USC University of Southern California

Information Sciences Institute

Space Engineering Research Center

SPACE ENGINEERING RESEARCH CENTER SPRING SEMINAR SERIES: LEAPFROG

February 20th 2020

SERC Seminar Series – Spring 2020

USC University of Southern California

February 2020:

LEAPFROG: USC's Flight Tesbted re-thinking Planetary Landers for Next Generation Exploration

Interested to Join SERC?
Fill out Application at
https://www.isi.edu/centers/serc/join_us

Spring 2020 2020-001

Space Engineering Research Center

Spring Seminar Series Announcement

New Seminar Series! The University community is invited to participate in the first seminar series presented by USC's Space Engineering Research Center (SERC). The SERC is a research center where graduate and undergraduate students can collaborate with professors and experienced engineers to gain hands-on experience with hardware-based projects in the space domain. Current research areas include: Microsatellites, Satellite Communications and Tracking, Lunar Lander technology (LEAPFROG), Satellite Servicing and Docking experimentation, technologies for Rendezvous and Proximity Operations, Advanced Propulsion, and Earth-based simulation testbeds for microgravity frictionless environments. Please visit our website for more information about the SERC.

Seminar Location on Campus: The seminars are from TBD to TBD in TBD room. Light refreshments will be provided at the beginning of the seminar.

Seminars Topics Planned for Spring 2020:

- **January TBD** – **"Big Ideas for Space: SERC projects for 2020".** Dave Barnhart, Director SERC. Abstract: The SERCs past/current projects will be presented, along with its approach to hands on space technologies and satellite development that involves students, faculty and staff at USC.
- **February TBD** – **"LEAPFROG: USC's Flight Testbed re-thinking Planetary Landers for Next Generation Exploration".** Alessia Russo and David Bernachia, Masters Candidates. Abstract: The SERCS LEAPFROG project will be presented and key technologies being developed to re-architecture how a lunar lander is used on the moons surface.
- **March TBD** - **"Genetic Algorithms for Space Swarms:".** Rahul Rughani, PhD Candidate. Abstract: Brand new technologies are being applied to operating multiple spacecraft in close proximity for safety and efficiency. Research using genetic algorithms applied to optimization will be presented, as well as investigations into using the ISI Quantum Computer to expand solution sets.
- **April TBD** – **"Trojans in Space: USC Satellite Flight Projects".** Dave Barnhart & Student Leads. Abstract: The SERC has built and launched USC's first satellites. Past and current satellite projects will be presented, along with concepts for collaboration for new science and research.
- **May TBD** – **"Talking to Space: USC' Satellite Ground Communications Station".** Claire TBD, Masters Student. Abstract: USC's satellite ground communications station exists on campus, and is used to teach graduate students how to communicate and control satellites. The Ground station will be presented with operations and research projects past and present.

The Space Engineering Research Center (SERC) is dedicated to disruptive space engineering, research, and education – including hands-on build, test and flight demonstrations of spacecraft and satellites. SERC seeks to challenge traditional methods of space R&D, manufacturing, and exploration with approaches that dramatically reduce costs, enable novel capabilities, and support vital democratization of the space domain.

www.isi.edu/centers/serc

USC's Space Engineering Research Center: What is it

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USC Viterbi School of Engineering — Department of Astronautical Engineering

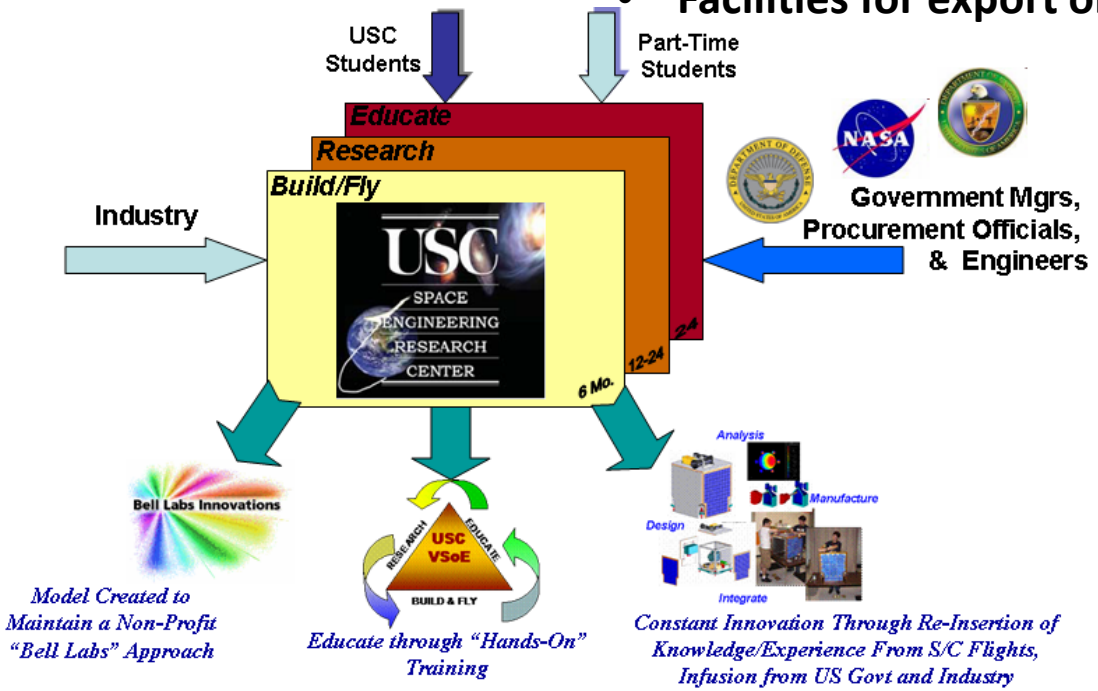
- Astronautical Engineering (ASTE)
  - Bachelor of Science
  - Bachelor of Science Minor
  - Master of Science
  - Engineer
  - PhD
  - Graduate Certificate

USC Viterbi School of Engineering — Information Sciences Institute

- Information Sciences Institute
  - Part of USC's Viterbi School in Marina del Rey, Arlington, VA, and Waltham, MA
  - >$80M/year from diverse sponsors
  - ~300 people, 2/3rds research staff
  - Facilities for export or restricted research

An academic industry membership run

"Space Engineering Teaching Hospital"



Space Engineering Research Center

~200 undergrad, graduate and PhD. students involved in all aspects of hands-on space engineering to-date

LEAPFROG at a glance

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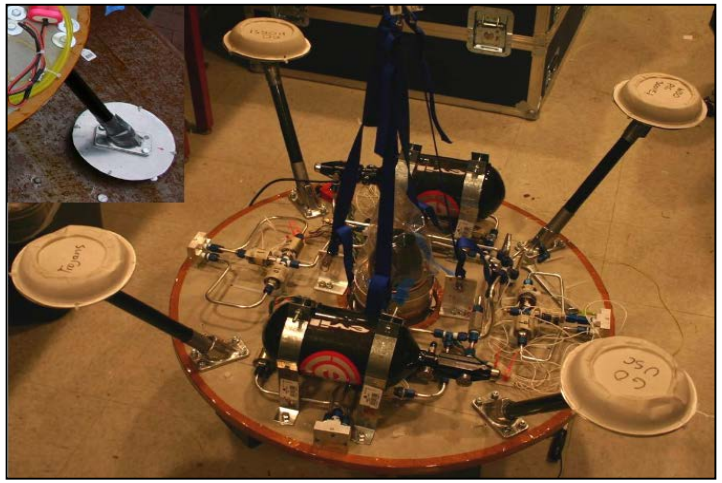
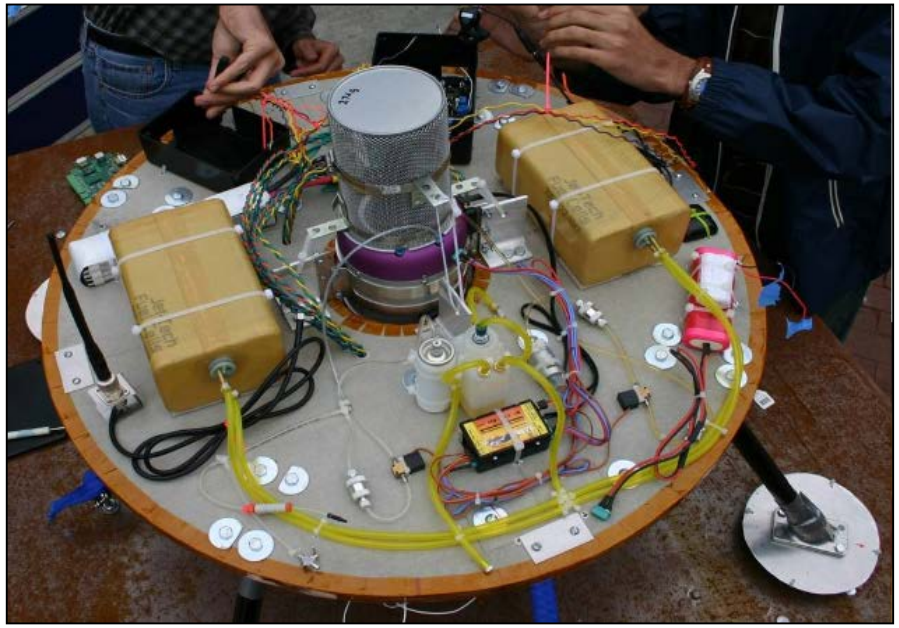
Topic	Presenter
• Introduction, Purpose & Background	• Alan Osmundson
• Past and Current Mission Architectures	• Ishan Puranik
• New Research Project Goals	• Aloisia Russo
• Gen-II LEAPFROG Design 1. Requirements 2. Basic Design Characteristics	• Michael Augrand • Antariksh Narain/Ishan Puranik
• Two Research Focus Areas • TVC Systems • Reconfigurable Robotic Arm and Adjoined Tool	• David Bernacchia/Michael Augrand • Aloisia Russo
• Next Steps for LEAPFROG	• Alan Osmundson

Introduction, Purpose & Background

LEAPFROG (**Lunar Entry and Approach Platform For Research On Ground**) was started as a multi-semester design-to-flight student hands-on training activity through the Astronautics and Space Technology Division and Information Sciences Institute at the University of Southern California in **2006**.

Mass *= ~ 23 kg*
T/W *= ~ 1.05 (w/o Payload)*
Flight Time *= Less than 1 min.*
Payload Capacity *= ~ 0.1 kg*
Engine *= JetCat P200*
Thrust **= ~** *230N*





LEAPFROG

Original LEAPFROG Architecture was meant to support Step-Wise Research

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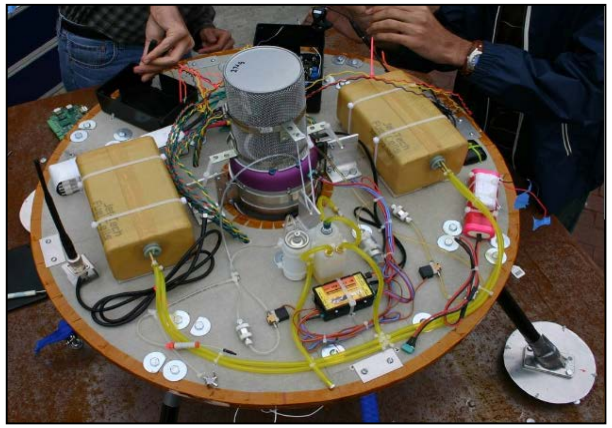
Gen-0, Proof of Concept

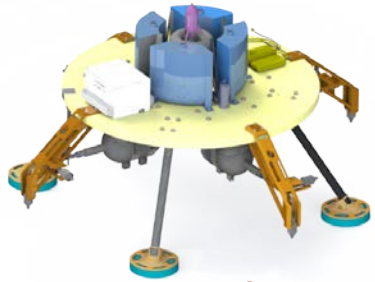
- Proof of Concept Flight Vehicle
  - Flight Time = 3-5 Minutes
  - Payload Capacity = 0.5 kg
  - Core Hover/Flight Avionics
  - COTS Components
  - Basic Pre-Loaded Flight Profile



- Development Cost/Schedule
  - Component Costs ~ $15k
  - Design to Flight ~ 3 Months

Gen-1, Prototype Testbed

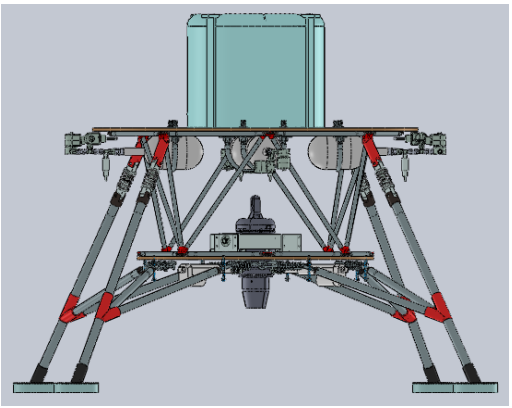
- Prototype Testbed
  - Payload Capacity = 0.5 to 2 kg
  - Core Hover/Flight Avionics
  - Aerospace COTS Components
  - Basic Pre-Loaded Flight Profile
  - Ability to Respond to Terrain
  - Swap out Core Sensors with New Lunar Landing Sensors
  - Test out New Landing Systems, Legs, Structures
  - Flight Time = 5-10 Minutes
  - Terrain Experimentation



- Development Cost/Schedule
  - Component Costs ~ $15k
  - Design to Flight ~ 6 Months

Gen-II, Prototype Testbed

- Prototype Testbed
  - Payload Capacity = 10 kg
  - Extended lander's functionality
  - Ingenious thrust vector control combining Gimbal and cold-gas systems
  - Origami-based solar panels
  - Multi-purpose robotic arm
  - Advantageous multi-platform design
  - Flight Time = 5-6 Minutes



- Development Cost/Schedule
  - Component Costs ~ $15k
  - Design to Flight ~ 12 Months

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LEAPFROG- Student led Innovative Lander Flight Prototype

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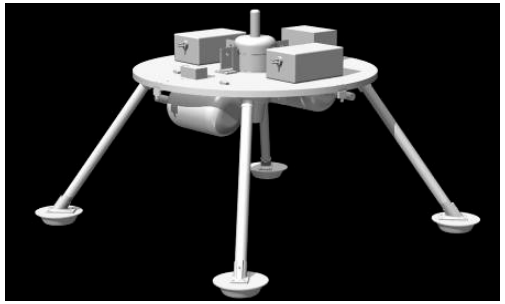
Generation 0



LEAPFROG

Gen-1 Activities Started July 2019 with Air Bearing Testbed

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Testbed Properties

Phase 1 goals:
- Create structure
- Design and test ACS
- Create avionics system that enables control of ACS
- Integrate all hardware with manual control software.

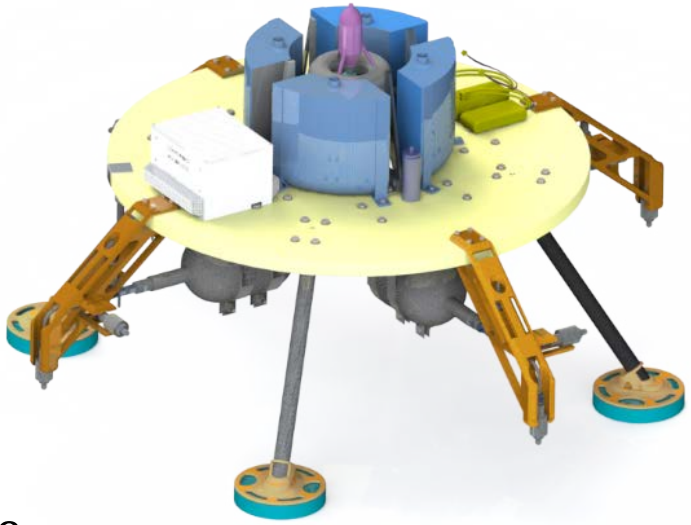
Flight Time = N/A

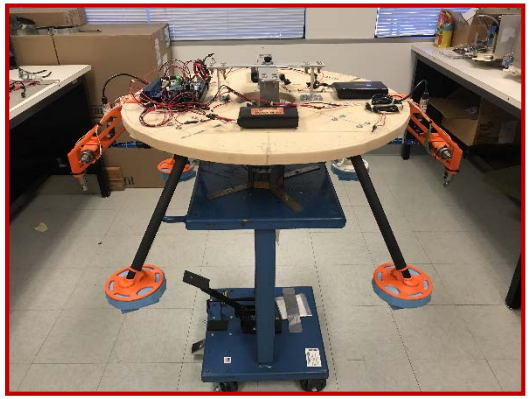
Payload Capacity = N/A

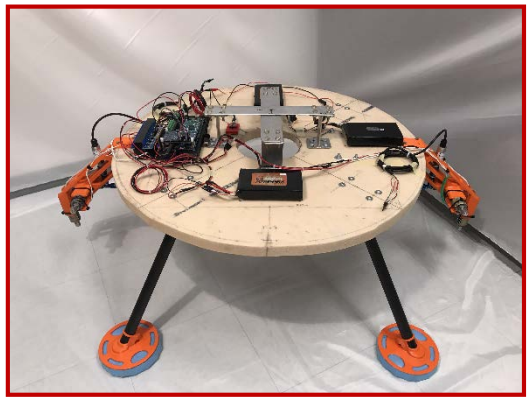
COTS Components

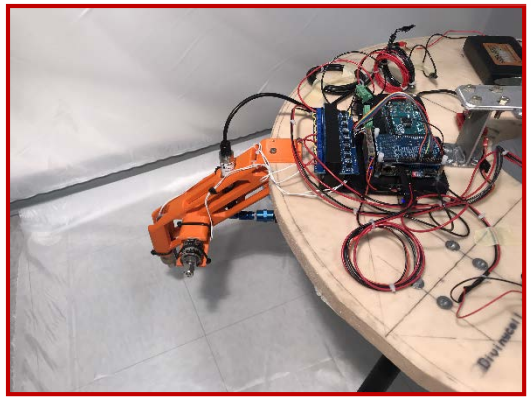
- Dual layer fiberglass reinforced main body (core)
- 3D printed flanges, arm-extensions and electronics mountings
- Unidirectional carbon-fiber legs
- Odroid XU-4 as onboard flight processor.

Basic **manual** attitude control system (ACS) profile









Gen-1 Initial Testing focused on Cold Gas RCS Changes

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Innovative Challenge in Lunar Lander Research:
Reconfigure the Lander!

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Innovative Design Focus

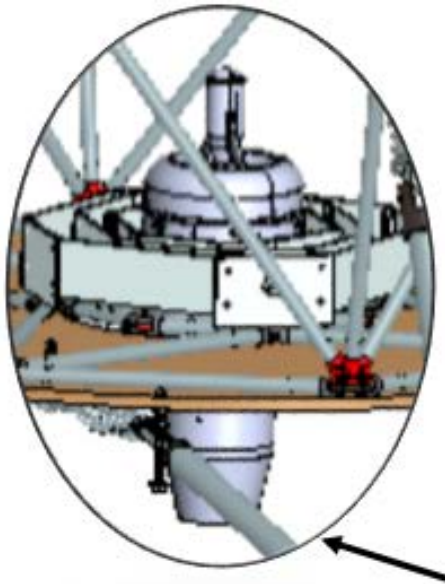
Re-think the function of a lander that can perform multiple activities: capable to change a single monolithic functioning lunar lander into a multi-functional platform that uses various techniques and new technologies to extend the use of the mass embedded in the makeup of the landing platform.

Increased Performance and Functionality

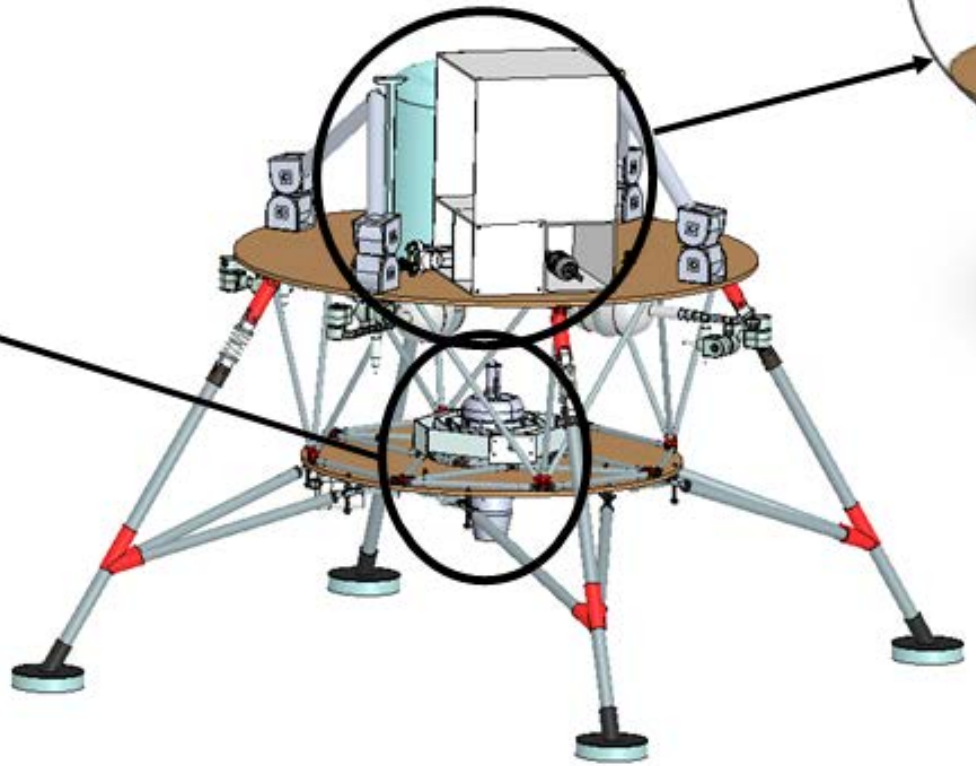
A lander should be able to:

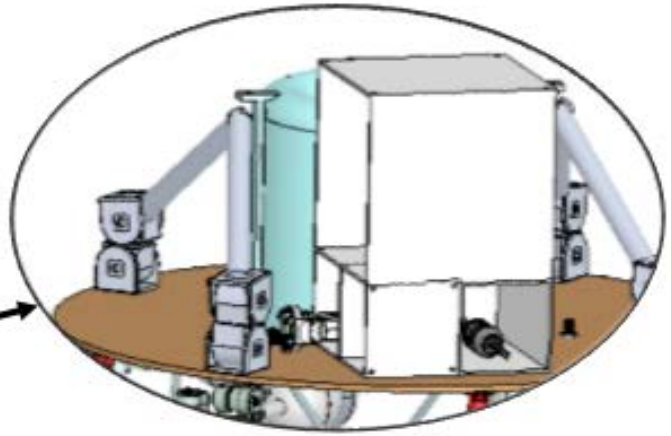
- ***Have increased flight performance***
- *Maintain total autonomy*
- *Transform to perform different activities after landing (i.e. structure becomes active, unfolds, changes shape etc.)*
- ***Prove multi-functionality using new techniques***

Focused Research on Reconfiguration and Advanced TVC that can be applied to Gen-II



Thrust Vector Control (TVC) Gimbal system





Reconfigurable Robotic Arm

- Gripper
- Drill
- Shovel
- Kirigami Array
- Etc.

LEAPFROG GEN-II Resultant Design Requirements

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LEAPFROG GEN II Performance Upgrades:

Mass	*= ~ 25 kg*
T/W	*= ~ 1.2 (w/o Payload)*
Flight Time	*= ~5 min.*
Payload Capacity	*= ~ 10 kg*

Gen-II Component	Mass [Kg]
Main structure	8
Engine P-300Pro JetCat	2.7
Fuel	3.9
Gimbal systems	1.486
Linear actuator	1.08 each (multiply by 2)
Electronics	3.5
TOTAL	**22.286**

To Support Advanced research Gen-II Structure uses simple monocoque & multiple platforms

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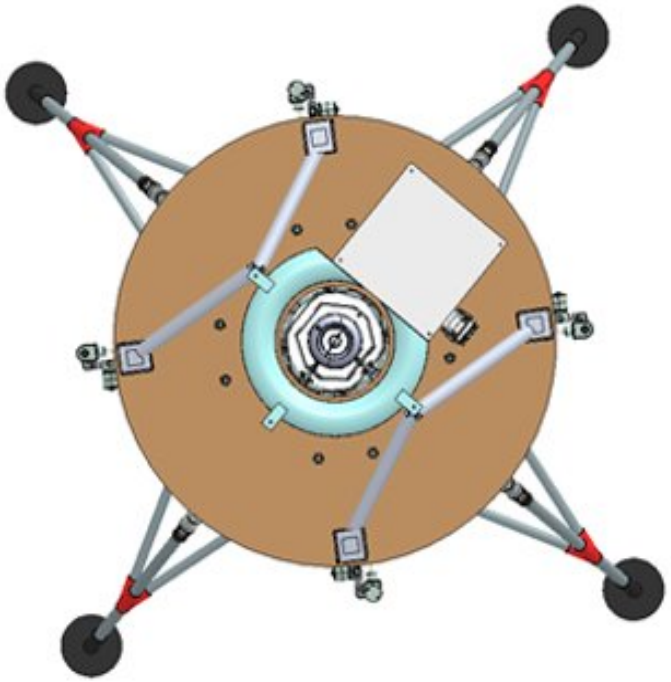
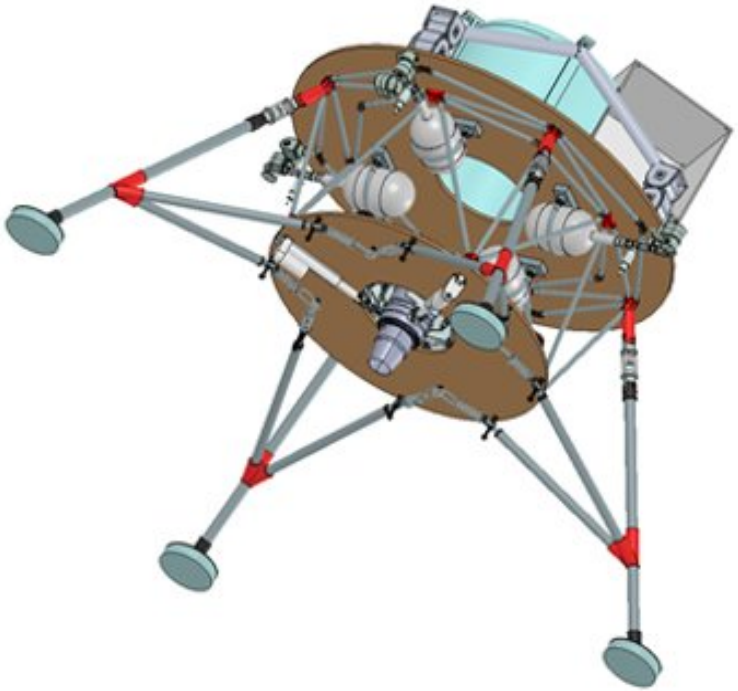
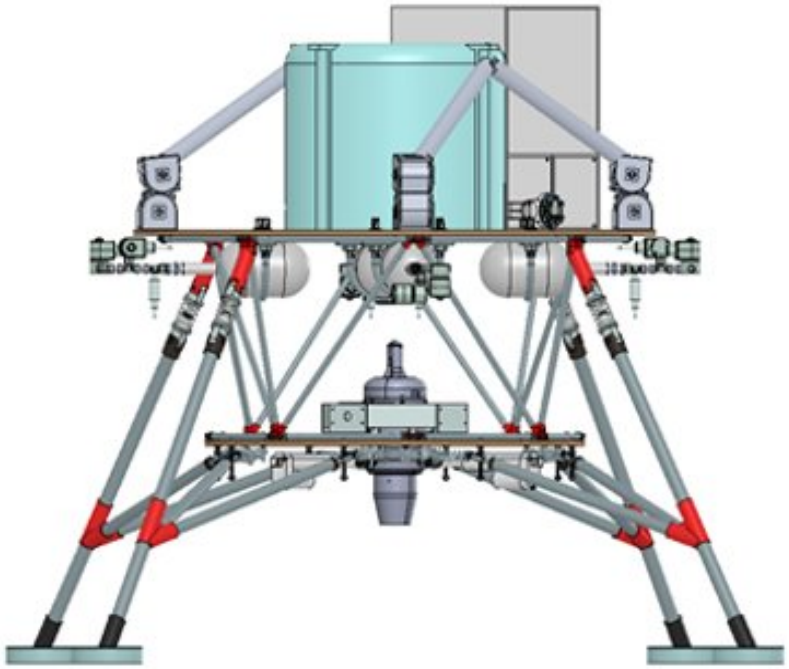
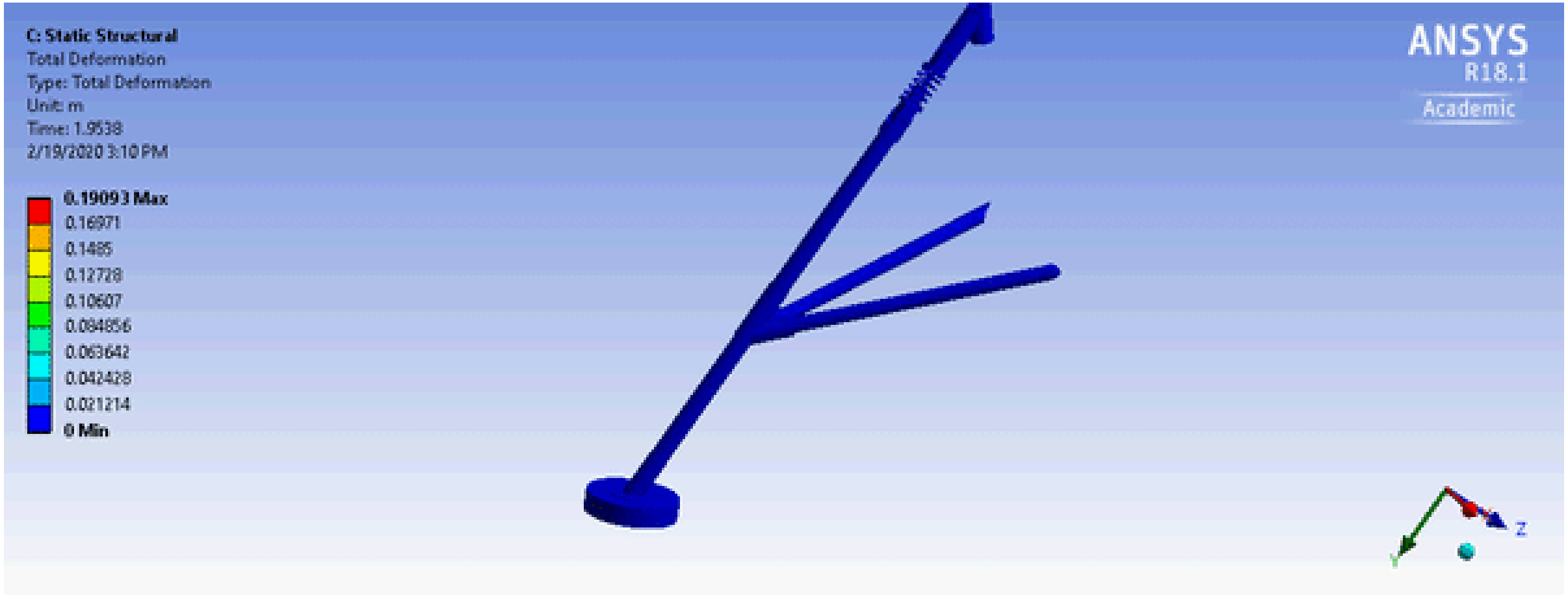


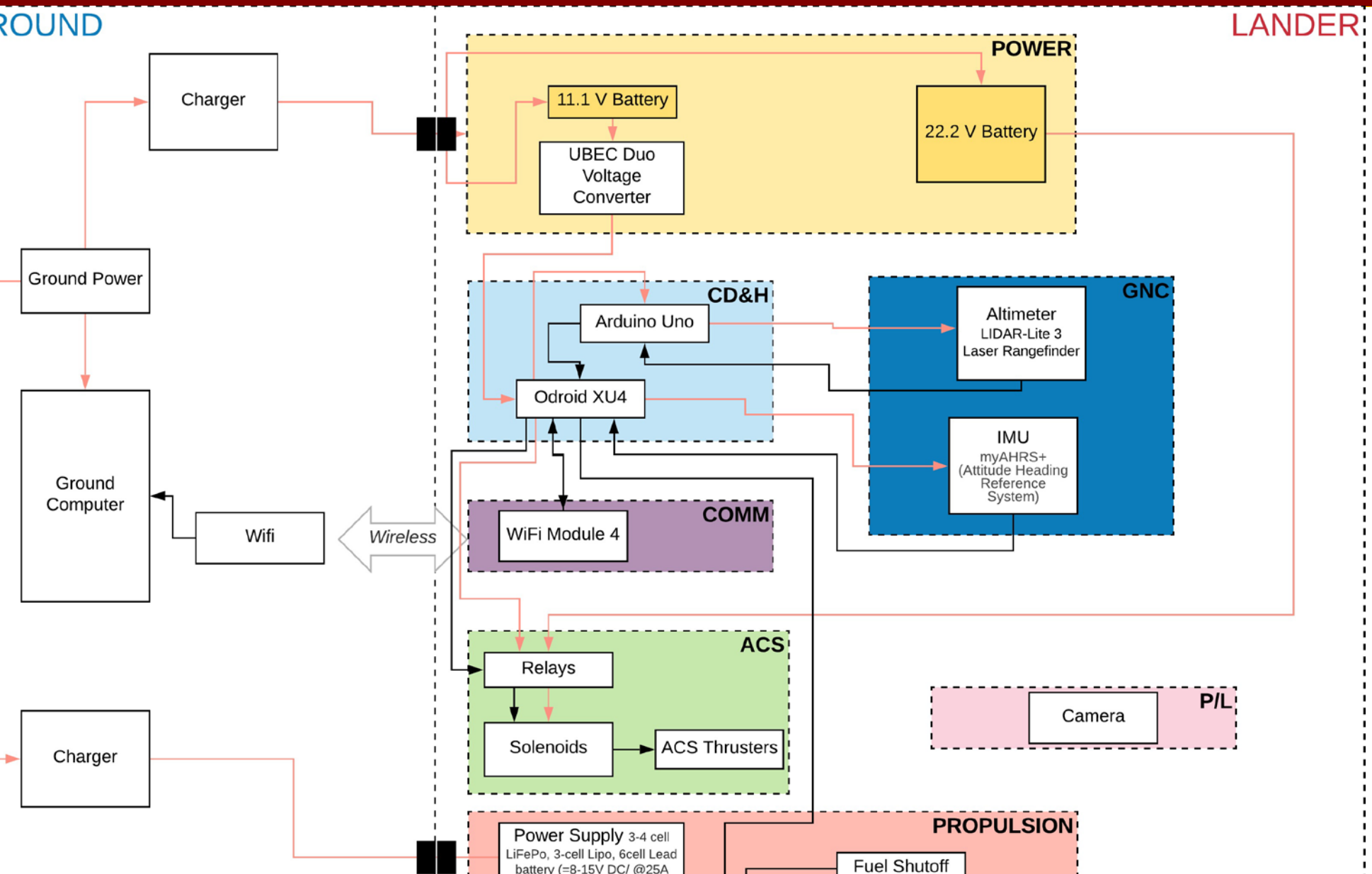




Structural elements modeled in NX and Ansys for stability and dynamics



LEAPFROG Gen-II Core System functions

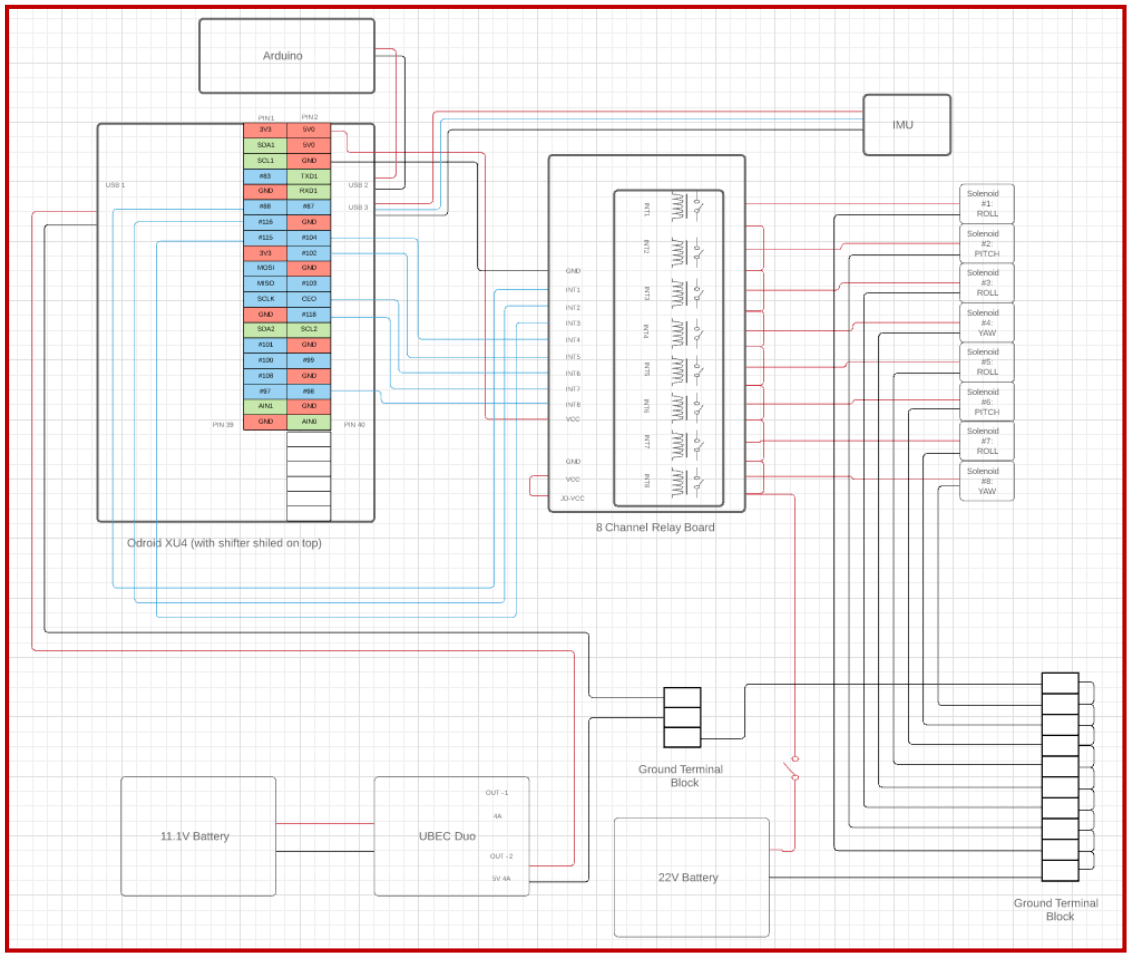


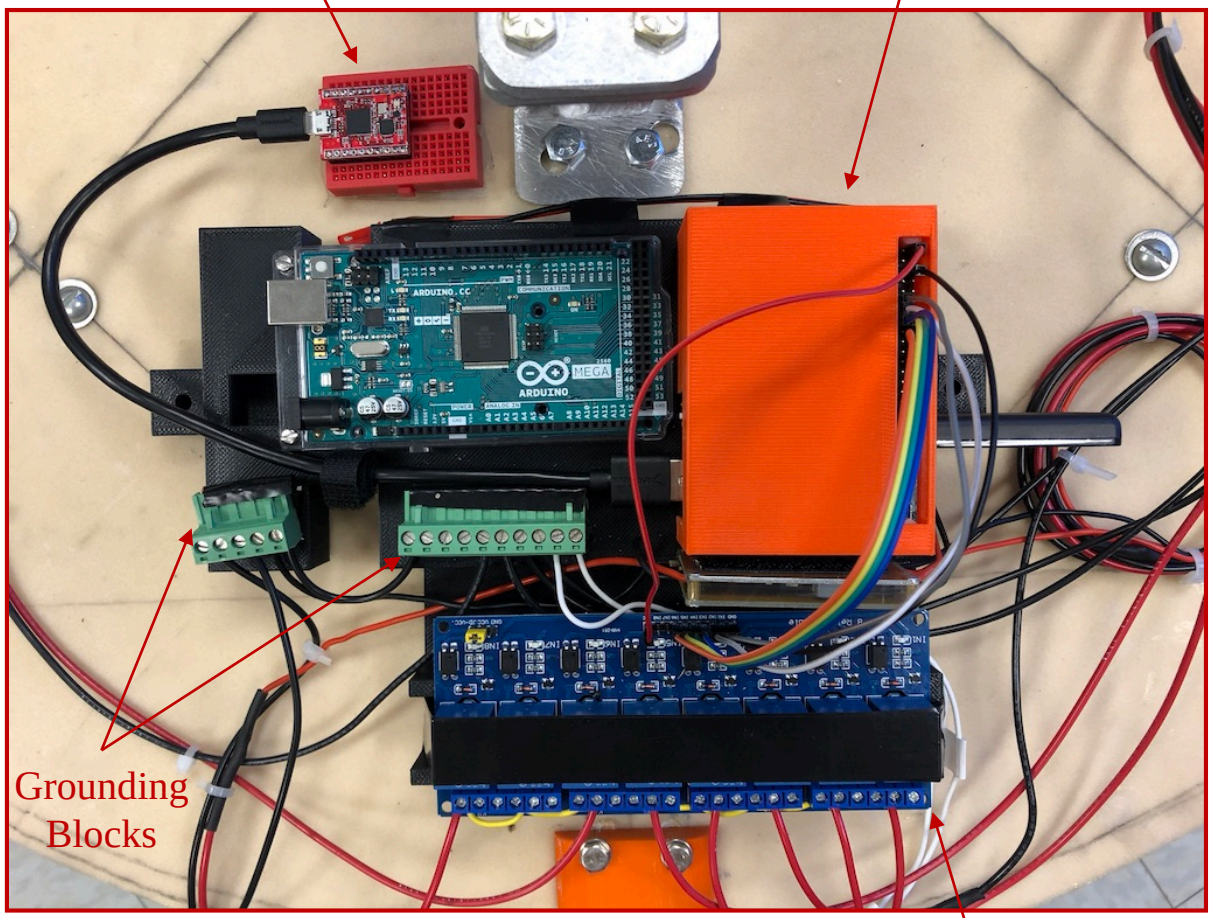
* GNC Sensors to be implemented

** Gimbal Electronics not shown

Avionics uses COTS Processor(s)

Current Circuit Design





Graduate Research Investigations

1. **Advanced multi-Actuator GNC Algorithms for Landing systems**
   - **David Bernacchia,** *Alma Mater Studiorum-University of Bologna, Italy*

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

2. **Reconfigurable Robotic Arm and Adjoined Tool**
   - **Aloisia Russo,** *Politecnico di Milano, Italy*

POLITECNICO
MILANO 1863

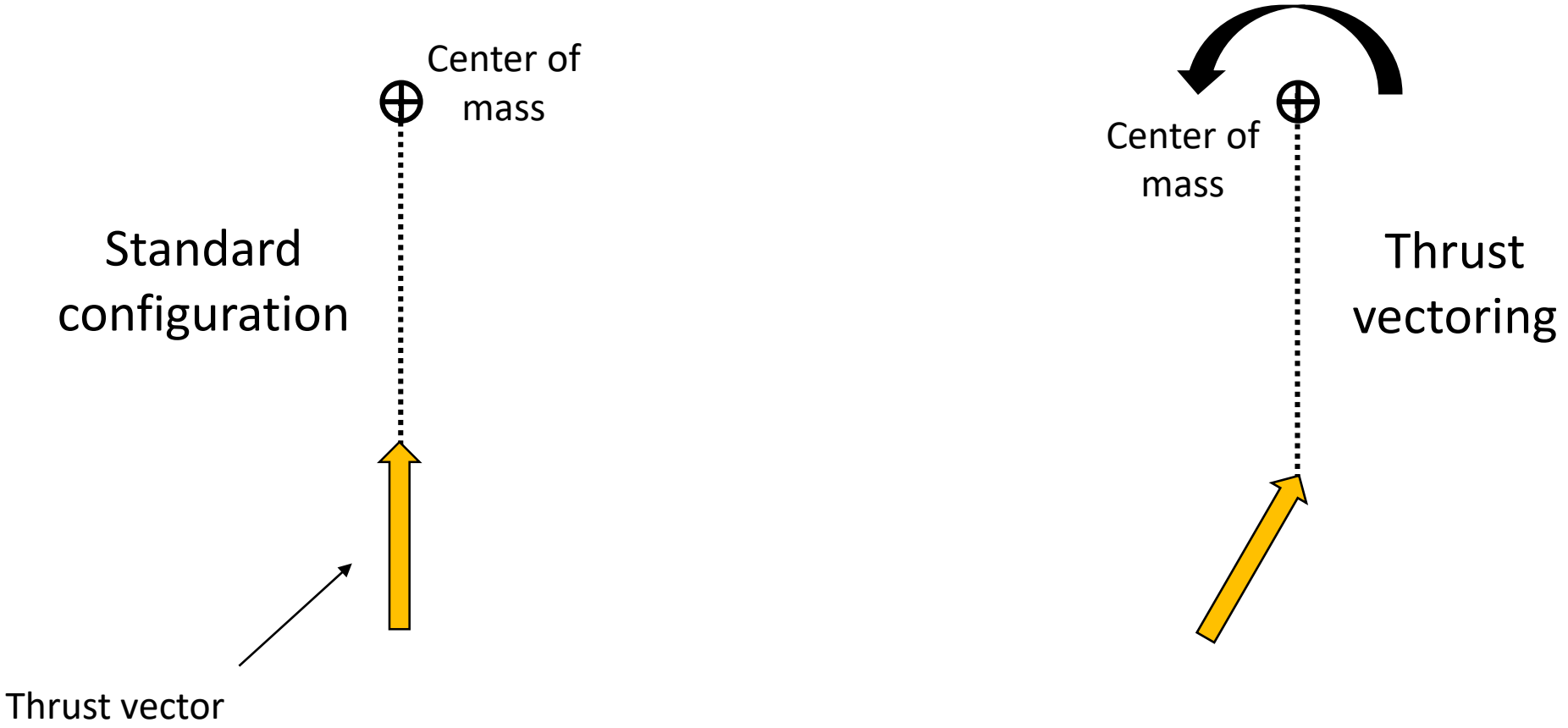
First Focused Research: Advanced GNC Algorithms for landing systems

Research Challenge: Apply advanced guidance navigation and control algorithms to a multi-actuator landing platform.

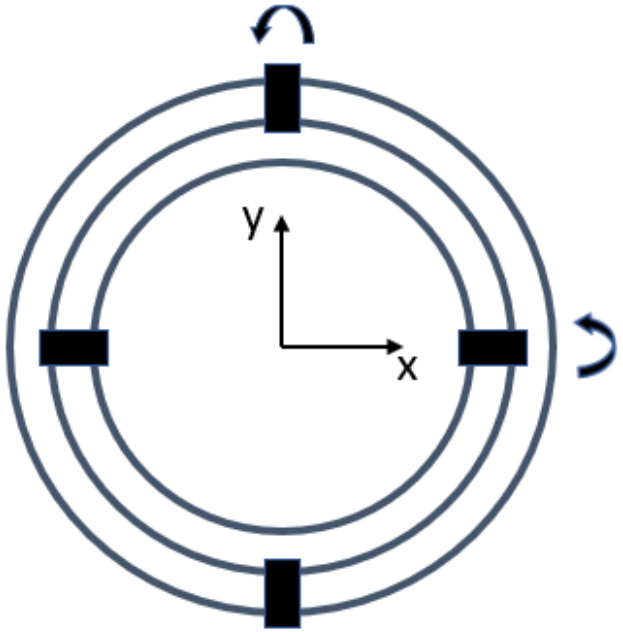
Testbed Platform: Gen-2 with both a Thrust Vector Control system and Reaction Control System

Approach: Investigate both linear (traditional) and sliding mode control algorithms that can optimize both RCS and TVC during a landers flight.

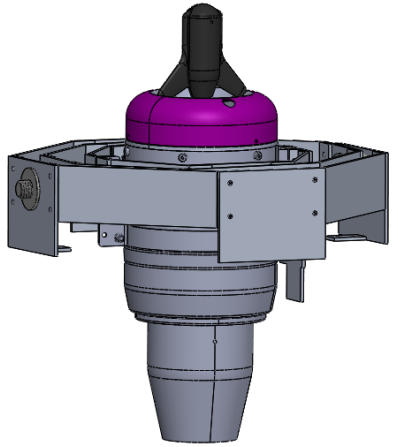
Thrust Vector Control: concept



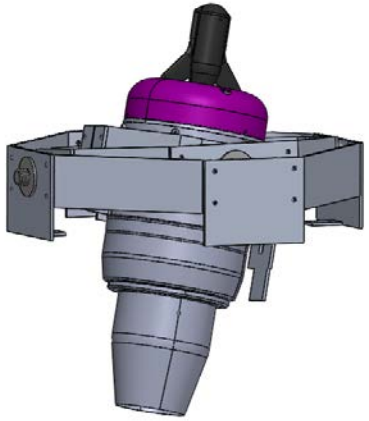
Gimbal ring: concept



- 3 concentric rings
- Relative rotations thanks to the presence of connecting pins
- Pins aligned with principal axis of inertia

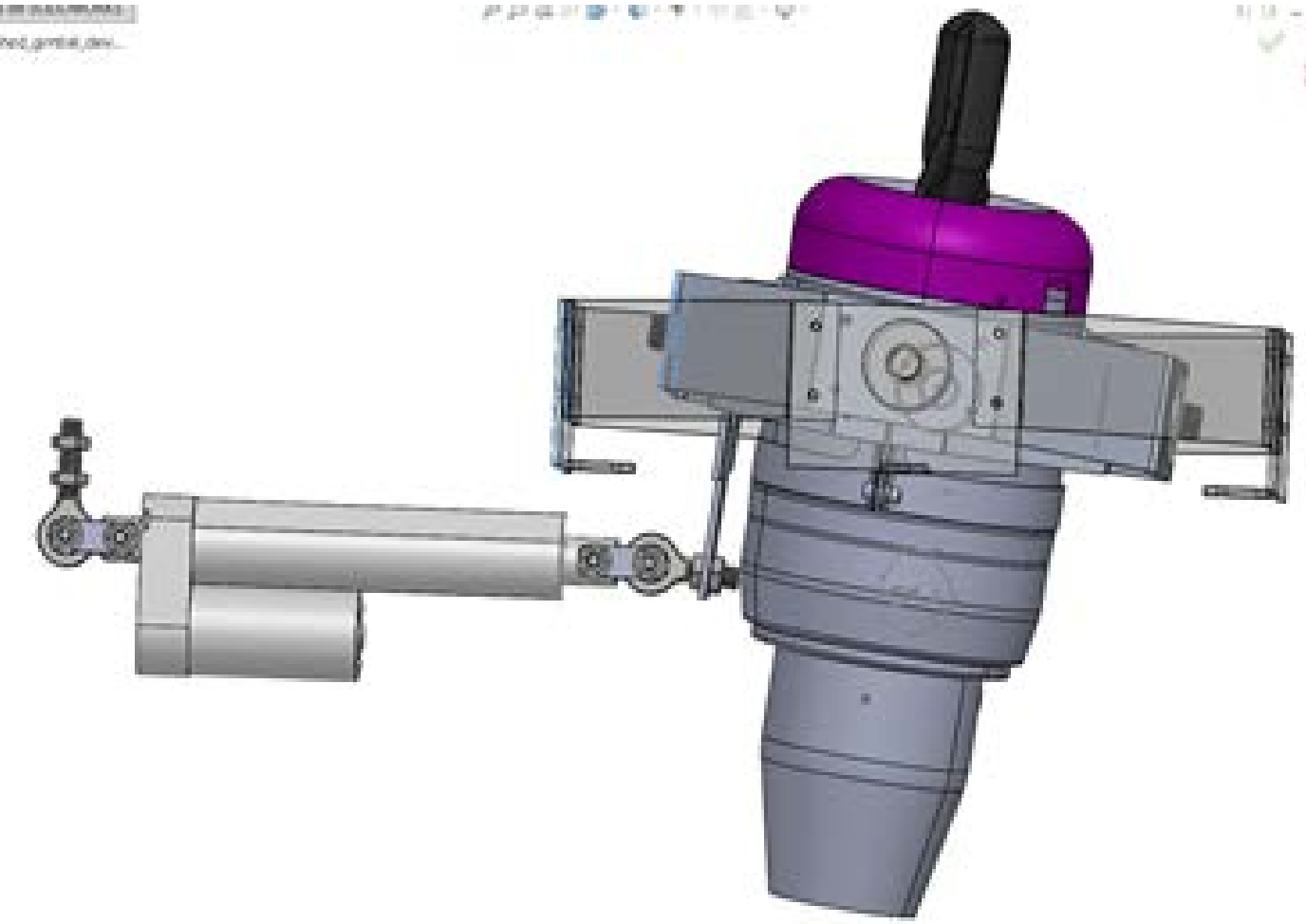


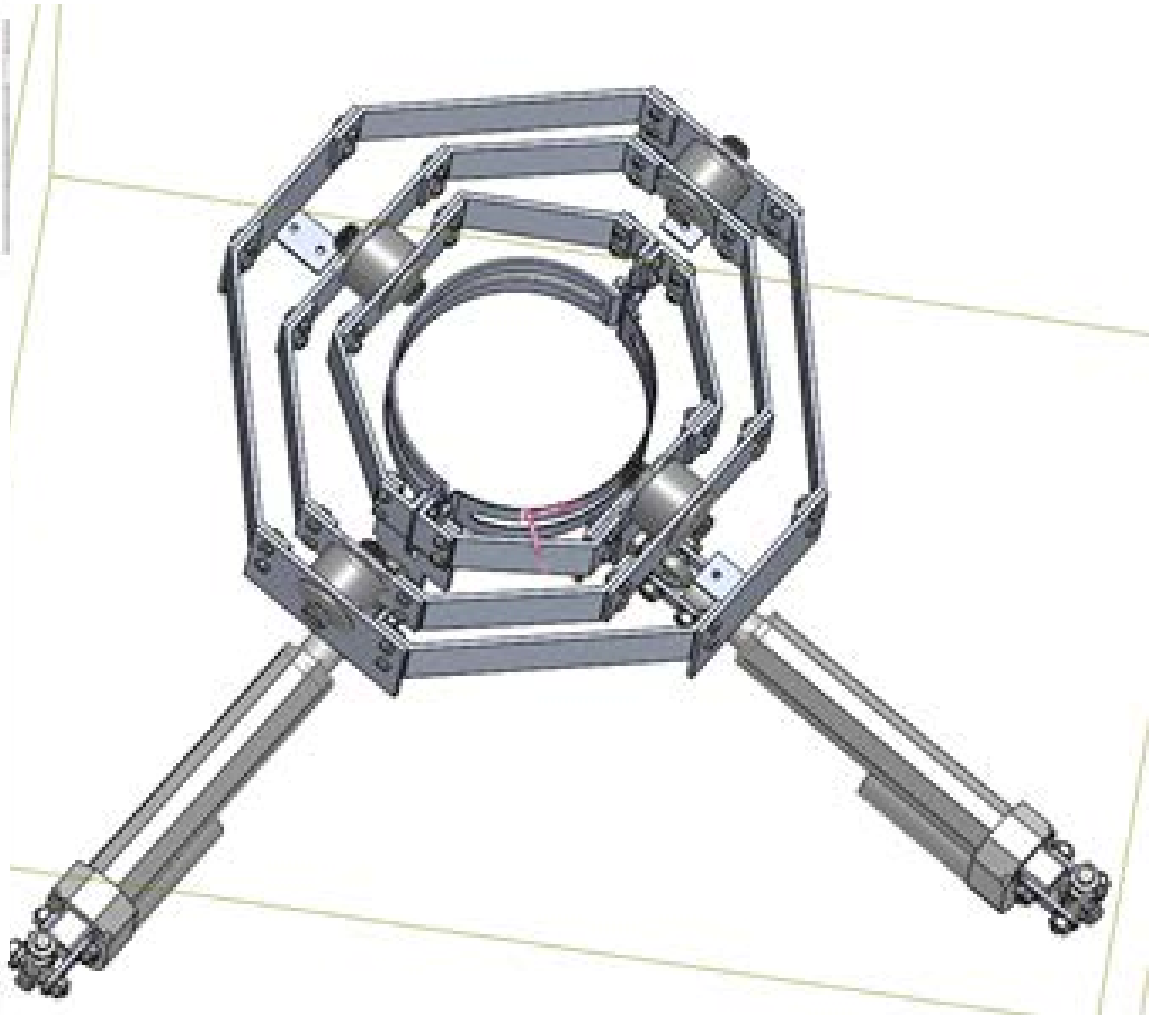
VERTICAL CONFIGURATION



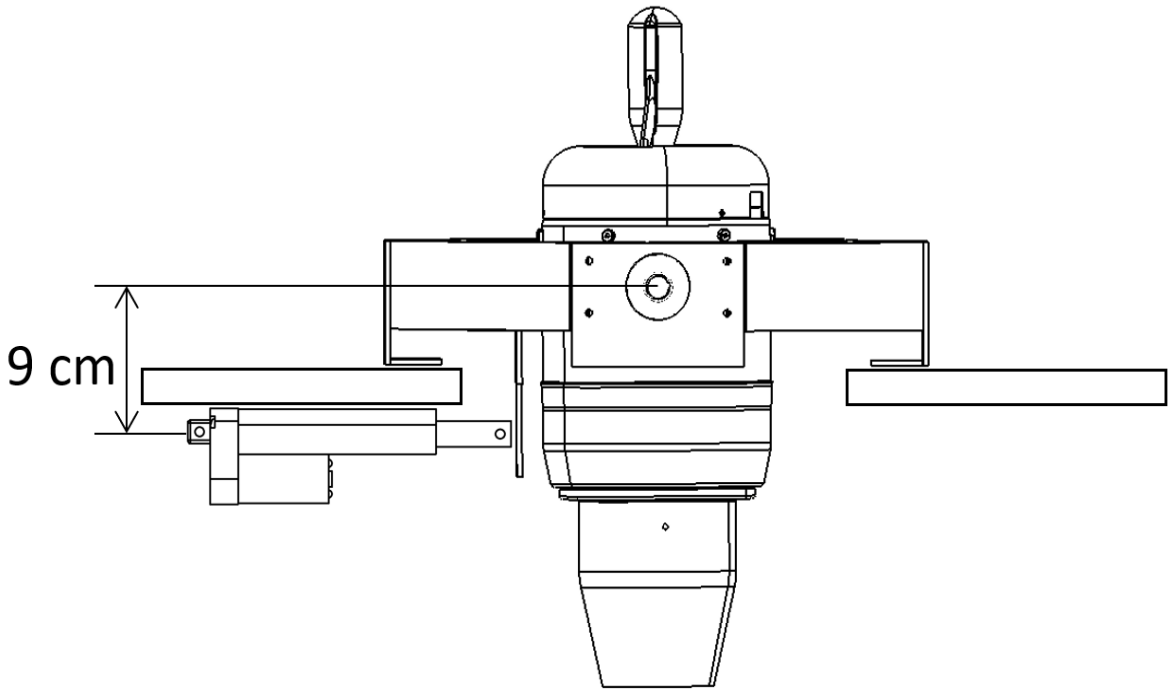
DISPLACED CONFIGURATION

Creation of 1st LEAPFROG TVC Gimbal mechanism

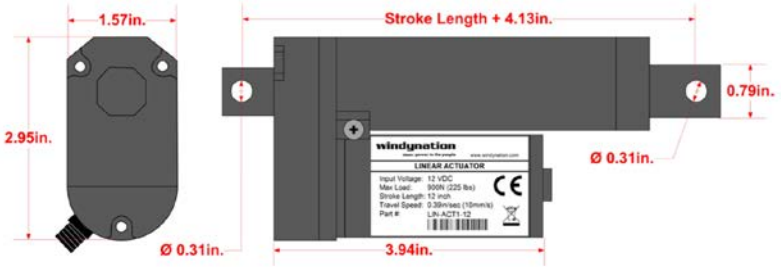




Thrust vector control: actuation system

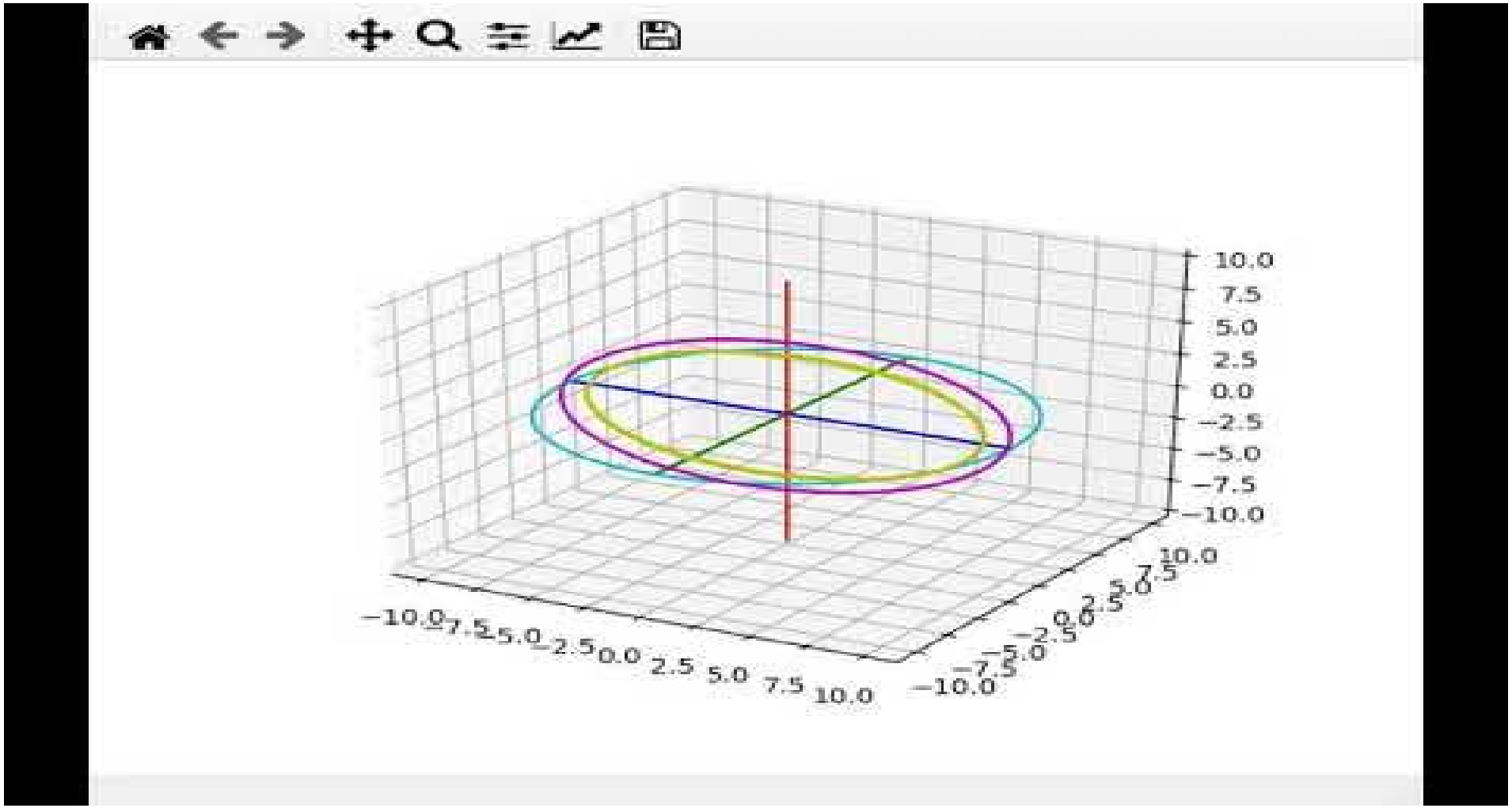


- Horizontal position to maximize actuation speed
- Reduced distance from the center of rotation to maximize angular displacement
- Aligned with principal axis of inertia
- 18.4 deg/s

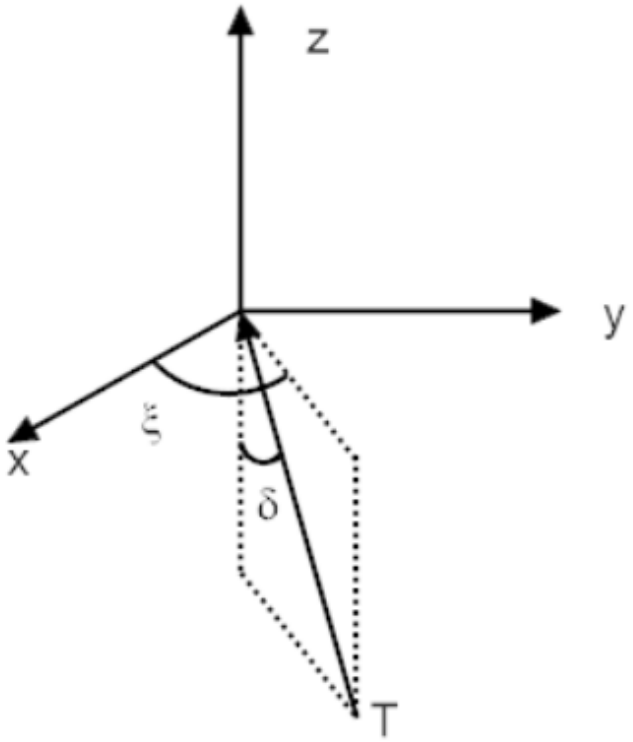


Gimbal System Prelim Analysis

Gimbal System



Thrust vector control: gimbal angles



- -90 < xi < 90
- -5 < delta < 5

Linear Quadratic Regulator

linear model:

$$\dot{x} = Ax + Bu$$

$$\mathrm{y} = Cx + Du$$

Cost function:

$$J = \frac{1}{2}\int (x^T Q x + u^T R u)dt$$

Optimal control law

$$u_{opt} = -K_{opt}x$$

Sliding mode control

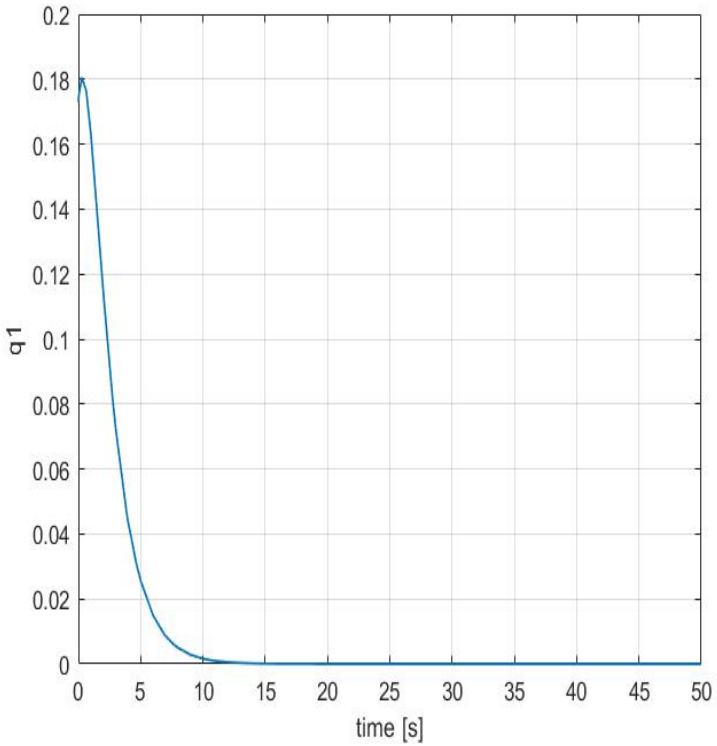
Definition of a sliding surface:

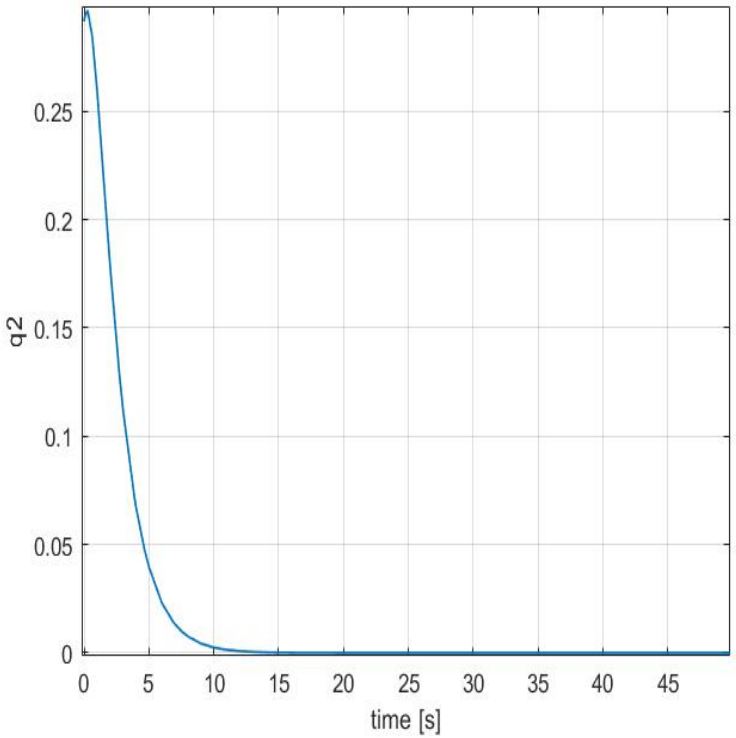
$$S = Pq_e + \omega_e$$

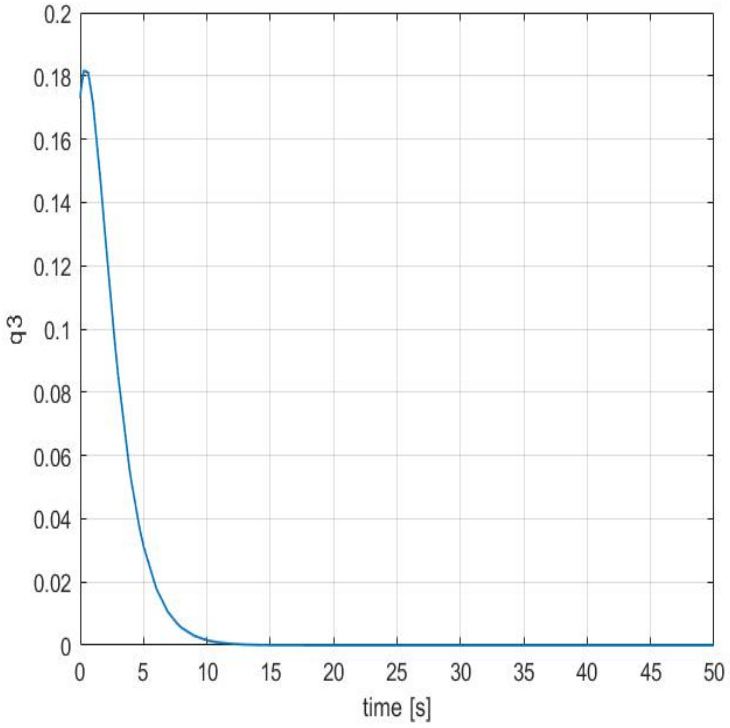
System forced to stay on the sliding surface and reach:

$$0 = Pq_e + \omega_e$$

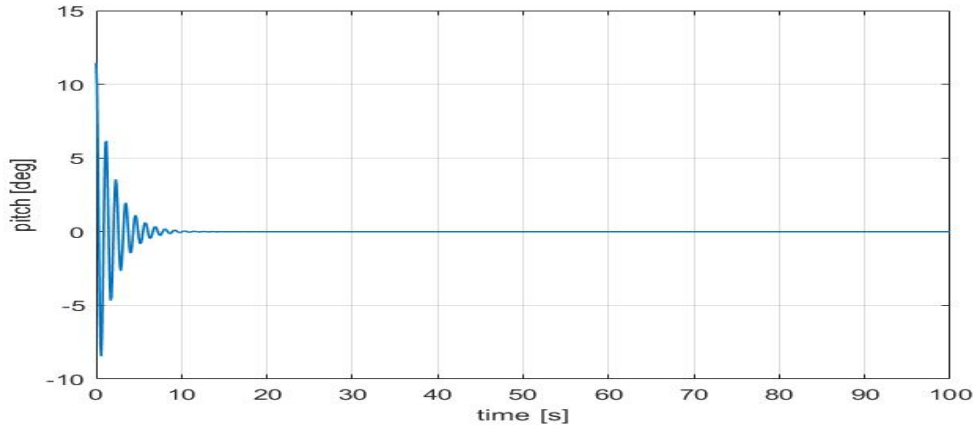
Linear Quadratic Regulator: ideal case

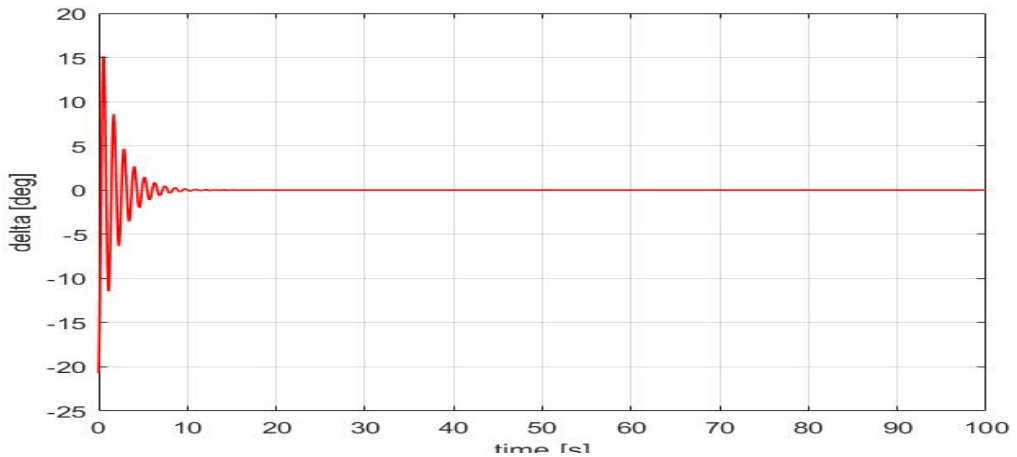


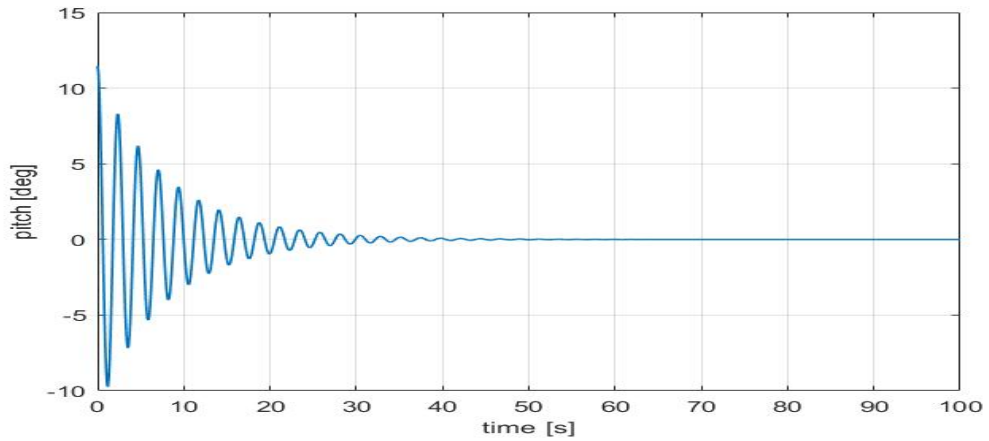


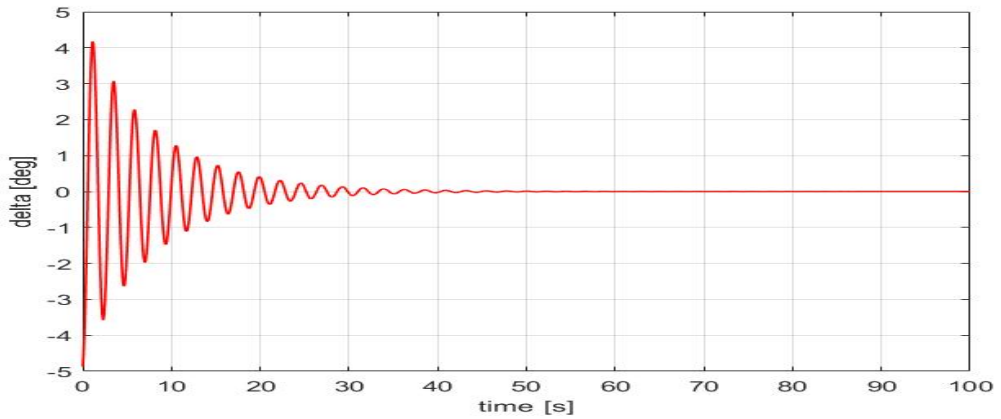


Sliding mode control: ideal case

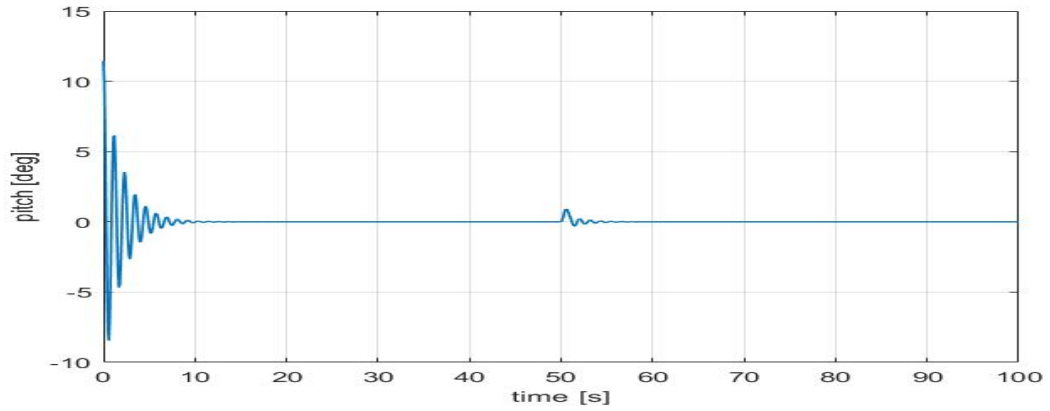


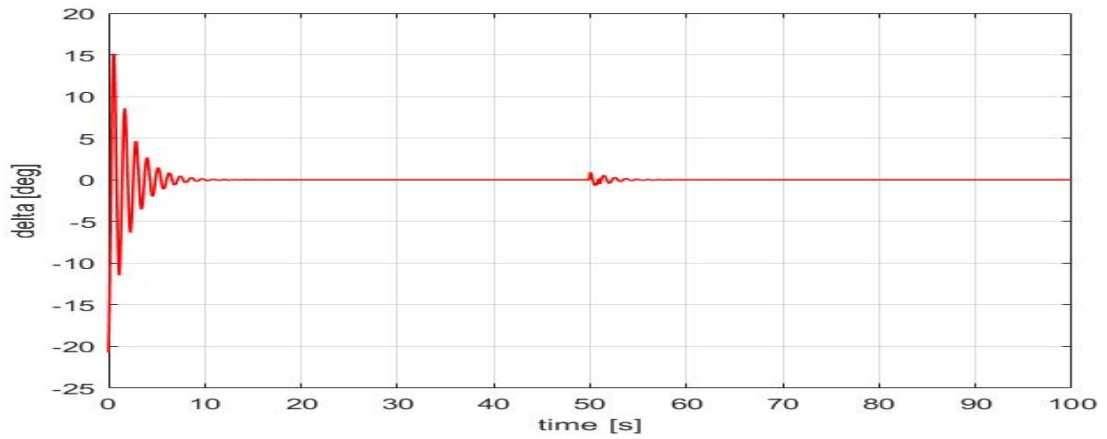


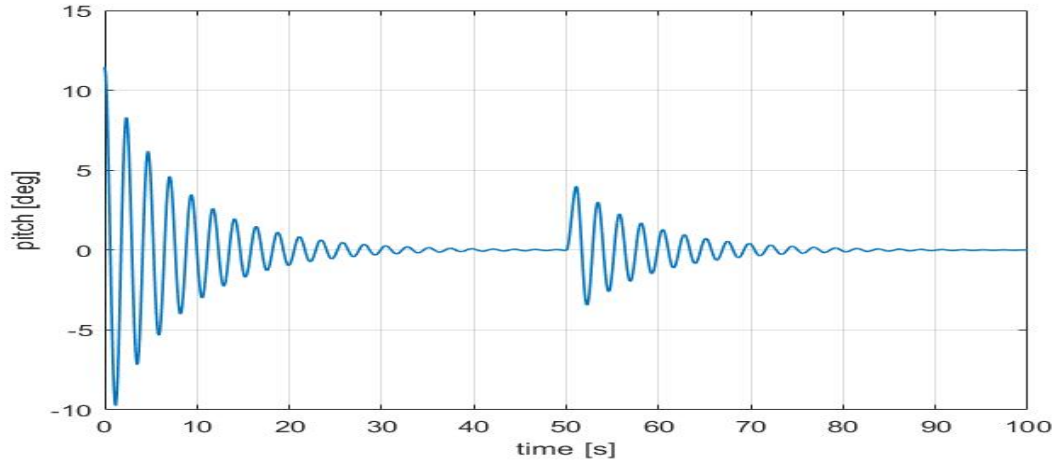


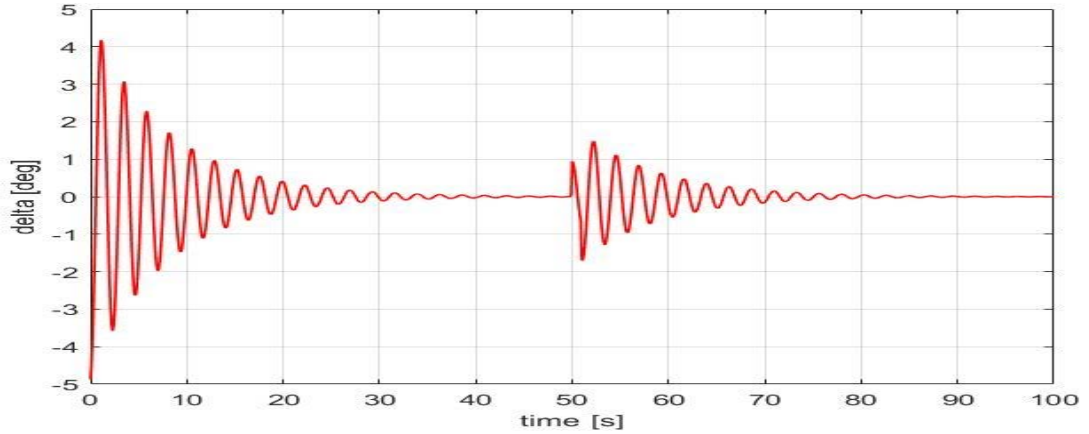


Sliding mode control: external disturbance

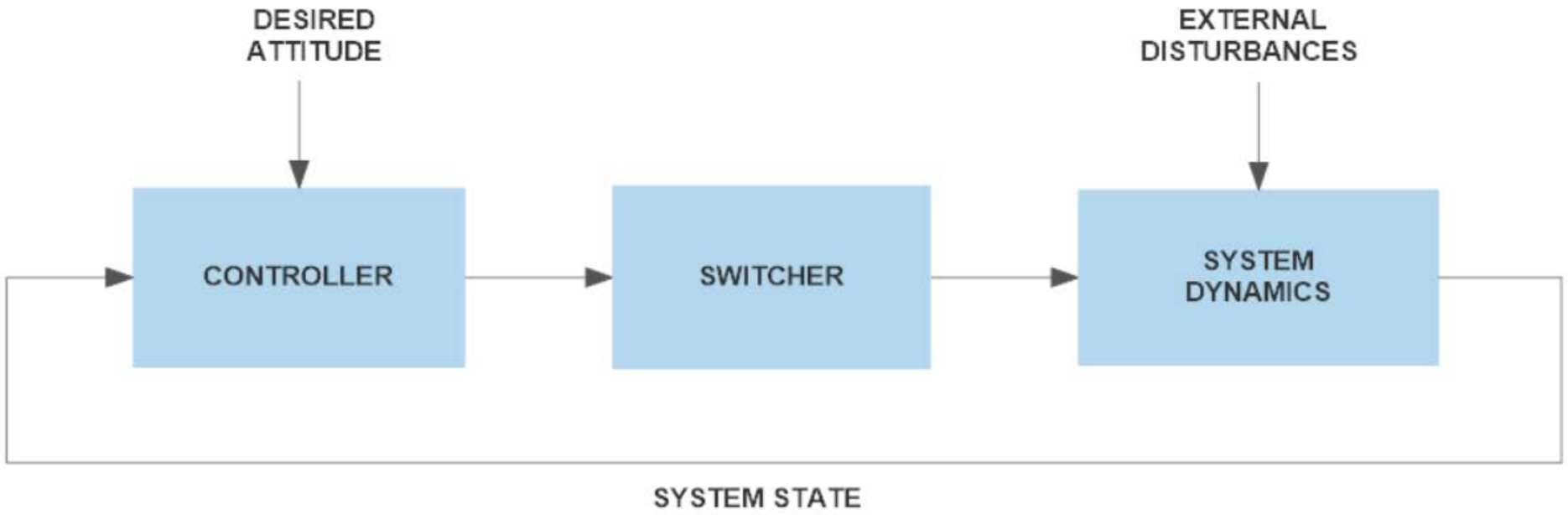








Control block scheme



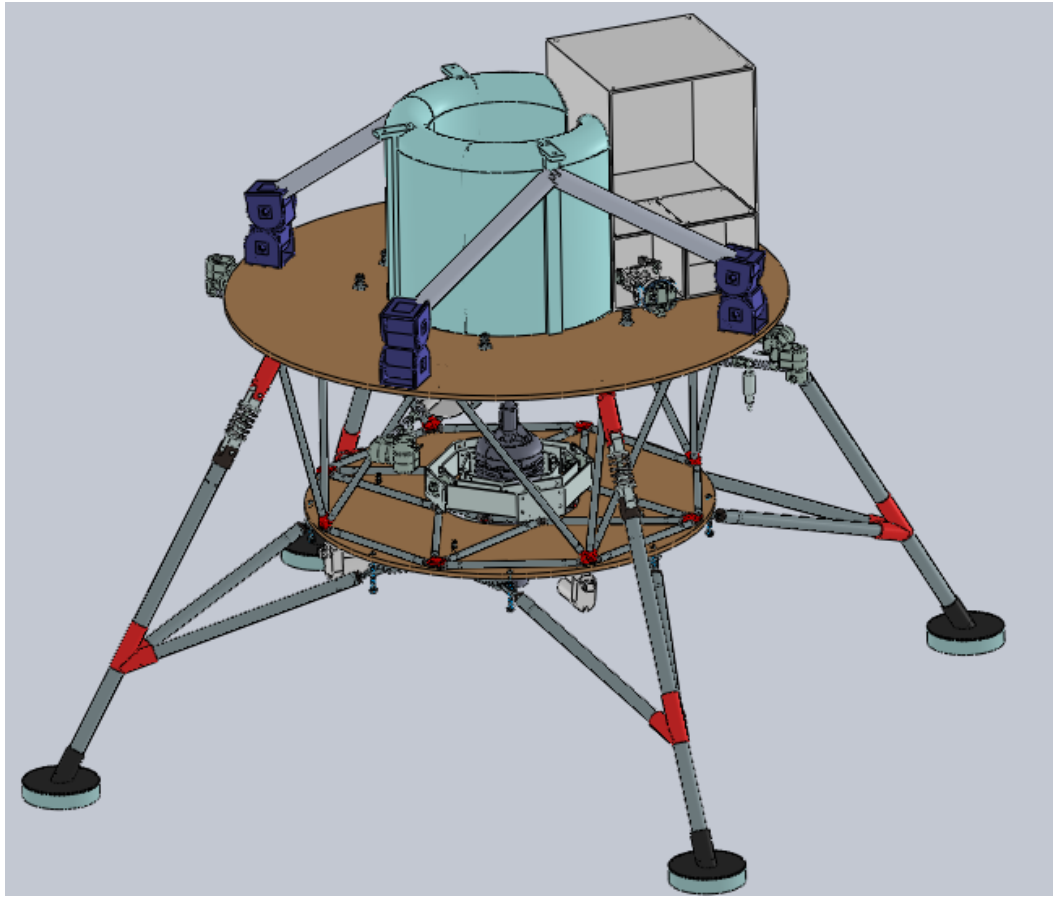
Second Focused Research: Robotic Reconfiguration

Research Challenge: Design a reconfigurable robotic arm which could perform soil activities, sustain a solar panel during the lander non-operative mode and act as a secondary structure on fuel tanks.

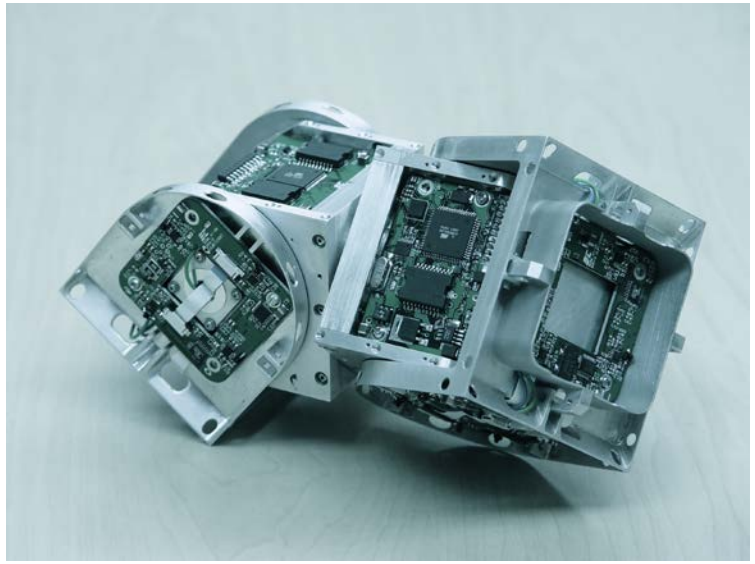
Testbed: For robotic arm, simulations; for adjoining tool (solar panel) use Kirigami based fold/unfolding 3D printed prototype.

Approach: Find the most suitable configuration of the robotic arm as well as the most compact and functional design for the on-board solar panel.

Investigation of dual use Robotic Arm leveraged Existing USC Robotic elements

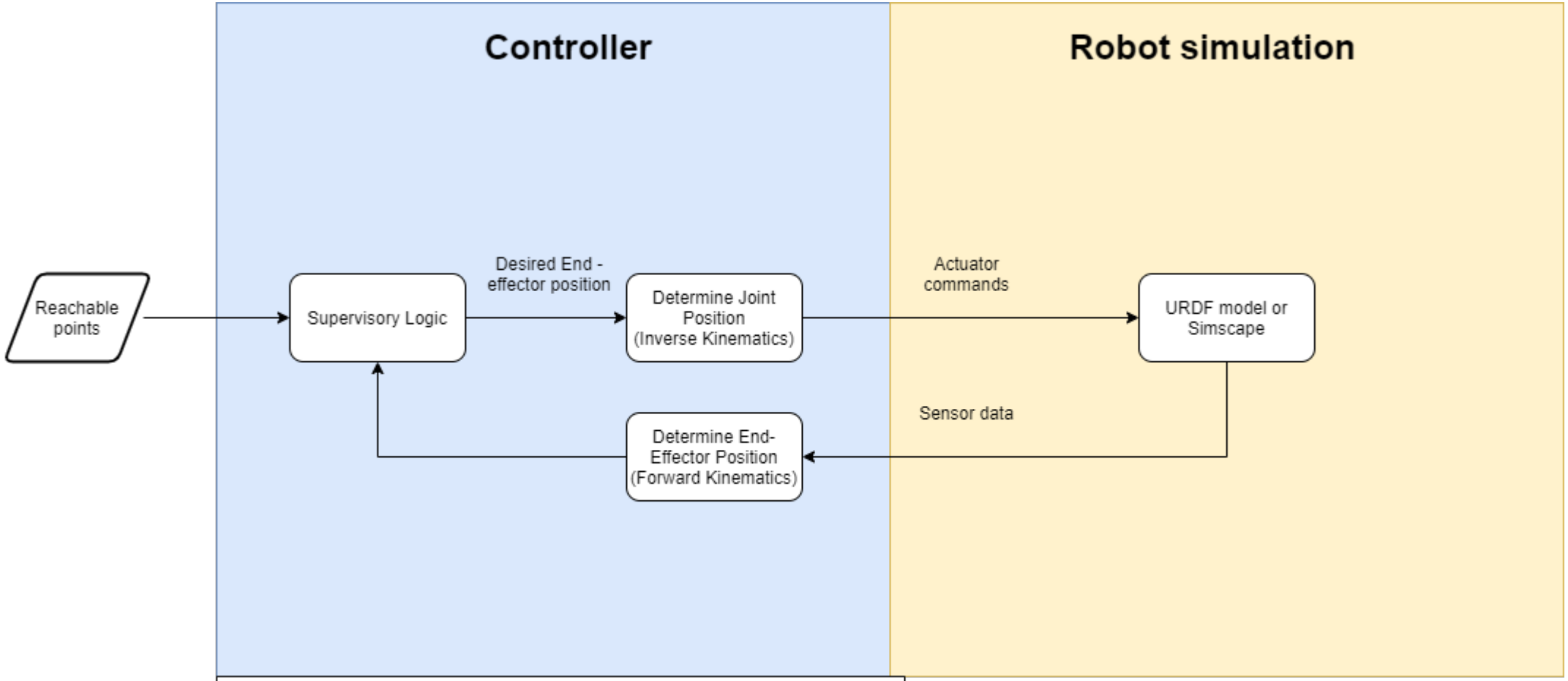


Credits: USC Polymorphic Robotics laboratory



2 units of SuperBot

Robotic Arm Basic System block diagram



RAMSES (Multifuncional SElf-reconfigurable Swarm Robotic Arm) Architecture
+ Controller: Simulnk
+ Robot simulation

MATLAB Dynamic Simulation used to determine path for Robotic movement after landing

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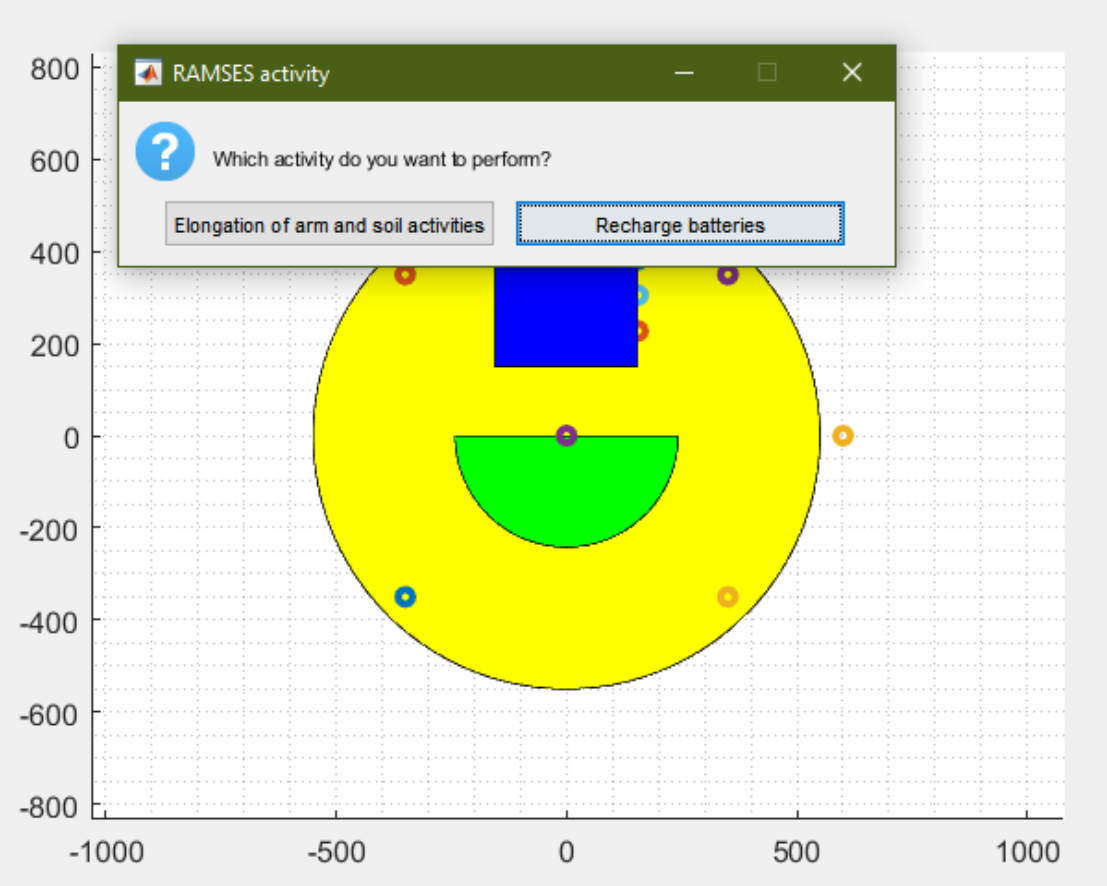
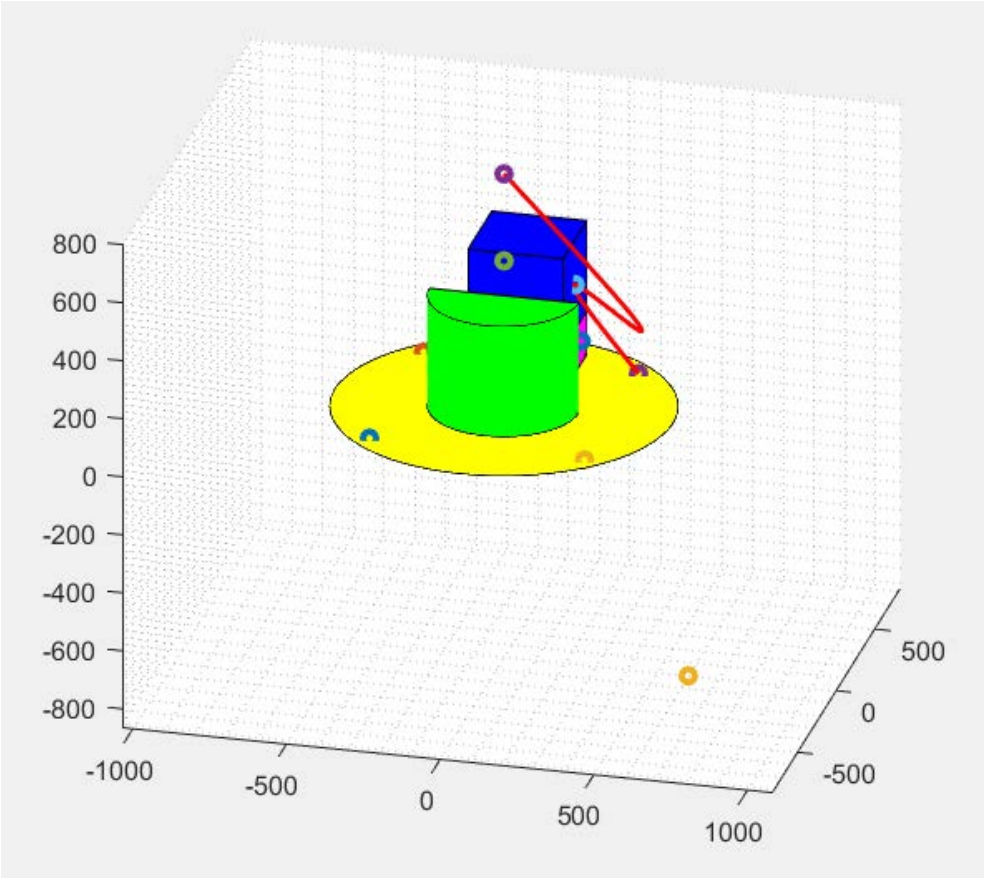
Information Sciences Institute

MATLAB simulations environment





Further Simulation then used dynamics and kinematic reach to resolve high DOF system

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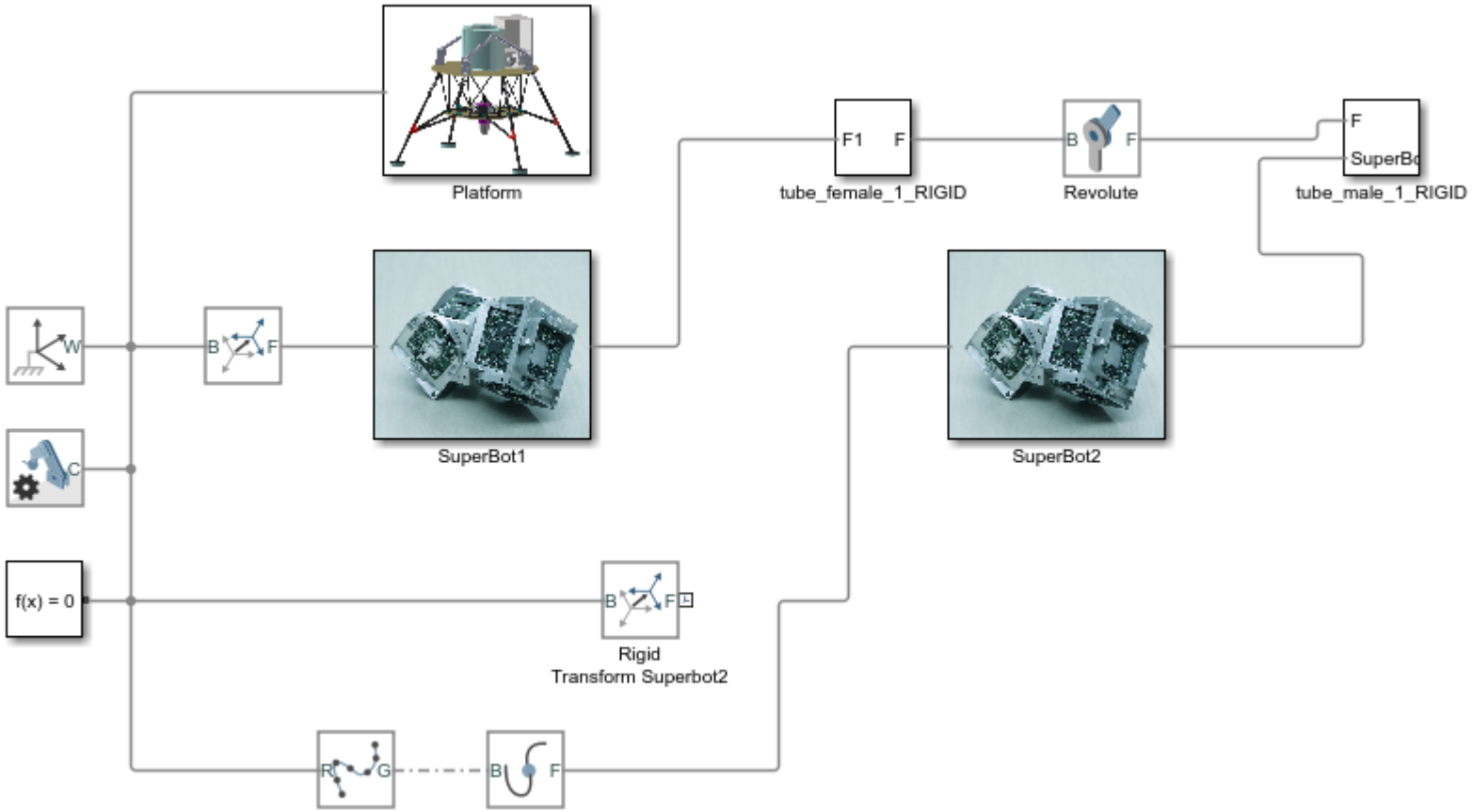
Information Sciences Institute

MATLAB simulations environment



Results of Robotic arm kinematics affecting an adjoining tool

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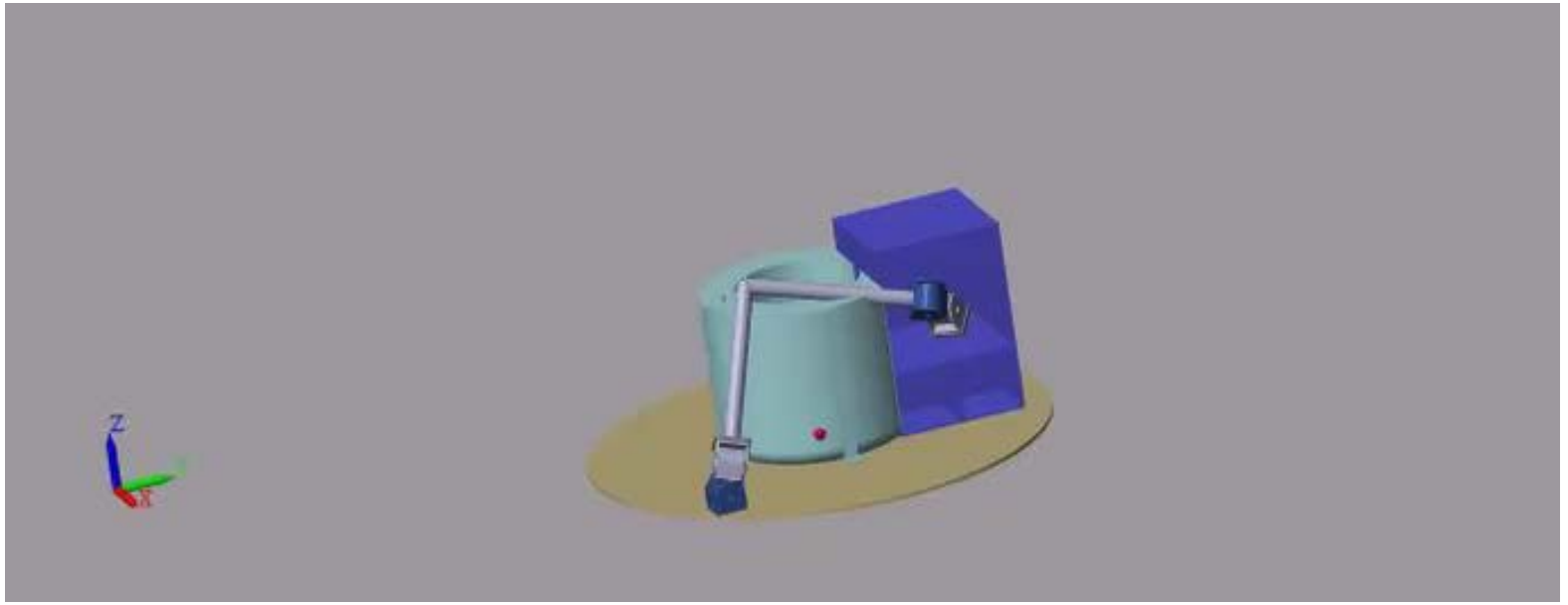
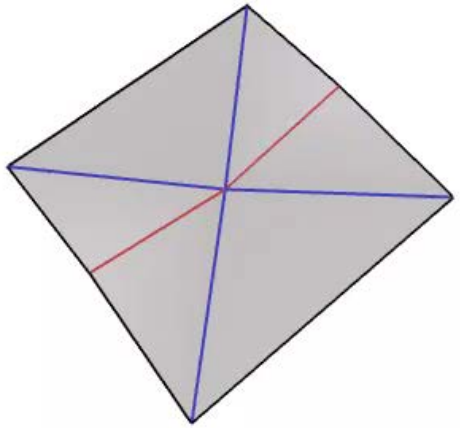
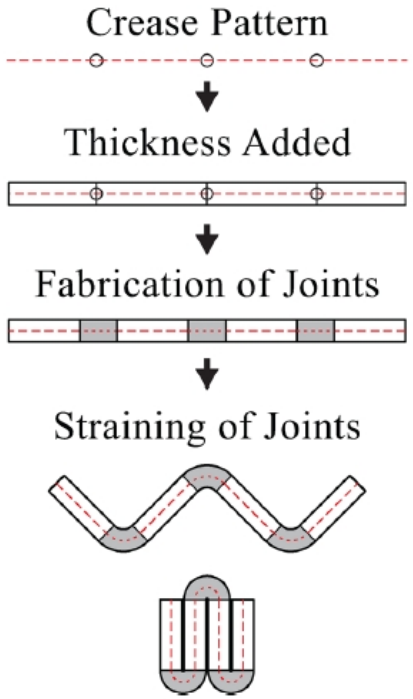
Information Sciences Institute

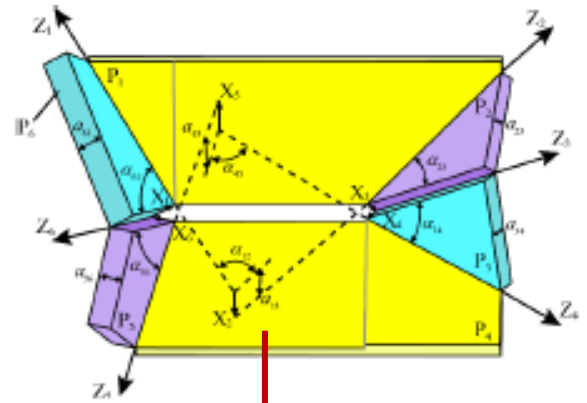
MATLAB simulations environment

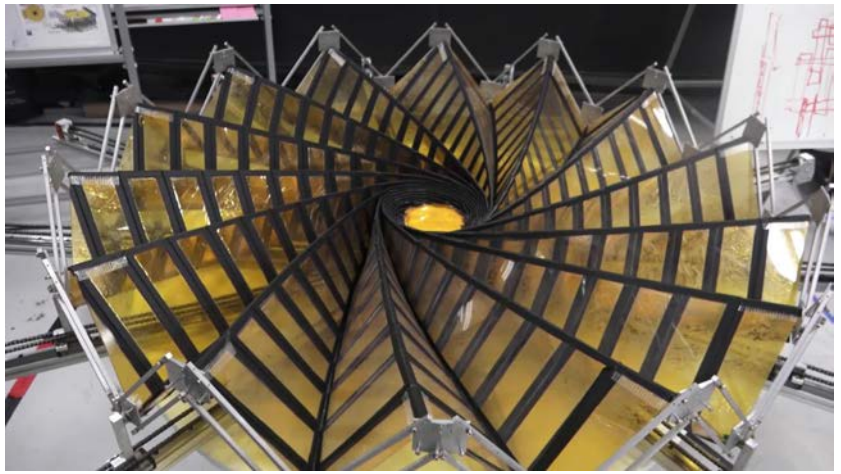


Another Reconfiguration Concept for dual use: Kirigami fold structure with thickness









First design of a deployable solar array from a thruster arm on the Gen-II LEAPFROG lander

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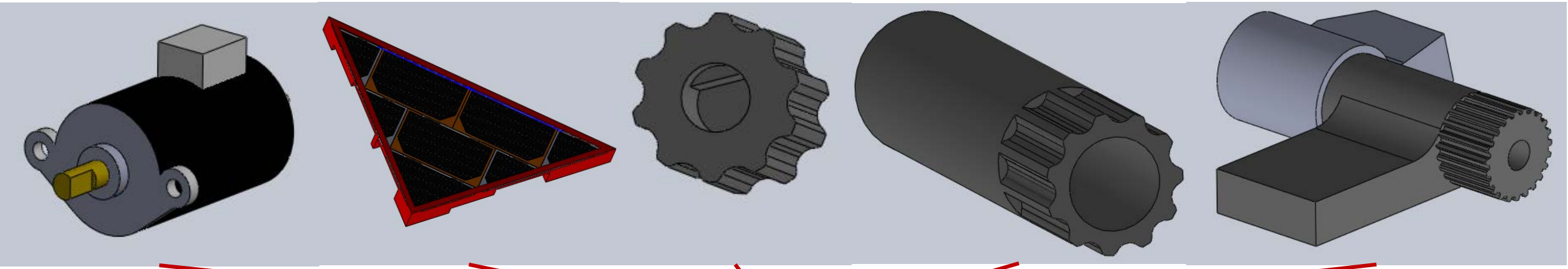
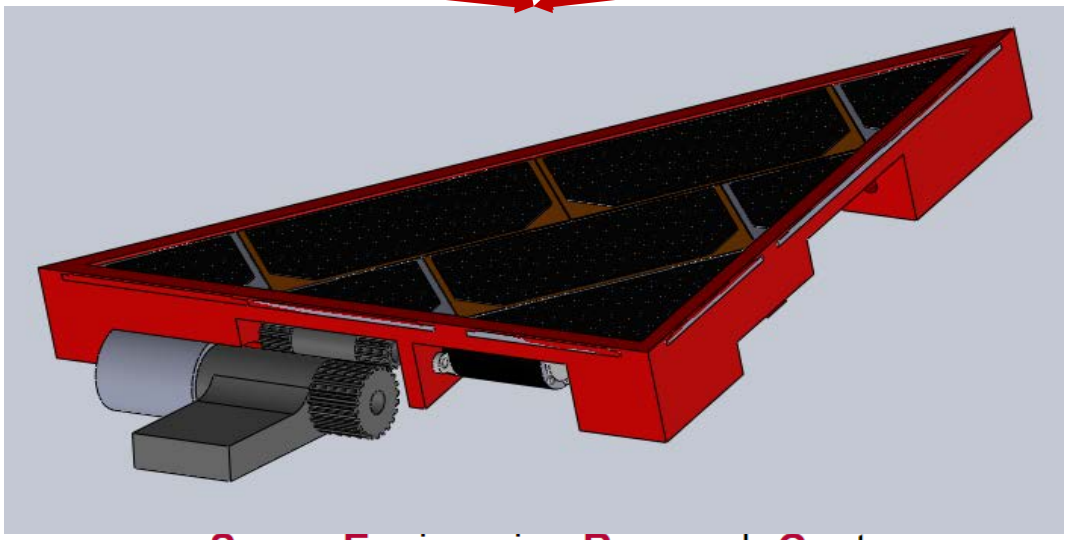
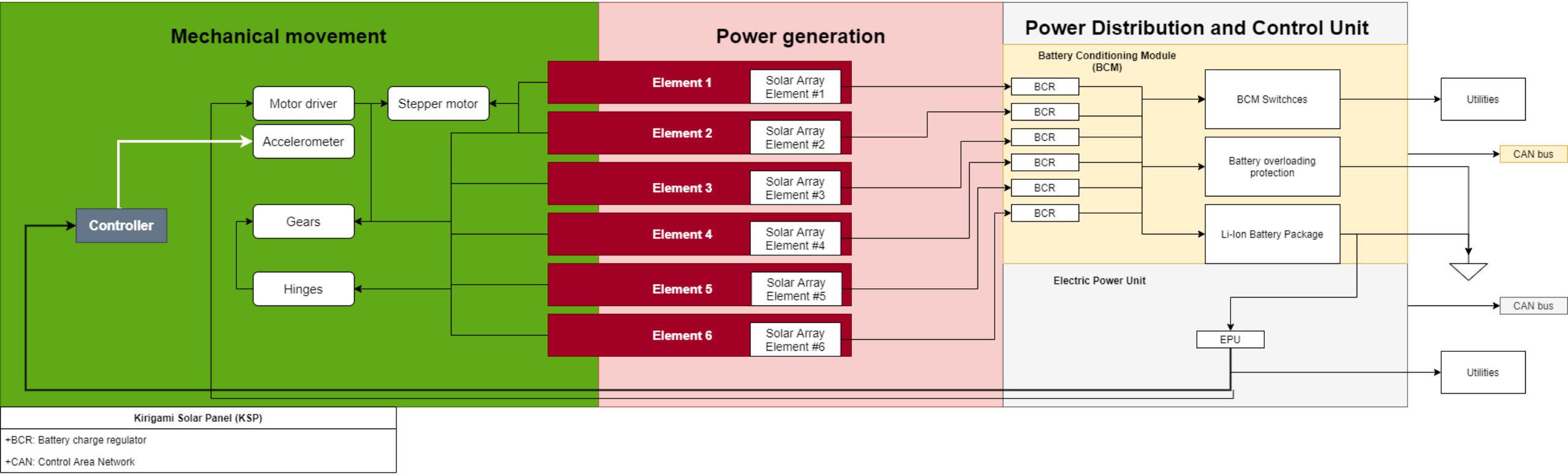
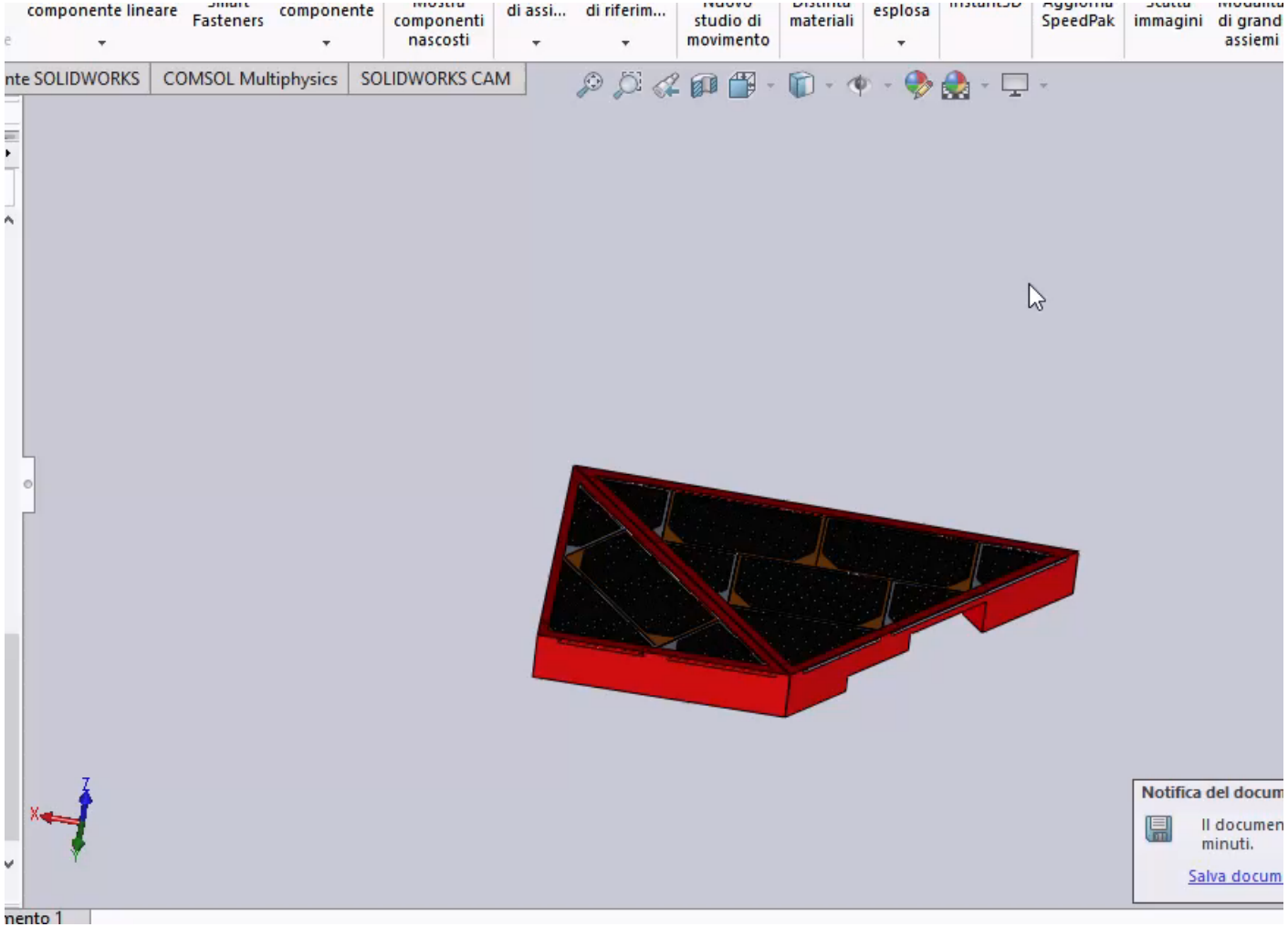




System Block Diagram of Kirigami



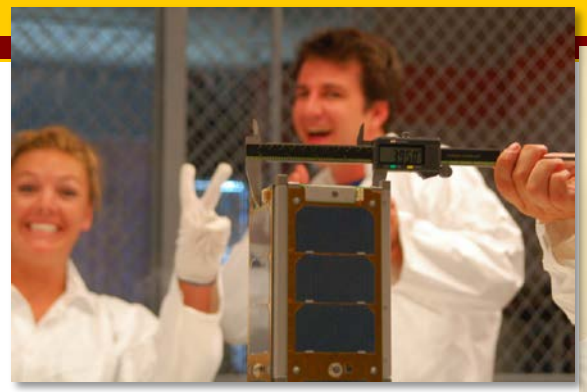
System demonstration: simulation results

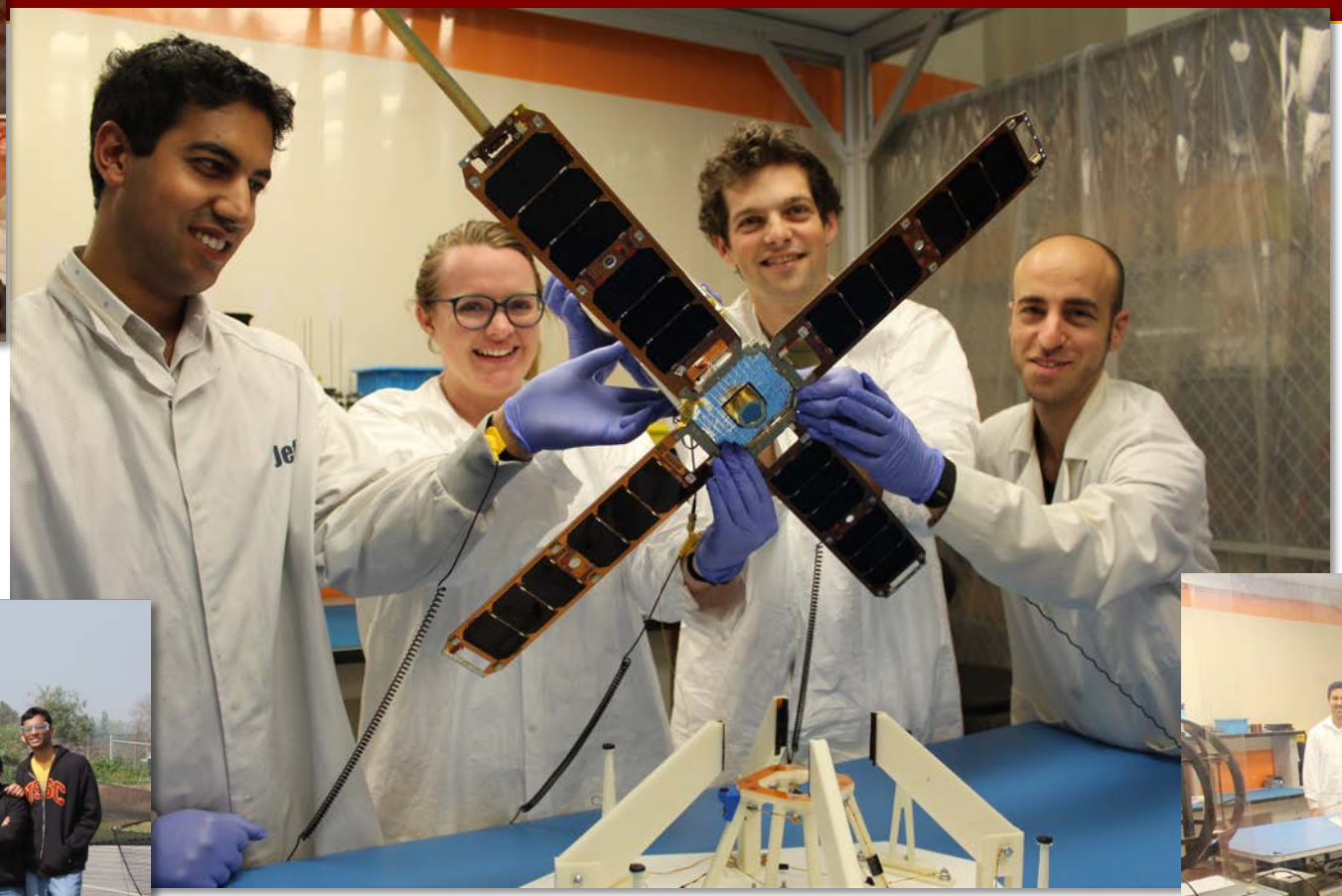


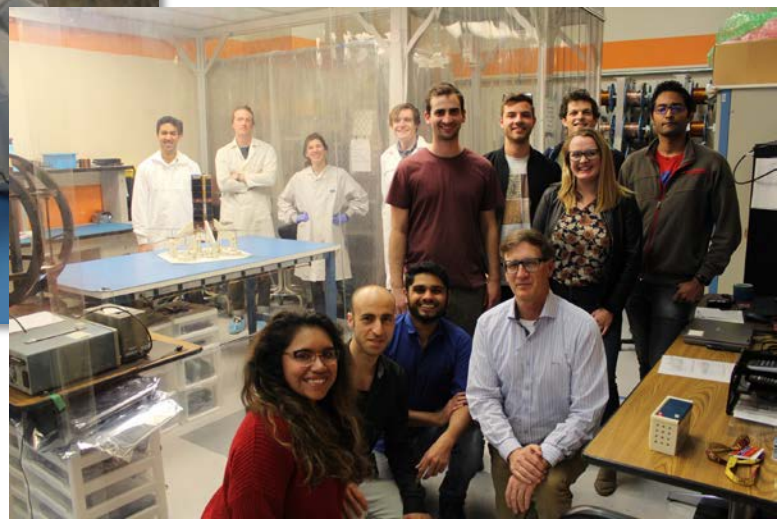
Next steps for LEAPFROG

- Complete building of Gen-II structure
- Add ACS to Gen-II structure
- Build Gimbal mechanism and control electronics
- Build and test first two Tassels and solar panel simulators
- Air Bearing test using the gimbal and ACS system, validate Sliding Mode Control Algorithms
- Test Avionics for Gen-II with Wi-Fi control
- Engine Static Hot Fire
- Free flight!
- LEAPFROG on the Moon?

"..inspirante ad astra.."







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Space Engineering Research Center

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Applications at
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