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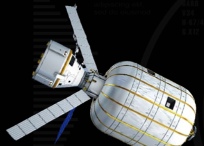
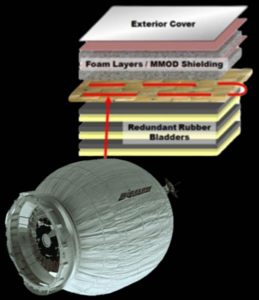
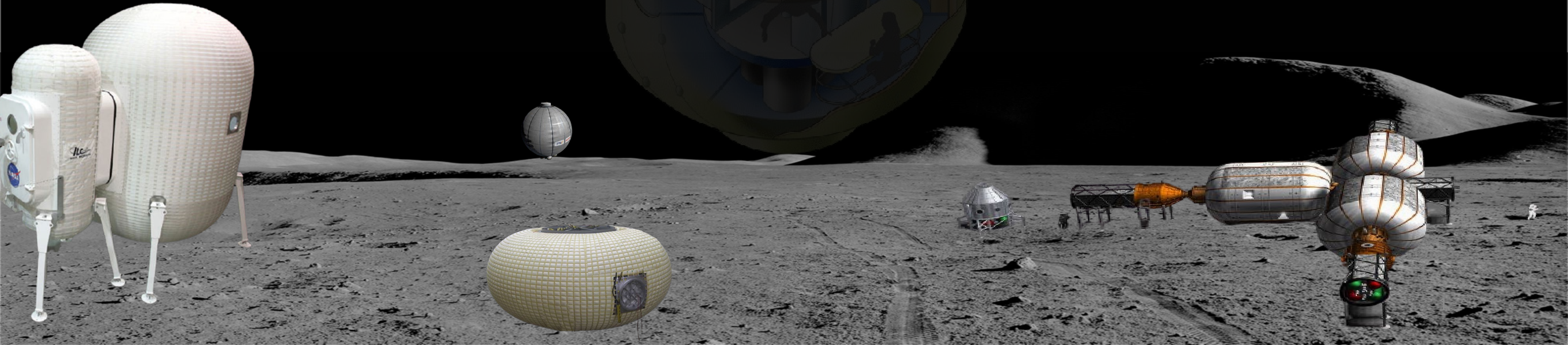


Integration of Intelligent Health Monitoring Systems Into Inflatable Hybrid Structures

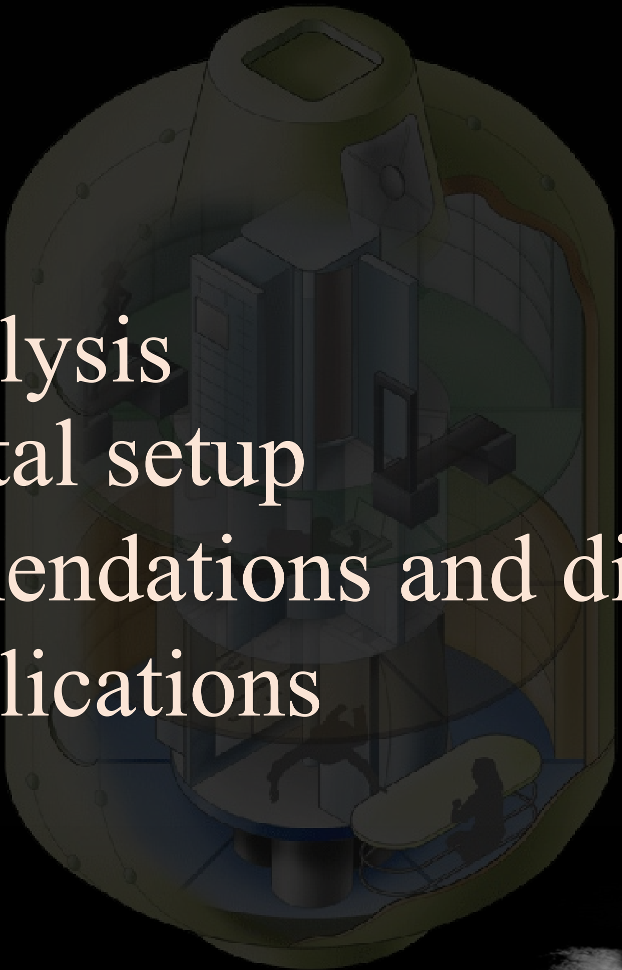
Jasleen Kaur (1653601)

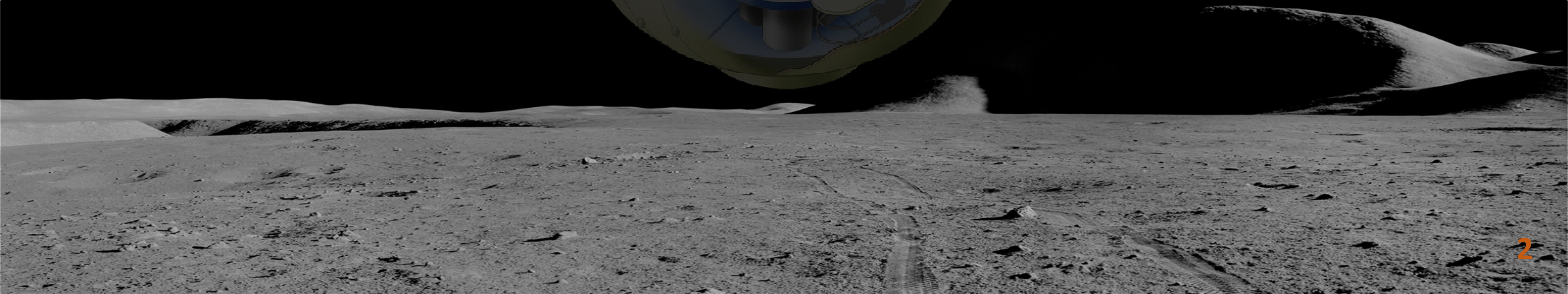




Agenda:

- Introduction
- Research Analysis
  - Experimental setup
    - Recommendations and discussions
  - Future Applications





Introduction

- Lunar and Mars colonization
- Long-term exposure to planetary environments
- Light weight and provide a greater volume of living space for a given mass.

Characteristics → Inflatables will be necessary

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Problems →
- Maintaining pressure critical
- Leakage is a real danger
- Detecting the leak at the early stage is challenging

NASA Roadmaps

- **12.2.1.6-** Develop inflatable structure technology for SHM including leak detection, repair, radiation protection, damage resistance, and dust mitigation **– 2025**
- **12.2.3.3-**Development of data acquisition systems with distributed lightweight sensors and installation techniques to report environmental and structural integrity information **- 2025**

Characteristics → Inflatables will be necessary

Problems →
- Maintaining pressure critical
- Leakage is a real danger
- Detecting the leak at the early stage is challenging

Way to address these problems → Integerating sensors for SHM to detect and protect leak

NASA Roadmaps

- **12.2.1.6-** Develop inflatable structure technology for structural health monitoring including leak detection, isolation and repair, radiation protection, damage resistance or tolerance, and dust mitigation **– 2025**
- **12.2.3.3-**Development of data acquisition systems with distributed lightweight sensors and installation techniques to report environmental and structural integrity information **- 2025**

VISION

Achieve Improved System Reliability and Performance; From the habitat structure to the life support systems, human space missions require an integrated and reliable set of systems to safely and efficiently live and work in space.

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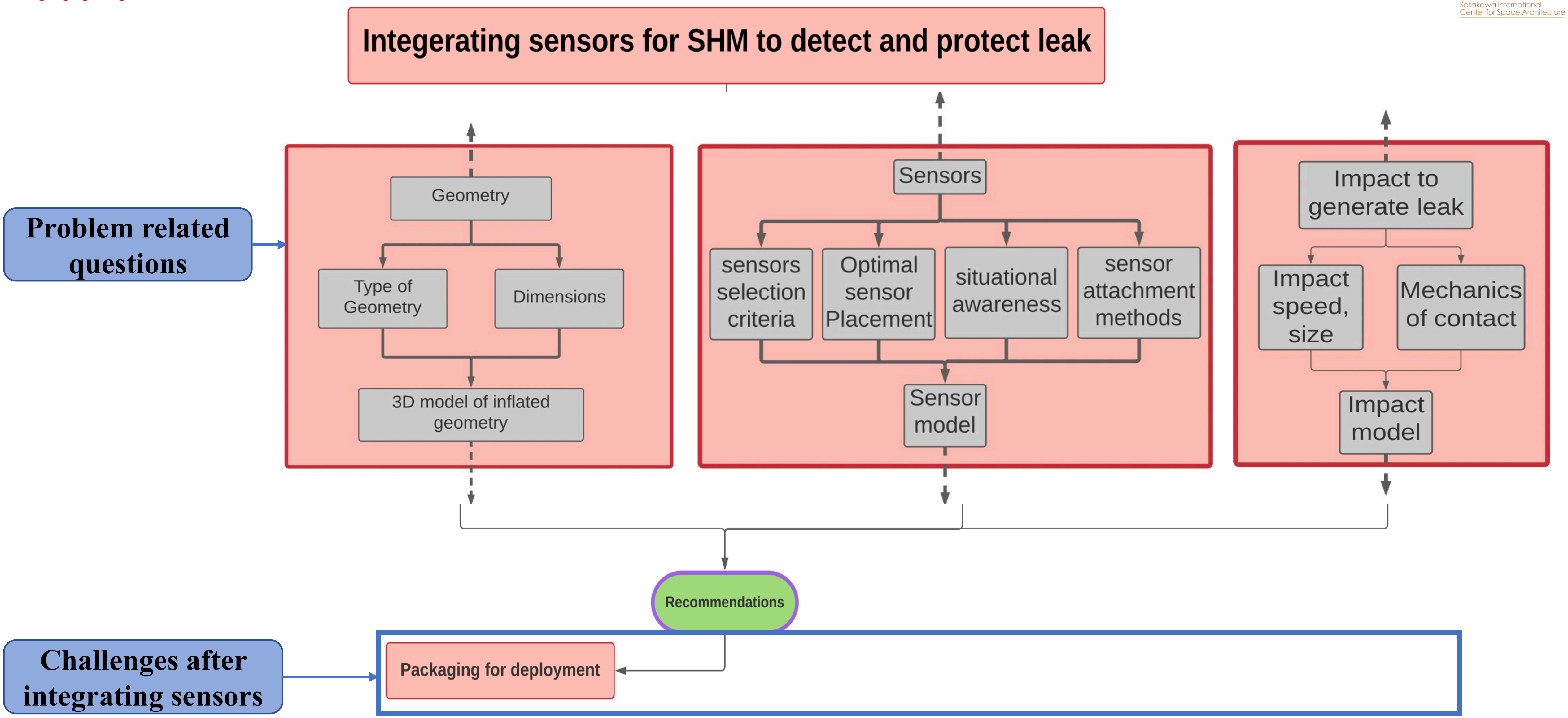

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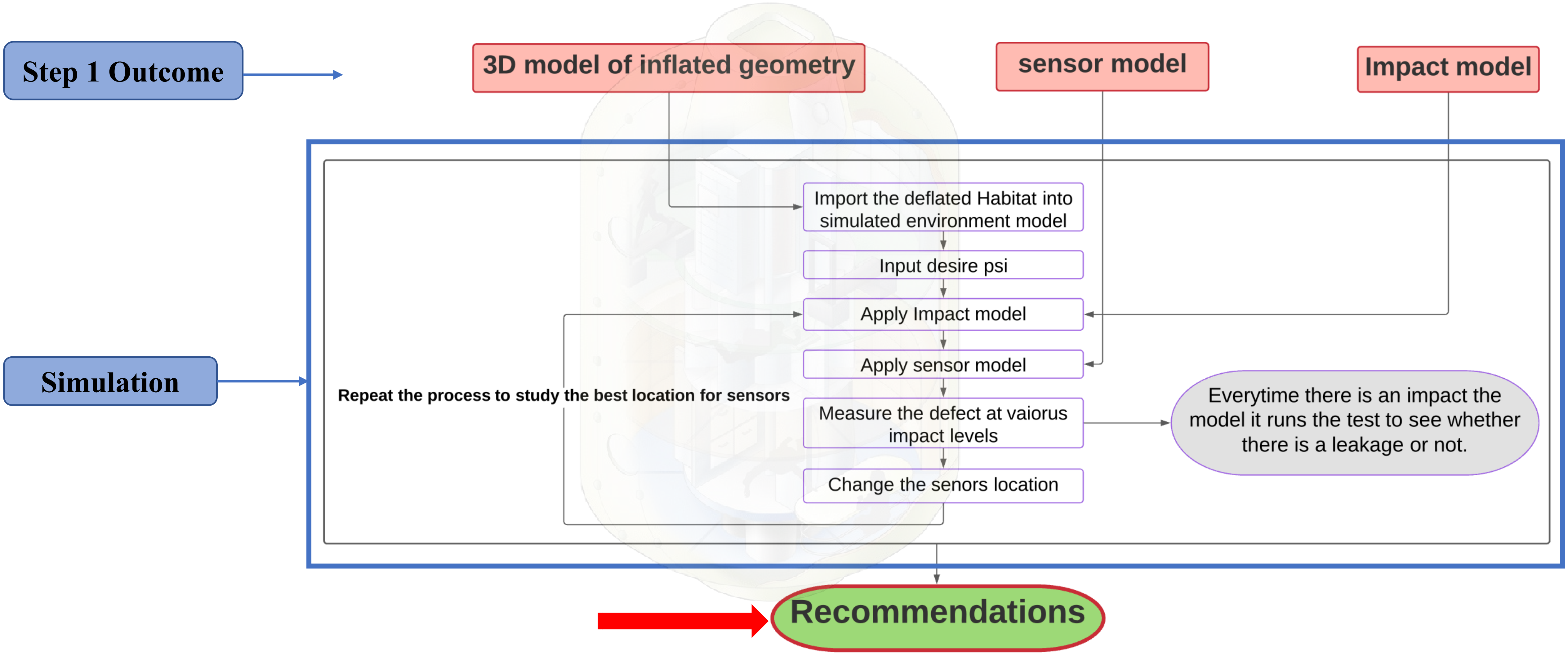
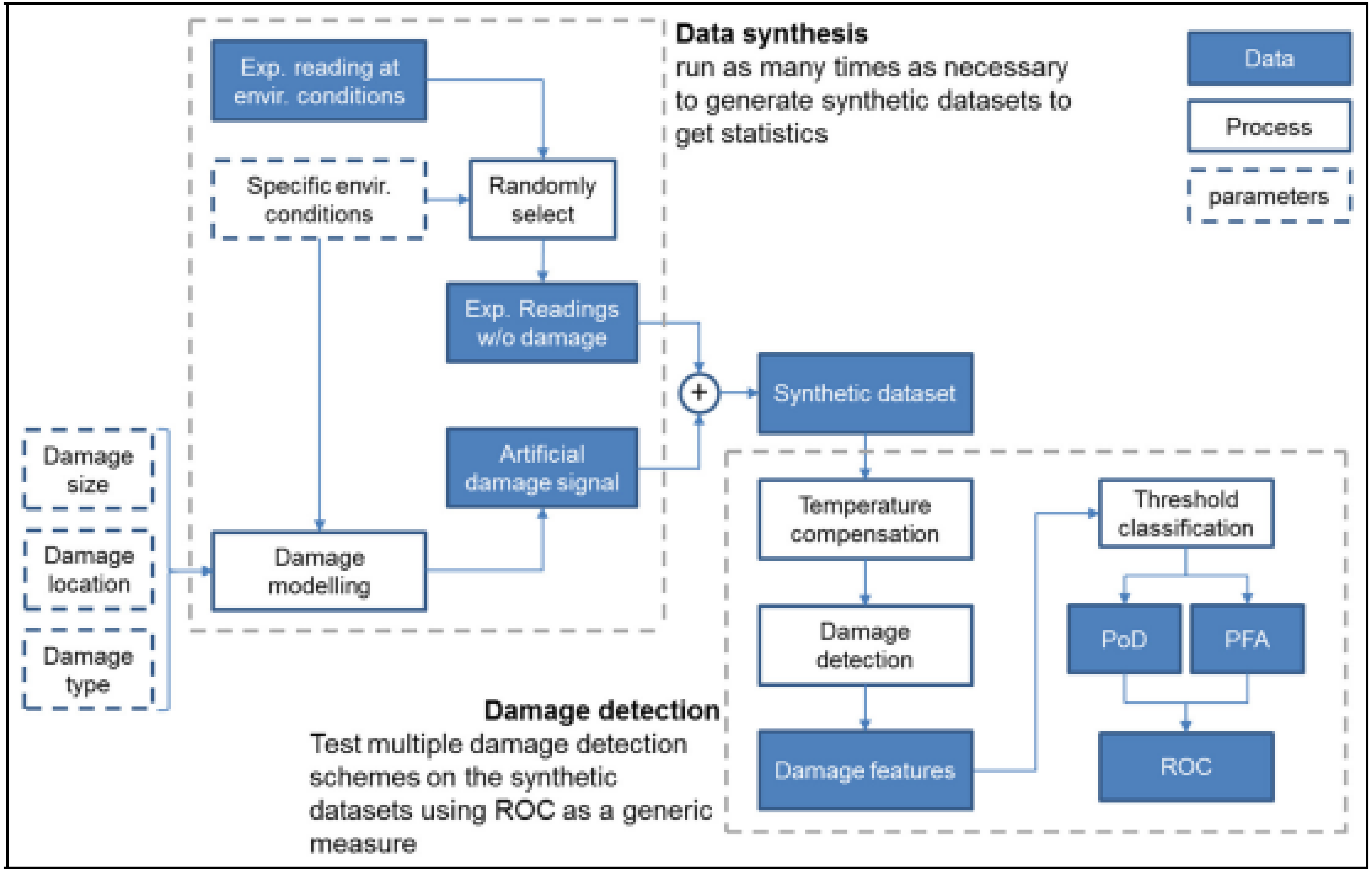
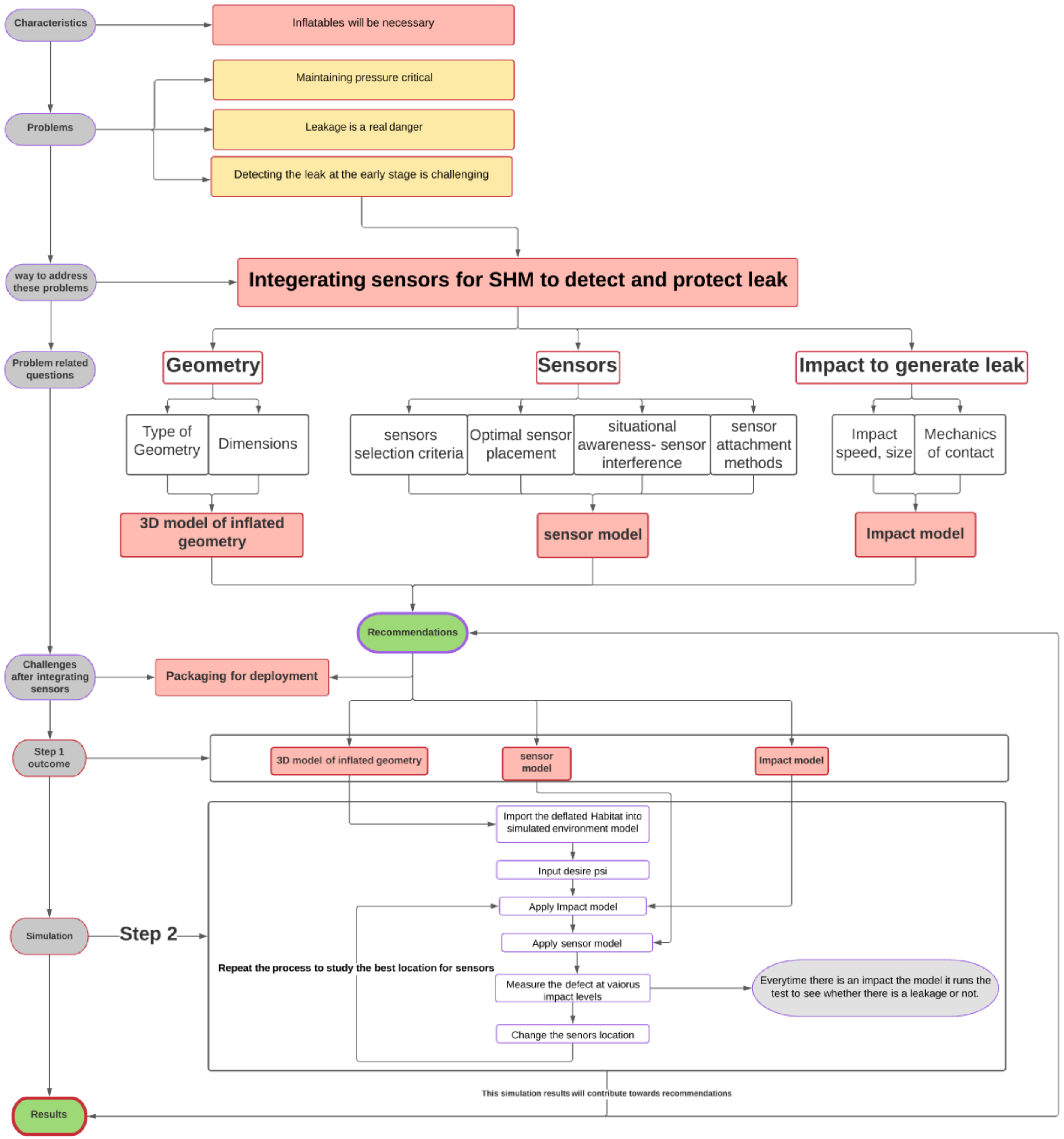



Data synthesis
run as many times as necessary to generate synthetic datasets to get statistics
Data
Process
parameters
Exp. reading at envir. conditions
Specific envir. conditions
Randomly select
Exp. Readings w/o damage
Artificial damage signal
Damage size
Damage location
Damage type
Damage modelling
+
Synthetic dataset
Temperature compensation
Damage detection
Damage features
Threshold classification
PoD
PFA
ROC
Damage detection
Test multiple damage detection schemes on the synthetic datasets using ROC as a generic measure

Expected Recommendations

- Catalog of Intelligent structure systems (sensors) to be placed for inflatable health monitoring.
- Recommendation on:
  - Optimal Sensor Placement for Inflatable Structures through simulations
  - No. of sensors needed
  - Packaging techniques using parametric modelling and a numerical simulation model.
  - Algorithms for Impact and leak detection using the sensors and deep learning/Machine learning.
- Command control Unit layout
- Leak protection techniques
- Geometry recommendations

Big Picture



Characteristics
Inflatables will be necessary
Problems
Maintaining pressure critical
Leakage is a real danger
Detecting the leak at the early stage is challenging
way to address these problems
Integerating sensors for SHM to detect and protect leak
Problem related questions
Geometry
Sensors
Impact to generate leak
Type of Geometry
Dimensions
sensors selection criteria
Optimal sensor placement
situational awareness- sensor interference
sensor attachment methods
Impact speed, size
Mechanics of contact
3D model of inflated geometry
sensor model
Impact model
Recommendations
Challenges after integrating sensors
Packaging for deployment
Step 1 outcome
3D model of inflated geometry
sensor model
Impact model
Import the deflated Habitat into simulated environment model
Input desire psi
Apply Impact model
Apply sensor model
Simulation
Step 2
Repeat the process to study the best location for sensors
Measure the defect at vaiorus impact levels
Everytime there is an impact the model it runs the test to see whether there is a leakage or not.
Change the senors location
This simulation results will contribute towards recommendations
Results

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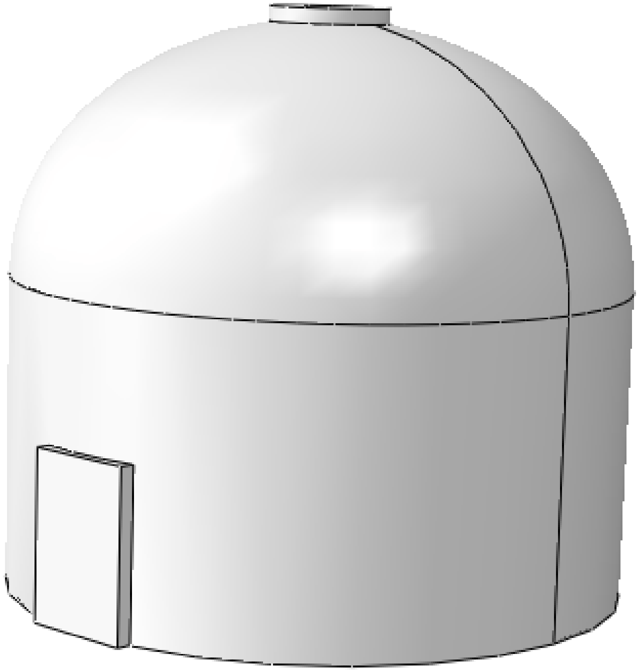
Type of Inflatable Structures

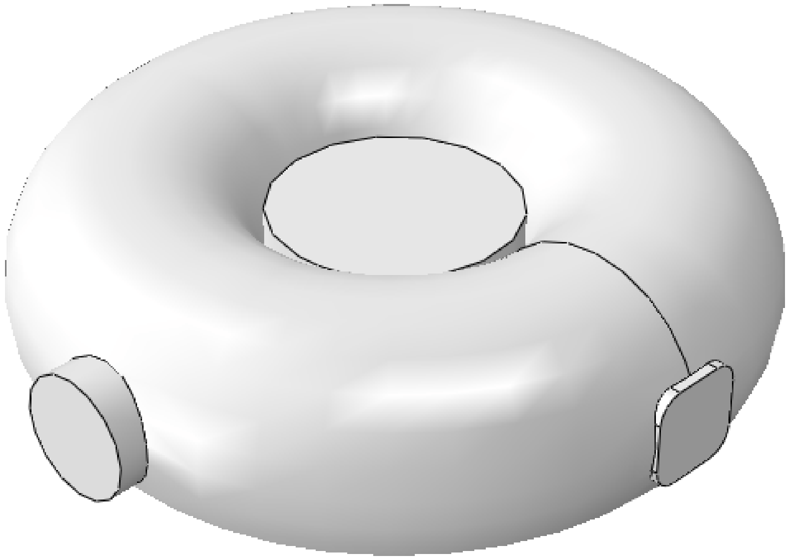
Cylindrical

Height: 13.7m
Diameter: 6.7m



Inflated Spherical dome

Height: 3.1 m
Diameter: 5m

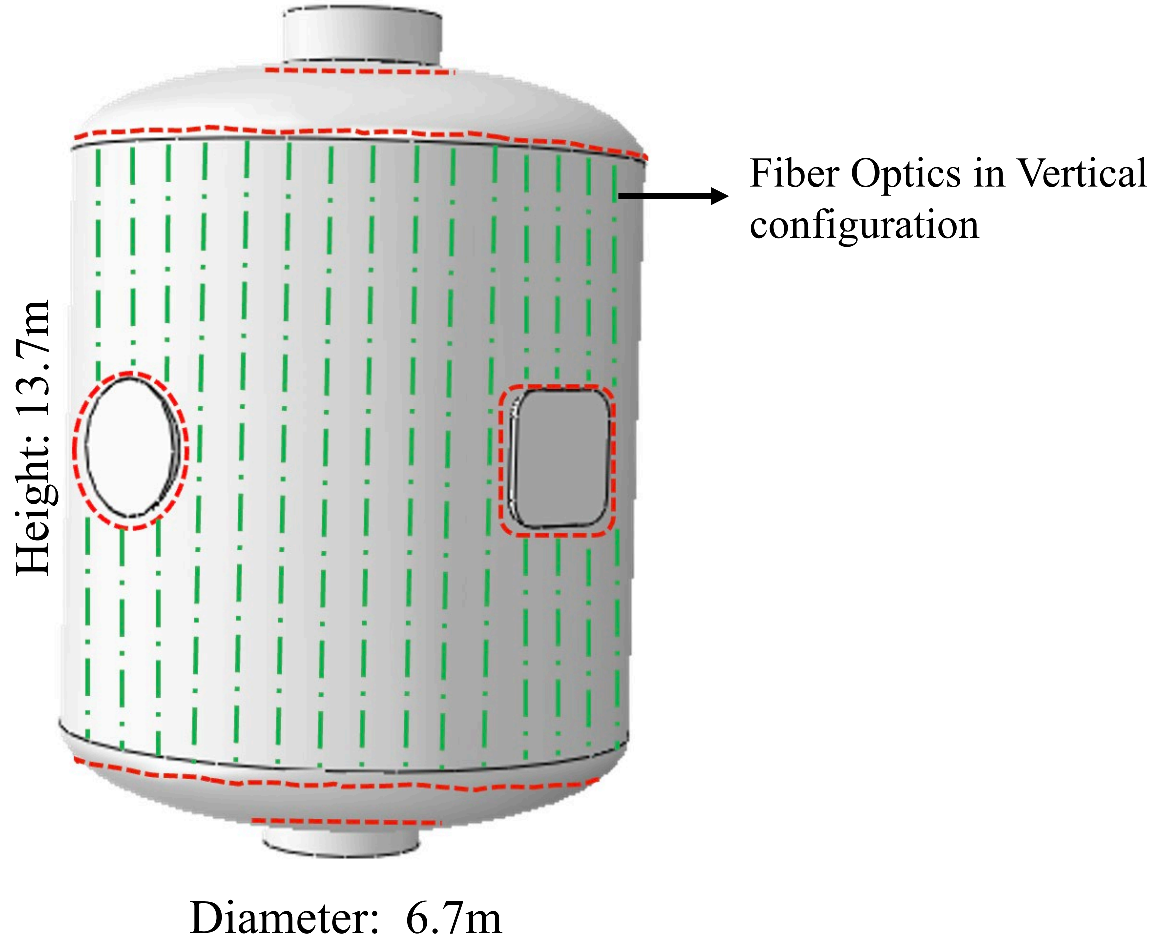


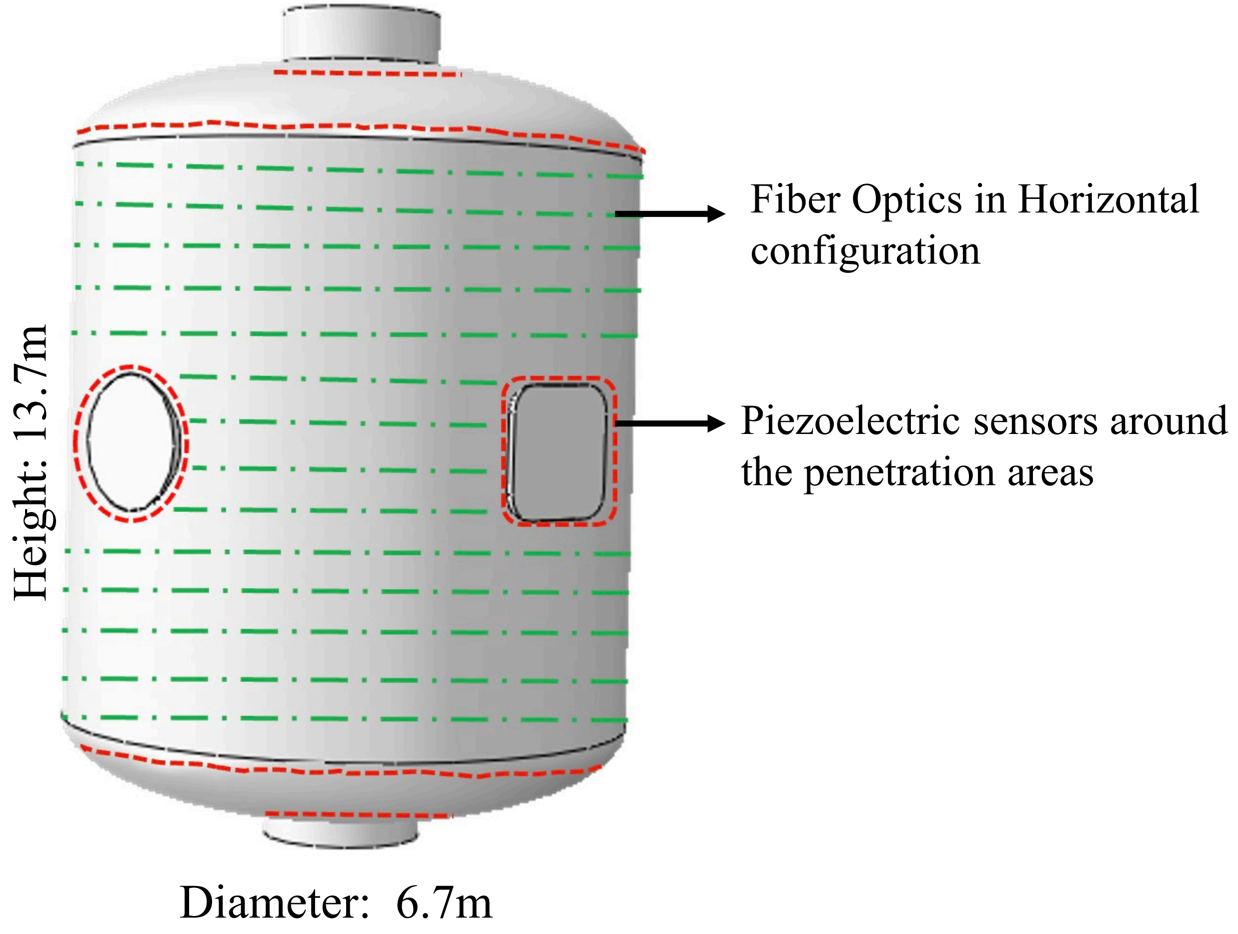
Torus

Height: 2.5m
Diameter: 8m

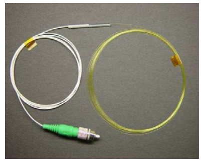
Geometry Related Questions | Type of Geometry | Size

Sensors for Leakage Detection

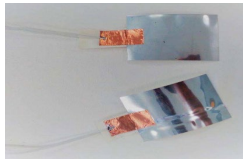




Sensor Related Questions → Type of sensors | Sensor selection criteria | Optimal sensor placement | Sensor attachment methods



Fiber Optics sensors



Piezoelectric sensors

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Sensor Selection Criteria

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Parameters	Piezoelectric sensors	Fiber Optic Sensors
Resolution (Strain)	10^{-12}	10^{-10}
Sensitivity	0.001-0.01	0.11 per fiber
Temperature Range	1832°F	-328°F *to* 572°F
Temperature stability	Good	Good
Max. Operating Voltage	Upto 5 volts	Upto 5 volts
Life	15-20 years	10 years

Quantitative Analysis

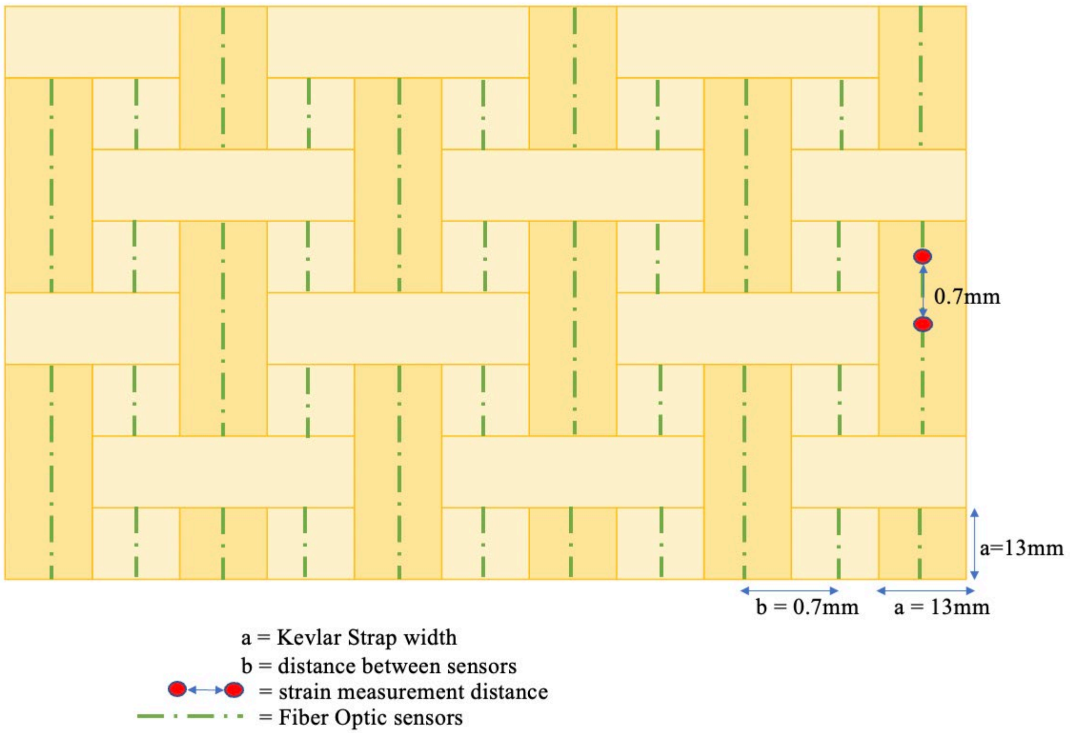
Characteristics	Piezoelectric	Fiber Optic
Sensitivity	High	High
Frequency Range	High	High
Spatial resolution	Low	High
Integratable	High	High
Distributive	Low	Medium
Power consumption	Medium	Medium
Portability	High	Medium

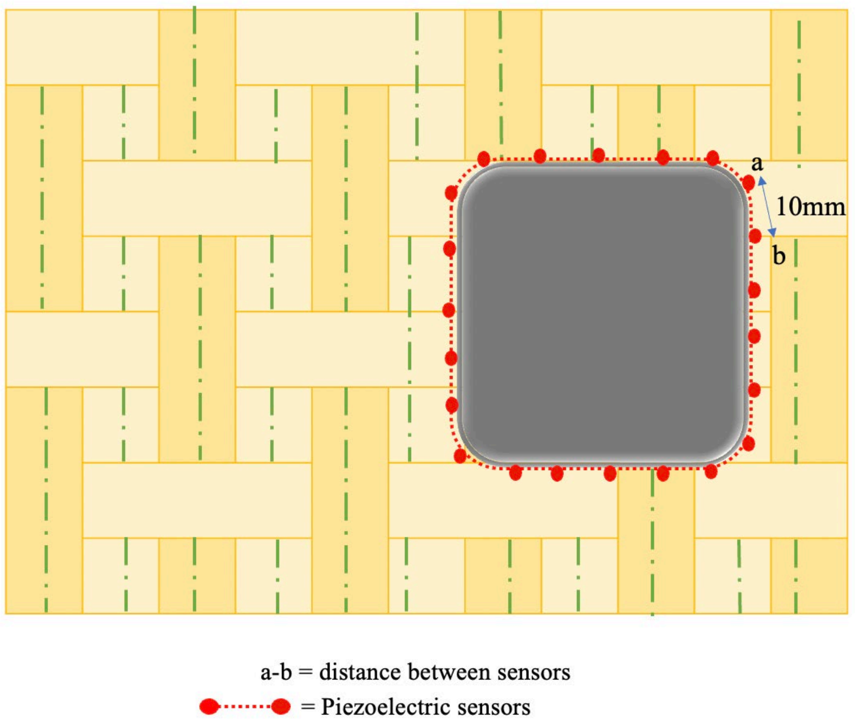
Qualitative analysis

Analysis

- Spatial resolution of Piezoelectric sensor is low compared to fiber Optic sensors
- Piezoelectric sensors are heavier in weight so distributing all over will be challenging
- Fiber Optic sensors can provide 1000 continuous array of strain measurements and temperature mappings
- Measuring areas with high strain gradients or evaluating strain over a larger area not identified by simulations.
- Provide more comprehensive validation and improvement of finite element (FE) models.

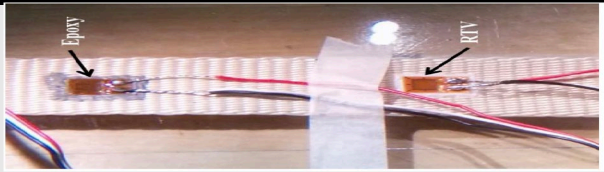
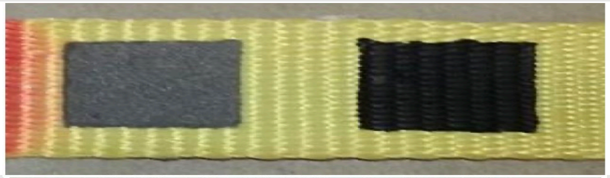
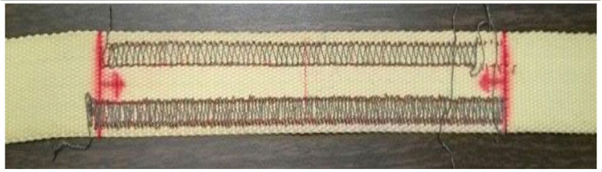
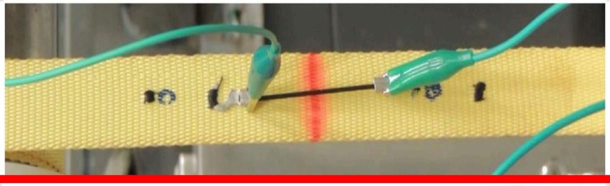
Leakage Detection Sensors Analysis





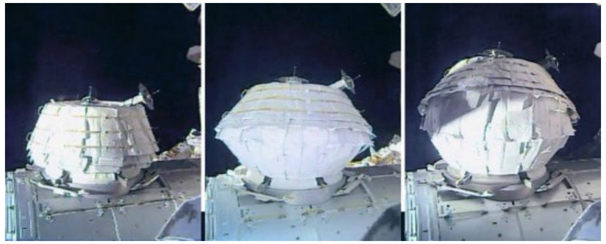
- Areas near to the penetrations are more prone to leakage so 2 type of sensors are suggested near windows, hatches, airlocks, and view ports.
- HD fiber optic sensors to collect the strain and temperature measurements.
- Piezoelectric sensors to perform leak detection using precursor-based technique.

Sensor Attachment Methods

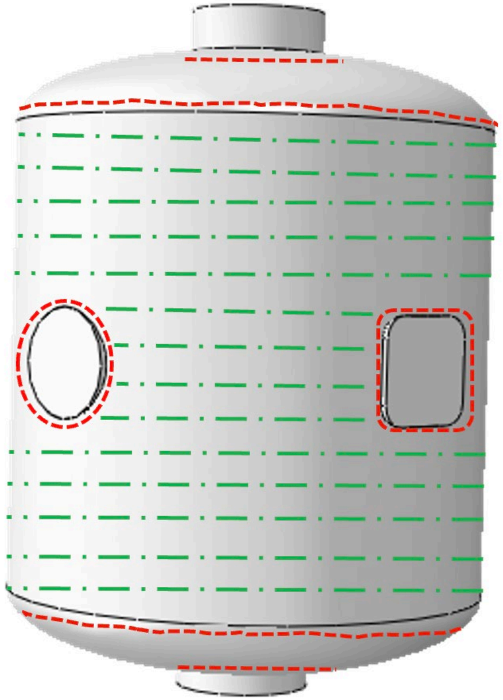
Sensor Type		Electronics	Installation Method	Tensile Performance	Creep Performance
High Elongation Foil Strain Gage		Resistive	Adhere to surface using resin adhesive	Poor linear trend due to adhesive methods	N/A
Conductive Paint/RTV		Resistive	Paint directly onto surface	Good linear trend with some noise	Severe hysteresis
Conductive thread cover stitch		Resistive	Stitch directly into substrate	Good linear trend with a lot of noise	Slight hysteresis
Conductive Polymer Cord		Resistive	Adhere to surface	Good linear trend to material limit	Slight hysteresis
Stretch Sense Fabric Sensor		Capacitive	Adhere to surface	Excellent linear trend with little noise	No hysteresis

StretchSense device is most promising gage for SHM of inflatables

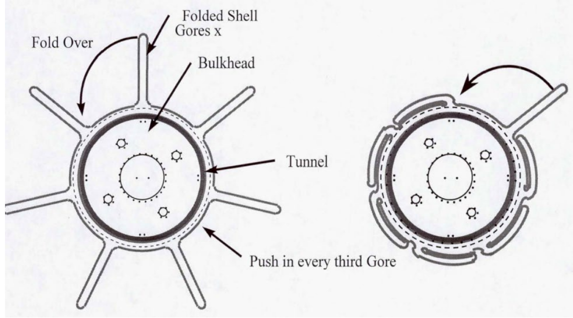
Folding Techniques Analysis



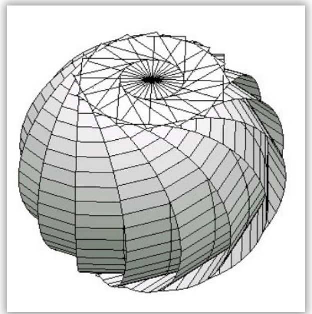
BEAM

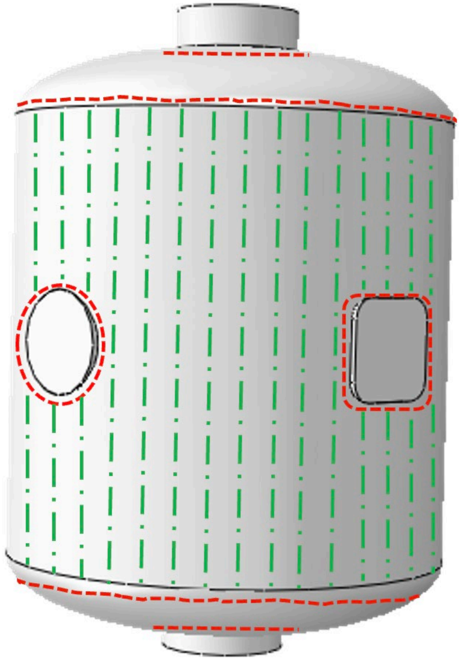


Horizontal Configuration



TransHab

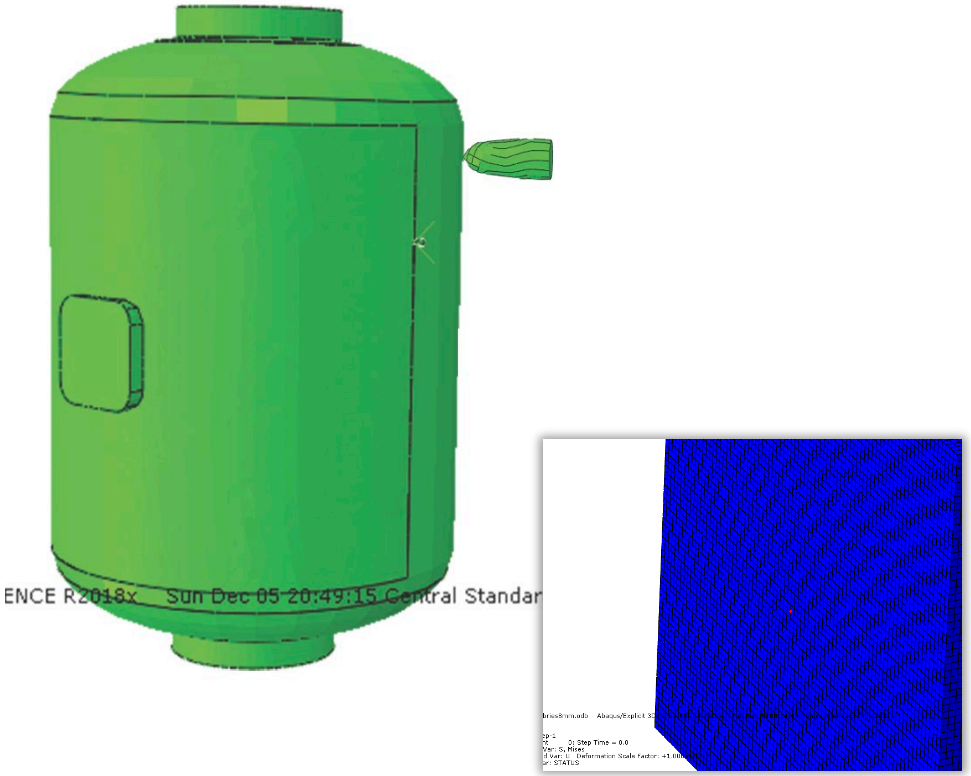




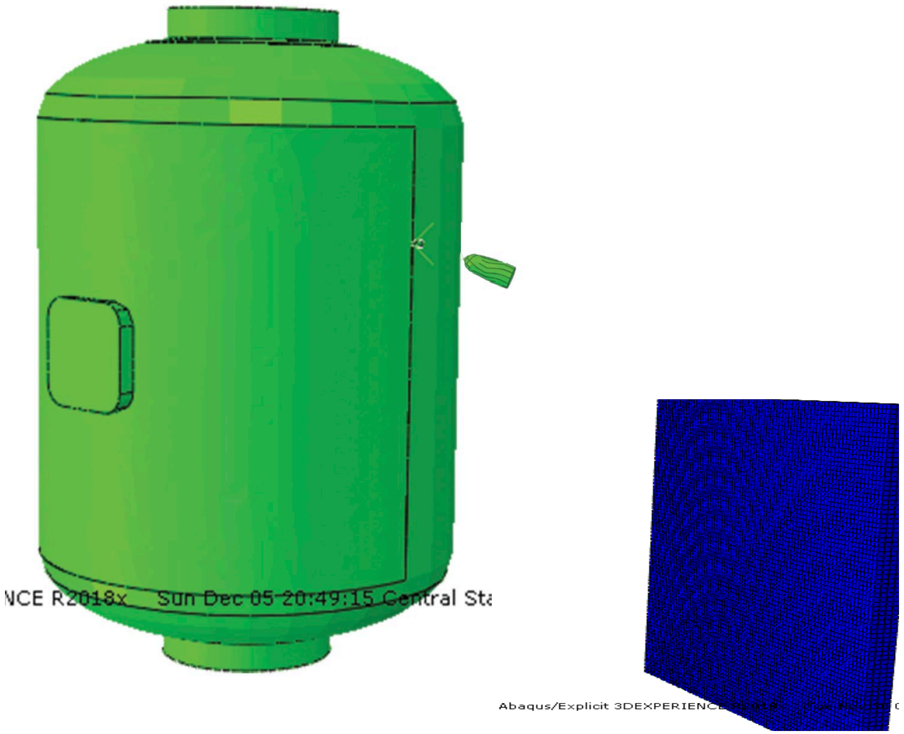
Vertical Configuration

- Sensor placement optimization in accordance with folding techniques is crucial
- The folding technique used in TransHab would be ideal, if the fiber optic sensors are in vertical configuration.
- Difficult to integrate hard structure in horizontal configuration.

Affected Area Analysis



Impact perpendicular to the habitat

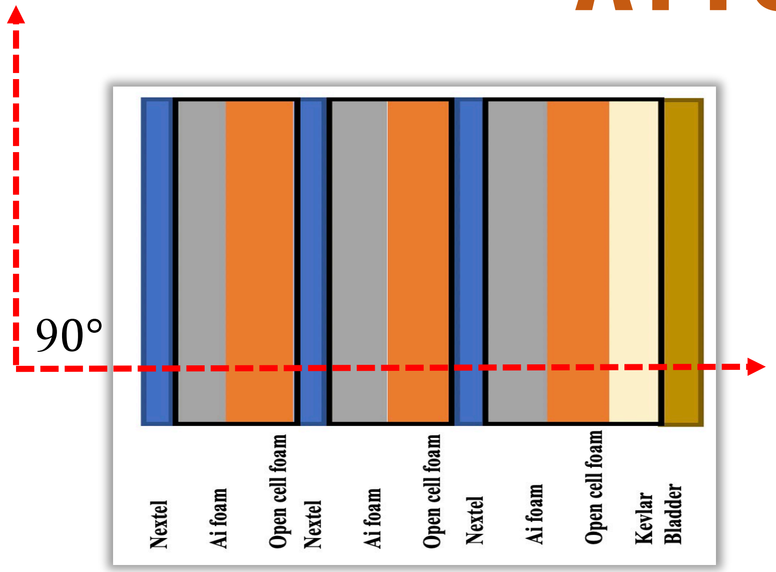


Impact at 30°

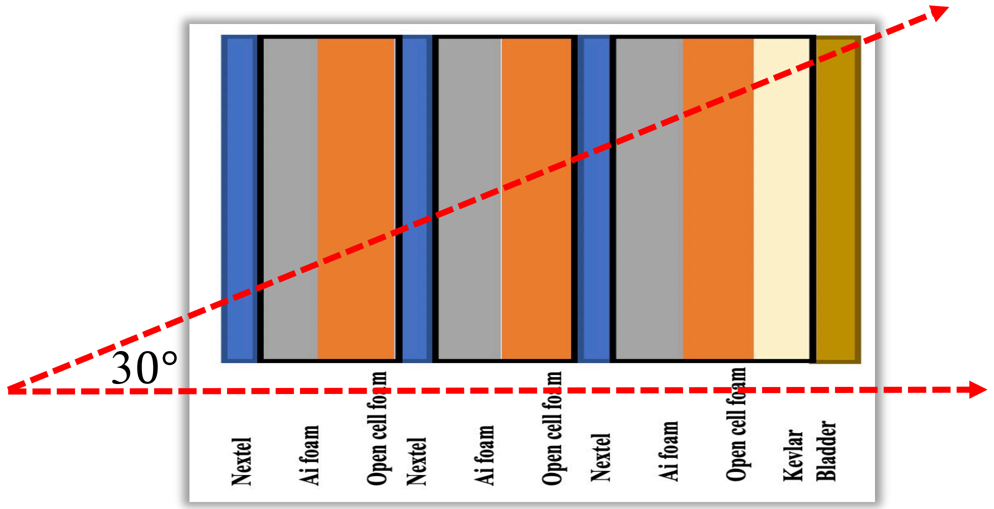
Impact speed : 7km/sec
Debris size: 1.8 mm

Affected area analysis → Impact size → Mechanics of Contact

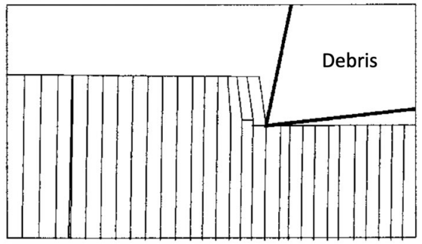
Affected Area Analysis



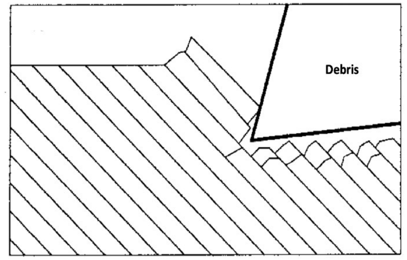
Impact at 90°



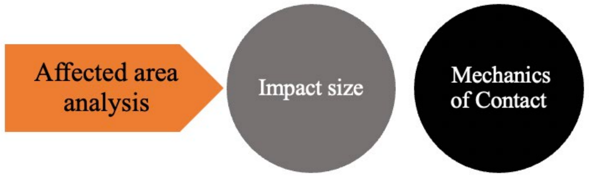
Impact at 30°

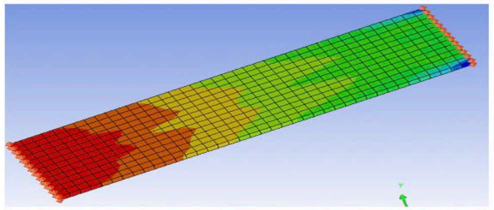


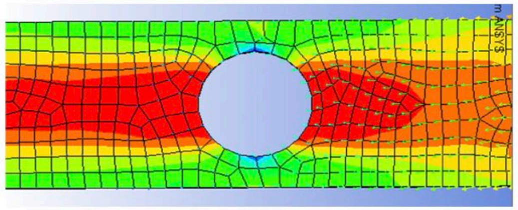
Close view of Kevlar strap at 90° cut



Close view of Kevlar strap at 30° cut

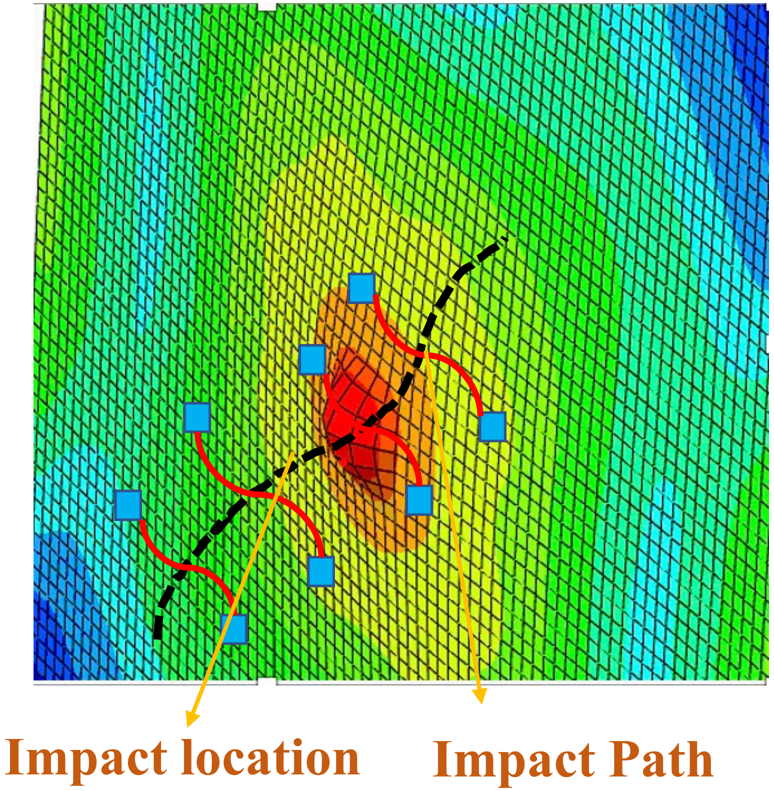


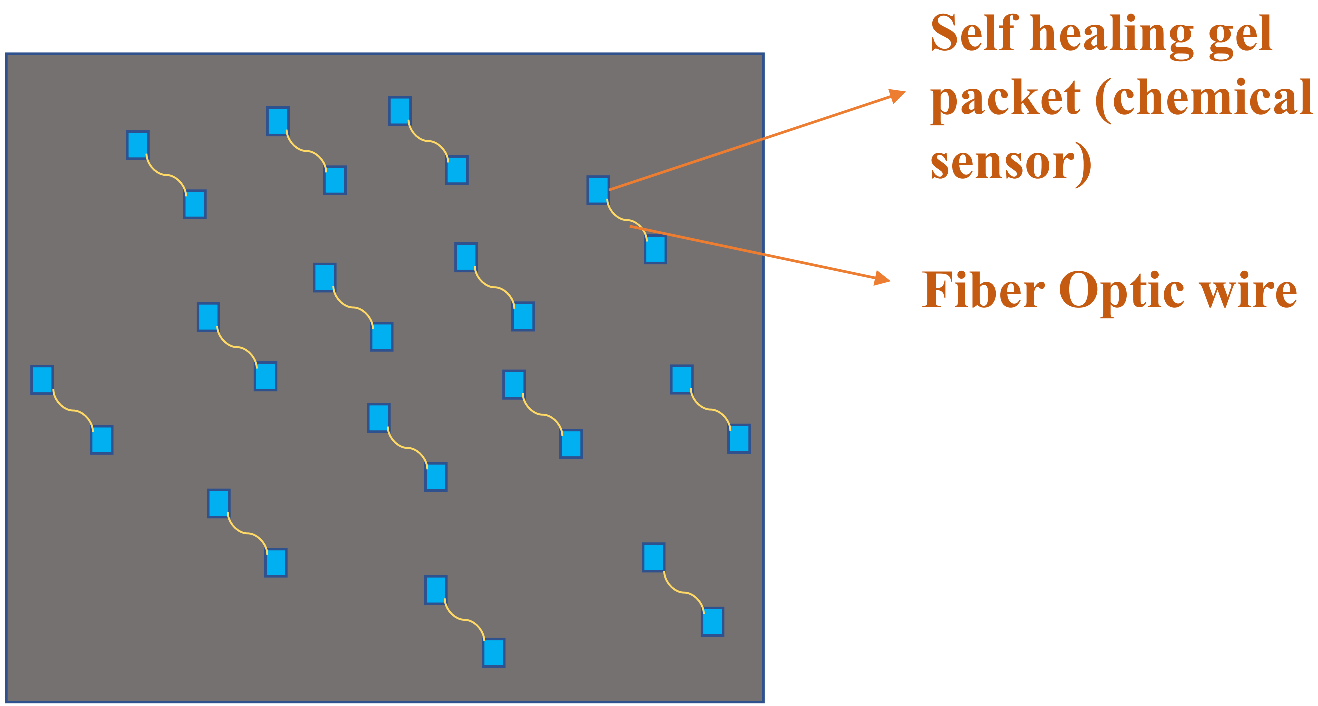


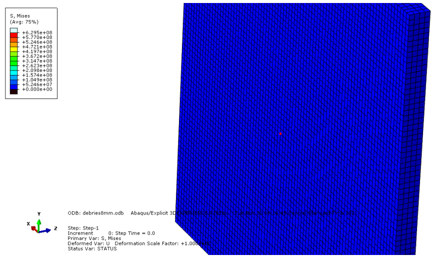


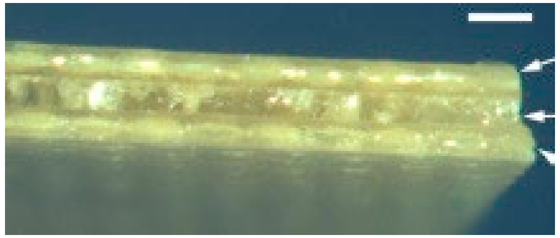
Kevlar strap without hole and with hole

Intelligent Material for Leak Protection



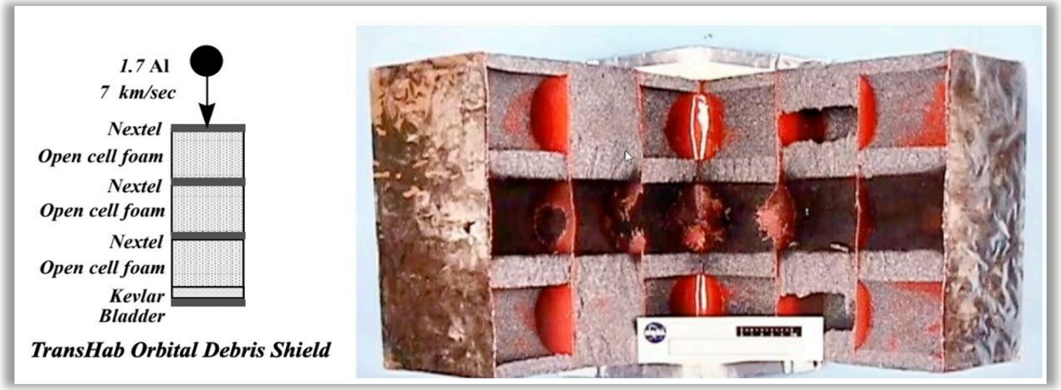




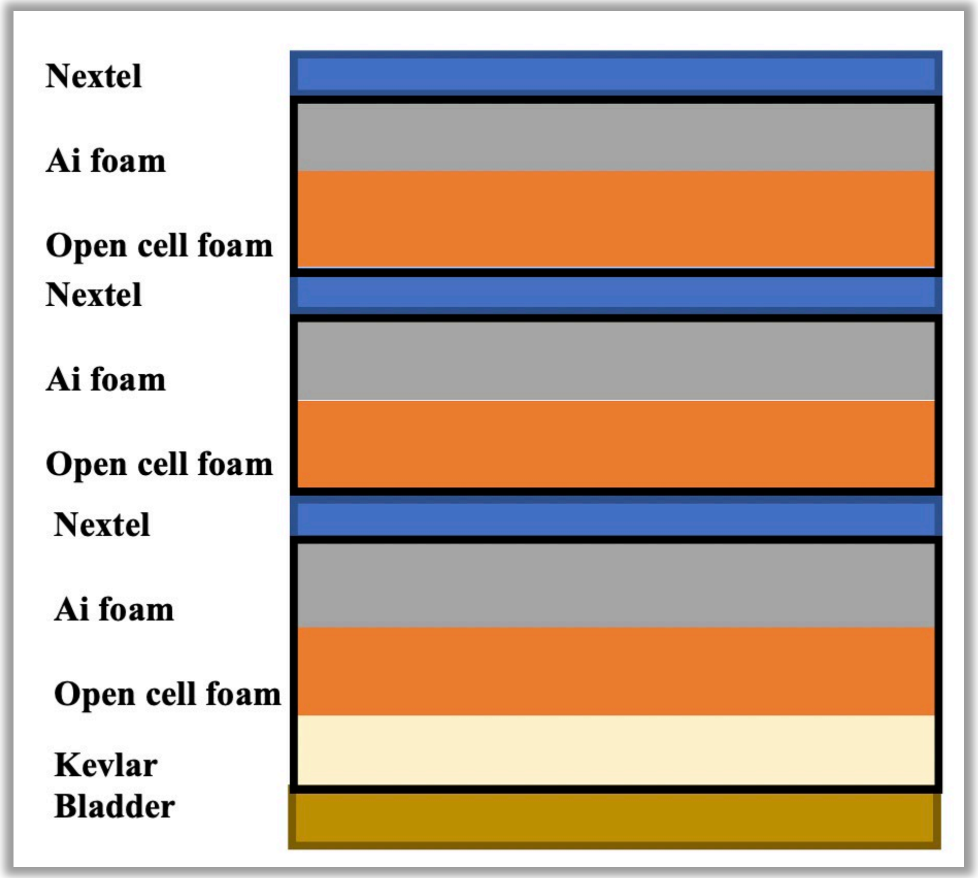


Self-healing elastomer- **Poly(dimethylsiloxane) (PDMS)**

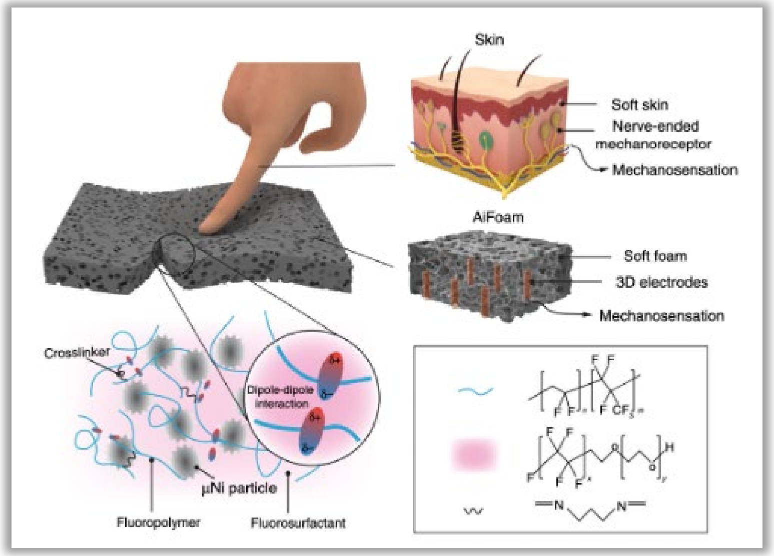
Intelligent Materials to Protect Leakage



TransHab Orbital Debris Shield

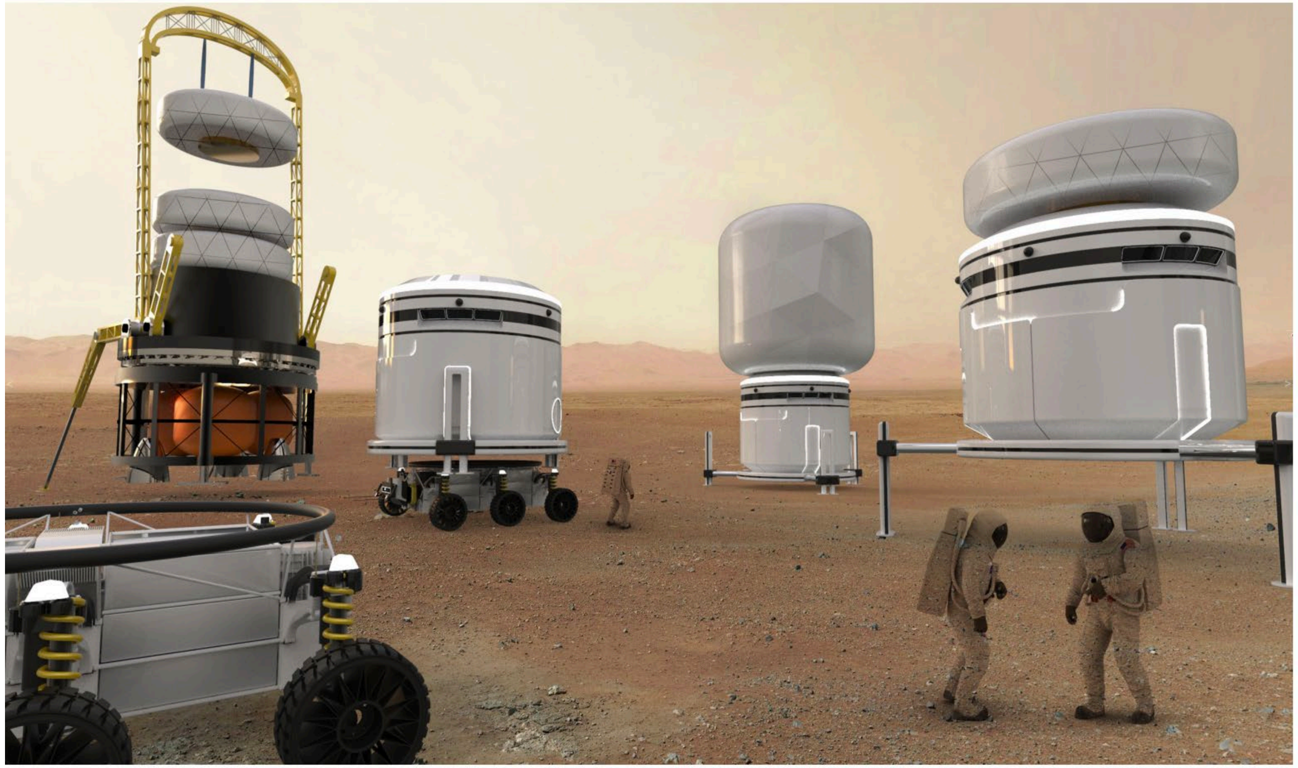


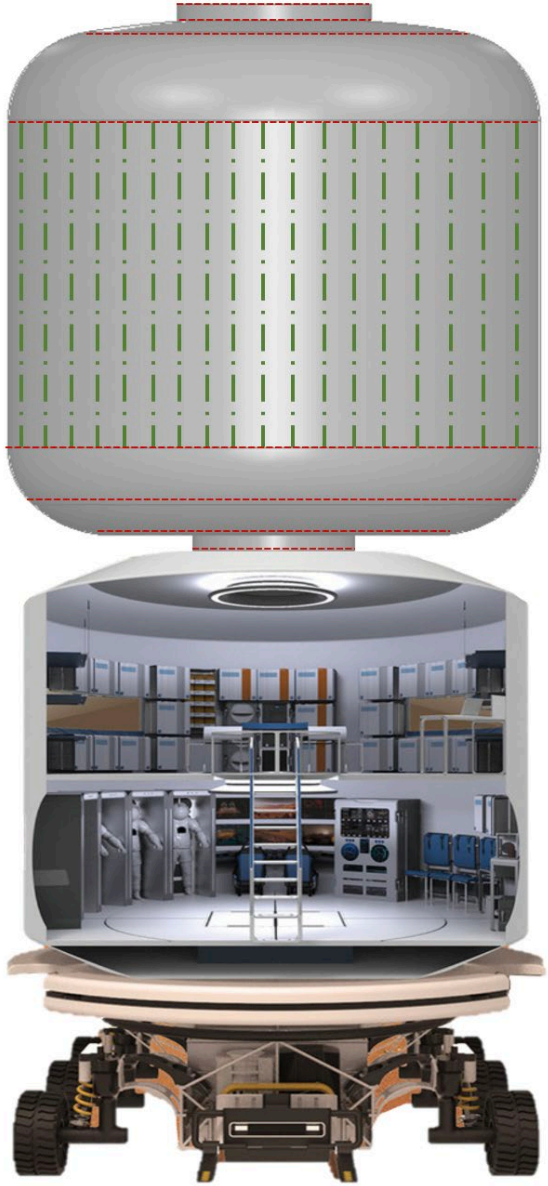
Introducing Ai foam into the Debris Shield



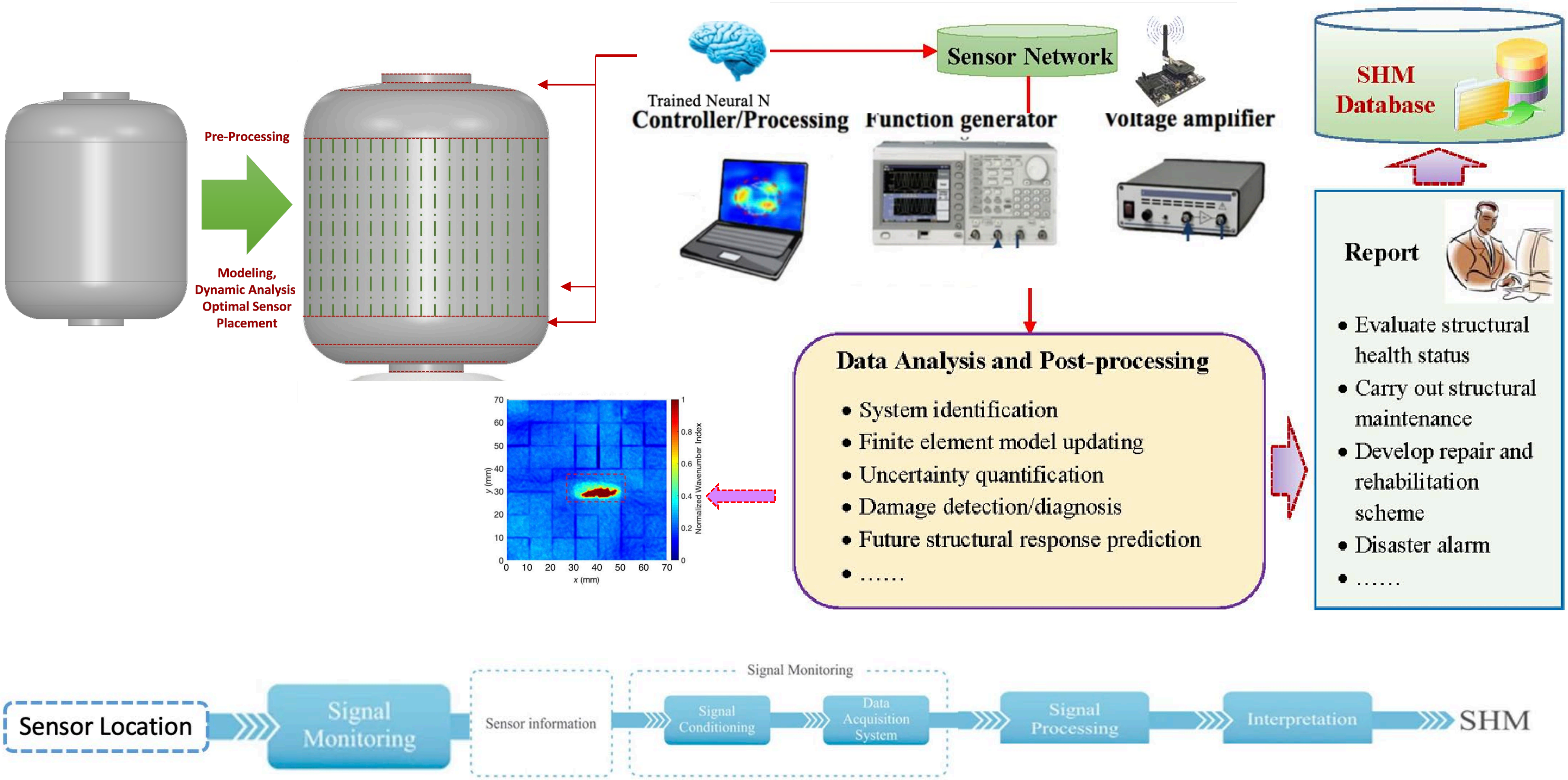
Bio-inspired Self-healing material

Reference Mission



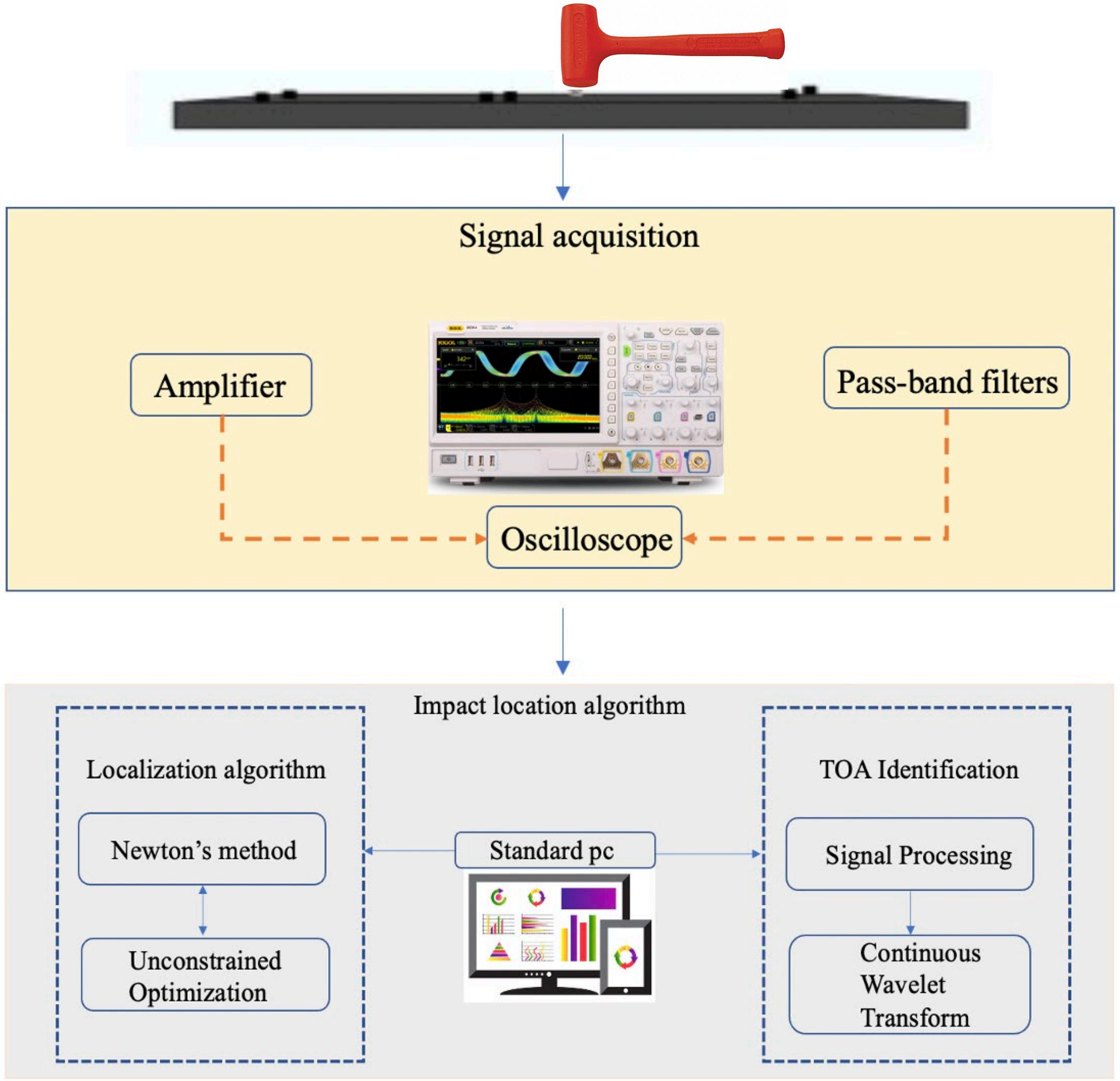


AI/Deep Learning Approach for SHM

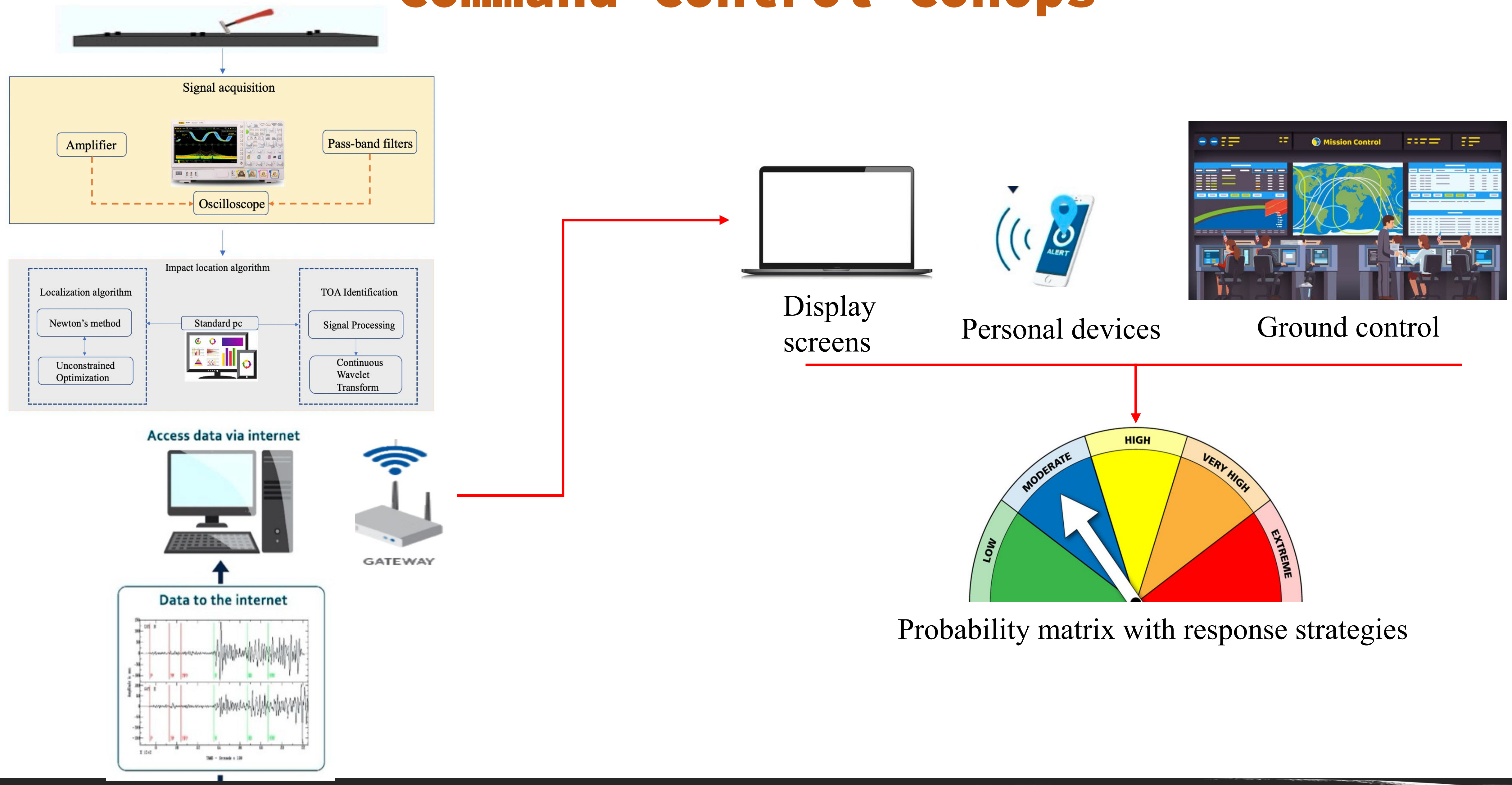


Architecture of Sensor Location System

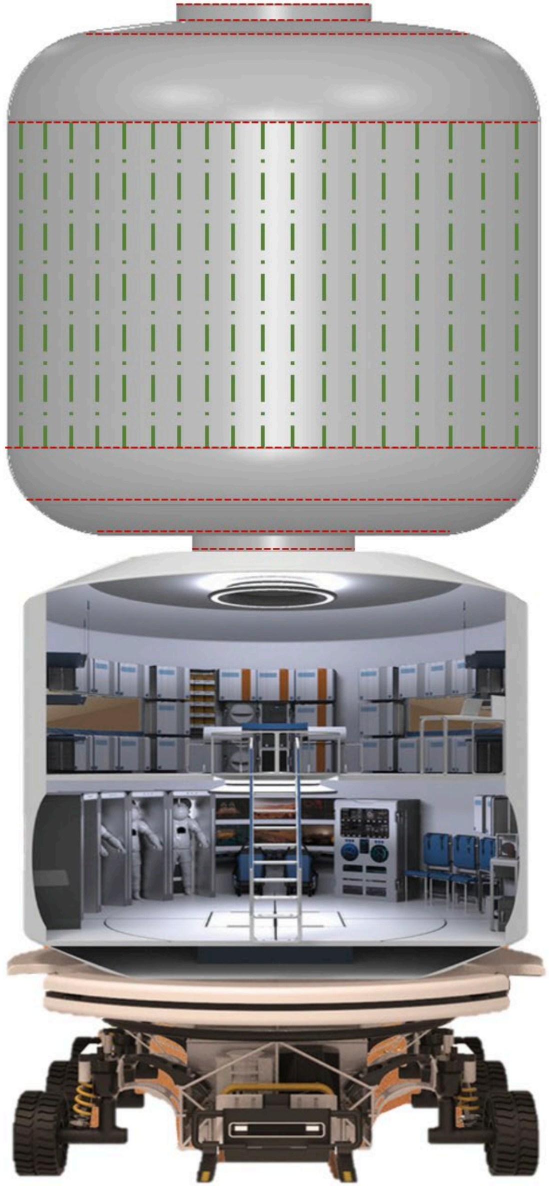
Acoustic emission Method

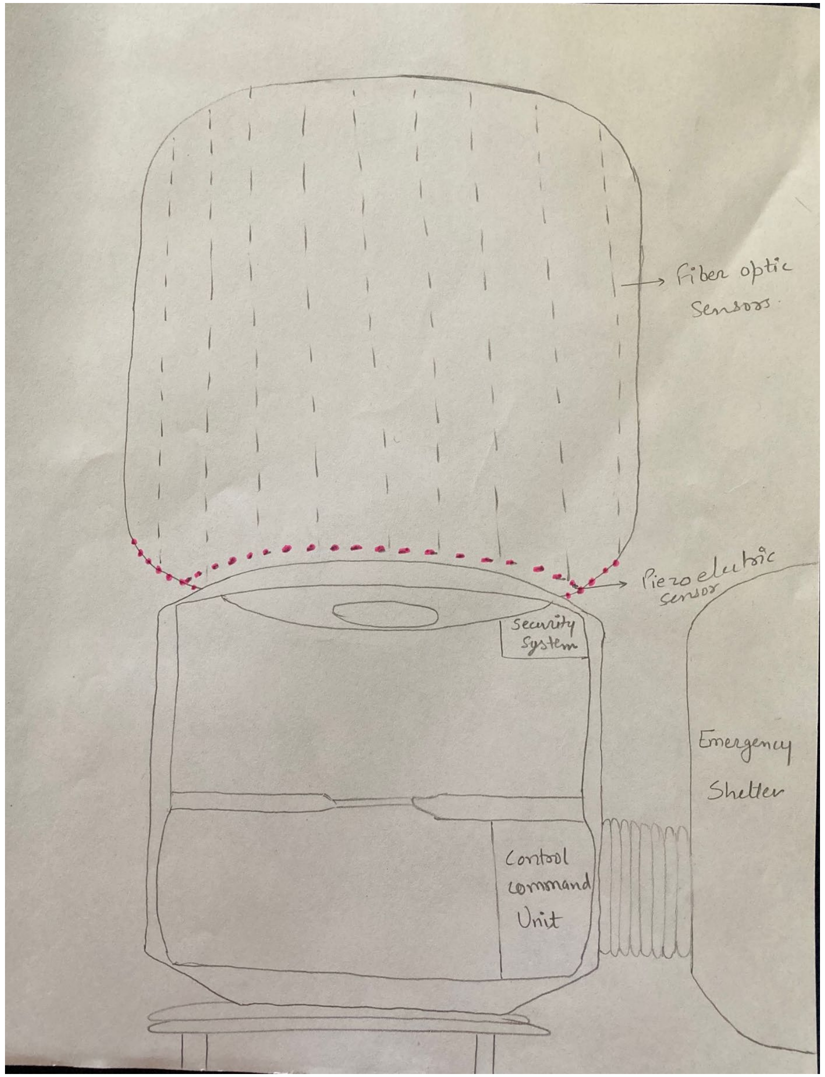


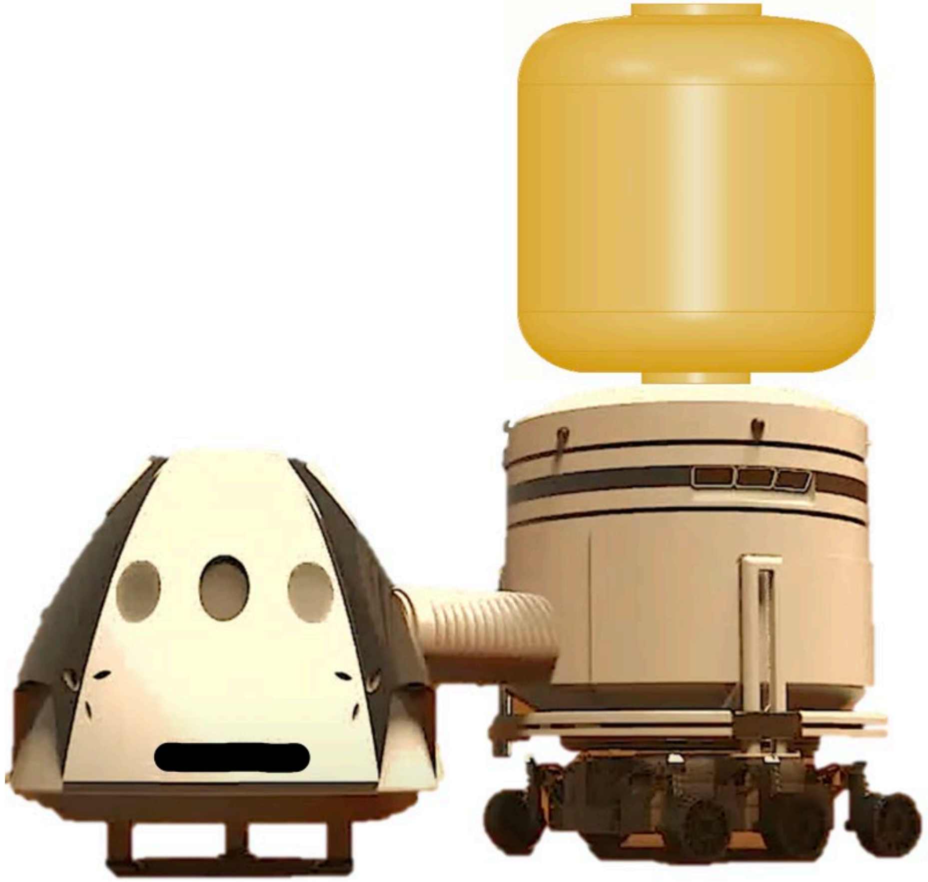
Command Control ConOps



Control room Unit Layout

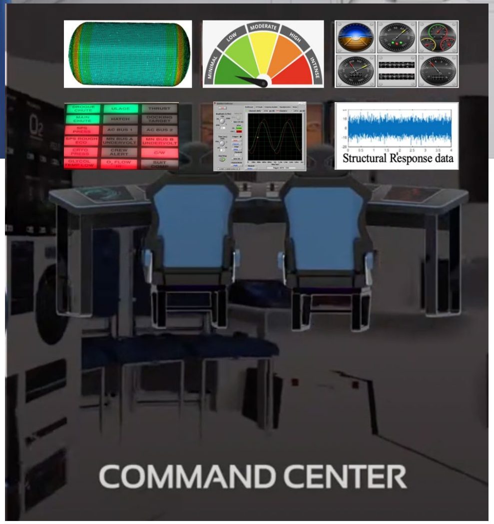






Emergency Shelter

Command Center



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Command Center Display Screen

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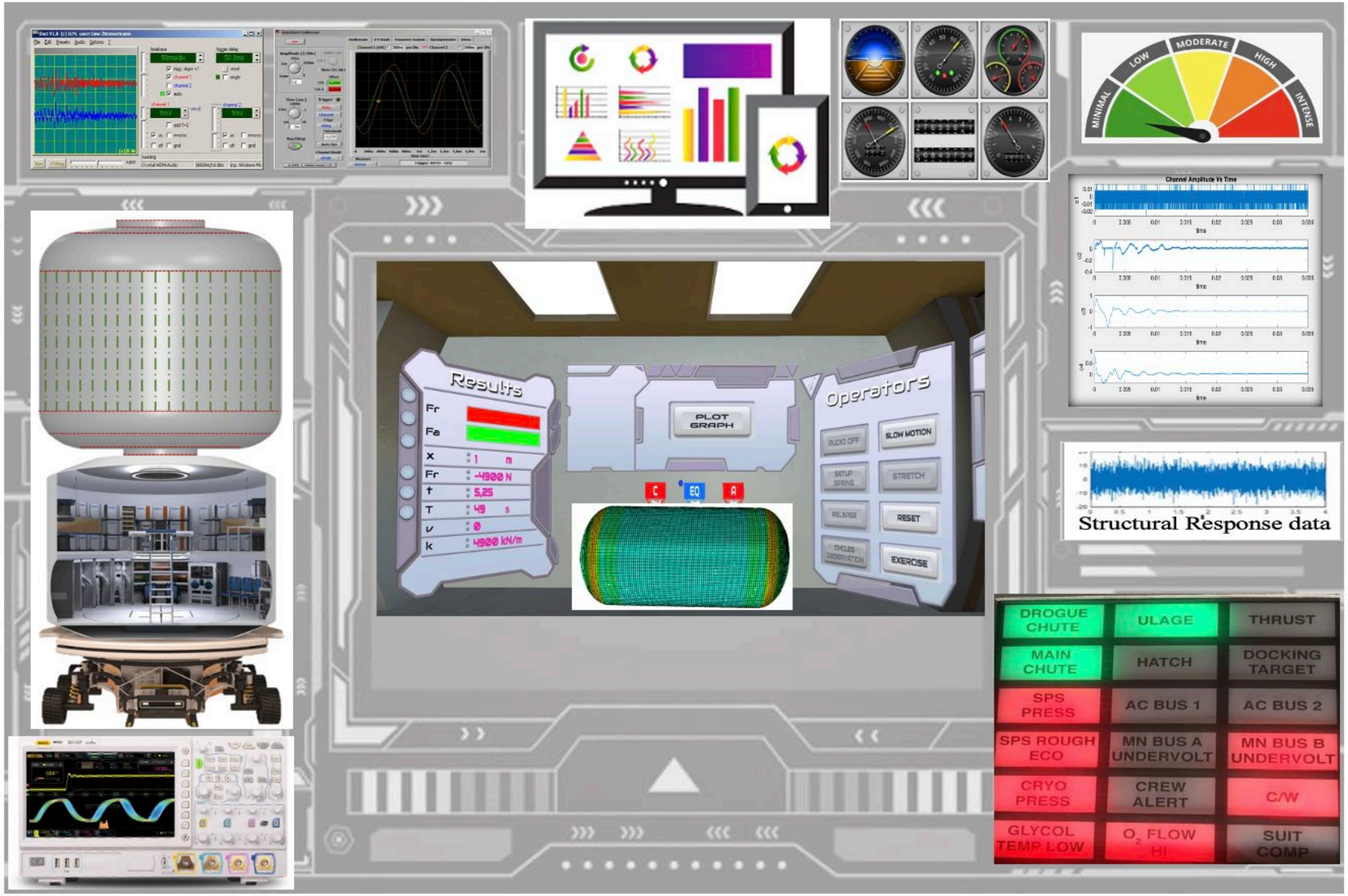
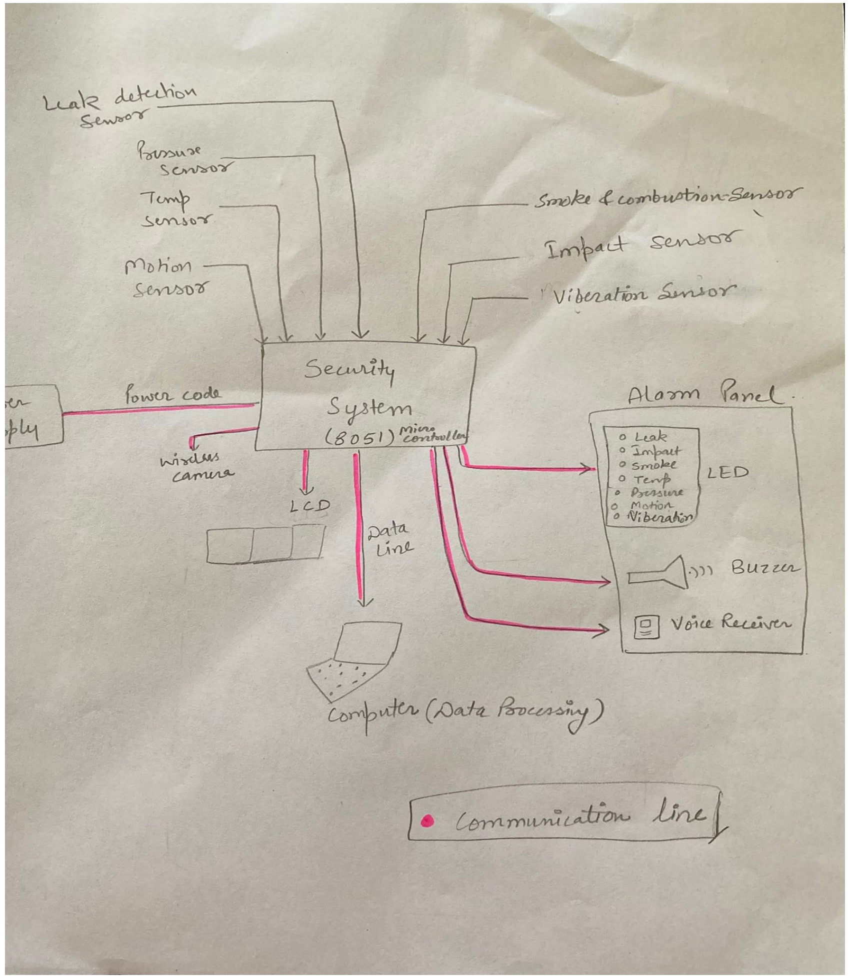




Risk Matrix

Probability	Severity			
	4	3	2	1
FREQUENT -A	High	High	Serious	Moderate
PROBABLE - B	High	Serious	Moderate	Minor
OCCASIONAL -C	Serious	Moderate	Minor	Low
REMOTE - D	Moderate	Minor	Low	Low

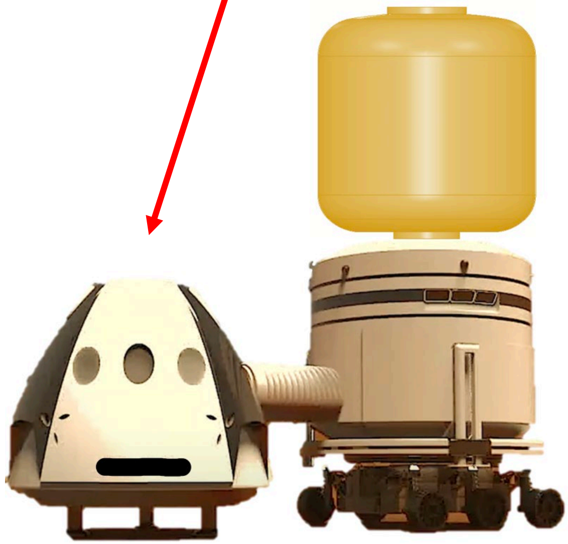
GREEN–Low risk: May be acceptable without further action.
BLUE–Minor risk: May be acceptable with review by appropriate authority, requires tracking and probable action. There are acceptable policies and procedures in place.
YELLOW –Moderate risk: May be acceptable with review by appropriate authority, requires tracking and probable action. There may be acceptable policies and procedures in place.
ORANGE–Serious risk: Unacceptable, requires investigation, resources and corrective action. There are no acceptable policies and procedures in place to manage the risk.
RED–High risk Imminent Danger: Unacceptable, requires the highest priority for investigation, resources, and corrective action.

Class	Severity			
	4	3	2	1
Accident or Incident	Accident with serious injuries or significant damage to habitat, equipment or resources.	Serious incident with injuries and/or substantial damage to habitat, equipment or resources.	Incident with minor injury and/or minor damage to habitat, equipment or resources.	Incident with less than minor injury and/or less than minor system damage.
Operational Event	State of emergency for an operational condition, impacting the immediate safe operation in a habitat.	Condition resulting in abnormal procedures, impacting the continued safe operation in a habitat.	Condition resulting in abnormal procedures with potential to impact safe operation in a habitat (i.e., battery charger failure, single source of electrical power etc.).	Condition resulting in normal procedures with potential to impact safe operation in a habitat (i.e., false indications).
Systems or Processes	Loss or breakdown of entire system, subsystem, or process.	Partial breakdown of a system, subsystem, or process.	System deficiencies leading to poor dependability or disruption.	Slight effect on system, subsystem or process.
Regulatory/ Procedural	Regulatory and/ or procedural deviation, impacting the immediate safety of astronauts, habitat and/ or resources.	Regulatory and/ or procedural deviation, with the potential to impact the safety of astronauts, habitat and/ or resources.	Regulatory and/ or procedural deviation, which does not impact the safety of astronauts, habitat and/ or resources.	Procedural deviation which does not impact the safety of astronauts, habitat and/ or resources.

Response Strategies

Functional Requirement	Integration	Packaging	Launch/Assent/Descent & Landing	Initial Operations	Long-term Operations	Decision Matrix Score	Desired State (Severity)
Locate leak in windows and seals that are cycled (hatches)							
Determine rate of leakage and time for repair or evacuation							
Monitor creep in flexible restraint layer							
Monitor strain around soft/hard materials interfaces							
Monitor Atmosphere (CO_2, smoke)							
Detect buckling of inflatable compression members							
Detect impacts and penetrations							
Detect punctures, tears or leaks in bladders							
Correct orientation and configuration after folding procedures							
On orbit identify leak magnitude and location in order to determine cause of damage							
Size of Impact, Size of penetration , Speed of Impact object							
• Strain and Temperature measurement range • Distributed sensing capability							
• Possibility of repair for accessible areas • Monitoring area • Data acquisition time • TRL level							
• Sensor Health • Sensor Power consumption • Sensor Life							

Emergency shelter



Experimental Prototype

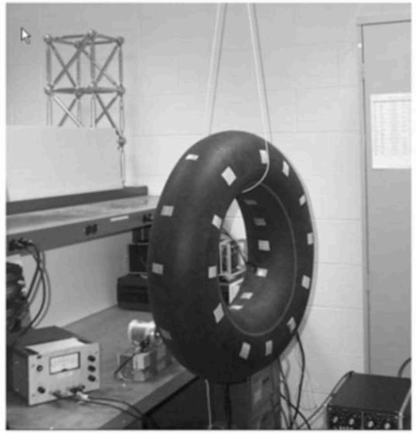


Figure 12: Inflatable test objects for dynamic analysis

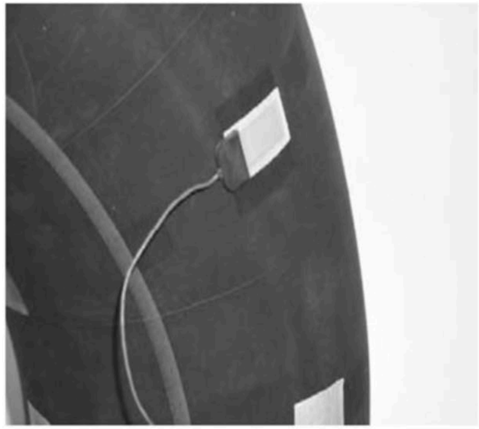


Figure 13: A shielded PVDF sensor bonded to the torus

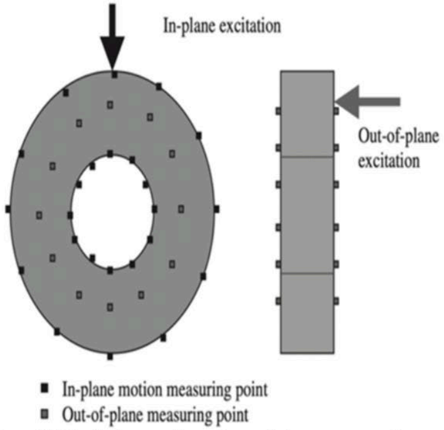


Figure 14: Excitation configuration and. Arrangement of sensors

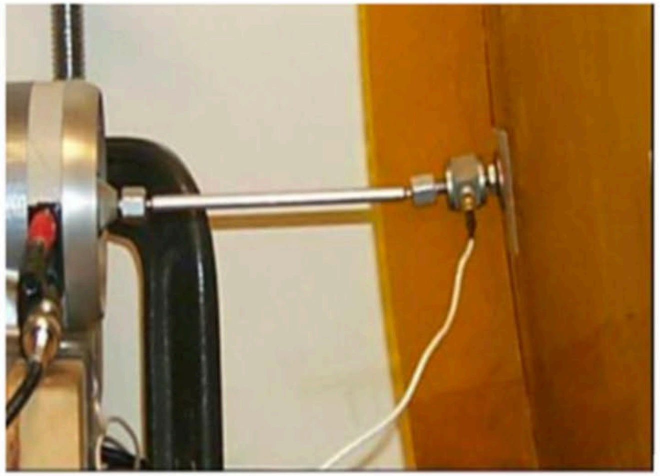


Figure 7: Connection between the shaker and the torus with the force transducer

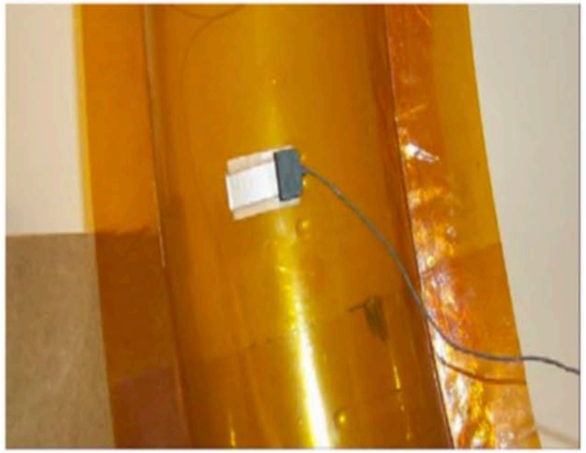


Figure 8: A shielded PVDF sensor bonded to the torus

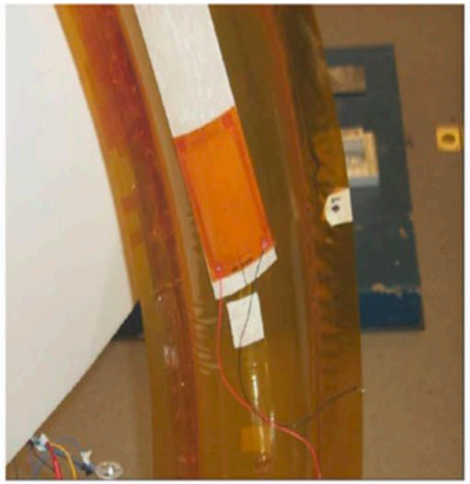


Figure 9: The MFC actuator attached to the torus

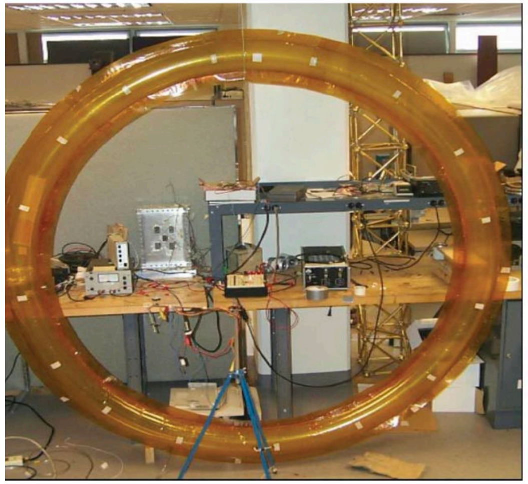
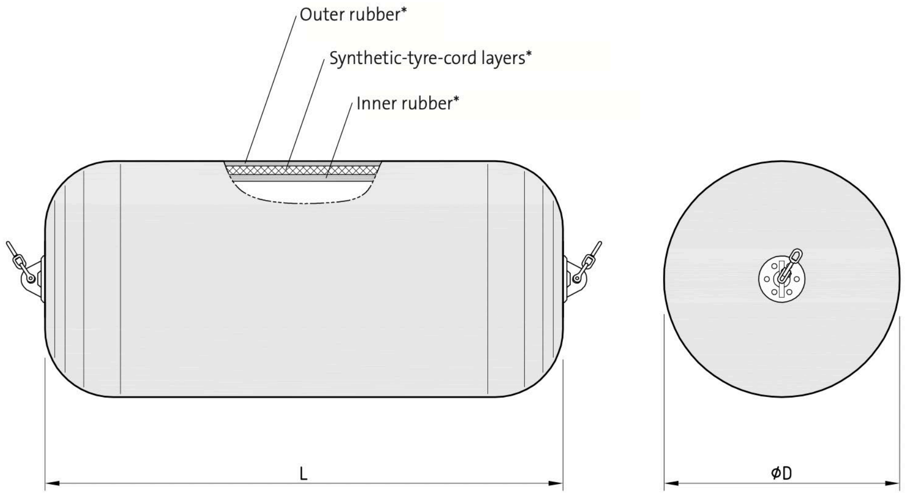


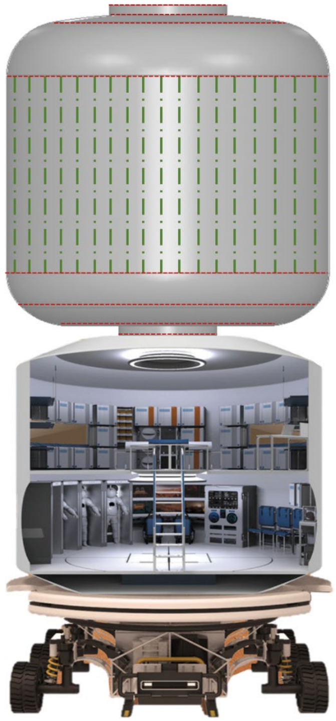
Figure 10: The Kapton torus for dynamic analysis

Equipment



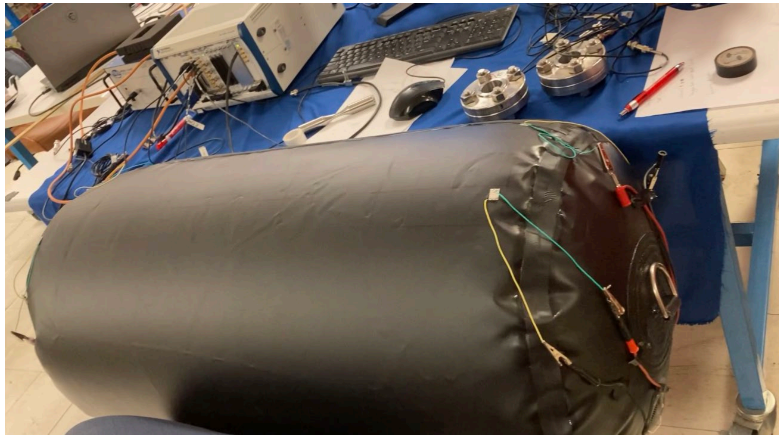
Dimensions: 3x1.5ft
Pressure: 7-10psi

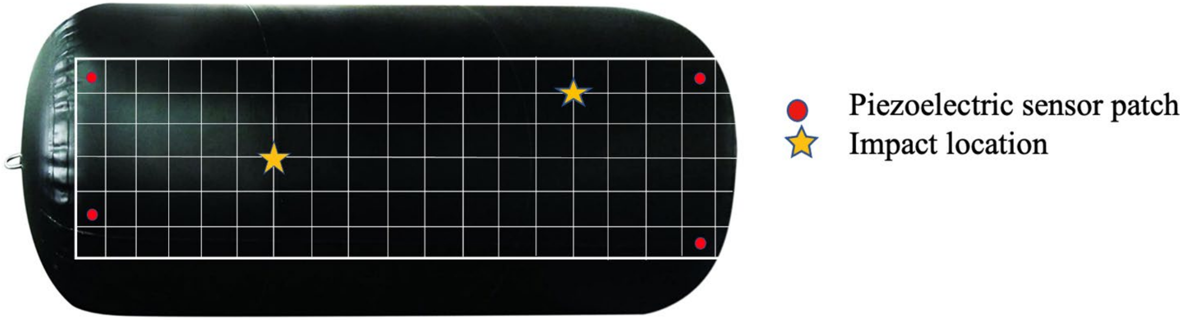
Dimensions: 40x27ft
Pressure: 14.7 psi



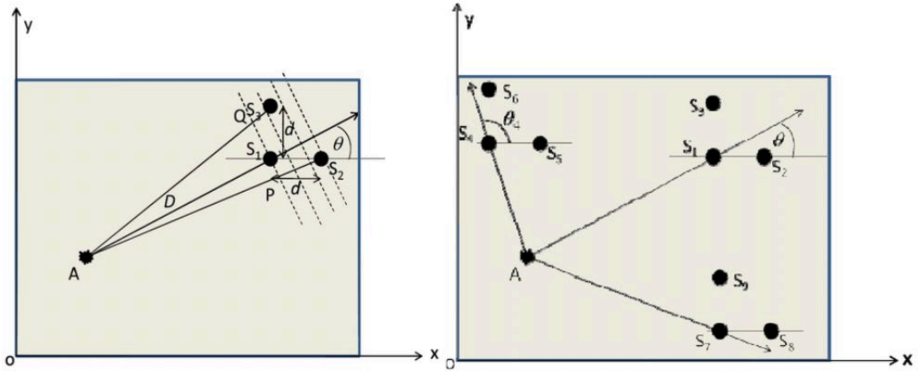
Scale: 1:13

Experimental Setup

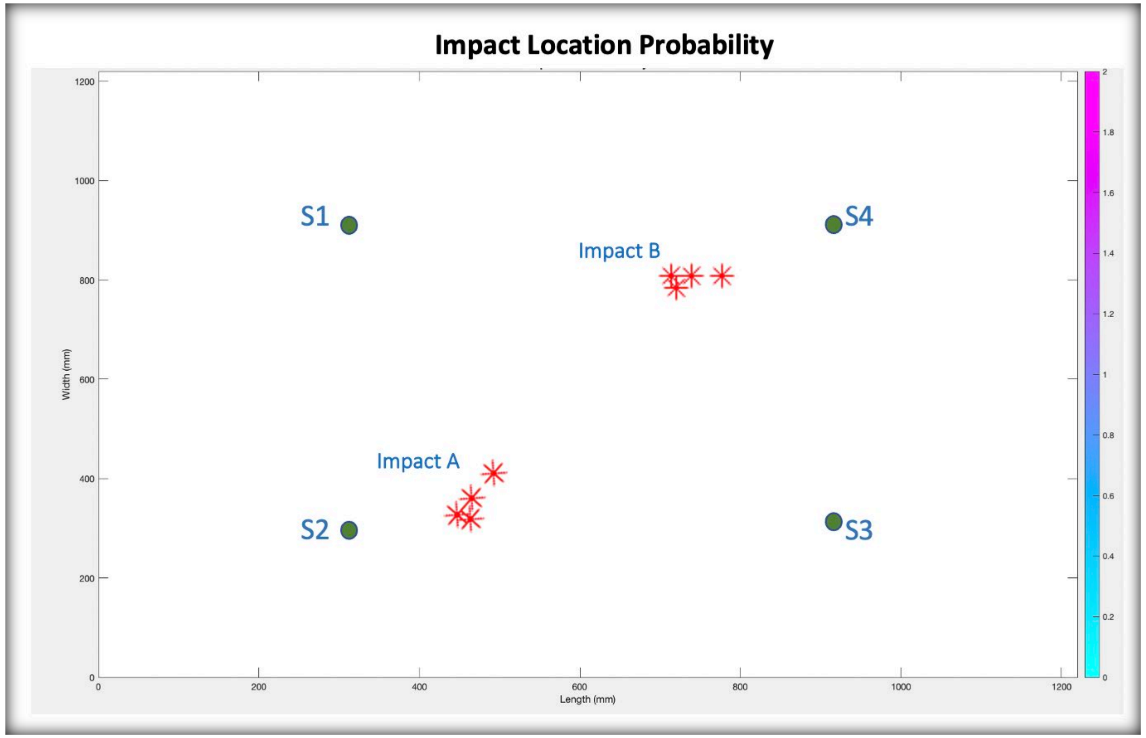


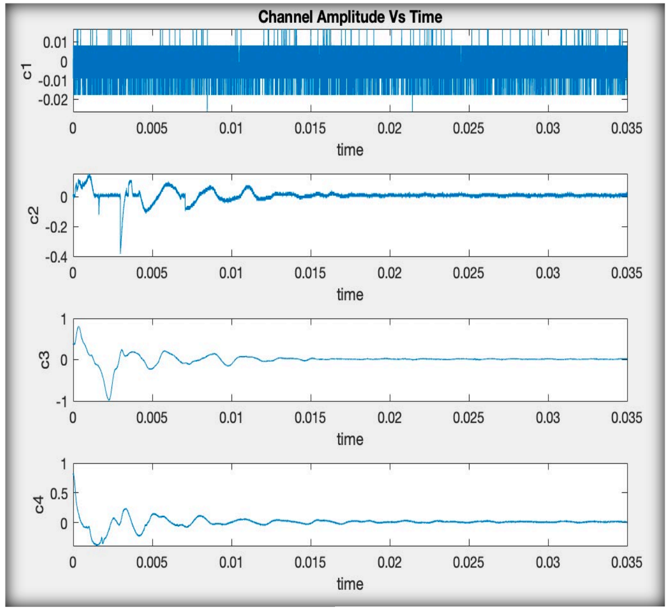


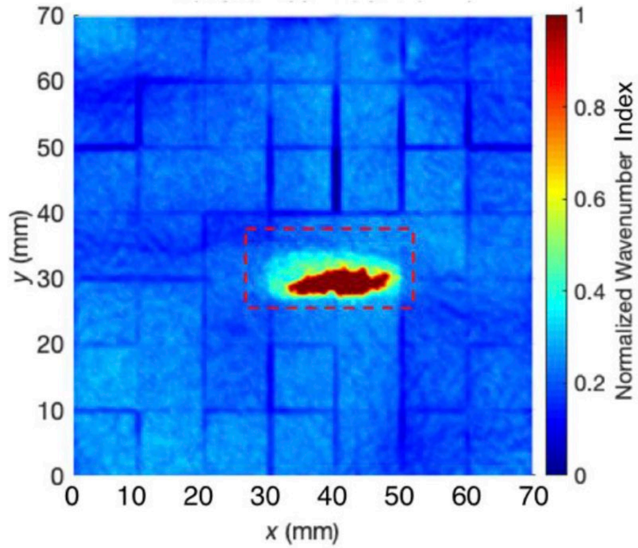
$$\theta = \tan^{-1}\left(\frac{\Delta t_{13}}{\Delta t_{12}}\right)$$



Sensor Architecture







Sensor position	Delays (s)	Predicted impact point	Imposed impact point	Estimated error (X,Y)
X1= 66	t1= 6.42e^{-7}	(150.26, 150.26)	(150,150)	(0.17%, 0.17%)
X2= 66	t2= 6.42e^{-7}	(153,150)	(151,150)	(0.34%, 0.27%)
X3= 234	t3= 6.42e^{-7}	(150,152)	(162,156)	(0.54%, 0.30%)
X4= 66	t4= 6.42e^{-7}	(150,153)	(158,152)	(0.24%, 0.17%)

Future Application