Preliminary Design Review

EASE

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

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

INTRODUCTION

ROADMAP

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- Budget

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INTRODUCTION
MEET THE TEAM

Leadership

Branch Lead
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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

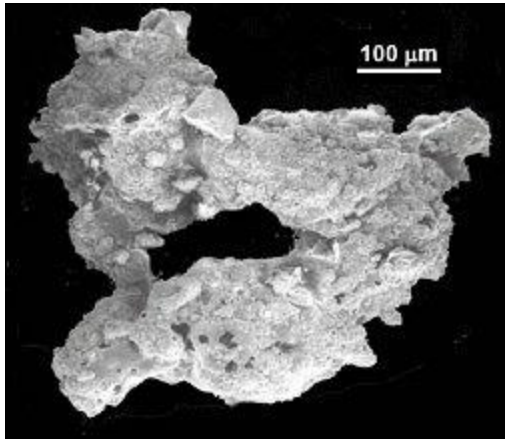
Exterior Dust Prevention, Tolerance, & Mitigation – to protect lunar surface systems or preclude dust from entering habitats and landers

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



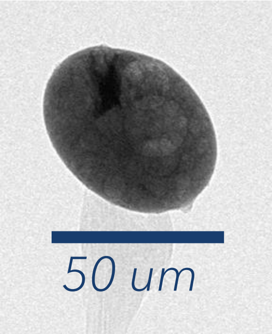
Lunar Dust Particle

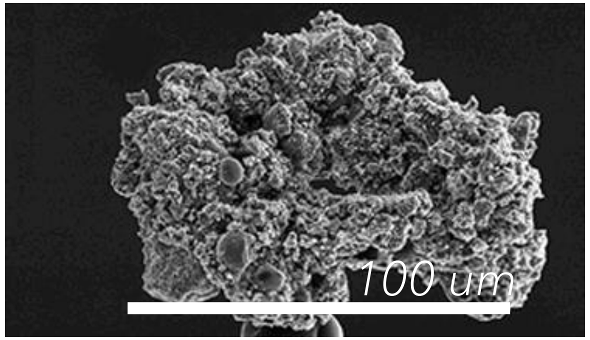
Considerations

- 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

INTRODUCTION
LUNAR DUST

Dust Properties





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

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

Issues Posed

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

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

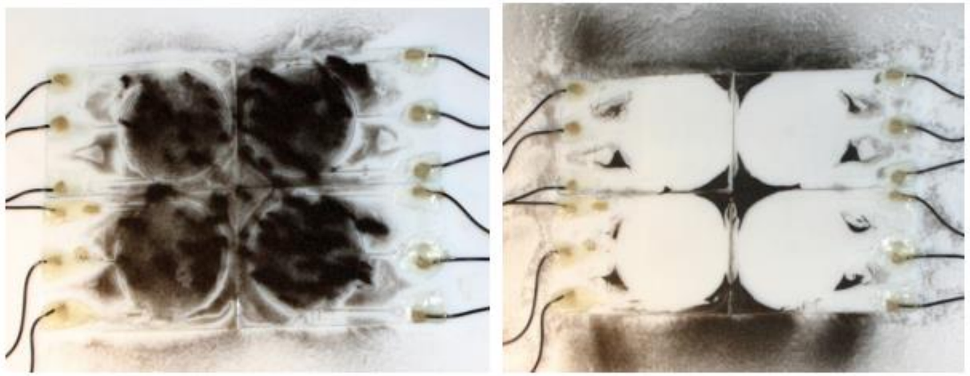


FIGURE 3–1. SIMULANT DUST REMOVAL WITH NASA KENNEDY SPACE CENTER'S EDS AT 10-6 KPA (CALLE ET AL. ACTA ASTRONAUT. 69, 2011: 1082-1088).

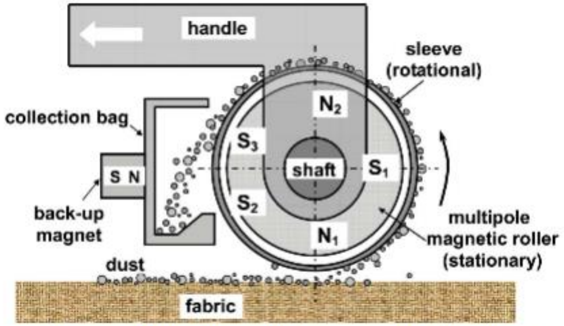
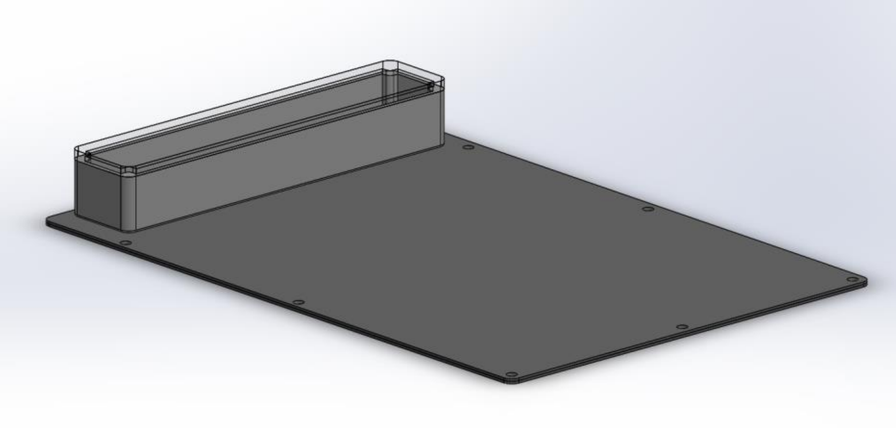


FIGURE 3–4. WASEDA UNIVERSITY'S MAGNETIC CLEANING DEVICE (KAWAMOTO, H. AND H. INOUE, J. AEROSP. ENG. 2012, 25: 139–142).

CONCEPT OVERVIEW
QUAD CHART

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: 1.4 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

CONCEPT OVERVIEW

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 standby mode until the pressure sensor is activated by the weight of the astronaut again.

REQUIREMENTS

Functional Requirements	Description
FR 1.0	Remove 90% 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

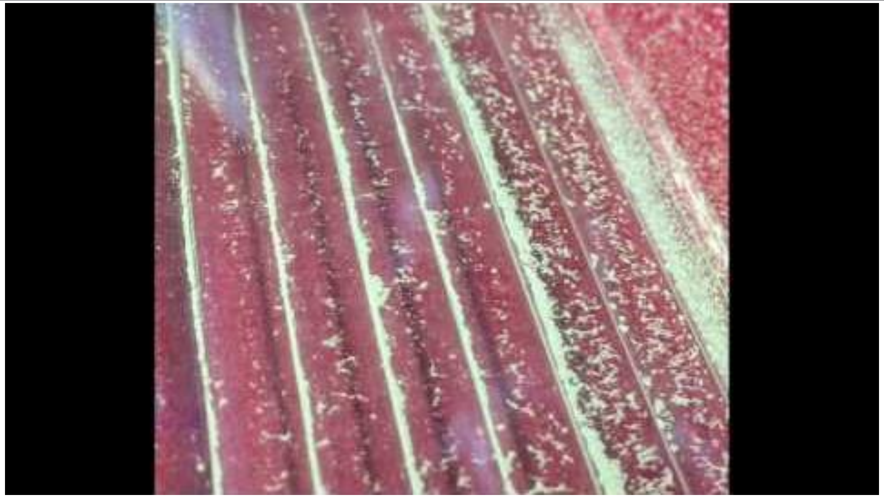
CONCEPT OVERVIEW

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)

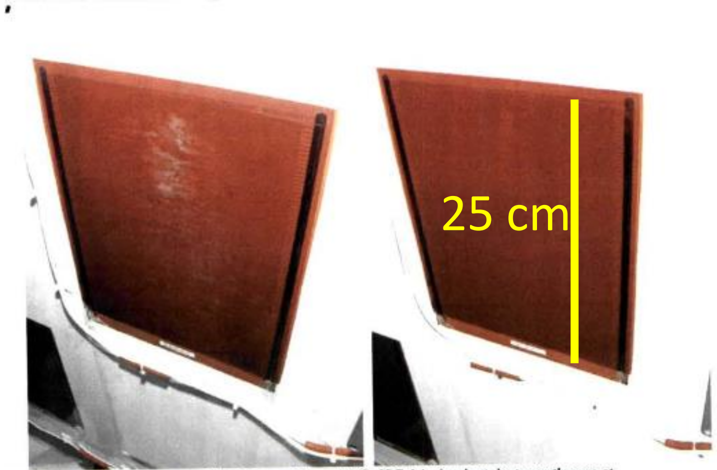
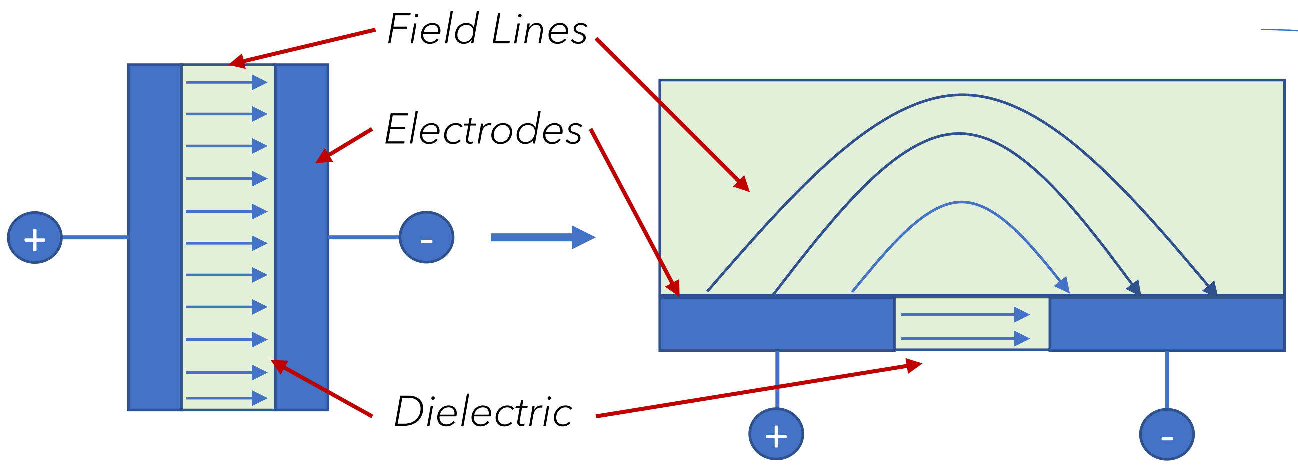


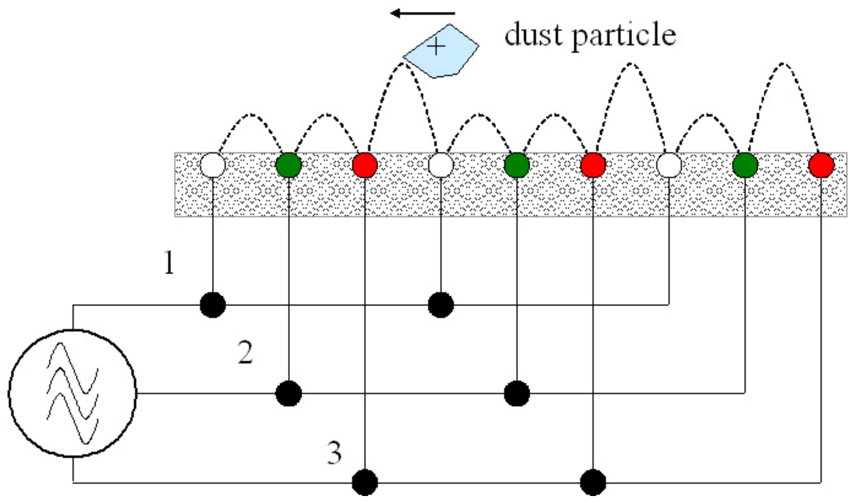
Fig. 7. Post installation tests of the 20 cm × 25 cm EDS. JSC-1A simulant dust was thrown at

EDS System mounted on sim. Lunar habitat

EDS OVERVIEW

INTERDIGATED CAPACITOR



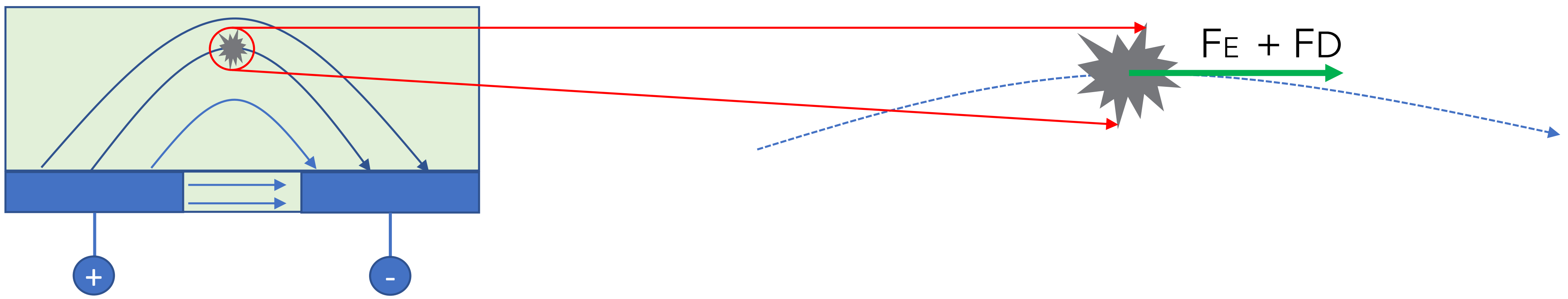


- Fringing electric field exerts force on charged dust particles
- 3 phased EDS Systems transport dust particles

(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

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

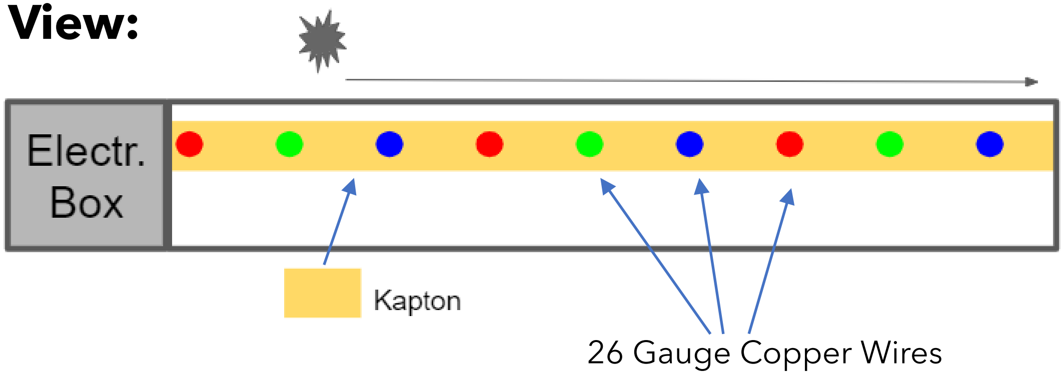
S : Image-charge static force

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

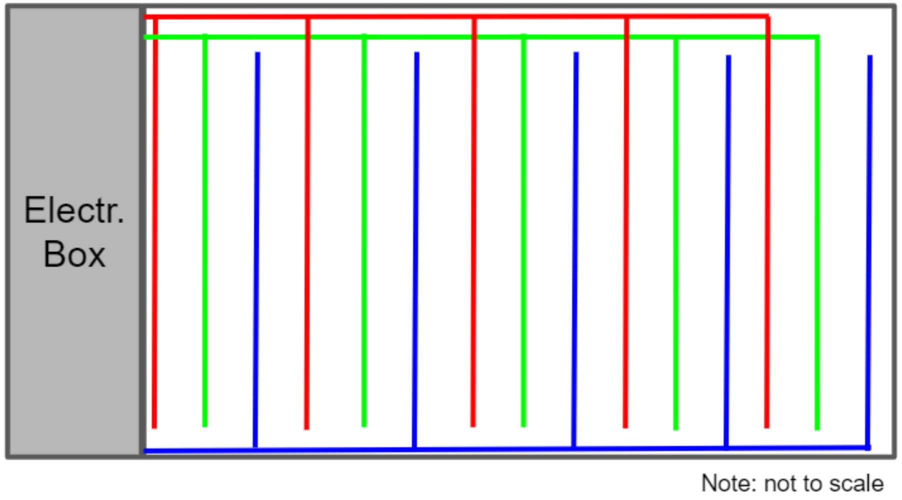
Feasible by analysis and prior implementations

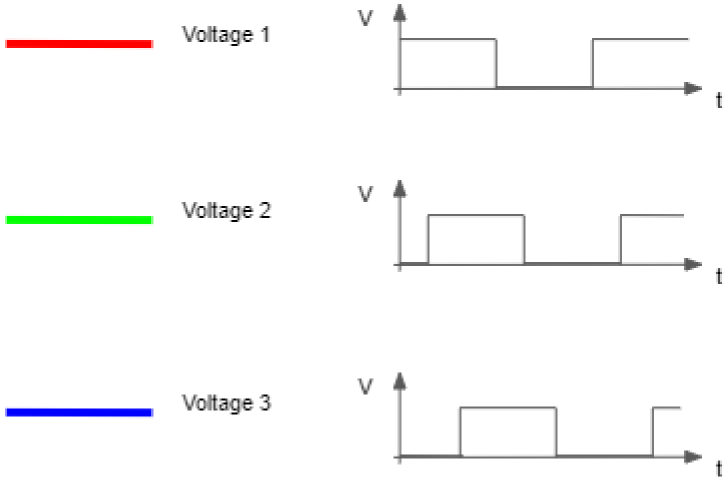
MECHATRONICS
LAYOUT AND PHASING

Side View:

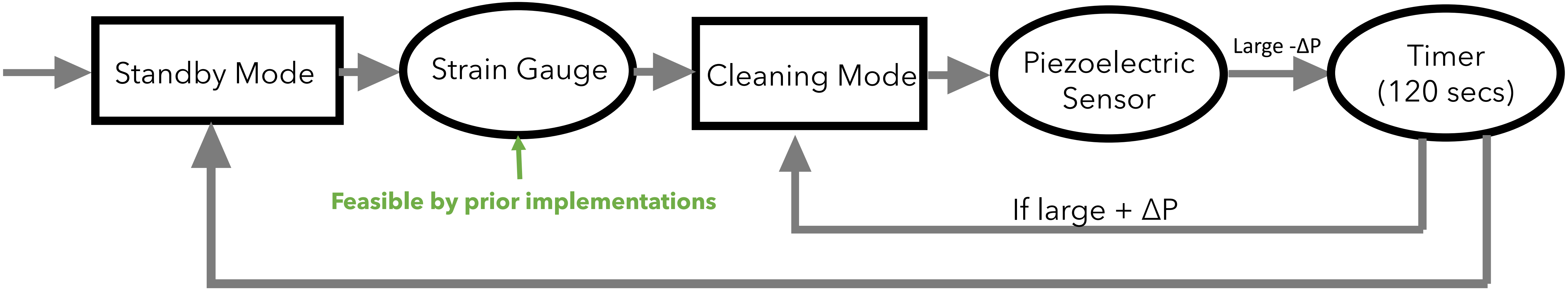


Top View:





- 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**

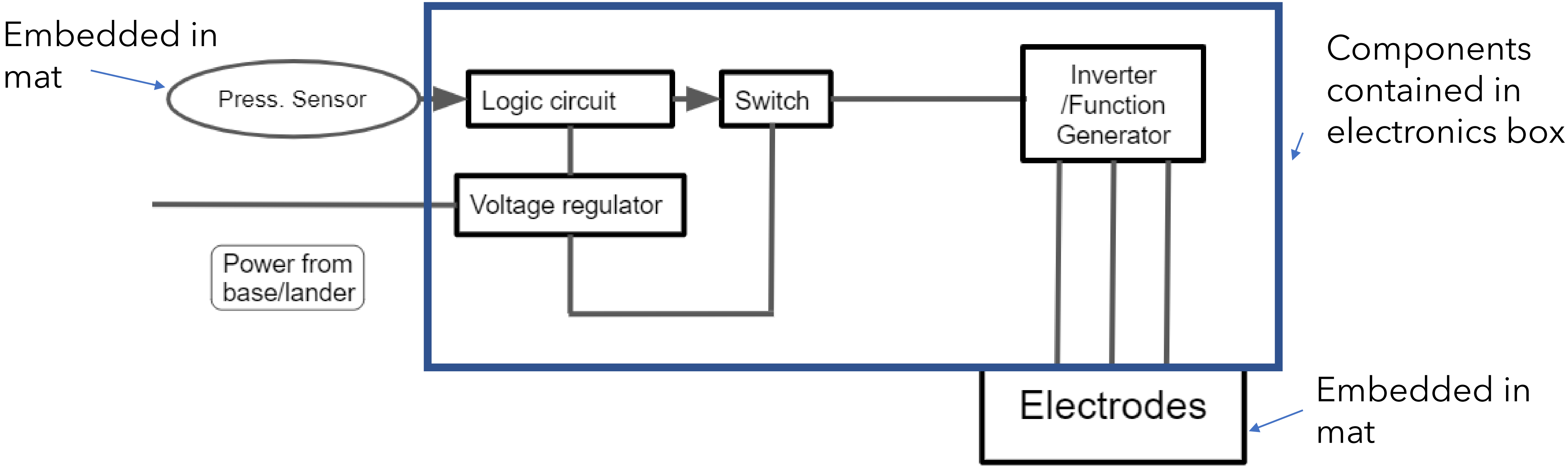


Operational Modes

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

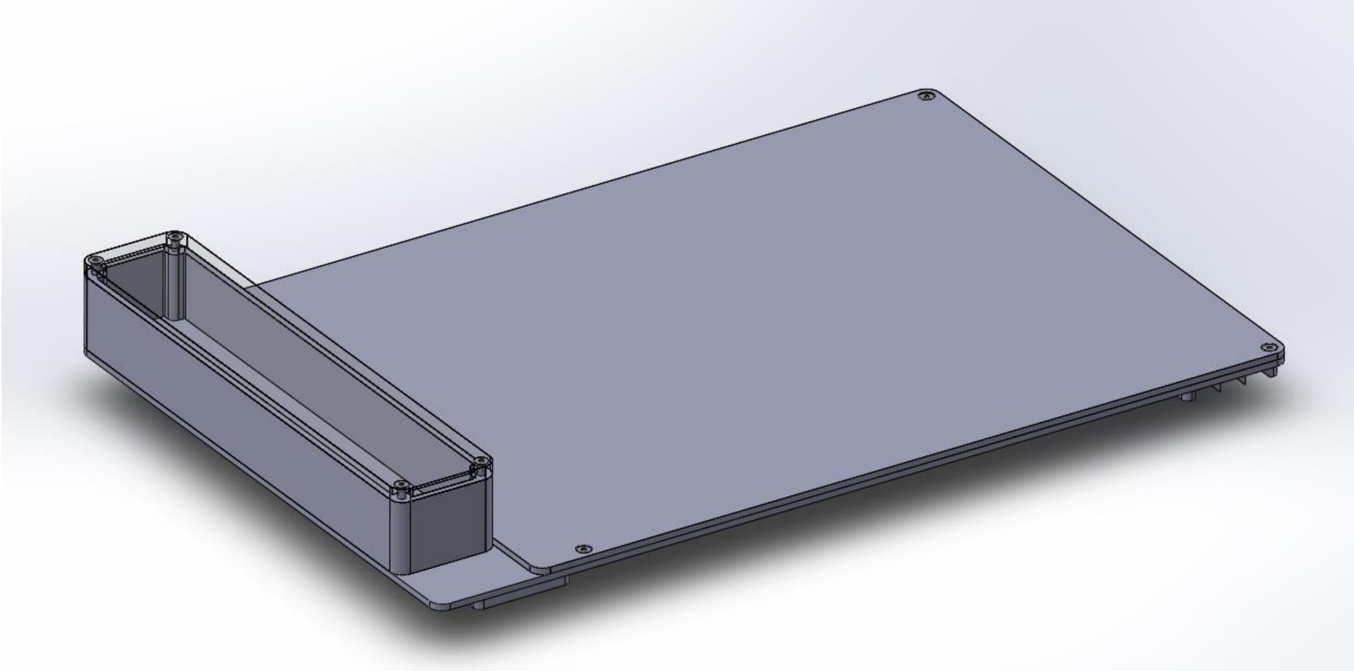
- Estimates based on finite difference time domain electrostatic simulation
  - Obtained mesh grid of electric field strength given electrode lay-out and voltage supply
  - Determined electromagnetic field strength necessary to overcome adhesive forces

Operational Mode	Time Estimate	Voltage (DC)	Power Requirements (W)
CLEANING	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

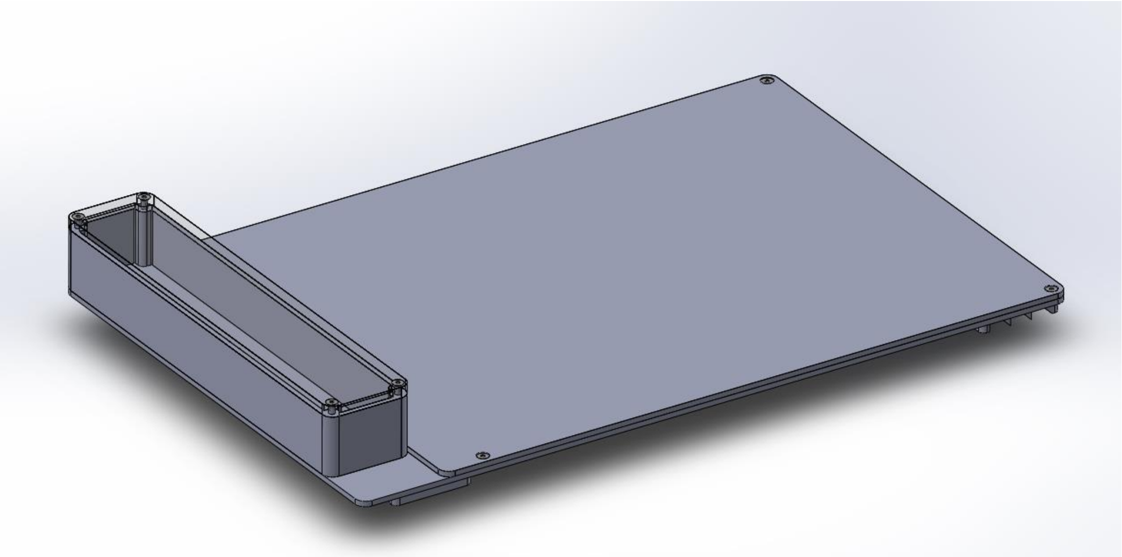
DESIGN OVERVIEW
MECHANICAL



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.

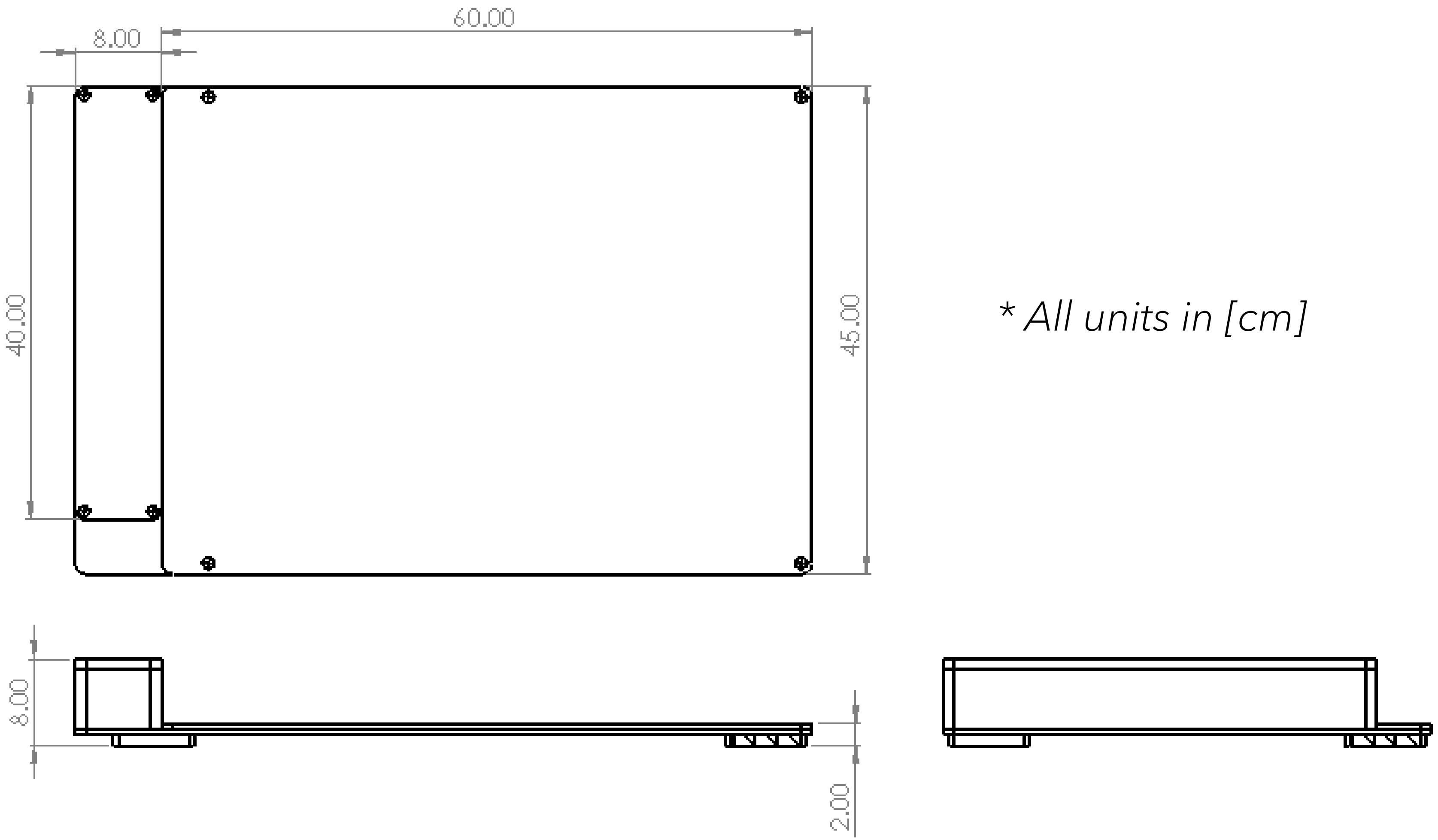
Trade Study:



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

DESIGN OVERVIEW

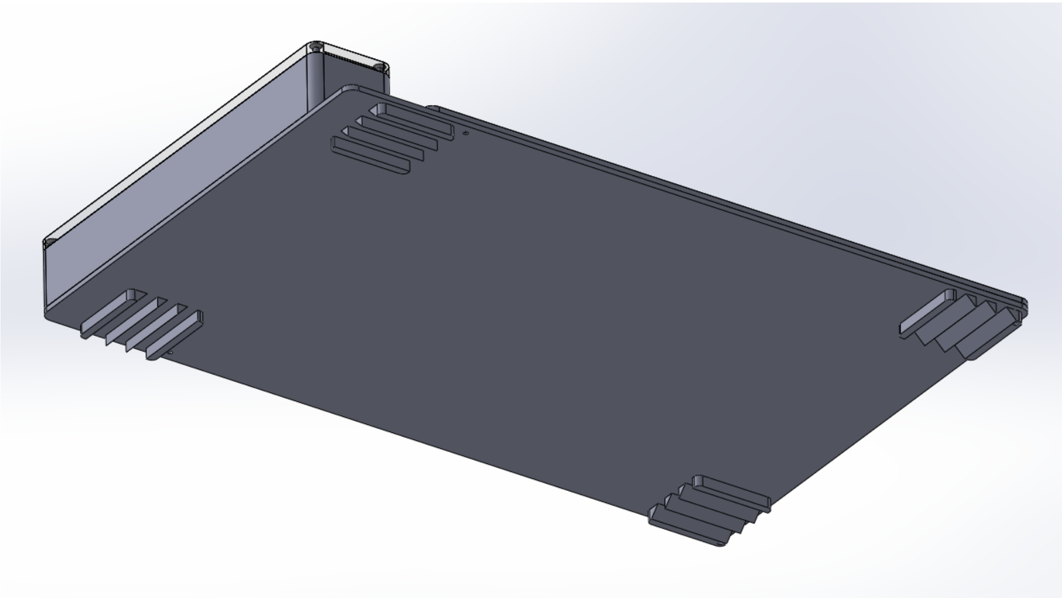
MECHANICAL



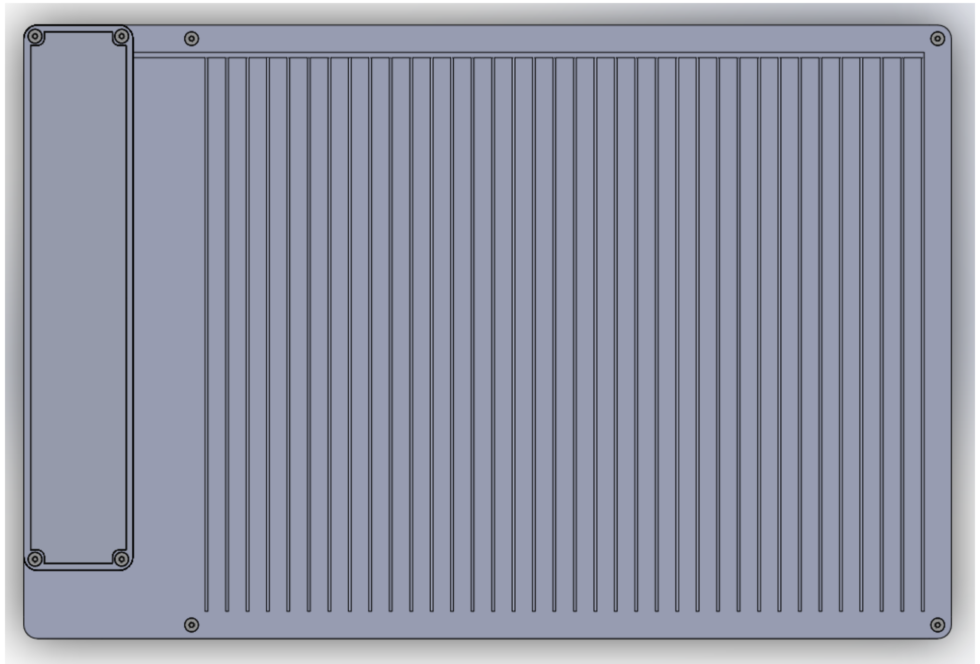
** All units in [cm]*

DESIGN OVERVIEW

MECHANICAL



Spikes for security



EDS System

PANEL COMPOSITION
MECHANICAL

Feasible by analysis

Mass estimate: 1.4 kg

MECHANICAL
MATERIAL SELECTION

	Alumina Ceramic (structure)	316 Stainless Steel (Bolt)	Kapton (dielectric)
Density	3.9 (g/cm^3)	8.0 (g/cm^3)	1.41 (g/cm^3)
Tensile Strength	260 (MPa)	482 (MPa)	230 (MPa)
Flexural Strength	379 (MPa)	290 (MPa)	120 (MPa)
Compressive Strength	2,600 (MPa)	170 (MPa)	172 (MPa)
Coefficient of Thermal Expansion	8.6 (10^{-6}/°C)	10.3 (10^{-6}/°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°C to 1,750°C	-252°C to 871°C	-267°C to 398°C

Note: we will use Cicoil wires

MECHANICAL

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MATERIAL SELECTION

MECHANICAL

Alumina	Kapton
Electrical insulator	Stability across wide temperature range
Low dielectric constant	Durability
Low thermal conductivity	Good dielectric qualities
Hardness	Used in spacecraft applications (Apollo launcher, Curiosity rover)
Strength	
Sufficient temperature range	
Abrasion resistant	
Used in many spacecraft applications	

MANUFACTURING

MECHANICAL

Top Plate:
- 3-axis CNC milling

Bottom Plate:
- 3-axis CNC milling

Electronics Box:
- Tungsten inert gas welding
- 3-axis CNC milling

- Design considerations: 0.5 mm tolerance, large external and internal fillets

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

Goal: Validate to TRL4

- Implement safety factor of 1.2 – 1.5

Key:
^ Under vacuum conditions
* Under thermal conditions
! Destructive test
† Full prototype needed

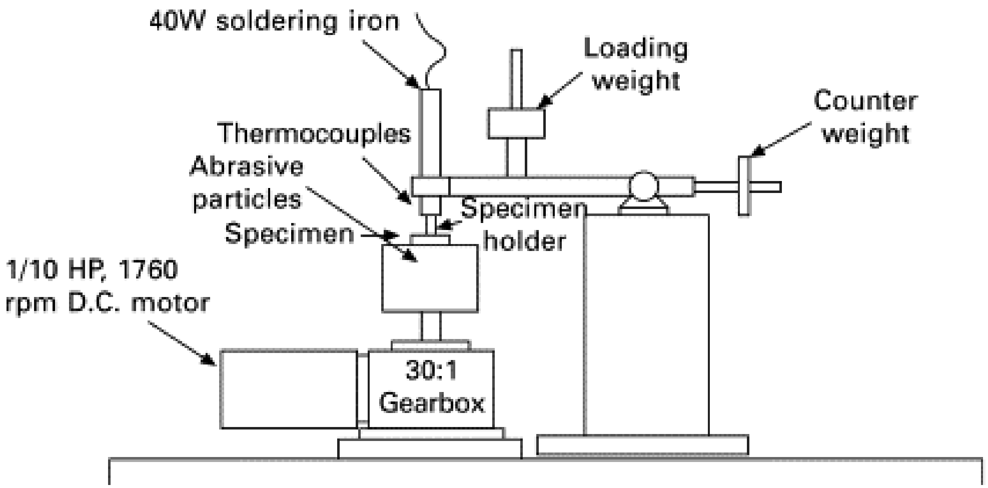
Miscellaneous:
- Vibration Test for Deployment †
- EMI Test for EDS System^*†
- Electronic Life Test for 45 years^*

Abrasion Test*!

Simulated Abrasion Test* → Operational Test^*†
Dust Exposure Test → Operational Test^*†

Mechanical Load Tests → Maximum Load Test*!
Mechanical Load Tests → 600 N Pulsating Fatigue Test*!
Mechanical Load Tests → Sharp Impact Test Simulating Micrometeorites*!

Equipment and Testing Conditions



Three-Body Abrasive Wear Test Rig

- Currently looking for resources for vacuum and cryochamber
- Lunar Simulant JSC-1A will be used for EDS-related testing
- Lunar Simulants OB-1 and Chenobi are the most recommended simulants for abrasion and dust exposure testing
- We will test from -260°C to 140°C to simulate lunar thermal conditions

(Roy, 2008)

LOGISTICS
BUDGETING

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

Note: Does not include machining or circuit component costs

Raw Material Costs Est.

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

CONCLUSION
FEASIBILITY REVIEW

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