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Legged drone for underground cave exploration

Irene Terlizzi - 39th Cycle

3rd year acceptance

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Project description:

The purpose is to design a system, that maximizes the benefits offered by both ground and aerial platforms:

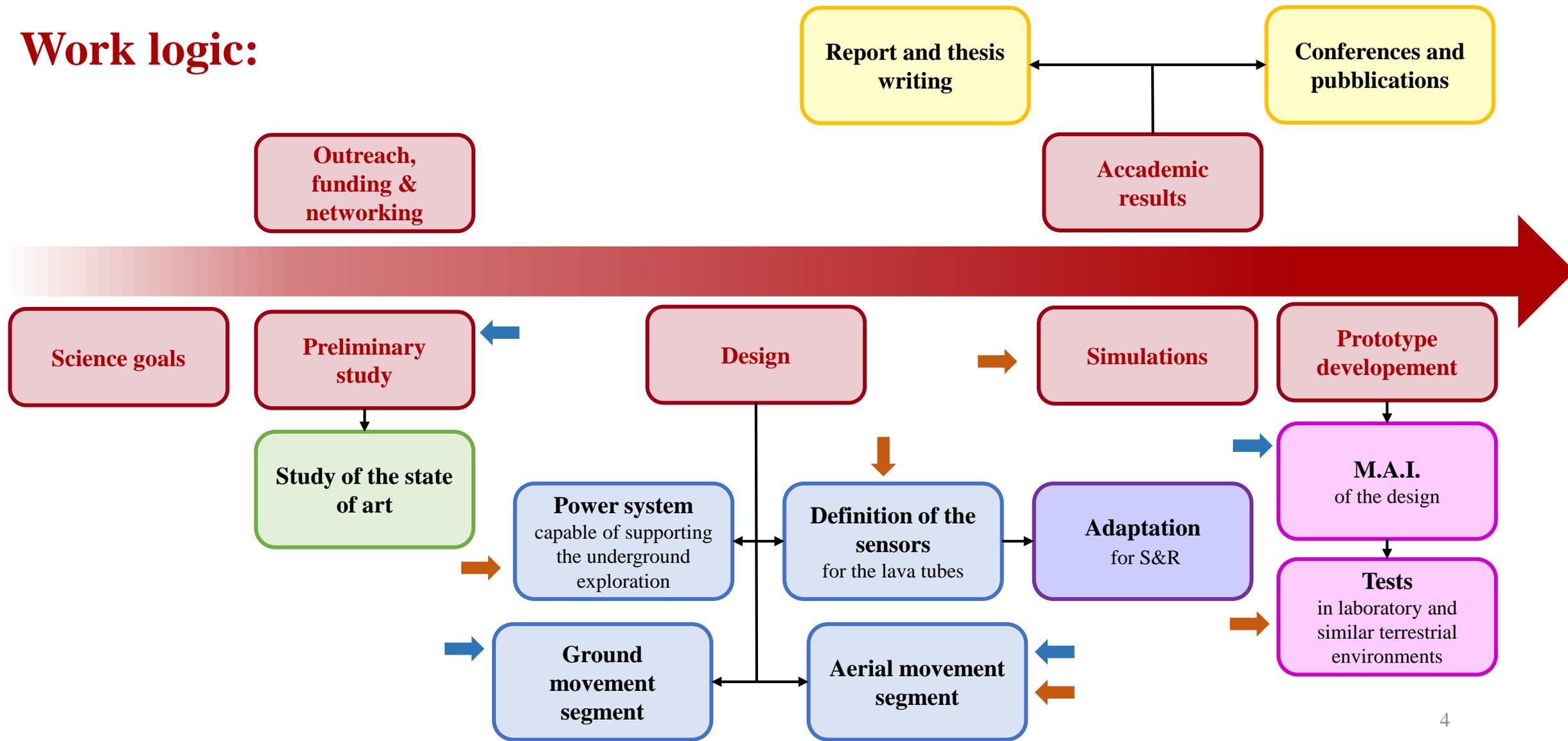
- Support lunar and planetary exploration by venturing into Martian and Lunar lava tubes
- Assisting in terrestrial operations like search and rescue or analyzing underground at-risk environments.

Both are environment of unknown features as slopes, dimensions and terrains.

The design considers two subsystem:

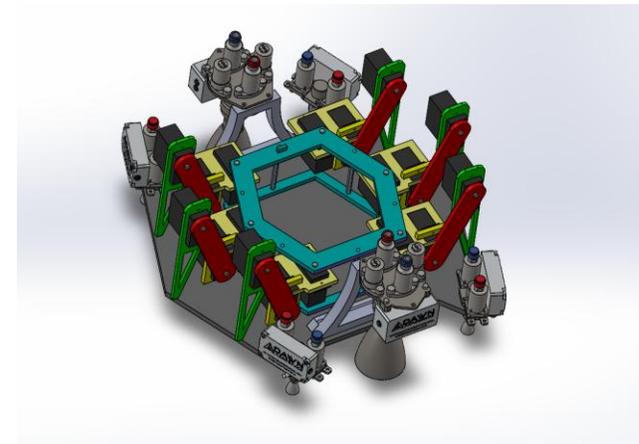
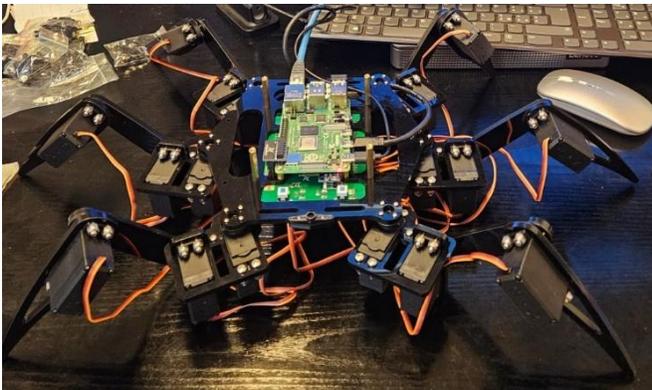
- **Legged hexapod** which composes the ground segment and hosts the sensor suite to analyse the environment
- **Thrusted system** which composes the aerial segment and has as objective to take the ground segment inside the cave (*Simulated*)

Work logic:



First year focus:

- The goals for the first year of the PhD were related to the drone architecture: various configurations were considered for both the ground and aerial segments.
- The problem of the ground segment was mainly related to the large number of actuators planned, but it has been decided to implement this solution as priority was given to the versatility
- For the aerial segment the thrusters were selected





Second year focus:

•Vertical Landing Simulation

- Modeled lunar descent with gravity & terrain effects
- Started developing attitude control strategy, tested in multiple iterations

•Aerial System Redesign

- Refined thruster configuration for better stability

•Power Supply Alternatives

- Investigated options beyond standard batteries (e.g., wireless power transfer, solar recharge at skylight)

•Period Abroad

- Learned new methodologies (system engineering, KPI-driven design)

• Sensor Suite Development

- Compact, modular suite (2P picosat volume)
- Includes stereo camera, thermal–humidity sensors, Geiger–Müller tube, and soil-contact humidity probes

Abroad period:

ispace, inc. Tokyo, Japan

MBSE (Model-based system engineering)

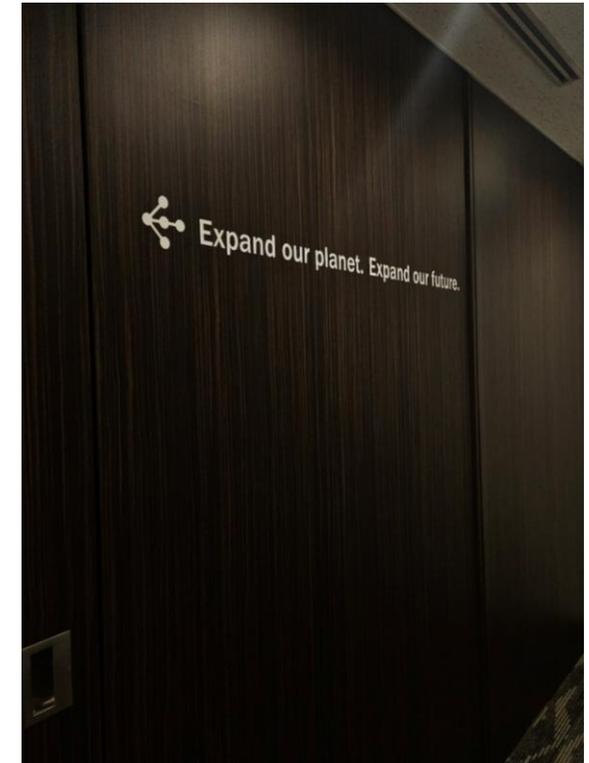
Systems engineering tasks and developed models (and tests) in python to support them.

Tasks were related to trade space simulations for feasibility studies for cis-lunar projects (landers, orbiters), together with the necessary documentation to analyze and report the results.

Main activities consisted in:

- Gimbal kinematic studies for pointing requirements, from the perspective of orbiters and landers
- Separation validation study with orbital mechanics
- Sensitivity studies of key performance indicators related to different areas (communication data rates and coverage, angular momentum budgets, power budgets) considering different hardware configurations, orbits and operations.





Abroad

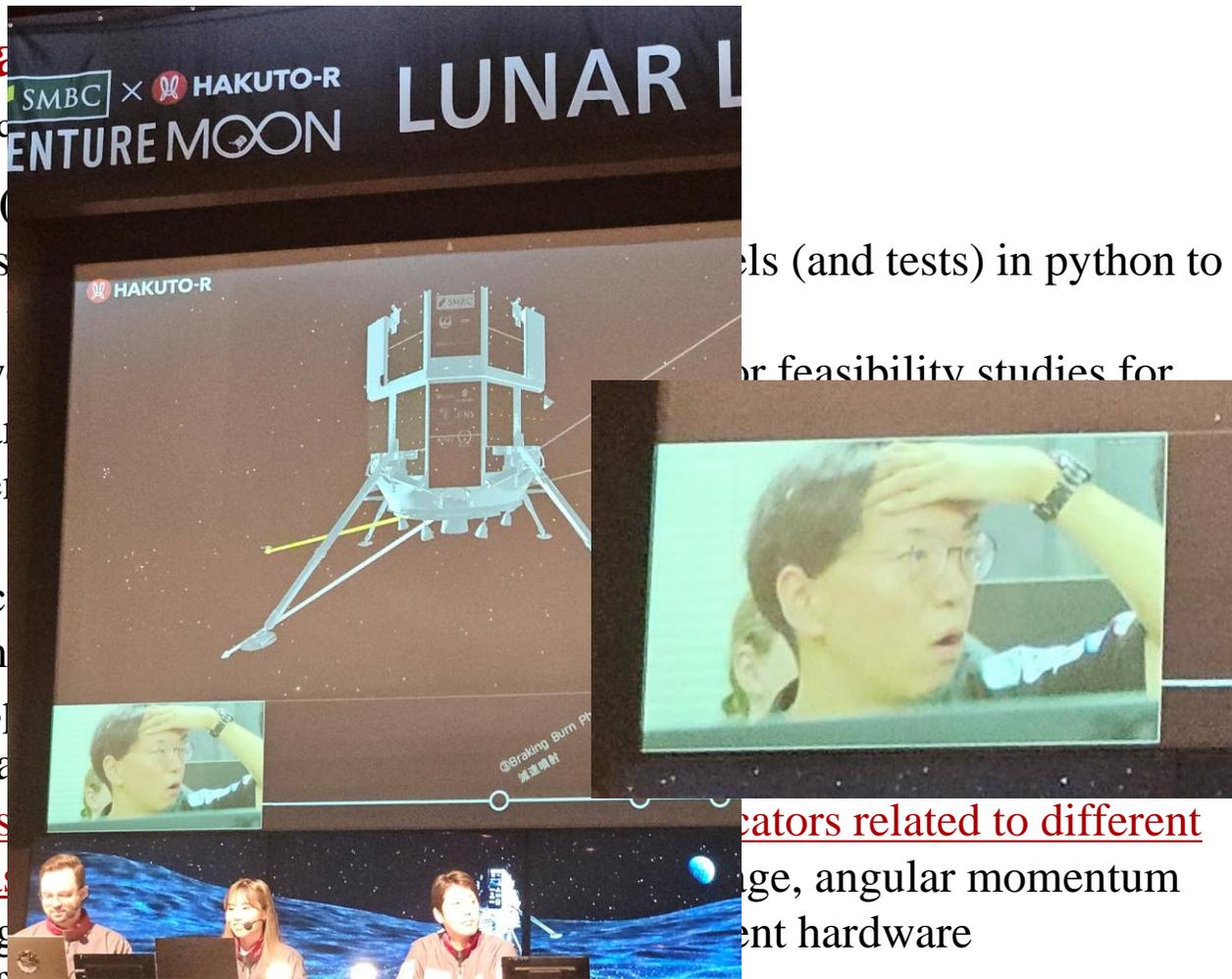
inspace, inc

MBSE (Model-Based Systems Engineering)

Systems
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Main activities

- Gimbal
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- configurations, orbits and operations.

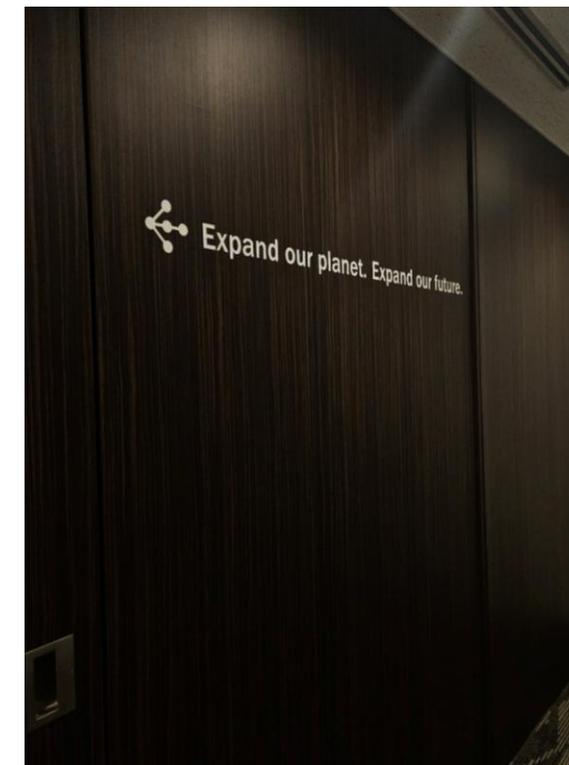


models (and tests) in python to

for feasibility studies for

parameters related to different

size, angular momentum
ent hardware



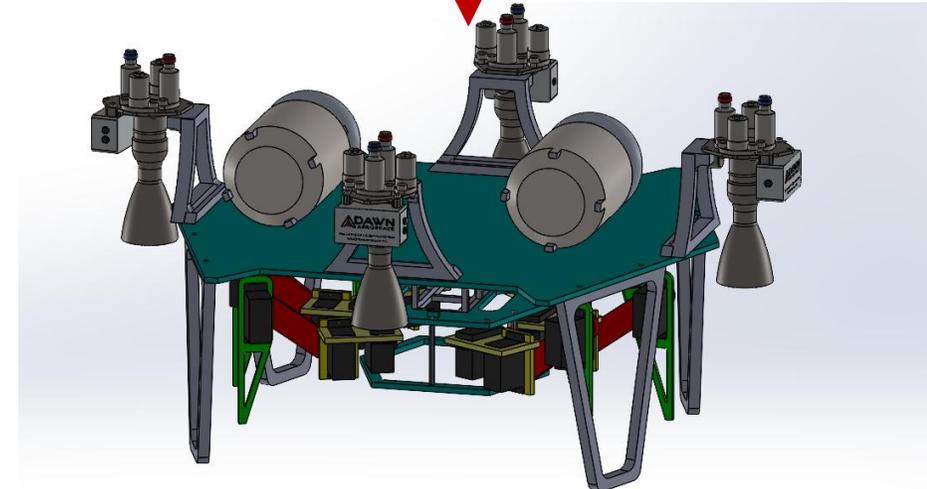
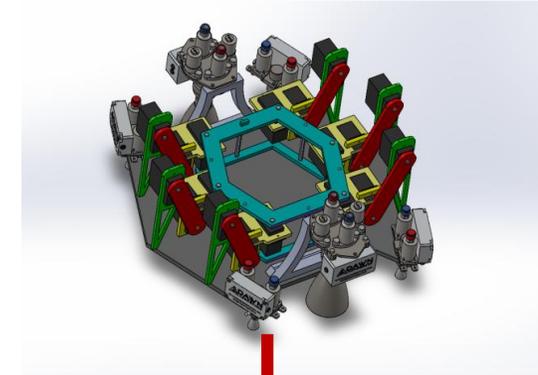
Aerial movement(1):

- Two main B20 retro-thrusters + four smaller B21 retro-thrusters (250g each and maximum thrust of 1,35N each). Arranged symmetrically around the drone to ensure balance



- Four B20 retro-thrusters. Instead of having the aerial platform at the bottom, the ground segment will be connected to them via an interface (to be studied).
- In the CAD thrusters are fixed, in the new iteration of the design they have one degree of freedom

Thruster dimensions	176 x 80 x 79 mm
Dry mass	695 g
Nozzle expansion ratio	100:1
Thrust, range	6.1 to 16.7 N
Specific impulse	277 s





Aerial movement(2):

•Redesign & Modelling

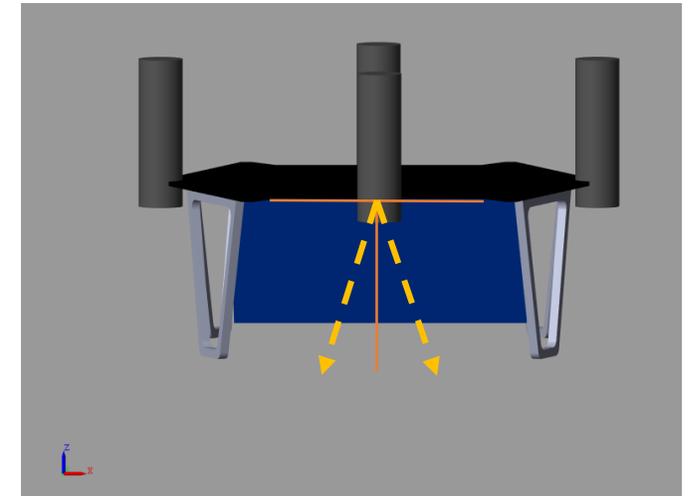
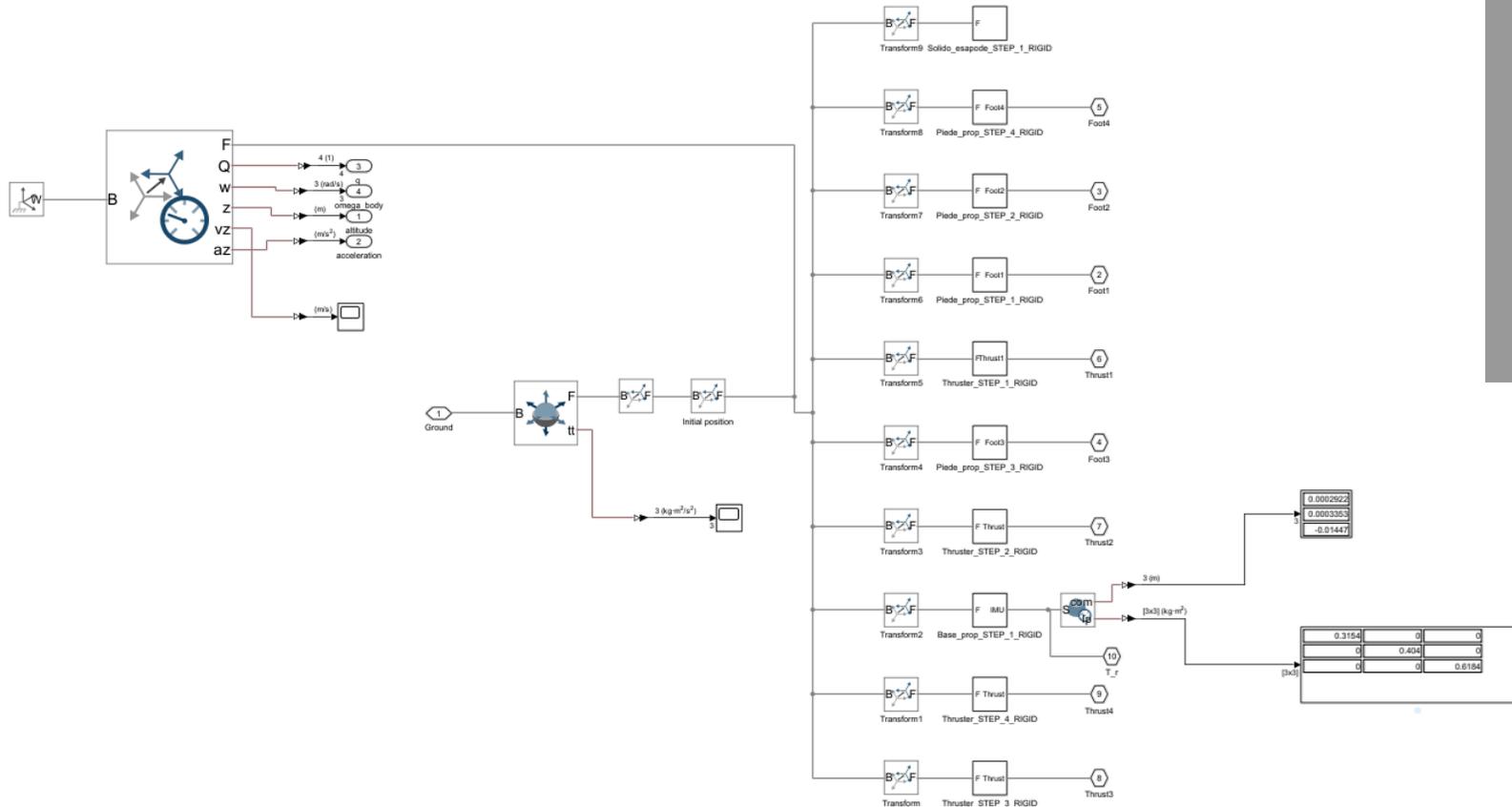
- System reconfigured for efficiency
- Simplified geometries for initial analysis
- Imported into **Simulink** with environmental factors:
 - Lunar gravity
 - Surface contact dynamics

•Control Approaches

- Initial:** Fixed thrusters exploiting natural symmetry
- Later iterations:** Optimization-based thrust allocation
- Each thruster with **1 degree of freedom**
- Achieved **full rotational control** across three axes

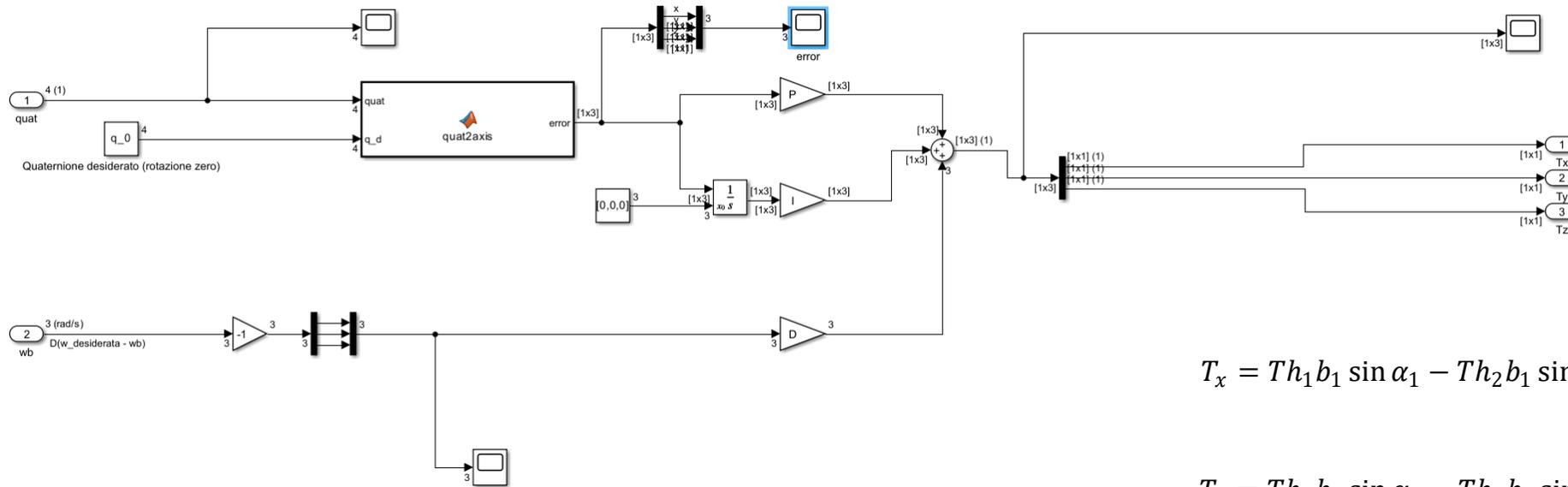
Aerial movement(3):

- Mech. subsystem



Aerial movement(4):

- Attitude control with PID



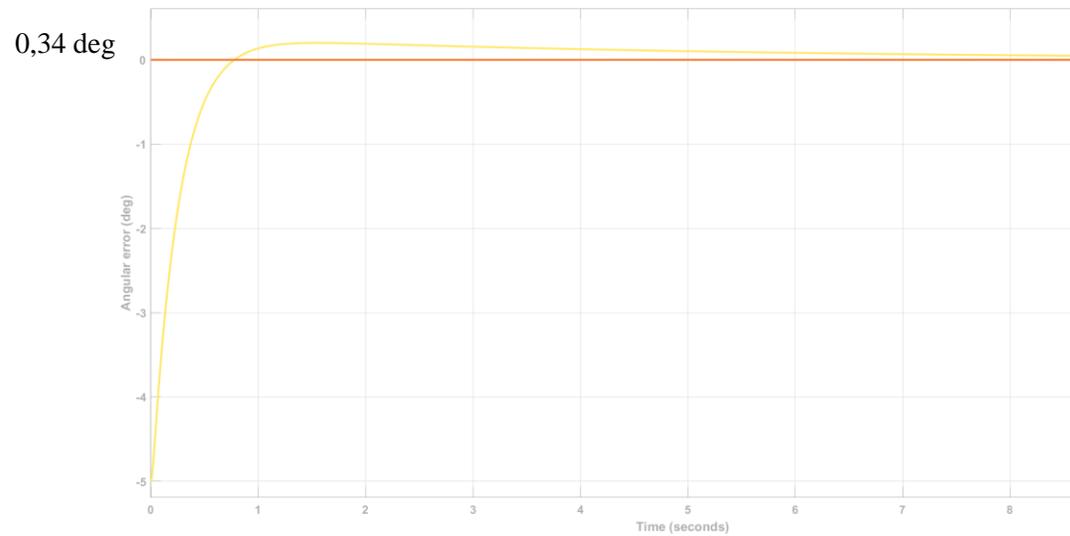
$$T_x = Th_1 b_1 \sin \alpha_1 - Th_2 b_1 \sin \alpha_2$$

$$T_y = Th_4 b_2 \sin \alpha_4 - Th_3 b_2 \sin \alpha_3$$

$$T_z = Th_1 b_1 \cos \alpha_1 + Th_2 b_1 \cos \alpha_2 + Th_3 b_2 \cos \alpha_3 + Th_4 b_2 \cos \alpha_4$$

Aerial movement(5):

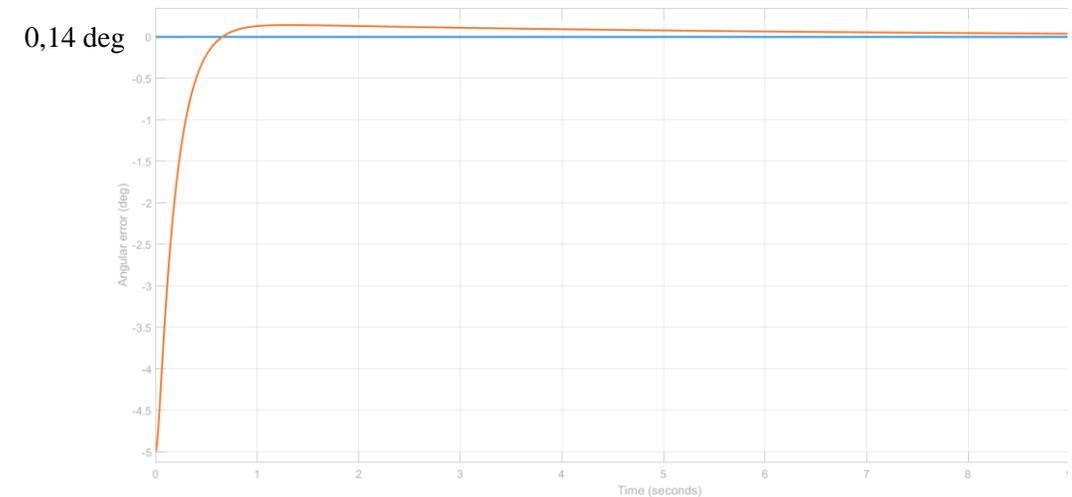
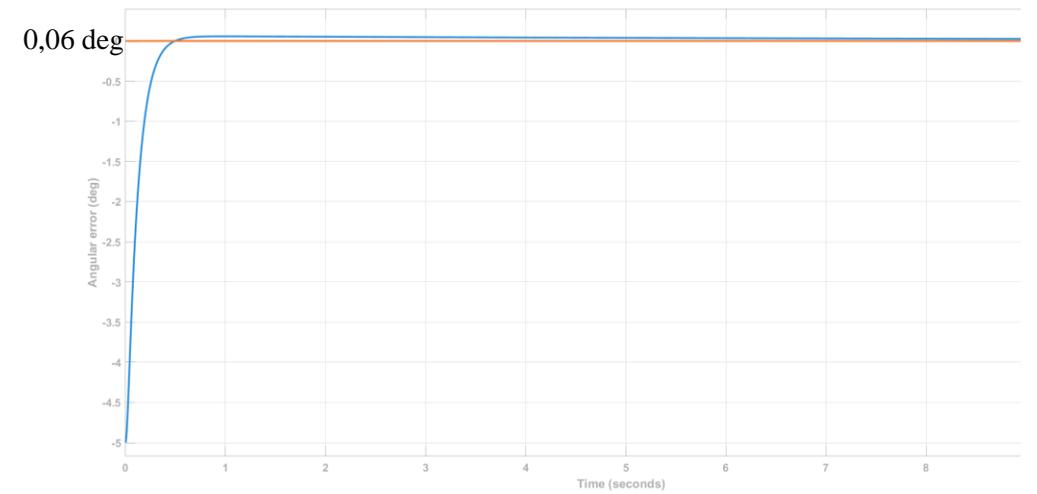
- PID



$P=[100, 100, 150];$

$I=[20, 20, 25];$

$D=[25, 25, 30];$



Sensor suite:

- **Compact & Modular Design**

- Fits within a **2P picosatellite volume**
- Mounted on **ground system**

- **Breadboard Components**

- Stereo camera → mapping of lava tubes
- Temperature & relative humidity sensor
- Geiger-Müller tube → radiation through basalt
- Extra humidity sensor in legs → detect water traces in regolith

- **Current Status**

- Sensors selected & awaiting delivery

- **Next Step**

- Breadboard assembly → integration into COTS platform
- Test sensor suite interaction with **ground segment movement**
- Define requirements for **exploration inside lava tubes**



Waveshare Binocular Camera Module



DHT11 Temperature-Humidity Sensor Module



Gravity Geiger Counter Module Ionizing Radiation Detector



Gravity Moisture Sensor

Mission design concept:

The mother rover remains on the surface.



The drone descends and drops the descent base below the pit opening.



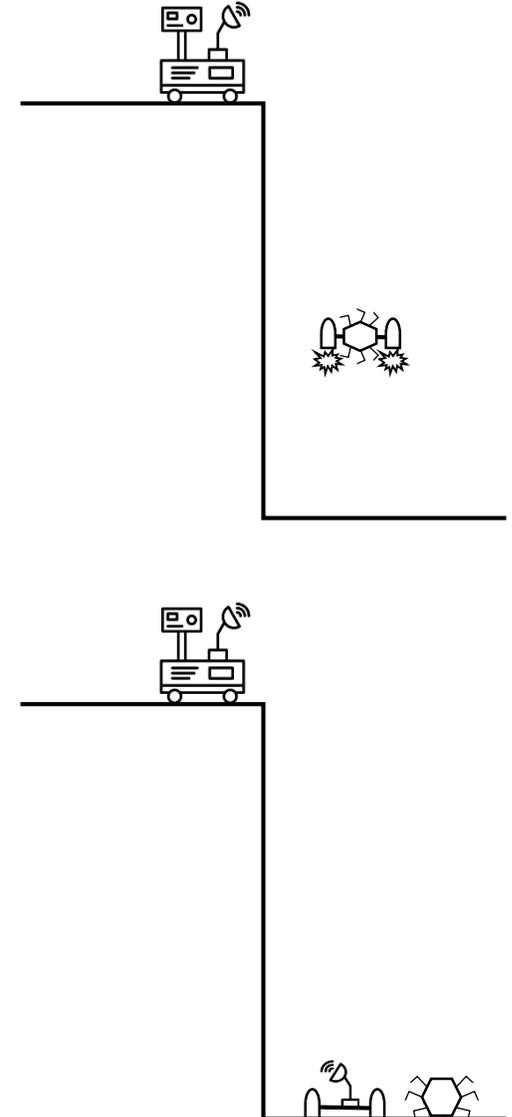
It ventures inside and goes in *freeze mode* to collect data.



After collecting the data, it goes to the designed spot to recharge



The drone transmits the data to the descent base, which acts as a router to the mother rover.



Power supply study:

Space Exploration Lab., Universitat polytechnica de Catalunya (UPC), Barcelona, Spain



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DE CATALUNYA
BARCELONATECH

- Power supply will be studied in the context of the second part of my mandatory period abroad.
- Space exploration Lab. Studies Power supply technologies for human and robotic activities
- A hybrid solution considering surface generation and wireless power transfer (WPT) will be studied and evaluated as a viable option
- After assessing the power requirement of the ground system considering movement and data acquisition operations within the tubes.

WPT technologies		Key advantages	Potential disadvantages
Near field	CPT	<ul style="list-style-type: none"> ● High power transfer up to several kilowatts ● Transfer power through metal objects without generating significant eddy currents losses ● Use metal plates to transfer power, which can reduce the cost ● Suitable for small size applications, but also can be used in large size applications, such as EV 	<ul style="list-style-type: none"> ● Limited efficiency at the range of 70%-80%, though it can reach 90% in some applications ● Short transmission distance, which is usually within the hundreds of mm range ● The challenge comes from the conflict among the transfer distance and power as well as the capacitance value
	IPT	<ul style="list-style-type: none"> ● High efficiency, which higher than 90% is possible ● High power transfer up to several kilowatts ● Good galvanic isolation ● Suitable for applications that from low power smartphones to high power EV 	<ul style="list-style-type: none"> ● Limited transmission distance, which vary from cm to m ● The significant eddy current loss is generated in nearby metals which limits its application area
Far field	MPT	<ul style="list-style-type: none"> ● Long effective transmission distance up to several km ● Suitable for mobile applications ● Potential to transfer several kilowatts power 	<ul style="list-style-type: none"> ● Low efficiency less than 10% for high power applications (such as transfer several kilowatts power or more) ● Complex implementation
	LPT	<ul style="list-style-type: none"> ● Long effective transmission distance up to several km ● Flexible device, suitable for mobile applications ● Potential to transfer several kilowatts power 	<ul style="list-style-type: none"> ● Low efficiency around 20% or less ● Line-of-sight to the receiver



Next steps:

• Define & Track KPIs

- Establish key performance indicators to guide design choices

• Identify Critical Design Variables

- Determine which parameters most significantly impact performance to focus optimization efforts.

• **Interface Development: Aerial & Ground Systems**

- Design and Control in Simulink environment of the dynamics between the aerial and the ground segment in mated and separated configurations.

• **Sensor Suite Integration & Testing**

- Integrate the sensors into the COTS platform, validate functionality, and test interactions under operational conditions

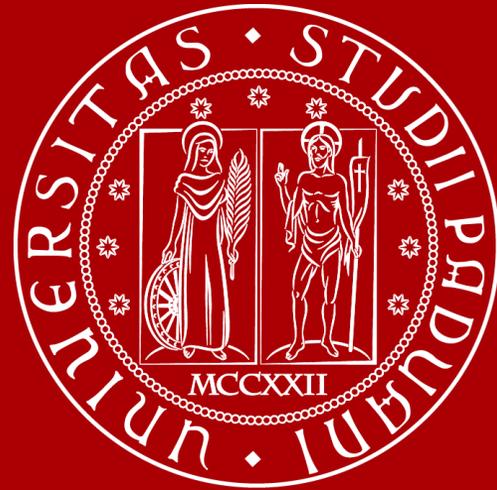
• **Trajectory Control Simulation**

- Simulate and optimize descent and navigation strategies to refine guidance, control, and stability

• **Power System Development**

- Design and validate power supply to meet the energy demands of all subsystems under mission scenarios.

Thank you for the attention



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