Preliminary Design Review

EASE

Electrodynamic Dust Shielding **A**ctivated **S**urface **E**mitter

SHAPING THE FUTURE OF AEROSPACE

AIAA Caltech Student Branch – 18/11/20
Advisor: Dr. Soon-Jo Chung

INTRODUCTION

ROADMAP

INTRODUCTION
- Meet the Team
- Competition Overview
- Competition Constraints
- Lunar Dust
- Problem Statement

CONCEPT OVERVIEW
- Quad Chart
- How it Works
- Requirements & Success Criteria
- Design Assumptions

MECHATRONICS
- EDS Overview
- EDS Layout
- Controls Diagram
- Circuit Diagram
- Simulation
- Power Requirements

MECHANICAL
- System Overview
- Material Selection
- FEA Results
- Manufacturing

MISSION INTEGRATION
- Concept of Operations
- Risk Assessment

VERIFICATION & VALIDATION
- Testing Program

LOGISTICS
- Schedule
- Budget

CONCLUSION
- Outstanding Issues
- Supplementary Material

INTRODUCTION

MEET THE TEAM

Leadership

CEO
Luis Pabon
MCE & Aero, '22
Houston, TX

CTO
Malcolm Tisdale
MCE & CDS, '22

COO
Isabella Dula
MCE & , '22

Advisor
Dr. Soon-Jo Chung

Mechanical

Lead
Polina Verkhovodova
MCE & PI, '22
Pasadena, CA

Lead
Leah Soldner
MCE , '24
S Pasadena, CA

Tanmay Gupta
MCE , '24
Ph / Astro
Kuala Lumpur, Malaysia

Nathan Ng
MCE , '24
Santa Clara, CA

Mechatronics

Lead
Isabella Dula

Athena Kolli
MCE , '24
Buffalo Grove, IL

Kemal Pulungan
MCE , '24
Troy, NY

Jules Penot
MCE & Aero , '24
Valbonne, France

Mission Integration

Lead
Calle Junker
MCE, '23
Aztec, NM

Kaila Coimbra
MCE , '23
San Diego, CA

Rithvik Musuku
MCE , '24
Gilbert, AZ

Parul Singh
MCE , '24
Tallahasee, FL

Artemis Missions – Feet on the moon by 2024 & sustainable missions by 2028. NASA BIG Idea Challenge Finalists implemented 2026

- University teams of 5 – 25 students
- Teams submit proposals (Dec 13th 2020) for funding to develop concepts for technical paper and BIG Idea Forum (Nov 15th 2021)
- Awards from $50,000 - $180,00

Landing Dust Prevention & Mitigation - to preclude or protect from plume/surface interactions which may result in damaged landers and nearby surface assets

Spacesuit Dust Tolerance & Mitigation - to limit dust adherence to spacesuits and other damaging effects to its subsystems

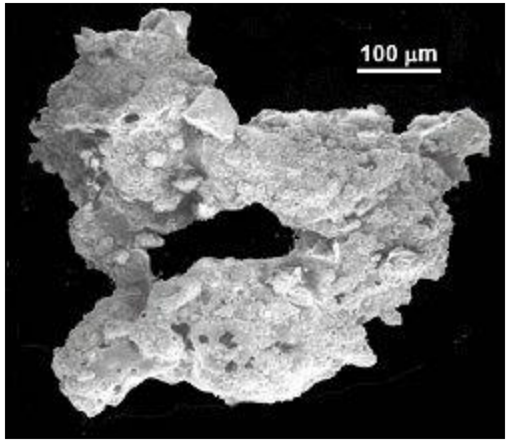
Exterior Dust Prevention, Tolerance, & Mitigation - to protect lunar surface systems or preclude dust from entering habitats and landers

Cabin Dust Tolerance & Mitigation - to clean habitable volumes and their interior surfaces, which helps prevent dust from making it back to Gateway and Orion when the lander returns to lunar orbit from the surface

Constraints

- Able to manage or mitigate lunar dust (~0.5-100 um)
- Minimal barrier to NASA adoption
    - Cost, power, mass, size …
- Minimum Technological Readiness Level 4 (->5)
- Lifespan of 15 - 30 years
- Removes dust "in minutes"
- Lunar environmental conditions
    - South pole temperatures between -232C and -49C
    - Permanently shadowed craters as low as -243C

Gene Cernan covered in lunar dust

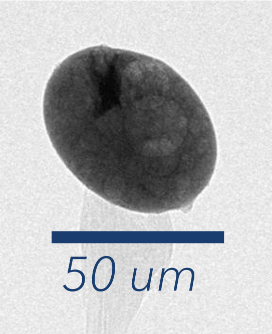


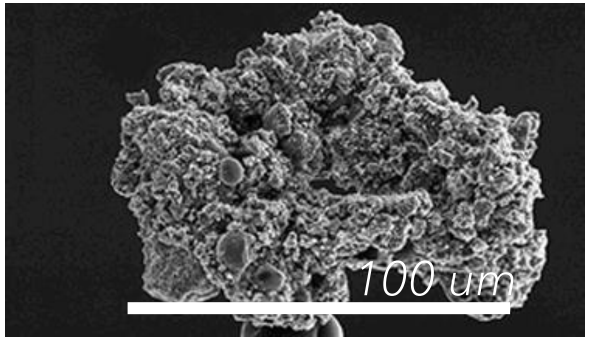
Lunar Dust Particle

Considerations

- Aiming for 2026 deployment in lunar missions
- Simplicity of operation and maintenance
- Deployment method from NASA or commercial surface lander
- Effective packaging for launch and Moon landing
- Credible fabrication and material selection

Dust Properties





PROPERTY	VALUE	UNITS
Size range	4 – 500	[nm] – [um]
Volume fraction	< 0.2	%
Relative permittivity	3 - 4	
Relative permeability	~ 1	
Specific gravity	~ 3	[g * cm^-3]
Charge	10^11 – 10^13	[C / kg]

Issues Posed

- Vision obscuration
- False instrument readings
- Dust coating and contamination
- Seal failures
- Abrasion of materials
- Inhalation and irritation risks
- **Loss of foot traction**

- Charged through solar emissions
- Trace magnetic elements
- 90% Silicate/Aluminosilicate minerals by volume
- Highly irregular and sharp
- Charge density increases with particle size

Problems Caused By Spacesuit Dust Ingress Into Habitable Volumes

- Increased loads on in-cabin dust mitigation technologies
- Incorrect readings during in-cabin experiments
- Performance reduction and possible failure of in-cabin equipment
- Astronaut health risks
- Dust brought to Gateway and Orion when lander returns to lunar orbit

Existing Solutions

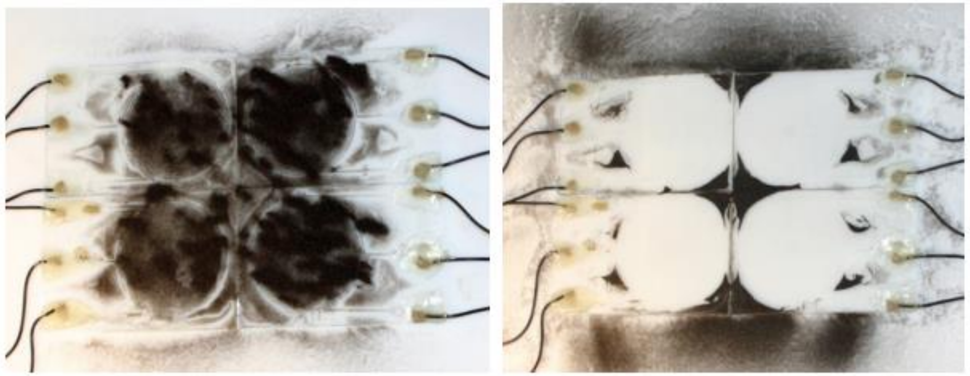


FIGURE 3–1. SIMULANT DUST REMOVAL WITH NASA KENNEDY SPACE CENTER'S EDS AT 10-6 KPA (CALLE ET AL. ACTA ASTRONAUT. 69, 2011: 1082-1088).

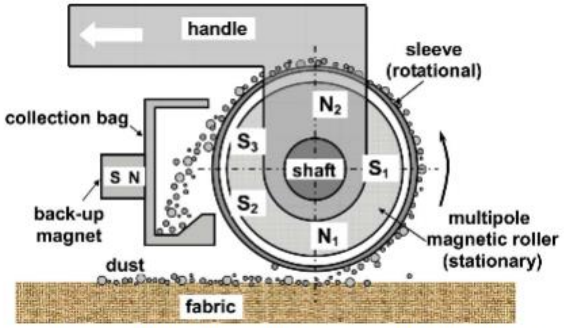
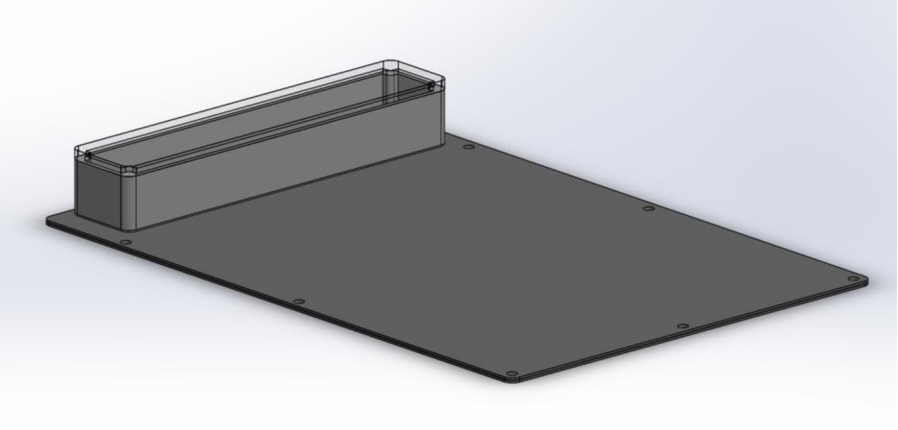


FIGURE 3–4. WASEDA UNIVERSITY'S MAGNETIC CLEANING DEVICE (KAWAMOTO, H. AND H. INOUE, J. AEROSP. ENG. 2012, 25: 139–142).

Objective:

- Minimize dust ingress into lunar habitat module on astronaut boots
- Increases traction of astronaut boots
- EASE is portable, durable, low SWaPs device
- Clears lunar dust from astronaut boots in < 2 mins and self cleaning
- Increases the state-of-the-art:
    - Largest, most compact, and durable implementation of electrodynamic shielding technology
- Develop and validate to **TRL 5**



Render of EASE

Approach:

Leverages 50-year-old dust mitigation technology currently being tested on ISS

- 3-Phase traveling square wave pushes dust particles off astronaut boots and EASE
- Touch-free operation using piezoelectric pressure sensors in mat
- Extensive validation and verification program though

Mass Estimate: 1.2 kg Power Estimate: 10 W max

Key Milestones:

Description	TRL	Deadline
Preliminary Design Review	2	11/18/20
Proposal	3	12/13/20
Functional Prototype	3	4/1/21
Midpoint Report	4	5/20/21
Technical Paper & Verification Demonstration	5	10/27/21

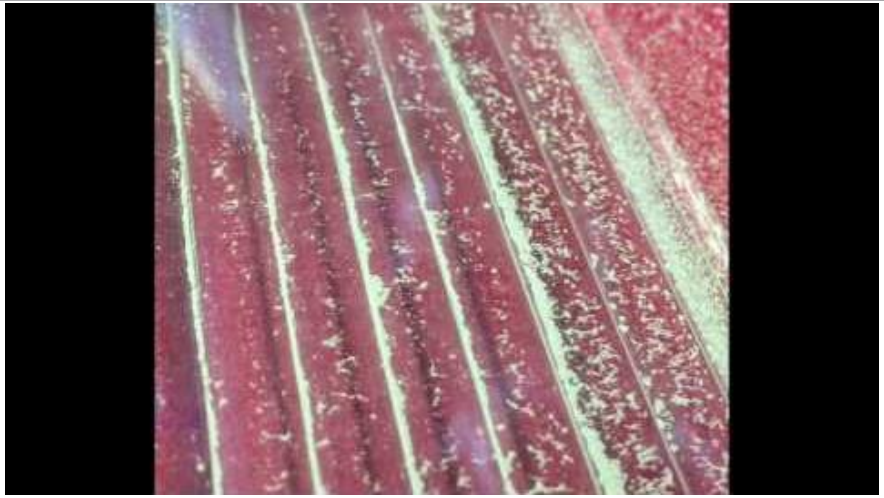
Functional Requirements	Description
FR 1.0	Remove 50% of dust from astronaut boots during cleaning period
FR 2.0	Self-cleaning after astronaut departure
FR 3.0	Minimum 15-year lifetime on lunar surface
FR 4.0	Capable of enduring forces involved in launch and landing
FR 5.0	Capable of enduring repeated impacts without loss in performance

DESIGN ASSUMPTIONS

Design Assumption	Description
DA 1.0	EASE placed on 1 m x 1 m cleared and leveled area of regolith
DA 2.0	28 V DC power supplied by lunar habitats and landers
DA 3.0	Lunar regolith compresses under load of mat and astronaut
DA 4.0	Disregard off nominal solar activity
DA 5.0	No more than one astronaut at a time maximum load

Electrodynamic **D**ust **S**hielding

- Parent technology developed in **1970s**
- Lifts and transports charged and uncharged particles using **electrostatic** and **dielectrophoretic** forces
- Works best for particle size regimes of **5-300 μm** (encompasses size regime for lunar dust particles)
- Technology currently being used in:
  - Solar panel maintenance (dust removal efficiency of **90%**)
  - Tested in mock lunar environments
  - In-Situ Experiments on ISS on thermal radiators and solar panels
    - Ongoing; showed that **EDS works in vacuum**
    - Solar panel effectiveness **22.5%→98.4%** after EDS implementation with lunar simulant



Demonstration of EDS on a glass plate; particle size < 20 μm (Guo, 2018)

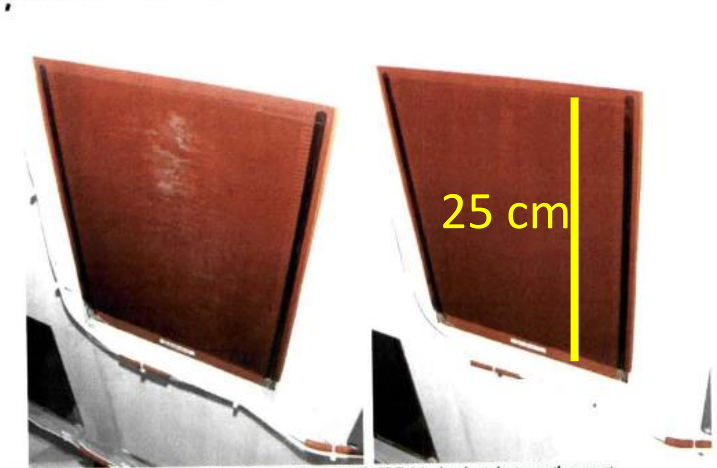
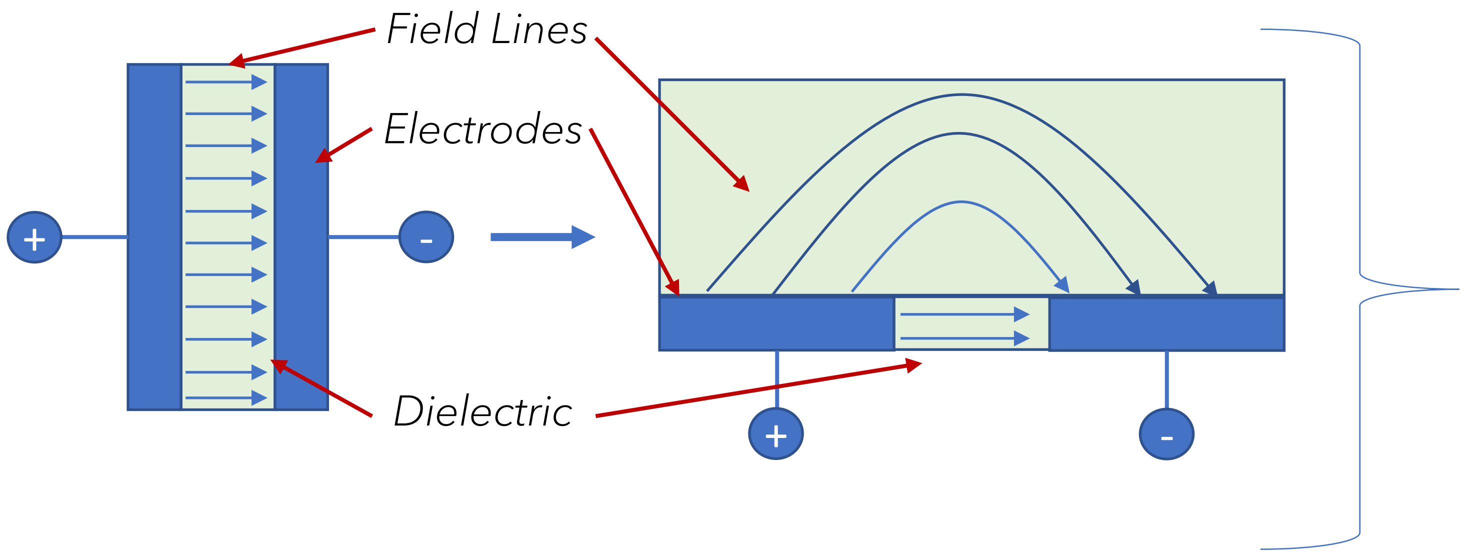
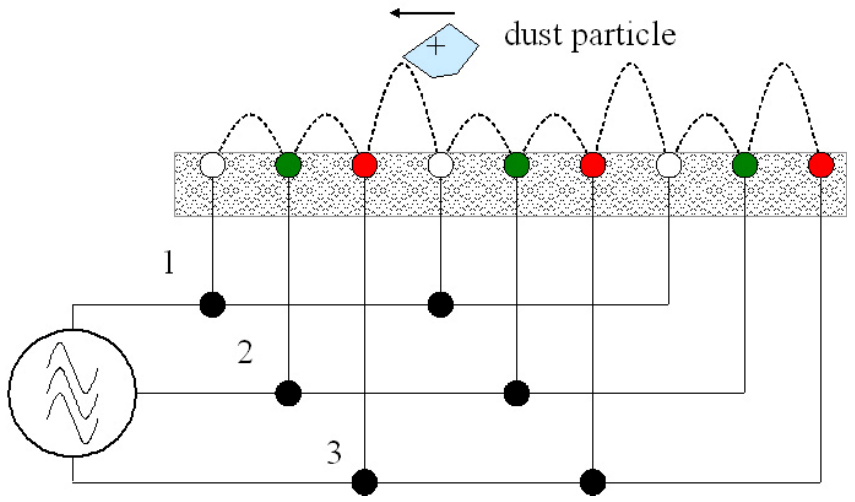


Fig. 7. Post installation tests of the 20 cm × 25 cm EDS. JSC-1A simulant dust was thrown at

EDS System mounted on sim. Lunar habitat

EDS OVERVIEW
INTERDIGATED CAPACITOR

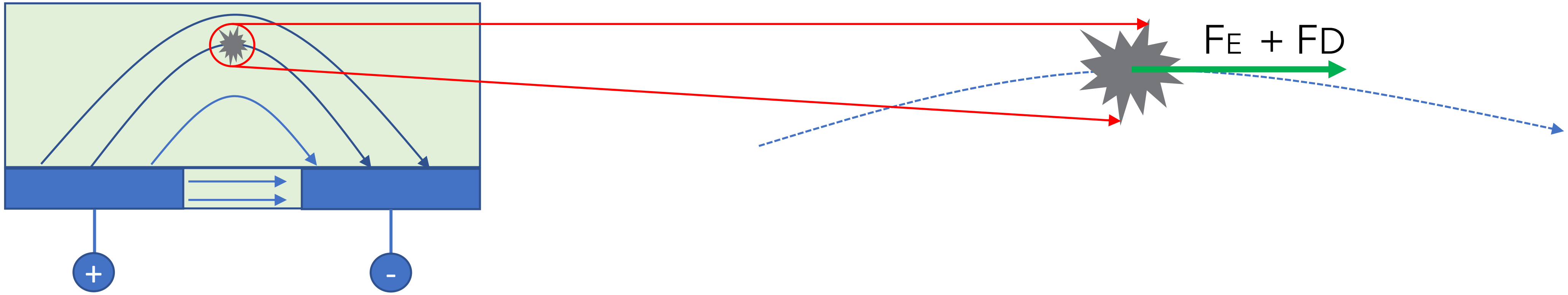




- Fringing electric field exerts force on charged dust particles
- 3 phased EDS Systems transport dust particles

(Calle, 2010)

EDS OVERVIEW
FORCES INVOLVED



Variables:
E = electric field strength
q = particle charge
ε_m = dielectric permittivity of medium
ε_o = dielectric permittivity of vacuum
R = particle diameter
γ = surface energy of adhering surface

Forces exerted by EDS:

FE : Electrostatic force

$$F_E = qE$$

FD : Dielectrophoretic force

$$F_D = 2\pi\varepsilon_o \frac{\varepsilon_m - 1}{\varepsilon_m + 2} R^3 \nabla E^2$$

>

Forces adhering particles to astronaut:

V : Van der Waals force

$$V = 4\pi R\gamma$$

S : Image-charge static force

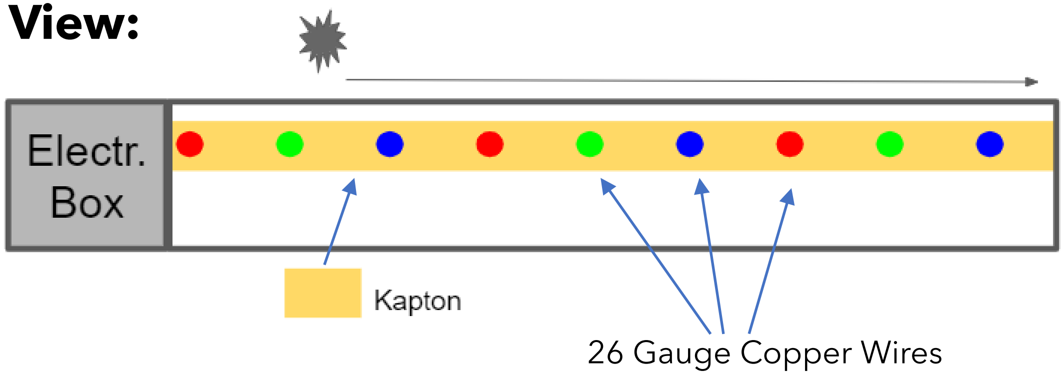
$$S = \frac{q}{4\varepsilon_o (2R)^2}$$

Feasible by analysis and prior implementations

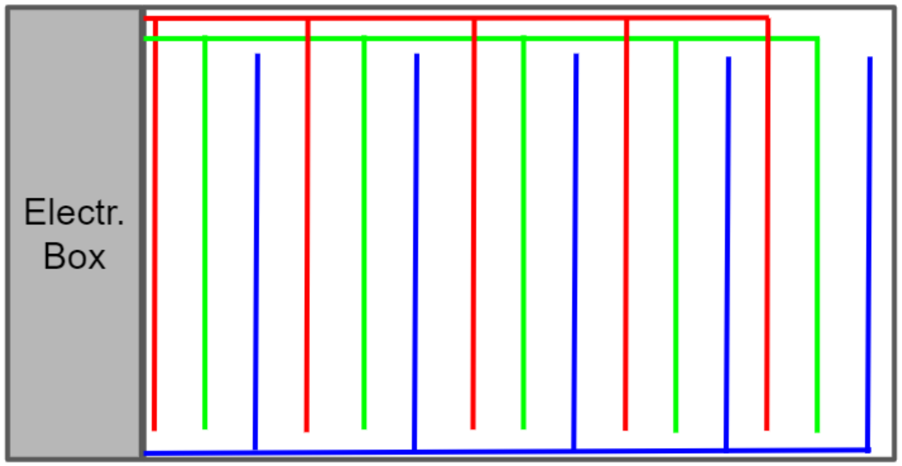
MECHATRONICS

LAYOUT AND PHASING

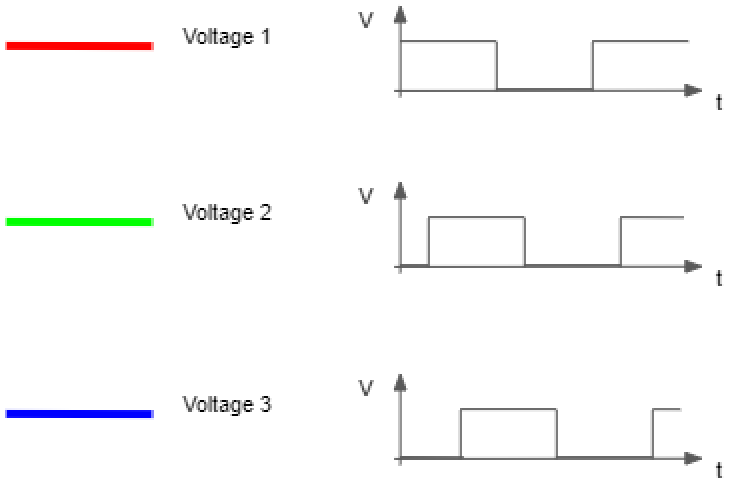
Side View:



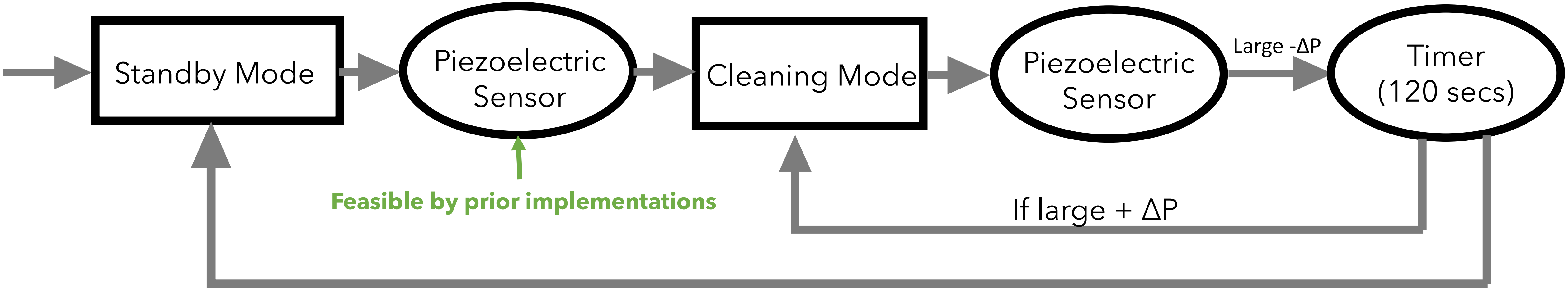
Top View:



Note: not to scale



- Electronics box made of aluminum and Multi-Layer Insulation (MLI) to **protect against thermal and radiative environment**
- Kapton dielectric rated for **-268°C to 399°C**

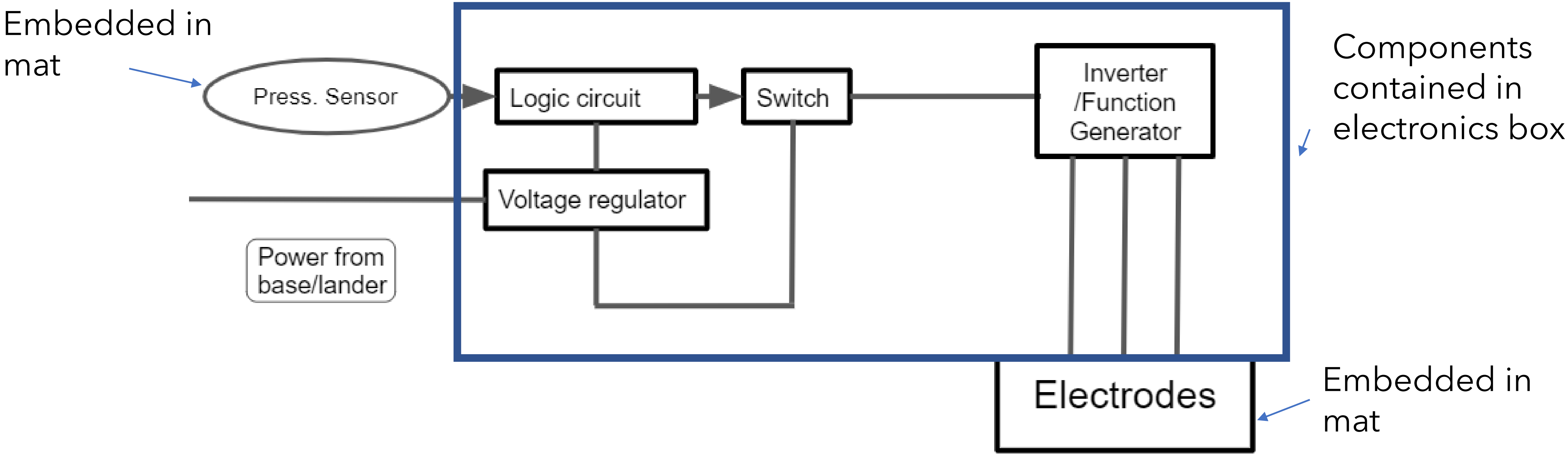


Operational Modes

Standby Mode: awaiting use, sensors are active
Cleaning Mode: capacitors are charged, suit is cleaned, dust removed from mat

MECHATRONICS

CIRCUIT DIAGRAM



Sensors and components to be selected/designed from existing NASA satellite and spacecraft payloads.

MECHATRONICS
POWER REQUIREMENTS

- Estimates based on finite difference time domain electrostatic simulation
  - Obtained mesh grid of electric field strength given electrode lay-out and voltage supply
  - Determined electromagnetic field strength necessary to overcome adhesive forces

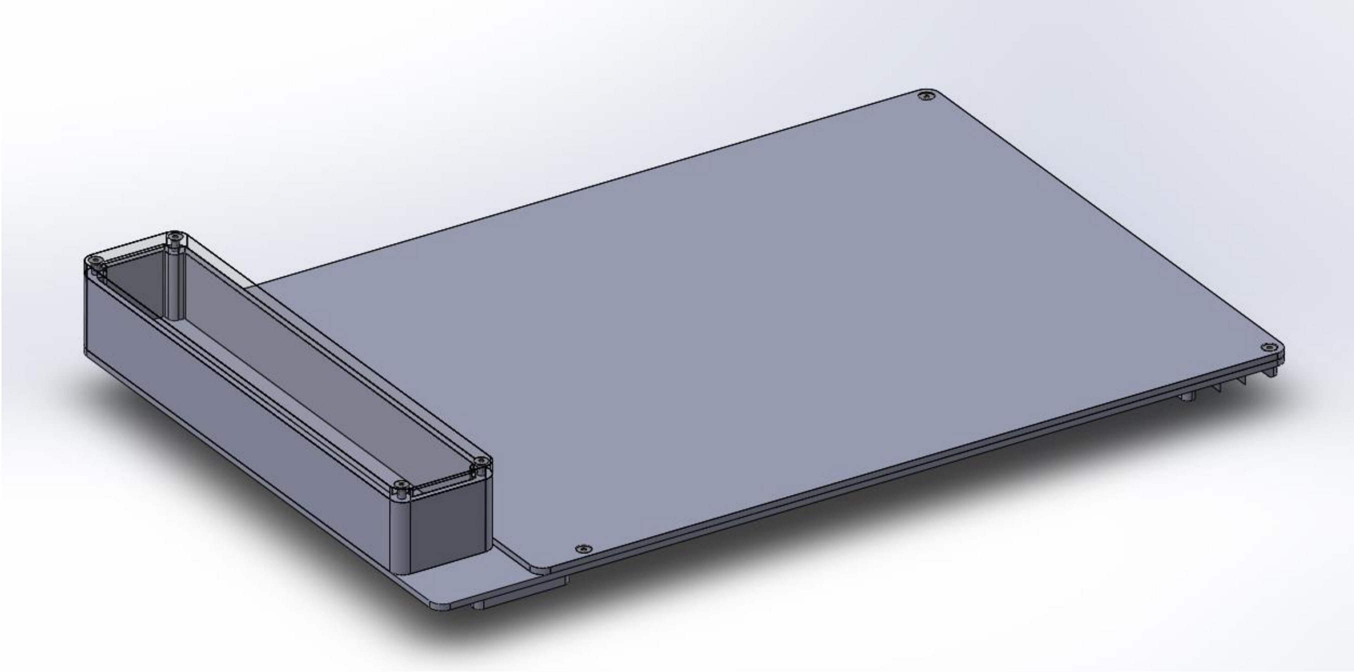
Operational Mode	Time Estimate	Voltage (DC)	Power Requirements (W)
ASTRONAUT	3 min/astronaut	28 V	10 W
STANDBY	VARIABLE	28 V	<100 mW

- Current estimates predict EASE will have **low power requirements**

Feasible by analysis and prior implementations

DESIGN OVERVIEW

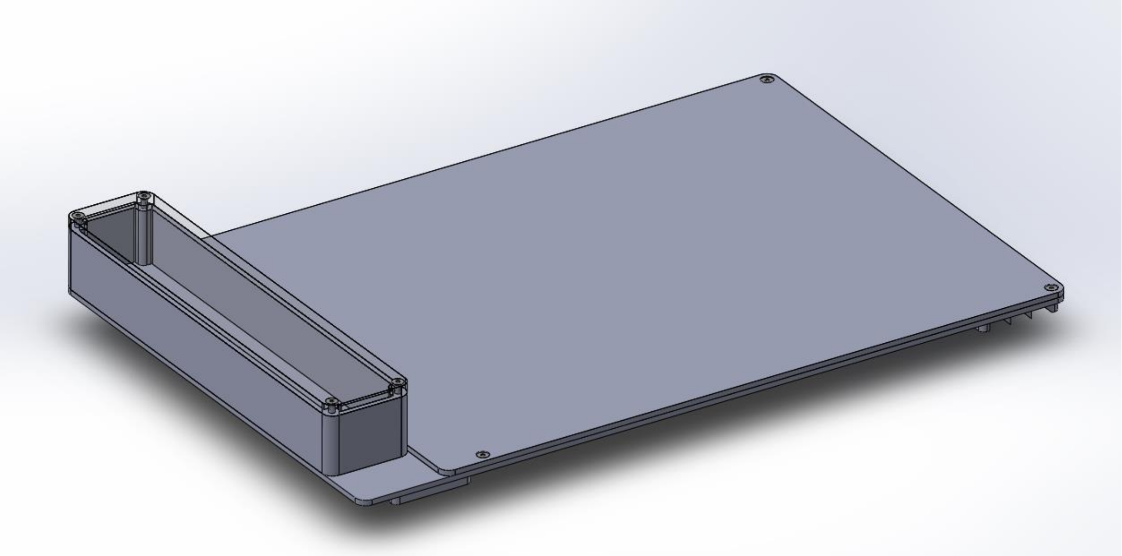
MECHANICAL



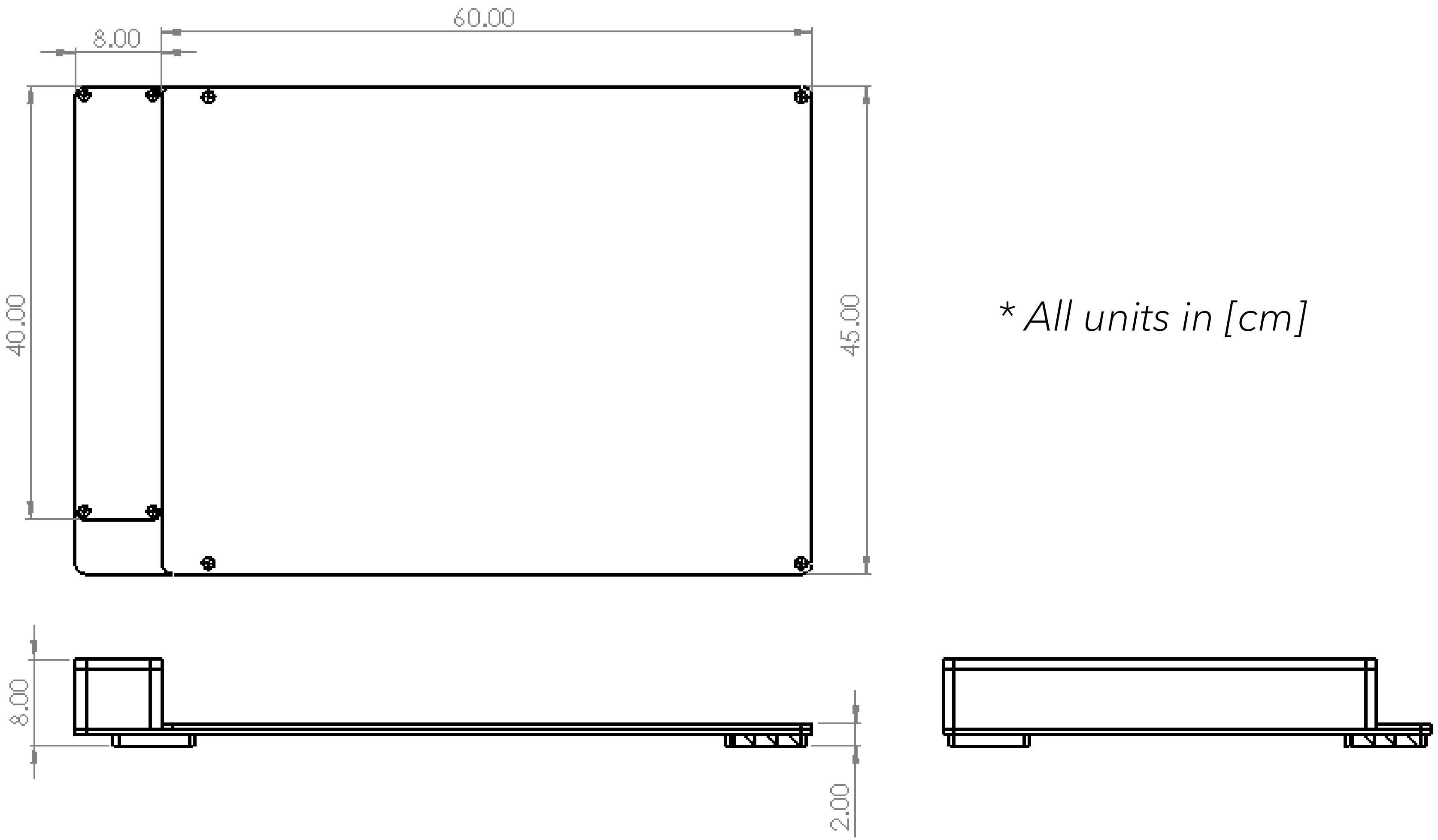
Objectives:

- Strong enough to sustain weight
- Easy to transport and use
- Large enough size to comfortably use
- Optimized for weight and volume
- Electronics are secured and protected
- Cost-effective solution
- Protected from the harsh lunar environment
- Use for 15-30 years.

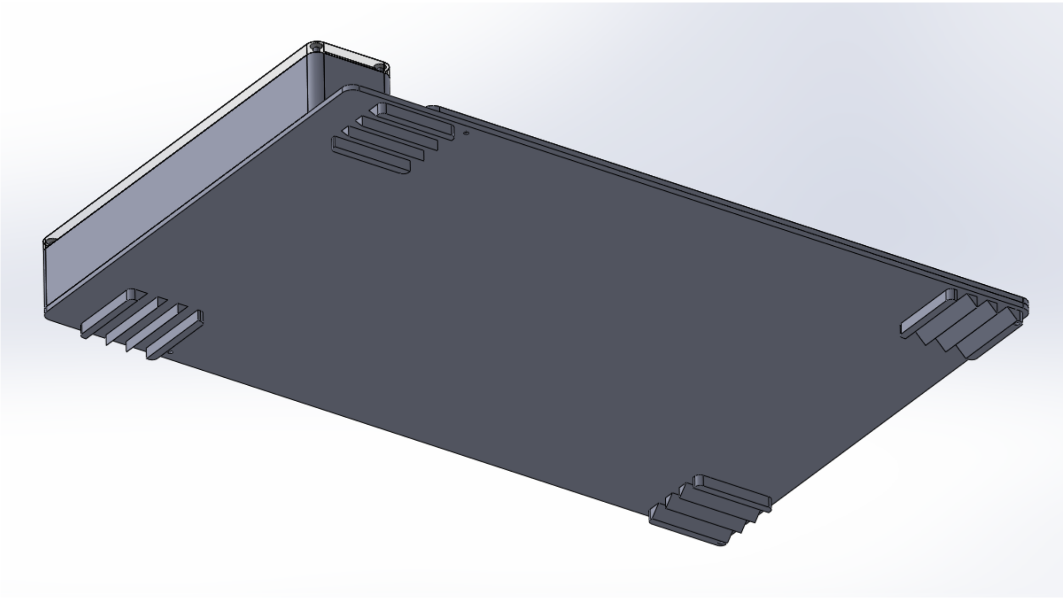
DESIGN OVERVIEW
MECHANICAL



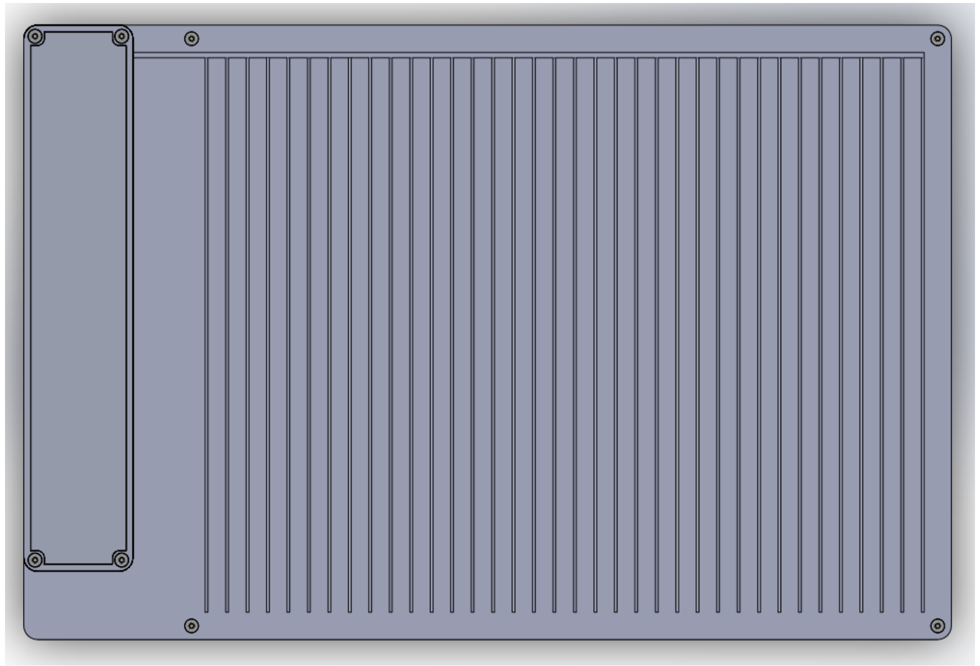
Metric	Weight	Single Panel	Single Fold Accordion
Use with EDS	10	9	5
Robustness	30	25	20
Weight and Volume	20	20	12
Storage, transportation, deployment	20	20	12
Life Cycle	20	20	16
Total	100	94	65



* *All units in [cm]*



Spikes for security



EDS System

PANEL COMPOSITION
MECHANICAL

Mass estimate: 1.4 kg

MECHANICAL
MATERIAL SELECTION

	Alumina Ceramic	Bolt	Beta-cloth	Kapton
Density	3.9 (g/cm^3)	8.0 (g/cm^3)	2.71 (10^{-3} g/cm^2)	1.41 (g/cm^3)
Tensile Strength	260 (MPa)	482 (MPa)	3,450 (MPa)	230 (MPa)
Flexural Strength	379 (MPa)	290 (MPa)	13.4 (MPa)	120 (MPa)
Compressive Strength	2,600 (MPa)	170 (MPa)	758 (MPa)	172 (MPa)
Coefficient of Thermal Expansion	8.6 (10^{-6}/°C)	10.3 (10^{-6}/°C)	9.3 (10^{-5}/°C)	8.1 (10^{-5}/°C)
Dielectric Constant	9.1 (at 1 MHz)	-	-	5.42 (at MHz)
Dielectric Strength	16.7 (kV/mm)	-	-	217 (kV/mm)
Temperature Range	-273.15 – 1,750 (°C)	-252 – 871 (°C)	-73 – 260 (°C)	-267 – 398 (°C)

Feasible by analysis and prior implementations

Note: we will also put LOTUS coating on the top layer of the alumina sheet and use Cicoil wires

MECHANICAL
MATERIAL SELECTION

	Alumina Ceramic	Bolt	Beta-cloth	Kapton
Density	3.9 (g/cm^3)	8.0 (g/cm^3)	2.71 (10^{-3} g/cm^2)	1.41 (g/cm^3)
Tensile Strength	260 (MPa)	482 (MPa)	3,450 (MPa)	230 (MPa)
Flexural Strength	379 (MPa)	290 (MPa)	13.4 (MPa)	120 (MPa)
Compressive Strength	2,600 (MPa)	170 (MPa)	758 (MPa)	172 (MPa)
Coefficient of Thermal Expansion	8.6 (10^{-6}/°C)	10.3 (10^{-6}/°C)	9.3 (10^{-5}/°C)	8.1 (10^{-5}/°C)
Dielectric Constant	9.1 (at 1 MHz)	-	-	5.42 (at MHz)
Dielectric Strength	16.7 (kV/mm)	-	-	217 (kV/mm)
Temperature Range	-273.15 – 1,750 (°C)	-252 – 871 (°C)	-73 – 260 (°C)	-267 – 398 (°C)

Note: we will also put LOTUS coating on the top layer of the alumina sheet and use Cicoil wires

MECHANICAL
MATERIAL SELECTION

	Alumina Ceramic	Bolt	Beta-cloth	Kapton
Density	3.9 (g/cm^3)	8.0 (g/cm^3)	2.71 (10^{-3} g/cm^2)	1.41 (g/cm^3)
Tensile Strength	260 (MPa)	482 (MPa)	3,450 (MPa)	230 (MPa)
Flexural Strength	379 (MPa)	290 (MPa)	13.4 (MPa)	120 (MPa)
Compressive Strength	2,600 (MPa)	170 (MPa)	758 (MPa)	172 (MPa)
Coefficient of Thermal Expansion	8.6 (10^{-6}/°C)	10.3 (10^{-6}/°C)	9.3 (10^{-5}/°C)	8.1 (10^{-5}/°C)
Dielectric Constant	9.1 (at 1 MHz)	-	-	5.42 (at MHz)
Dielectric Strength	16.7 (kV/mm)	-	-	217 (kV/mm)
Temperature Range	-273.15 – 1,750 (°C)	-252 – 871 (°C)	-73 – 260 (°C)	-267 – 398 (°C)

Note: we will also put LOTUS coating on the top layer of the alumina sheet and use Cicoil wires

MECHANICAL
MATERIAL SELECTION

	Alumina Ceramic	Bolt	Beta-cloth	Kapton
Density	3.9 (g/cm^3)	8.0 (g/cm^3)	2.71 (10^{-3} g/cm^2)	1.41 (g/cm^3)
Tensile Strength	260 (MPa)	482 (MPa)	3,450 (MPa)	230 (MPa)
Flexural Strength	379 (MPa)	290 (MPa)	13.4 (MPa)	120 (MPa)
Compressive Strength	2,600 (MPa)	170 (MPa)	758 (MPa)	172 (MPa)
Coefficient of Thermal Expansion	8.6 (10^{-6}/°C)	10.3 (10^{-6}/°C)	9.3 (10^{-5}/°C)	8.1 (10^{-5}/°C)
Dielectric Constant	9.1 (at 1 MHz)	-	-	5.42 (at MHz)
Dielectric Strength	16.7 (kV/mm)	-	-	217 (kV/mm)
Temperature Range	-273.15 – 1,750 (°C)	-252 – 871 (°C)	-73 – 260 (°C)	-267 – 398 (°C)

Note: we will also put LOTUS coating on the top layer of the alumina sheet and use Cicoil wires

MECHANICAL
MANUFACTURING

Top Plate:

- 3-axis CNC milling
  - Outsource
  - Order: grooves for EDS, screw holes, outer edge, countersink screw holes
  - Design considerations: 0.5 mm tolerance, space for Kapton, large external fillets

Bottom Plate:

- 3-axis CNC milling
  - Order: grooves for EDS, screw holes, tapping screw holes, outer edge
  - Design considerations: 0.5 mm tolerance, space for Kapton, large external fillets

MECHANICAL
MANUFACTURING

Electronics Box:

- Tungsten inert gas welding:
  - Weld the sidewalls of the electronics box together
- 3-axis CNC milling:
  - Order: drill holes for mounting electronics on box, drill holes for mounting lid to box
- Manually tap holds
- Design considerations: 0.5 mm tolerance, large external and internal fillets

MISSION INTEGRATION
CONCEPT OF OPERATIONS

1 Astronaut should ensure the surface is relatively flat and cleared

2 Astronaut lays out E.A.S.E in front of the lunar habitat and connects it to power source

3 After moonwalk and sample collection, astronaut returns to stand on E.A.S.E, which senses the weight and begins attracting dust off the astronauts' boots and repelling it off itself, cleaning the astronaut and itself

4 Astronaut leaves and E.A.S.E enters rest mode until the pressure sensor is activated by the weight of the astronaut again.

MISSION INTEGRATION
RISK ASSESEMENT

	Negligible	Minor	Moderate	Significant	Severe
Very Likely					
Likely				-Abrasion of surface, materials, or electrodes due to long-term use -Wear on bottom of panels	
Possible		-Dust penetration between layers			-Concentrated force application onto panels/hinges by rocks, etc on surface
Unlikely		-Impact of radiation and cold temperatures on panel materials	-Moves out of correct positon -Stress created by differing thermal expansion coefficients -Impact of EDS system on suit electronics	-Impact of radiation and cold temperatures on electronics	
Very Unlikely				-Power supply integration with habitat	-Micrometeorite impact

VERIFICATION
TEST PROGRAM

Vibration Test for Deployment

EMI Test for EDS System

Miscellaneous

Goal: Validate to TLR4

-All tests under thermal and vacuum conditions
-Implement safety factor of 1.2 – 1.5

Abrasion Test

Dust Exposure Test

Operational Test

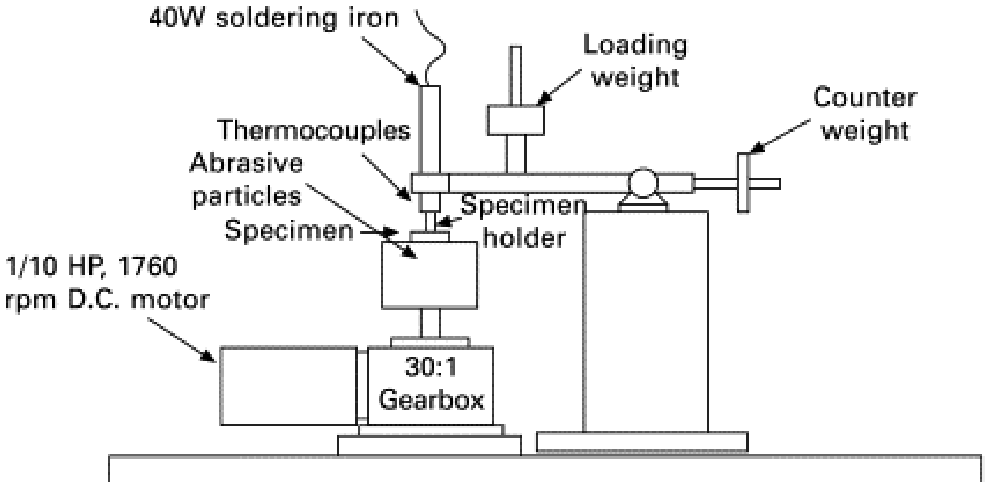
Mechanical Load Tests

Maximum Load Test

600 N Pulsating Fatigue Test

Sharp Impact Test Simulating Micrometeorites

VERIFICATION
EQUIPMENT



Three-Body Abrasive Wear Test Rig

- We will construct a vacuum chamber for our verification tests
- Looking for resources for cryochamber
- Lunar Simulant JSC-1A will be used for all verification tests
  - Similar compositional and mineralogical features to actual lunar regolith

(Roy, 2008)

[Logistics]

[Budgeting and Limitations]

DESCRIPTION	INDIVIDUAL COST	QTY	SUBTOTAL
Alumina Ceramic Sheet	$657.00	5	$3,285.00
316 Stainless Hex Bolt	$8.27	5	$41.35
Electrical-Grade Kapton Polyimide Film	$28.66	5	$143.30
Lotus FX Ceramic Coating	$44.99	5	$224.95
Multi-Layer Insulation		5	$0.00
Cicoil		5	$0.00
PTFE-Coated Fiberglass Fabric Sheet	$42.72	5	$213.60
Piezo Element	$1.50	5	$7.50
Teensy 4.0	$19.95	5	$99.75
Nickel-clad Copper	$87.27	1	$87.27
			$4,102.72

Raw Material Costs Est.

- 4 prototypes without EDS System
- 1 complete prototype
  - Costs will increase if a need for iteration arises

Note: Does not include machining or circuit component costs

CONCLUSION

FEASABILITY REVIEW

Function / Characteristic	Solution	Feasible?
Transport dust	EDS	YES
Touch-free operation	Piezoelectric transducer	YES
Rugged housing	Ceramic & Beta-cloth	YES