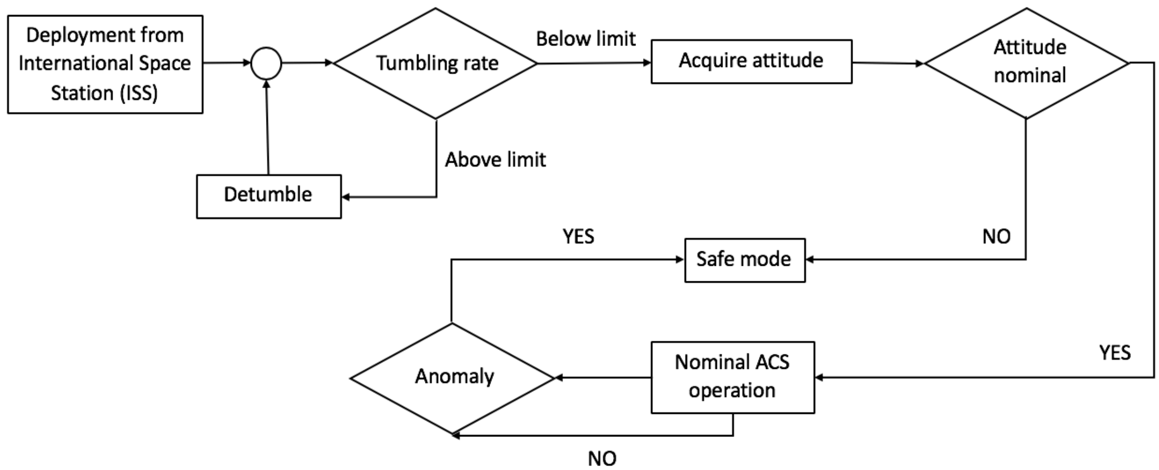

Figure 2: Operational Modes of the Attitude Determination System

3. Control Law

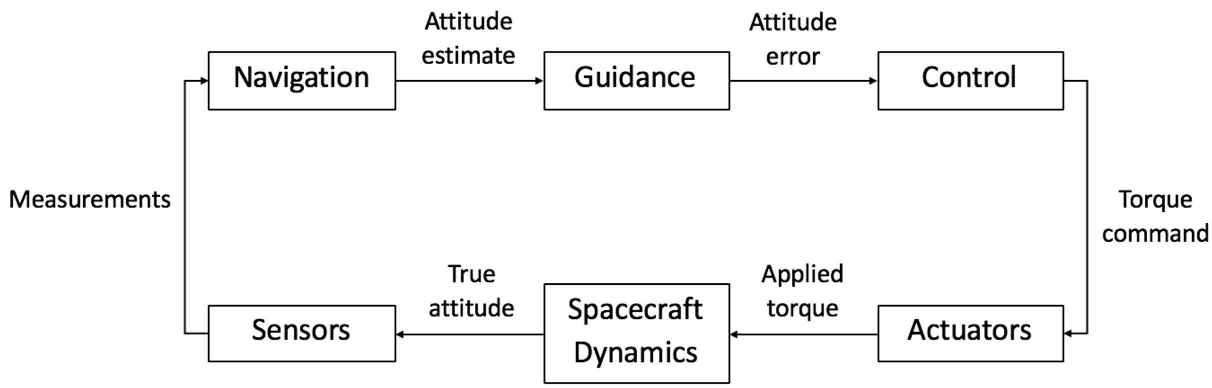

Figure 3: Control Law Diagram

3.1. Common Attitude Stabilization Methods

Common Detumbling Control Law (BDot)

The common detumbling control law (BDOT) is used with magnetometers and magnetorquers.

$$m = -\frac{k\dot{b}}{||b||^2}$$

- m: magnetic torquer dipole moment
- k > 0: control gain
- b: measured Earth magnetic field vector in spacecraft body coordinates

If the angular velocity measurements are available, one can avoid differentiating the magnetic field vector by using control law.

$$m = -\frac{k\dot{b} \times \omega}{||b||^2}$$

Other Common Control Laws

1) Common attitude control law
2) Common momentum management law
3) Common attitude determination methods
    a. QUEST
    b. TRIAD
    c. Extended Kalman filter
4) Passive magnetic stabilization
5) Active magnetic stabilization
6) Bias momentum stabilization
7) Attitude control with reaction wheels

4. Sensors & Actuators

4.1. Sensors

All sensor measurements are taken in the sensor coordinate system and must be converted into the spacecraft coordinate system. Two linearly independent vector measurements need to be taken in order to determine attitude at any point.

Analog Sun Sensors

- Analog sun sensors are solar cells whose current input is related to the sun vector/sensor normal angle as $i(\theta) = i(0)\cos(\theta)$.
- One analog sun sensor provides a cone of possible sun directions; three analog sun sensor measurements can resolve the direction of the sun.
- Simple in design, low mass, low cost, but poor accuracy.

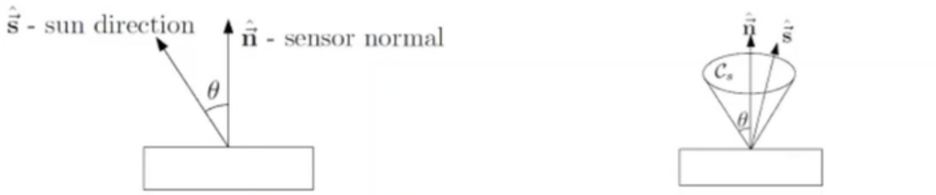

Figure 4: Analog Sun Sensor Diagrams

Magnetometers

- Three-axis magnetometers measure the local magnetic field vector.
- It is the most commonly used attitude sensor due to its low power consumption, compactness and robustness.
- Magnetometers are highly sensitive and reasonably priced.
- They are relatively inaccurate, but has no field of view or eclipse limitations.
- Its accuracy is dependent on the magnetic field model (IGRF2000) as well as residual magnetics from other devices on the spacecraft.

Gyroscopes

- A gyroscope is used to measure the orientation and angular velocity of a device using Earth's gravity.
- The gyroscopes will be used to provide and maintain a reference direction.

Please note that magnetorquers and magnetometers cannot be used at the same time; they must be run asynchronously as the magnetorquer creates a magnetic field while the magnetometer measures a magnetic field.

4.2. Actuators

Magnetorquers

- Magnetorquers are used for attitude control, detumbling and stabilization in a satellite system.
- The generated torque will always be perpendicular to the Earth's local magnetic field.

4.3. Objectives

1) Lightweight
2) Compact
3) Not emit any toxic fumes
4) Not require propellant handling
5) Low power consumption
6) Withstand external forces and torques during transportation and deployment
7) Reliable
8) Withstand thermal cycling
9) Low cost
10) Meet voltage requirements

4.4. Go/No-Go Matrices

Go/No-Go Matrix for Sensors in the Detumbling Phase

	1	2	3	4	5	6	7	8	9	10
3-Axis Digital Compass IC HMC5883L Magnetometer	G	G	G	G	G	G	G	NG	M	NG
3-Axis Digital Magnetometer IC	G	G	G	G	G	G	G	M	G	G
Tronics GYPRO2300	NG	G	G	G	G	G	G	M	G	G
Precision Navigation and Pointing Gyroscope	G	G	G	G	G	G	G	M	G	G
Precision Angular Rate Sensor	NG	G	G	G	G	G	G	M	G	G

Figure 5: Go/No-Go Matrix for Sensors in the Detumbling Phase

Go/No-Go Matrix for Actuators in the Detumbling Phase

	1	2	3	4	5	6	7	8	9	10
Mai -400 Reaction Wheel	G	G	G	G	M	G	G	G	NG	G
ISIS Magnetorquer Board	NG	NG	G	G	M	G	G	G	NG	G
NCTR-Moo2 Magnetorquer Rod	G	M	G	G	G	G	G	G	G	G
Cube Torquer and Cube Coil Bundle	G	M	G	G	M	G	G	G	G	G

Figure 6: Go/No-Go Matrix for Actuators in the Detumbling Phase

Go/No-Go Matrix for Sensors During Normal Operation

	1	2	3	4	5	6	7	8	9	10
3-Axis Digital Compass IC HMC5883L Magnetometer	G	G	G	G	G	G	G	NG	M	NG
3-Axis Digital Magnetometer IC	G	G	G	G	G	G	G	M	G	G
Tronics GYPRO2300	NG	G	G	G	G	G	G	M	G	G
Precision Navigation and Pointing Gyroscope	G	G	G	G	G	G	G	M	G	G
Precision Angular Rate Sensor	NG	G	G	G	G	G	G	M	G	G
CubeSense Sun and Nadir Sensor	M	NG	G	G	G	G	G	G	M	G
NSS Sun Sensor	G	G	G	G	M	G	G	G	G	G
Nadir Sensor from MAI	G	M	G	G	M	G	G	G	NG	G

Figure 7: Go/No-Go Matrix for Sensors During Normal Operation

Go/No-Go Matrix for Actuators During Normal Operation

	1	2	3	4	5	6	7	8	9	10
Mai -400 Reaction Wheel	G	G	G	G	M	G	G	G	NG	G
ISIS Magnetorquer Board	NG	NG	G	G	M	G	G	G	NG	G
NCTR-Moo2 Magnetorquer Rod	G	M	G	G	G	G	G	G	G	G
Cube Torquer and Cube Coil Bundle	G	M	G	G	M	G	G	G	G	G

Figure 8: Go/No-Go Matrix for Actuators During Normal Operation

4.5. Pairwise Comparison Chart

Detumbling Phase and Normal Operation

	1	2	3	4	5	6	7	8	9	10	Total	Weight
1	1	0.33	3	3	0.33	5	5	5	0.2	7	29.86	0.129
2	3	1	5	3	0.33	7	5	5	0.33	7	36.66	0.158
3	0.33	0.2	1	0.33	0.2	5	3	3	0.2	5	18.26	0.079
4	0.33	0.33	3	1	0.2	5	5	3	0.2	5	23.06	0.100
5	3	3	5	5	1	7	7	5	0.33	7	43.33	0.187
6	0.2	0.14	0.2	0.2	0.14	1	0.33	0.33	0.2	3	5.74	0.025
7	0.2	0.2	0.33	0.2	0.14	3	1	0.33	0.2	3	8.6	0.037
8	0.2	0.2	0.33	0.33	0.2	3	3	1	0.14	5	13.4	0.058
9	5	3	5	5	3	7	5	7	1	9	50	0.216
10	0.14	0.14	0.2	0.2	0.14	0.33	0.33	0.2	0.11	1	2.79	0.012
Total											**231.7**	**1**

Figure 9: Pairwise Comparison Chart for the Detumbling Phase and Normal Operation

4.6. Selection Matrices

Selection Matrix for Sensors in the Detumbling Phase

	Weight	3-Axis Digital Compass IC HMC5883L Magnetometer	3-Axis Digital Magnetometer IC	Tronics GYPRO2300	Precision Navigation and Pointing Gyroscope	Precision Angular Rate Sensor
1	0.129	0	0	-1	0	-1
2	0.158	0	0	0	0	0
3	0.079	0	0	0	0	0
4	0.100	0	0	0	0	0
5	0.187	0	0	0	0	0
6	0.025	0	0	0	0	0
7	0.037	0	0	0	0	0
8	0.058	0	1	1	1	1
9	0.216	0	1	1	1	1
10	0.012	0	1	1	1	1
Total	**1**	**0**	**0.286**	**0.157**	**0.286**	**0.157**

Figure 10: Selection Matrix for Sensors in the Detumbling Phase

Selection Matrix for Sensors in the Detumbling Phase

	Weight	CubeWheel Small	Mai-400 Reaction Wheel	ISIS Magnetorquer Board	NCTR-Moo2 Magnetorquer Rod	Cube Torquer and Cube Coil Bundle
1	0.129	0	0	-1	0	0
2	0.158	0	0	-1	-1	-1
3	0.079	0	0	0	0	0
4	0.100	0	0	0	0	0
5	0.187	0	-1	-1	0	-1
6	0.025	0	0	0	0	0
7	0.037	0	0	0	0	0
8	0.058	0	0	1	0	0
9	0.216	0	0	1	1	1
10	0.012	0	0	1	0	0
Total	**1**	**0**	**-0.187**	**-0.474**	**0.058**	**-0.129**

Figure 11: Selection Matrix for Sensors in the Detumbling Phase

Selection Matrix for Sensors During Normal Operation

	Weight	3-Axis Digital Compass IC HMC5883L Magnetometer	3-Axis Digital Magnetometer IC	Tronics GYPRO2300	Precision Navigation and Pointing Gyroscope	Precision Angular Rate Sensor	CubeSense Sun and Nadir Sensor	NSS Sun Sensor	Nadir Sensor from MAI
1	0.129	0	0	-1	0	-1	-1	0	0
2	0.158	0	0	0	0	0	-1	0	-1
3	0.079	0	0	0	0	0	0	0	0
4	0.100	0	0	0	0	0	0	0	0
5	0.187	0	0	0	0	0	0	-1	-1
6	0.025	0	0	0	0	0	0	0	0
7	0.037	0	0	0	0	0	0	0	0
8	0.058	0	1	1	1	1	1	1	1
9	0.216	0	1	1	1	1	0	1	-1
10	0.012	0	1	1	1	1	1	1	1
Total	**1**	**0**	**0.286**	**0.157**	**0.286**	**0.157**	**-0.217**	**0.099**	**-0.491**

Figure 12: Selection Matrix for Sensors During Normal Operation

Selection Matrix for Sensors in the Detumbling Phase

	Weight	CubeWheel Small	Mai-400 Reaction Wheel	ISIS Magnetorquer Board	NCTR-Moo2 Magnetorquer Rod	Cube Torquer and Cube Coil Bundle
1	0.129	0	0	-1	0	0
2	0.158	0	0	-1	-1	-1
3	0.079	0	0	0	0	0
4	0.100	0	0	0	0	0
5	0.187	0	-1	-1	0	-1
6	0.025	0	0	0	0	0
7	0.037	0	0	0	0	0
8	0.058	0	0	1	0	0
9	0.216	0	0	1	1	1
10	0.012	0	0	1	0	0
Total	**1**	**0**	**-0.187**	**-0.474**	**0.058**	**-0.129**

Figure 13: Selection Matrix for Sensors During Normal Operation

5. Test Bed

5.1. SolidWorks Model of Test Bed

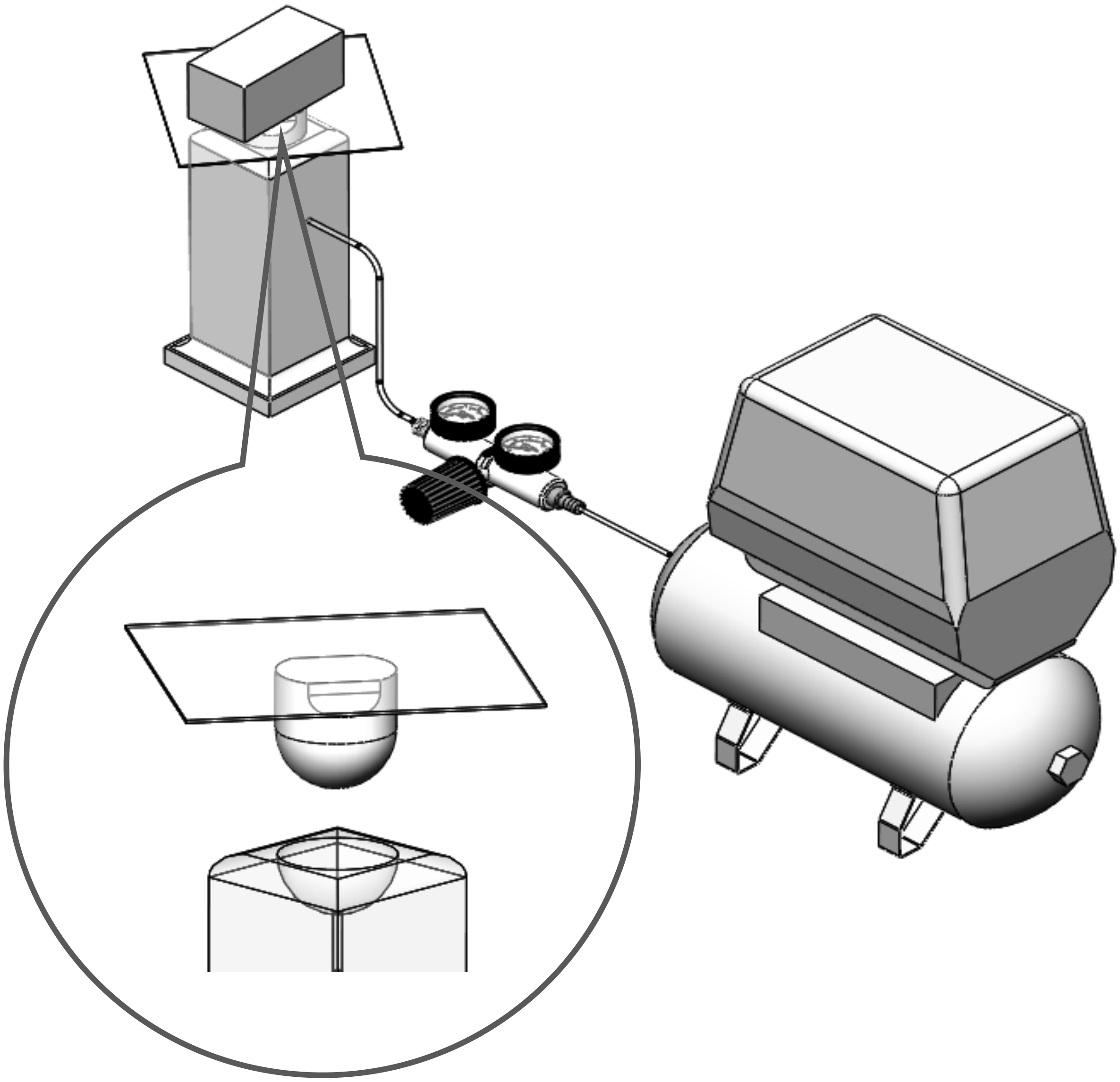

Figure 14: SolidWorks Model of Test Bed

- The purpose of the test bed is to represent a space environment as best as possible to test the final ADCS system design.
- Some features include:
    - Reaction wheels implemented to counteract the moment created from the platform;
    - Gyroscopes attached to the platform to measure the angular velocity and allow for accurate and repeatable test;
    - A spherical air bearing allowing 360 degrees of rotation in one axis and partial rotation in the other two axes, with limited friction in the bearing.
- The test bed will allow for testing in the detumbling mode and the normal mode of operation.

5.2. Y-Thompson Spin

- It essentially involves turning a 3-axis tumble into a tumble about only 1-axis; the y-axis in this case.
- It requires the inertia about the y-y axis is at least 5% greater than the inertia about the z-z axis.

5.3. Test Bed Go/No-Go Matrix

Go/No-Go Matrix for Test Bed

	Inexpensive	Rotation in 3 Axes	Limited Reaction Forces and Moments
Air Hockey Table	NG	NG	NG
String Suspension System	G	G	NG
Spherical Air Bearing	G	G	G

Figure 15: Go/No-Go Matrix for Test Bed

6. Glossary

ADCS: Attitude Determination and Control System
CSA: Canadian Space Agency
Detumbling: Returning the CubeSat to a controllable angular spin rate.
Dipole: A pair of equal and oppositely charged poles separated by a distance.
Drag: The force exerted on an object moving through a fluid such as air.
Micro-gravity: Small gravitational force experienced by the orbiting spacecraft due to the increased distance between the orbiting spacecraft and central body. It is governed by the universal law of gravitation:
$F = \frac{G(m_1 \times m_2)}{r^2}$; r is the distance between bodies
Radiation: The emission of energy as electromagnetic waves or as moving subatomic particles.
Solar pressure: Pressure spacecraft experience from the suns radiation (except when eclipsed by a larger body).
Vacuum: A space entirely devoid of matter.

7. Appendix

7.1. Gantt Chart