Project Of 1DOF Attitude Control System of 1U CubeSat Based On Reaction Wheel

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Introduction

Aim of the project:

- Develop and design an Attitude Determination and Control Subsystem (ADCS) for a 1U CubeSat using Reaction Wheels.

What does the final result look like:

1. **Attitude data** is measured by the Inertial Measurement Unit (IMU) of the ADCS.
2. **Modes of the satellite**: Detumbling mode, Pointing mode, Emergency mode, Default mode, among others.
3. **Bi-directional communication** between ground station and the nanosatellite for telemetry and telecommands.

PLATHON project

- Integration of an **Orbital Propagator**.
- Design and manufacturing of an emulator **Hardware-in-the-Loop (HiL)** to test engineering models of CubeSat.

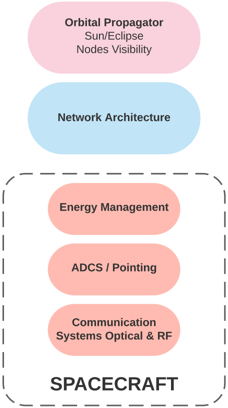


Figure 1: PLATHON diagram. Source: PLATHON [1].

PLATHON project

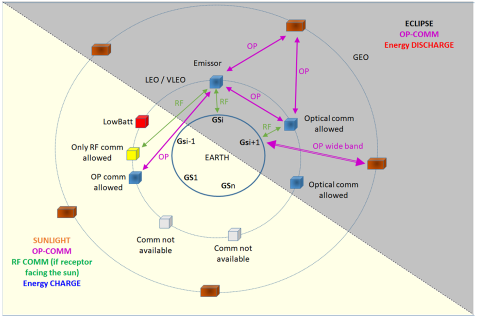


Figure 2: PLATHON Constellation diagram. Source: PLATHON [1].

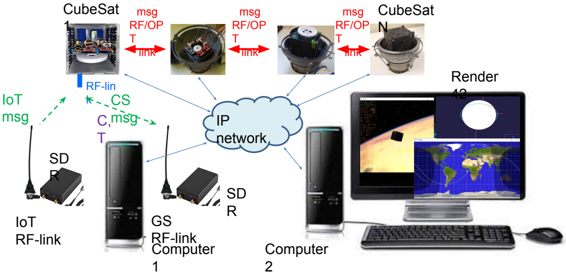


Figure 3: PLATHON system architecture diagram. Source: PLATHON [1].

State of the Art

- What is a **nanosatellite**?
  - Different sizes (1U, 2U, 3U, etc.)
  - For a 1U CubeSat:
    - Size: $10 \times 10 \times 10 \text{ cm}^3$
    - Mass: $1 - 1.33 \text{ kg}$

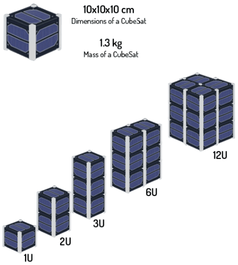


Figure 4: CubeSat sizes. Source: Alen Space [2].

- Why are nanosatellites such as CubeSats **important** compared to conventional satellites?
  - Shorter development period.
  - Reduced size and mass.
  - Lower budget needed (Inexpensive).

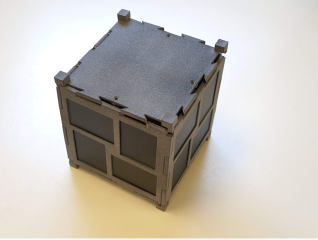


Figure 5: PLATHON CubeSat. Source: Own.

State of The Art

Why do we want to develop an Attitude Determination and Control Subsystem (ADCS)?

- Attitude Determination: Gather sensor inputs with spacecraft dynamics orientation information.
- Attitude Control: Control the orientation with the gathered data using physical actuators.

Attitude Determination and Control Subsystem

- Attitude Determination sensors and and Control Subsystem actuators

Table 1: ADCS Sensors and actuators. Source: Own.

Attitude Determination	**Attitude Control**
Sun Sensor	Thrusters
Magnetometer	Magnetorquers
Earth Horizon Sensor	Reaction Wheels
Star Trackers	
Gyroscopes	
Inertial Measurement Unit	

Reference frames

Earth-Centered Inertial (ECI) Reference Frame

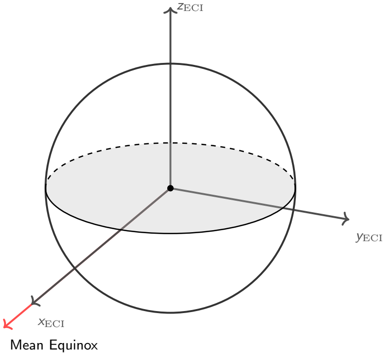


Figure 6: ECI reference frame with x_{ECEF} pointing towards the mean Equinox. Source: Own.

Earth-Centered Earth Fixed (ECEF) Reference Frame

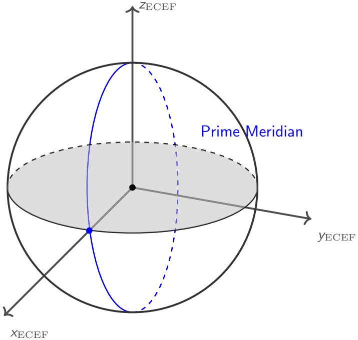


Figure 7: ECEF reference frame with the x-axis pointing to the fixed point on the Prime Meridian. Source: Own.

Reference frames (cont.)

Orbit Reference Frame

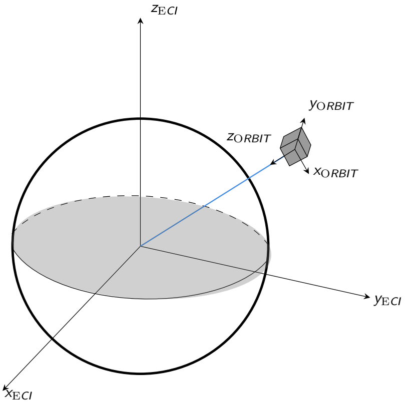


Figure 8: Orbit Reference Frame. Source: Own.

Body Reference Frame

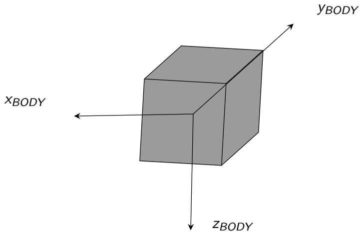


Figure 9: Body Reference Frame. Source: Own.

Euler angles and quaternions

Euler Angles

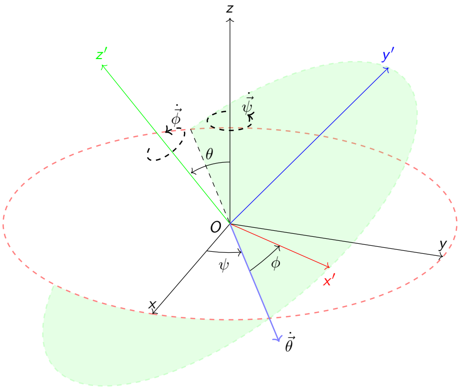


Figure 10: Euler Angles. Source: Own.

Angles:

- Yaw: ψ
- Roll: ϕ
- Pitch: θ

Problem: Euler Gimbal Lock

- Loss of 1DOF when two of three gimbals are driven into parallel configuration.

URL: Quaternions animation

URL: Gimbal Lock animation

Disturbance torques modelling

External disturbance torques

Any spacecraft orbiting Earth is subject to some perturbations and disturbance forces and torques. These perturbations come from various sources and their magnitude and direction depend on different physical properties of the satellite such as its weight, shape, material, etc. Whenever a force is not acting through the COM of the satellite it will result in a net torque.

The most important ones are:

- Aerodynamic Drag
- Gravity gradient torque
- Geomagnetic field torque
- Solar Radiation Pressure

Disturbance torques modelling (cont.)

Total effect of the disturbances torques

Table 2: Summary of external disturbance torques and their contribution. Source: Own.

	Disturbance Torque	**Magnitude** $[\mathrm{Nm}]$
τ_D	Aerodynamic	$3.9939 \cdot 10^{-7}$
τ_{gg}	Gravity Gradient	$2.3594 \cdot 10^{-10}$
τ_{m}	Geomagnetic Field	$4.9763 \cdot 10^{-5}$
τ_{SRP}	Solar Radiation Pressure	$2.1979 \cdot 10^{-9}$
τ	TOTAL	$5.0165 \cdot 10^{-5}$

Reaction Wheel Design

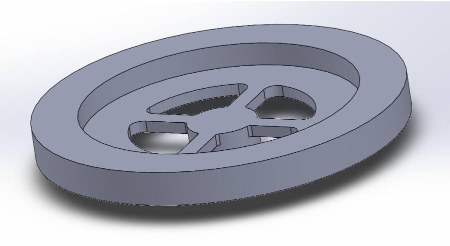


Figure 11: Reaction wheel CAD design. Source: Own.

Table 3: Reaction Wheel design parameters

Part	**Parameter**	**Value** [mm]
Disk radius	r_{disk}	60
Ring radius	r_{ring}	80
Disk height	h_{disk}	2.5
Ring height	h_{Ring}	7.5

Material Used

- PLA with a density of 1.24 $\mathrm{g/cm^3}$

Inertia

- Inertia of 0.2720 $\mathrm{Nm^3}$

ADCS board diagram

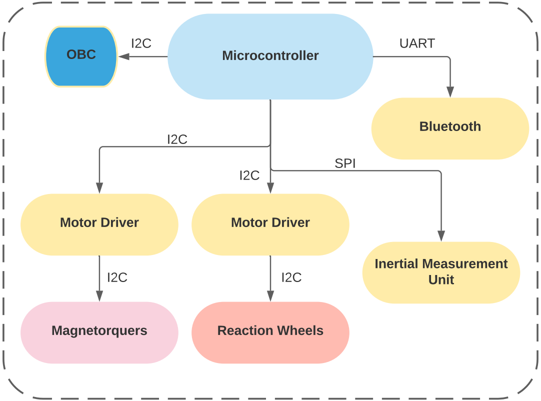


Figure 12: ADCS Board diagram. Source: Own.

ADCS board assembly

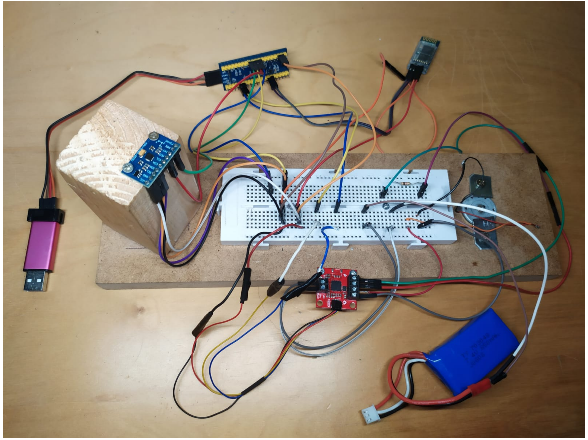


Figure 13: ADCS breadboard assembly. Source: Own.

PCB design

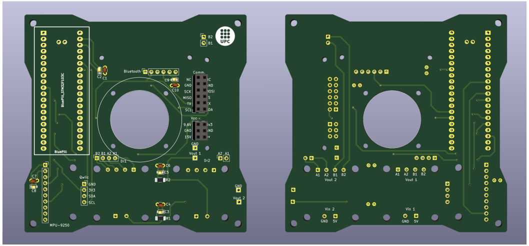


Figure 14: PCB layout (front and back). Source: Own.

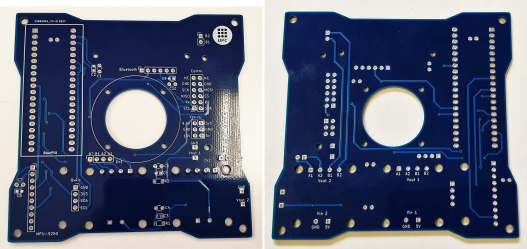


Figure 15: Physical PCB (front and back). Source: Own.

PCB design

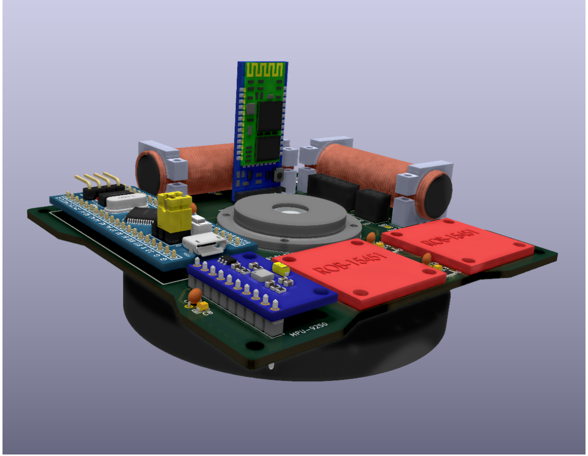


Figure 16: Final PCB assembly render. Source: Own.

PCB design

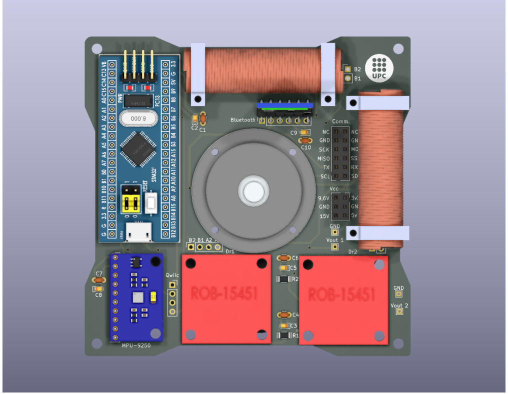


Figure 17: Final PCB assembly top render view. Source: Own.

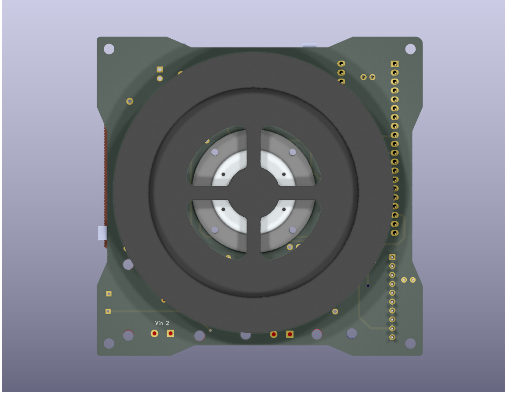


Figure 18: Final PCB assembly bottom render view. Source: Own.

PCB design

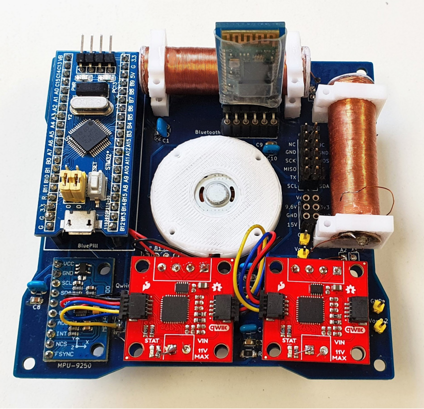


Figure 19: PCB layout top view. Source: Own.

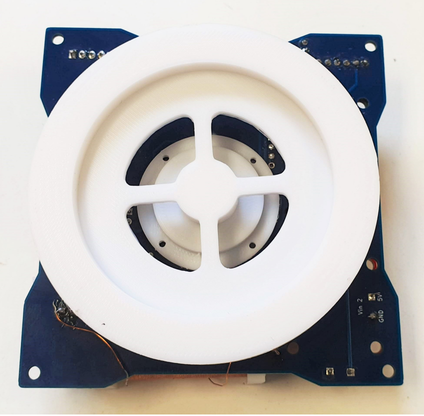


Figure 20: PCB layout bottom view. Source: Own.

PCB design

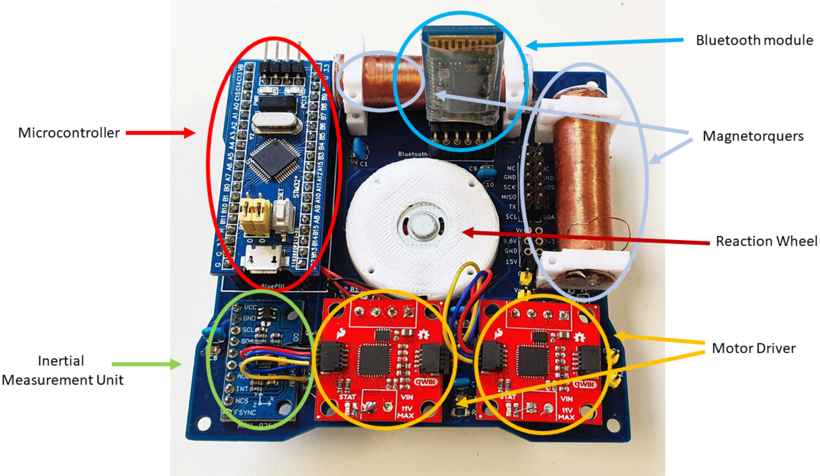


Figure 21: Components on the PCB. Source: Own.

Final mount

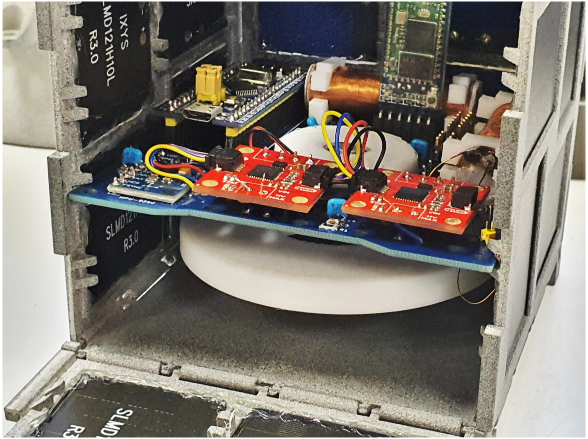


Figure 22: ADCS board inside the CubeSat. Source: Own.

Expected result: URL: ADCS Control video

Control algorithm

Body Reference Frame: Components coordinate system

Control modes

- Input wait mode
- IMU reading mode
- Motor ON/OFF mode
- Set velocity mode
- Emergency stop mode
  - Coarse pointing mode
  - Fine pointing mode

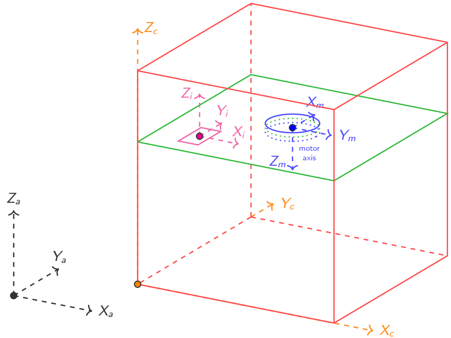


Figure 23: CubeSat reference frames. Source: Own.

Coarse Pointing mode

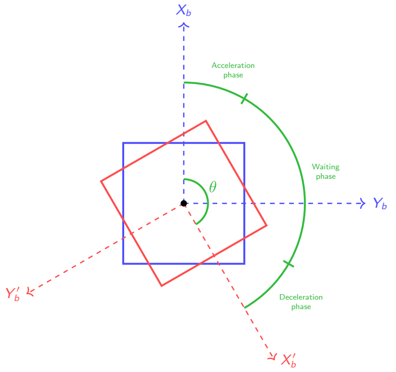


Figure 24: Coarse pointing mode manoeuvre. Source: Own.

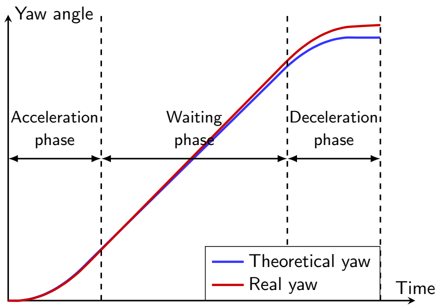


Figure 25: Yaw angle diagram (Sketch). Source: Own.

Fine Pointing mode

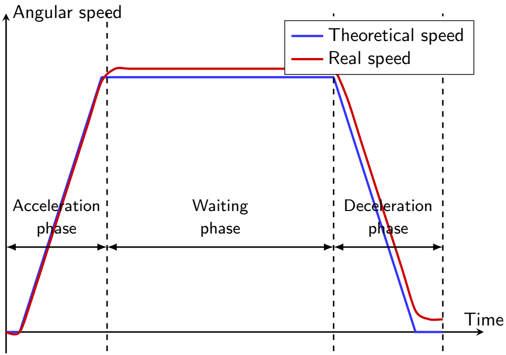


Figure 26: Angular speed diagram (Sketch). Source: Own.

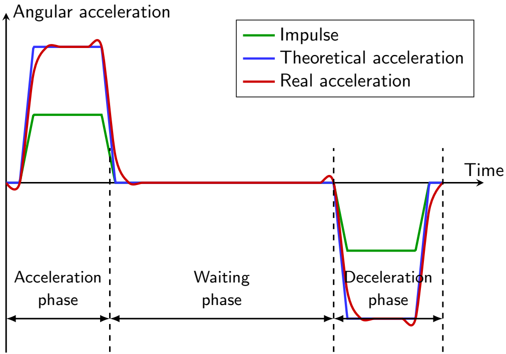


Figure 27: Angular acceleration diagram (Sketch). Source: Own.

Coarse pointing mode

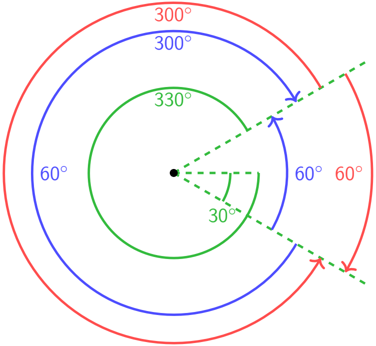


Figure 28: Turn diagram. Source: Own.

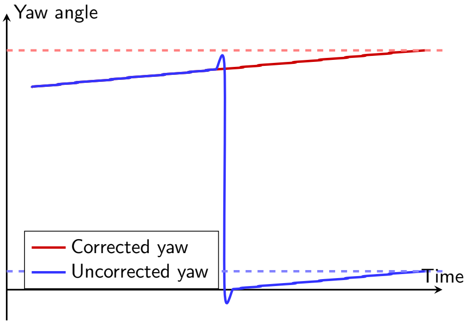


Figure 29: Yaw angle diagram when the CubeSat passes through 0° angle (Sketch). Source: Own.

Fine Pointing mode

The formula of a PID controller is defined as follows:

$$u(t) = \underbrace{K_p e(t)}_{\text{Proportional}} + \underbrace{K_i \int e(t)\mathrm{d}t}_{\text{Integral}} + \underbrace{K_d \frac{\mathrm{d}e}{\mathrm{d}t}}_{\text{Derivative}} \quad (1)$$

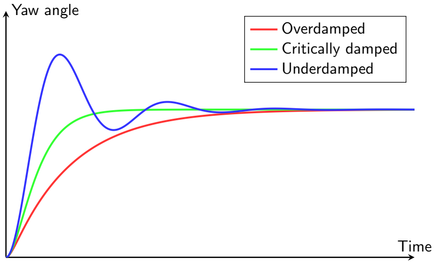


Figure 30: System's possible response outcomes [yaw angle] (Sketch). Source: Own.

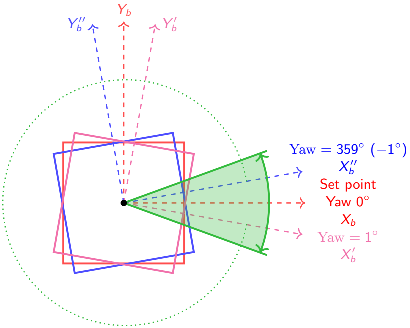


Figure 31: Fine Pointing diagram. Source: Own.

Performance and Tests

3D visualization of the results

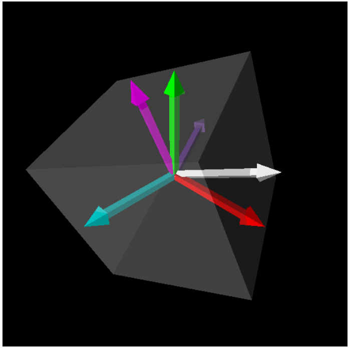


Figure 32: Real-time Python visualization. Source: Own.

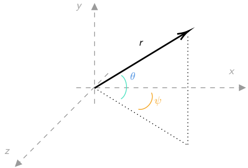


Figure 33: Pitch, Roll and Yaw angles in absolute reference frame (see Figure 23). Source: Own.

The x, y and z position of any point can be expressed as:

$$x = r\cos\phi\cos\theta \quad (2)$$

$$y = r\sin\phi\cos\theta \quad (3)$$

$$z = r\sin\theta \quad (4)$$

Performance and Tests

Experiment setup

(a) Air bearing structure. Source: Own.

(b) Air bearing with CubeSat mount. Source: Own.

Figure 34: Air bearing. Source: Own.

(a) Cubesat mounted on Air Bearing. Source: Own.

(b) Full CubeSat structure mounted on Air Bearing. Source: Own.

Figure 35: Cubesat on Air Bearing. Source: Own.

Results

Stable velocity

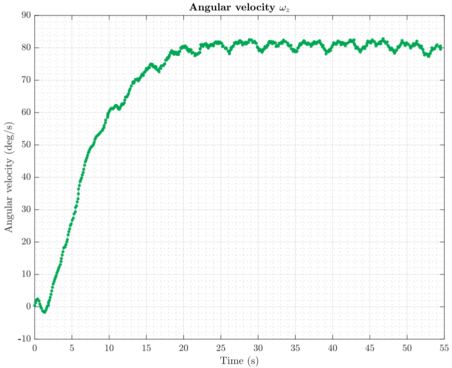


Figure 36: Maximum velocity reached in acceleration phase. Source: Own.

Results

Coarse pointing mode

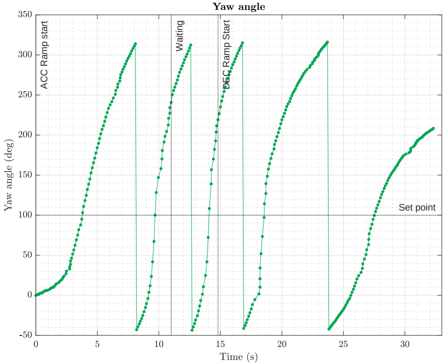


Figure 37: Maximum velocity reached in acceleration phase. Source: Own.

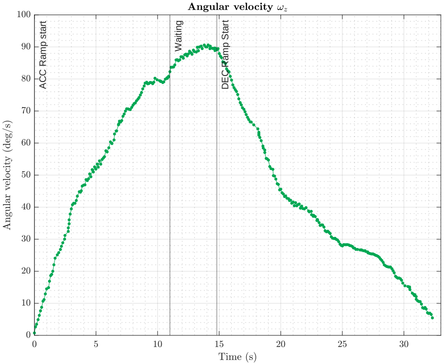


Figure 38: Maximum velocity reached in acceleration phase. Source: Own.

Results

Coarse + Fine pointing mode (PD)

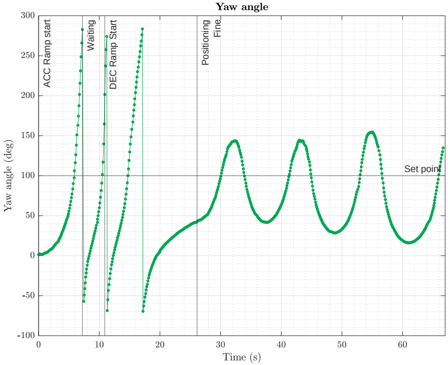


Figure 39: Maximum velocity reached in acceleration phase. Source: Own.

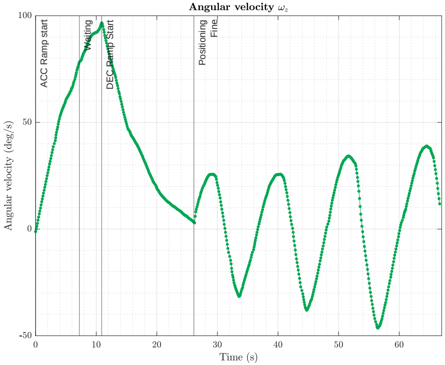


Figure 40: Maximum velocity reached in acceleration phase. Source: Own.

Results

Coarse + Fine pointing mode (PID)

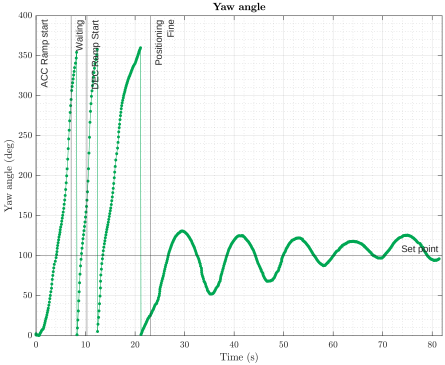


Figure 41: Maximum velocity reached in acceleration phase. Source: Own.

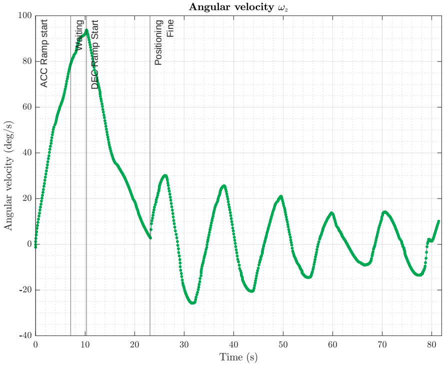


Figure 42: Maximum velocity reached in acceleration phase. Source: Own.

Results

PID output

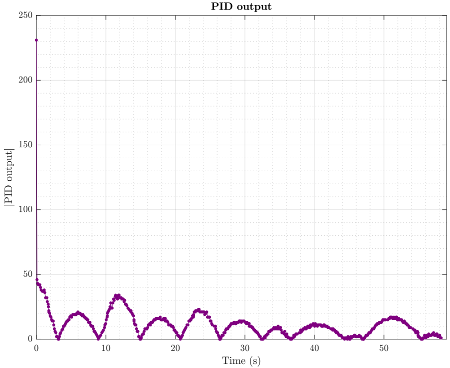


Figure 43: Maximum velocity reached in acceleration phase. Source: Own.

Conclusions

Budget

Table 4: Total budget. Source: Own.

Total budget	
Concept	**Budget (€)**
Electrical components	347.49 €
3D printed pieces	802.52 €
PCB manufacturing	36.96 €
Software licenses	2133.40 €
Personnel salary	9710.44 €
TOTAL	**13030.81 €**

Conclusions

Enviromental impact

Table 5: Power consumption and kg CO_2 emission

Activity	**Time** $[\mathrm{h}]$	**Power** kW	**Impact factor** $[\mathrm{kg}\ CO_2/\mathrm{kg}\cdot\mathrm{h}]$	kg CO_2
Laptop	382	0.30	0.2	22.92
3D manufacturing	32	0.35	0.2	2.24

Conclusions

What have I contributed to PLATHON's project?

1. Review of the mathematical and physical equations regarding **quaternions** and **Euler angles**.
2. Analytical estimation of the worst-case **disturbance torques** effects for the mission.
3. Development of a a detailed control algorithm for **fine pointing** and **coarse pointing** modes in the orbit as well as a **3D real-time monitoring** interface.
4. **Design of the Reaction Wheel** following the technical requirements set by the project specifications and PCB assembly.
5. **Hardware-in-the-loop testing and optimization** of the control algorithm.

Future Work and improvements

What is the next step?

- Employ **quaternions** instead of Euler angles to extrapolate to a **3DOF control**.
- **Vibrations** are induced to the IMU, use a better low-pass filter or place the IMU in another board or include a **damping system**.
- Reduce the **size of the Reaction Wheel** as results demonstrate it has too much inertia.
- Use a motor with a **higher torque** and faster response.
- Make use of a **ramp signal** instead of a step impulse to better control the velocity.
- Add the **influence of disturbances torques** to the control algorithm.
- **Join** magnetorquer's team **detumbling mode** with B-dot algorithm with Reaction Wheels control code.
- Develop a **graphical interface** instead of commands.

Future Work and improvements

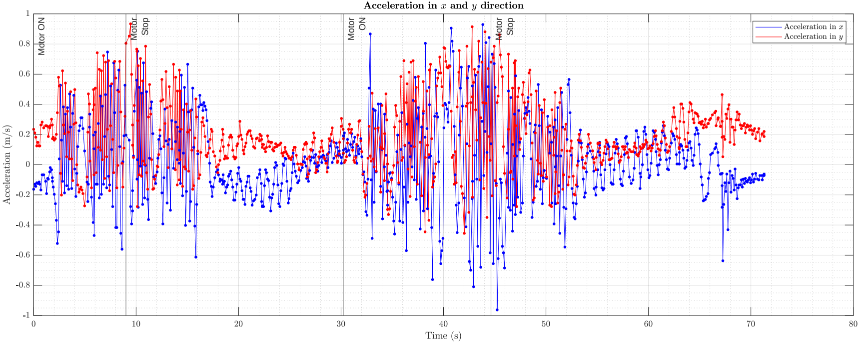


Figure 44: Acceleration in x and y direction. Source: Own.

Work

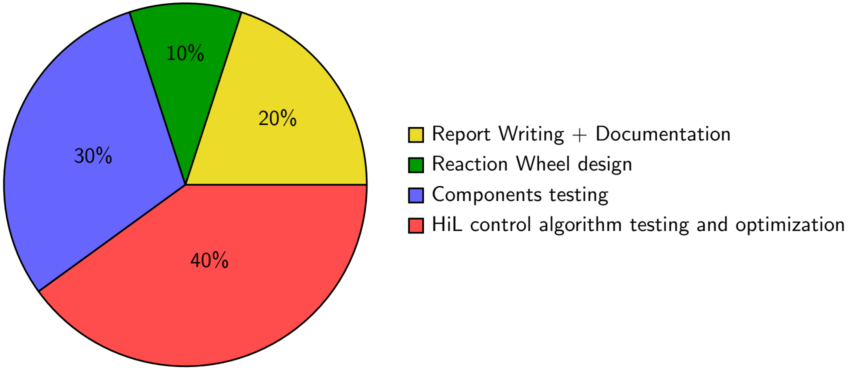


Figure 45: Work organisation. Source: Own.

Questions

Thanks for your attention!
Questions turn

References

[1] Gonzalez, David. (2021). Integrated Hardware in the loop simulation PLATform of Optical communications in Nanosatellites. UPC. (Cit. on pp. 5, 6).

[2] Alén Space. (2021). A Basic Guide to Nanosatellites — Alén Space. Retrieved May 16, 2021, from https://alen.space/basic-guide-nanosatellites/. (Cit. on p. 8)

[3] NASA. (1971). *Vehicle Design Criteria - Spacecraft Aerodynamic Torques* (tech. rep.). (Cit. on p. 54).

[4] NASA. (1969a). *Vehicle Design Criteria - Spacecraft Gravitational Torques* (tech. rep.). (Cit. on p. 56).

[5] NASA. (1969b). *Vehicle Design Criteria - Spacecraft Magnetic Torques* (tech. rep.). http://www.dept.aoe.vt.edu/$%5Csim$cdhall/courses/aoe4065/NASADesignSPs/sp8018.pdf. (Cit. on p. 56)

[6] NASA. (1969c). *Vehicle Design Criteria - Spacecraft Radiation Torques* (tech. rep.). http://www.dept.aoe.vt.edu/$%5Csim$cdhall/courses/aoe4065/NASADesignSPs/sp8027.pdf. (Cit. on p. 56)

State of The Art

- **How much does it cost to develop and launch a CubeSat?**

  According to NanoSatLab team from UPC, it can cost 500 thousand € compared to conventional ones that can rise up to 500 million €.

- **What are their orbits and how long does their operational life last?**

  Low-Earth Orbits ($400 - 600$ km) at approximately 8 km/s.

- **Why do we want to develop an Attitude Determination and Control Subsystem (ADCS)**?
  - Attitude Determination: Gather sensor inputs with spacecraft dynamics orientation information.
  - Attitude Control: Control the orientation with the gathered data using physical actuators.

- **What are the applications of nanosatellites?**

  Earth Observation, Communication and Internet of Things (IoT), Scientific Applications, among others.

Mathematical Description of the Physics

Orbit Classification

- Low-Earth Orbit (LEO): $\approx 400\ \mathrm{km}$
- Closed Elliptical $0 < e < 1$ orbit.

Table 6: Conic sections of an orbit. Source: Own.

Orbit type	Height[1]
Low-Earth Orbit (LEO)	$400 - 2000\ \mathrm{km}$
Medium-Earth Orbit (MEO)	$2000 - 20000\ \mathrm{km}$
High-Elliptic Orbit (HEO)	$> 20000\ \mathrm{km}$

Table 7: Conic sections of an orbit. Source: Own.

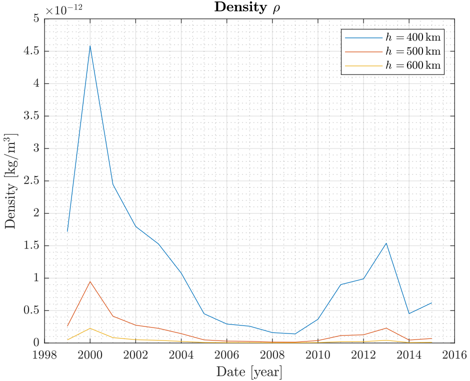
Eccentricity	Conic section	Trajectory
$e = 0$	Circle	Closed
$0 < e < 1$	Ellipse	Closed
$e = 1$	Parabola	Open
$e > 1$	Hyperbola	Closed

[1] Above Earth's surface

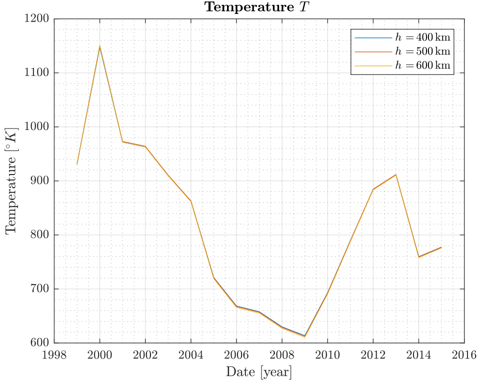
Disturbance torques modelling

Aerodynamic Drag [3]

$$\mathrm{d}\tau_{D,\max} = \left\{\rho\left[\left(2-\sigma_{\mathrm{n}}-\sigma_{t}\right)\left(v^{\mathrm{T}} n_{\mathrm{d}A}\right) n_{\mathrm{d}A}+\sigma_{\mathrm{t}} v\right] v^{\mathrm{T}} n_{\mathrm{d}A} \mathrm{d}A\right\} \cdot\left(r_{\mathrm{d}A}-r_{\mathrm{cg}}\right) \tag{5}$$



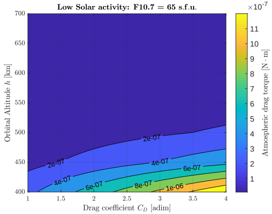
(a) Density from 1999 to 2015. Source: Own.



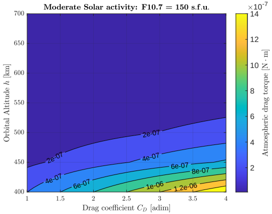
(b) Temperature from 1999 to 2015. Source: Own.

Figure 46: Density and temperature fluctuation from 1999 to 2015 using JB2008. Source: Own.

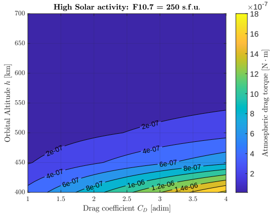
Disturbance torques modelling (cont.)



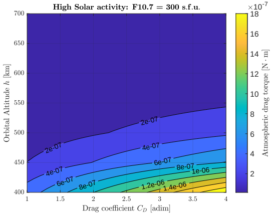
(a) Low Solar activity: F10.7 = 65 s.f.u.. Source: Own.



(b) Moderate Solar activity: F10.7 = 150 s.f.u.. Source: Own.



(c) High Solar activity: F10.7 = 250 s.f.u.. Source: Own.



(d) High Solar activity: F10.7 = 300 s.f.u.. Source: Own.

Figure 47: Evolution of the atmospheric torque in terms of h, C_D and the solar activity using JB2008. Source: Own.

Disturbance torques modelling (cont.)

Gravity gradient torque [4]

$$\tau_{\mathrm{gg,max}} = \frac{3\mu_{\mathrm{Earth}}}{2R^3_{\mathrm{Orbit}}}\left(I_{\mathrm{sat,max}} - I_{\mathrm{sat,min}}\right) \cdot \sin(2\theta_{\mathrm{dev}}) \tag{6}$$

Geomagnetic field torque [5]

$$\tau_{\mathrm{m,max}} = M_{\mathrm{sat}} \cdot \frac{2 \cdot R^3_{\mathrm{Earth}} H_0}{\vec{R}^3_{\mathrm{Orbit}}} \tag{7}$$

Solar Radiation Pressure [6]

$$\tau_{\mathrm{SRP,max}} = \left\{ \frac{I_{\mathrm{SRP}}}{c} \left\{ -\left[(1 + c_{rs}) \cos\alpha + \frac{2}{3} c_{rd} \right] \hat{n} + (1 - c_{rs}) \sin\alpha \ \hat{s} \right\} \cos\alpha \ \mathrm{d}A_{\mathrm{inc}} \right\} \cdot (r_{\mathrm{d}A} - r_{\mathrm{cg}}) \tag{8}$$

Reaction Wheel Inertia

The inertial momentum of the disk is given by the following equation:

$$I_{\mathrm{RW,disk}} = \frac{m_{\mathrm{RW,disk}}\ r^2_{\mathrm{disk}}}{2} = \frac{0.0335 \cdot 0.06^2}{2} = \boxed{6.03 \cdot 10^{-5}\ \mathrm{kg} \cdot \mathrm{m}^2} \tag{9}$$

The inertial momentum of the ring is given by the following equation:

$$I_{\mathrm{RW,ring}} = \frac{m_{\mathrm{RW,ring}}\ r^2_{\mathrm{ring}}}{2} = \frac{0.0818 \cdot (0.08^2 + 0.06^2)}{2} = \boxed{4.09 \cdot 10^{-4}\ \mathrm{kg} \cdot \mathrm{m}^2} \tag{10}$$

Finally, with the known design parameters, the inertial momentum of the reaction wheel can be deduced:

$$I_{RW} = I_{\mathrm{disk}} + I_{\mathrm{ring}} = \boxed{4.693 \cdot 10^{-4}\ \mathrm{kg} \cdot \mathrm{m}^2} \tag{11}$$

The torque

$$\tau_{\mathrm{RW}} = m_{\mathrm{RW}} \cdot r_{\mathrm{ring}} \cdot v_{\mathrm{RW}} + I_{\mathrm{RW}} \cdot \alpha = 0.1153 \cdot 0.08 \cdot 29.49 + 0 = \boxed{0.2720\ \mathrm{N} \cdot \mathrm{m}} \tag{12}$$

considering the Cubesat is in stationary phase (no angular acceleration $\alpha = 0$) and $v_{\mathrm{RW}} = \omega_{\mathrm{RW}} r_{\mathrm{ring}} = 29.49\ \mathrm{m/s}$

Algorithm flowchart

URL: Flowchart algorithm

Code repository

URL: Code repository