Wireless Applications for Structural Monitoring of Inflatable Habitats

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Structural Health Management System (SHMS)

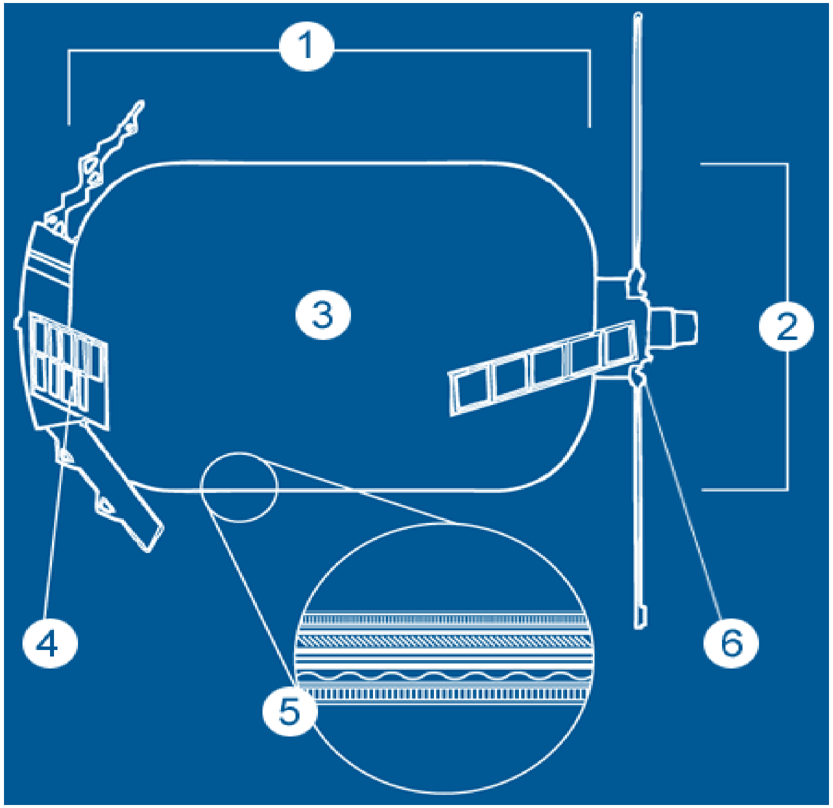
1.0 Background

History

- Inflatable space structures have been with NASA almost as long as the agency itself
- Extended NASA studies of space stations and surface habitats
- NASA first expandable satellite ECHO was launched 1960
- Russians use of expandable airlock – 1965
- Inflatables envisioned for large space antennas and solar arrays
- The re-entry of the Lavochkin/Daimler Chrysler ballute - 2000
- 1998 NASA began to look at inflatable structure to house astronauts in transit to Mars as well as a habitat once they were on the surface. TransHab evolved to a TRL of 6 before being shelved in 2000
- 2004 provided a presidential vision for return to moon and beyond that includes the use of inflatables as lunar structures.
- In 2006 Bigelow Aerospace launches a subscale inflatable demonstrator called Genesis I.
- Investigating Infaltables that are Rigidazable and Hybrid modules

NASA Inflatable Structures

Genesis I



Launch Date:
July 12, 2006

Launch Location:
ISC Kosmotras Space and Missile Complex, Russia

NORAD Identifier:
#29252

1 4.4 Meters in Length

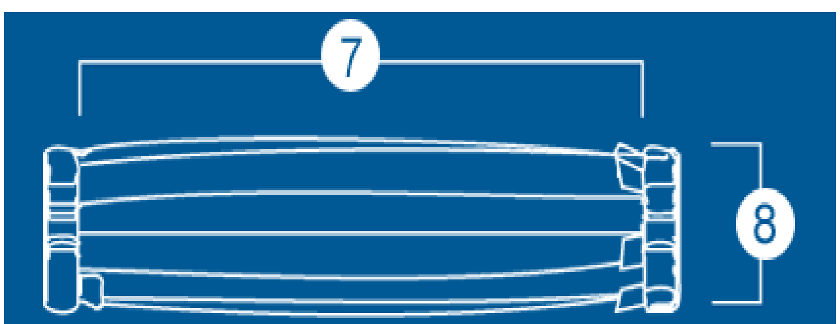
2 2.54 Meters in Diameter

3 11.5 Cubic Meters of Usable Volume

4 Solar Arrays (8 total)

5 Shell Skin:
6 Inches Thick, Multilayer System

6 Communications Antenna



7 4.4 Meters in Length

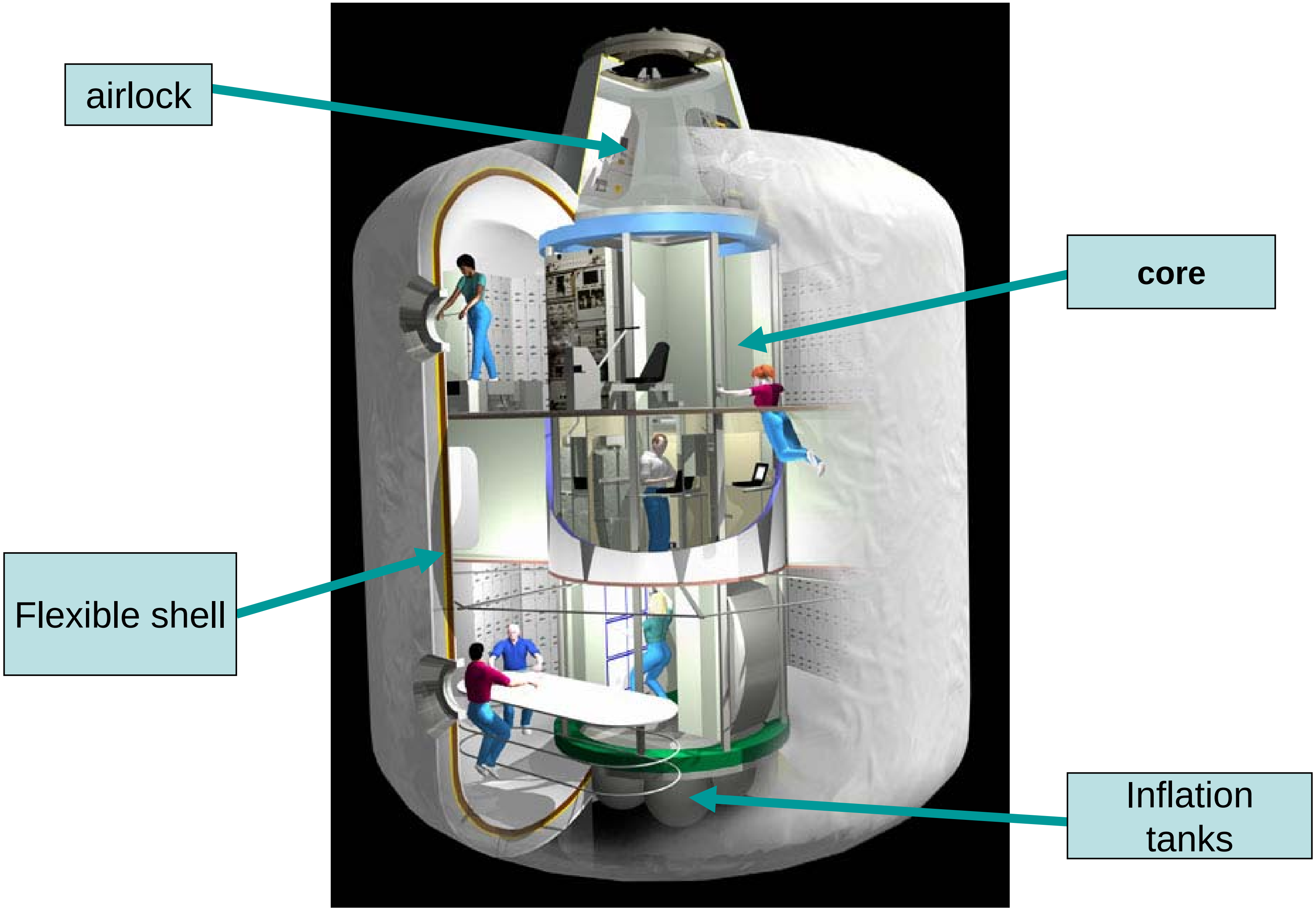
8 1.6 Meters in Diameter

Inflation Rate: 15 Minutes
Internal Temperature: 79 Degrees
Windows: 1
Internal Cameras: 6
External Cameras: 7
Speed: 16,928 MPH
Altitude: +/- 350 Miles
Earth Orbit: Once every 96 Minutes
Anticipated Lifespan: 3-13 Years

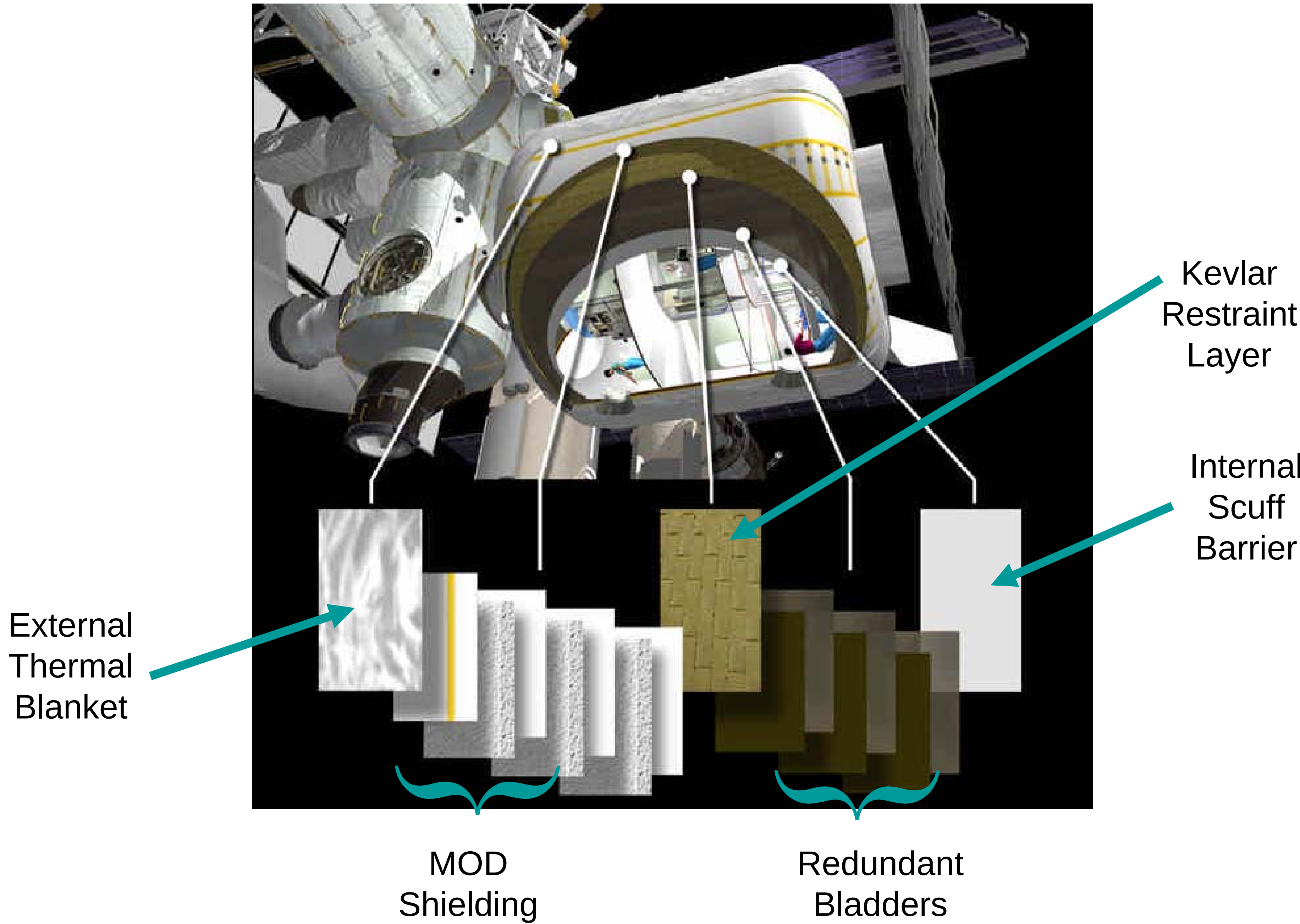
Fundamentals of Current Inflatable Technology

- Structural core is made of metallic or composite materials and serves as backbone for launch of inflatable spacecraft.
- Shell consists of impermeable bladder, restraint and layers of micrometeoroid protection (figure following page).
- Manned subsystems include avionics, power and life support.
- During inflation, the shell moves radially outward approximately the original diameter of the core (usually 6-10 feet to allow for crew translation).
- Portions of the secondary structure and subsystems will require repositioning into the expanded volume.
- Most of the larger utility lines will remain in pre-integrated positions within core.
- However the majority of the structural health sensors need to follow the shell as it moves outward significant distances (feet) from the core.

TransHab Concept



Multi-Layer Inflatable Shell Overview



Inflatable Advantages

- Inflatable/deployable structures are attractive as orbiting or surface habitats for four key reasons:

1) **<u>High volume-to-mass ratio</u>** – the livable habitat volume that can be delivered to orbit or lunar surface per unit mass of payload can be maximized. (TransHab volume approx. 2.5 times rigid ISS module).
2) **<u>High packing efficiency</u>** – Inflatable/deployable structures provide for a more flexible launch manifest, whereby the structure can be designed more efficiently around the launch vehicle.
3) **<u>Minimal need for on-site construction materials</u>** – With these unique habitats, virtually all of the assembly mechanism is inherent to the structure (although lunar regolith maybe added for more protection)
4) **<u>Fewer secondary radiation effects</u>** – Use of soft goods reduces the destructive effects of secondary ionizing particles, commonly seen with metallic structural materials.

Structural Health Monitoring

As for all human space vehicles, the need to maintain the safety of the crew is paramount.

Need for an integrated structural health management system (SHMS)

It is anticipated that the utilization of softgoods in inflatable structures will call for new monitoring techniques such as embedded sensors in a distributed network architecture

Since the flight experience with inflatables in space is limited, both professionally and in the public eye, assurance is needed in several critical areas, with a priority in these:

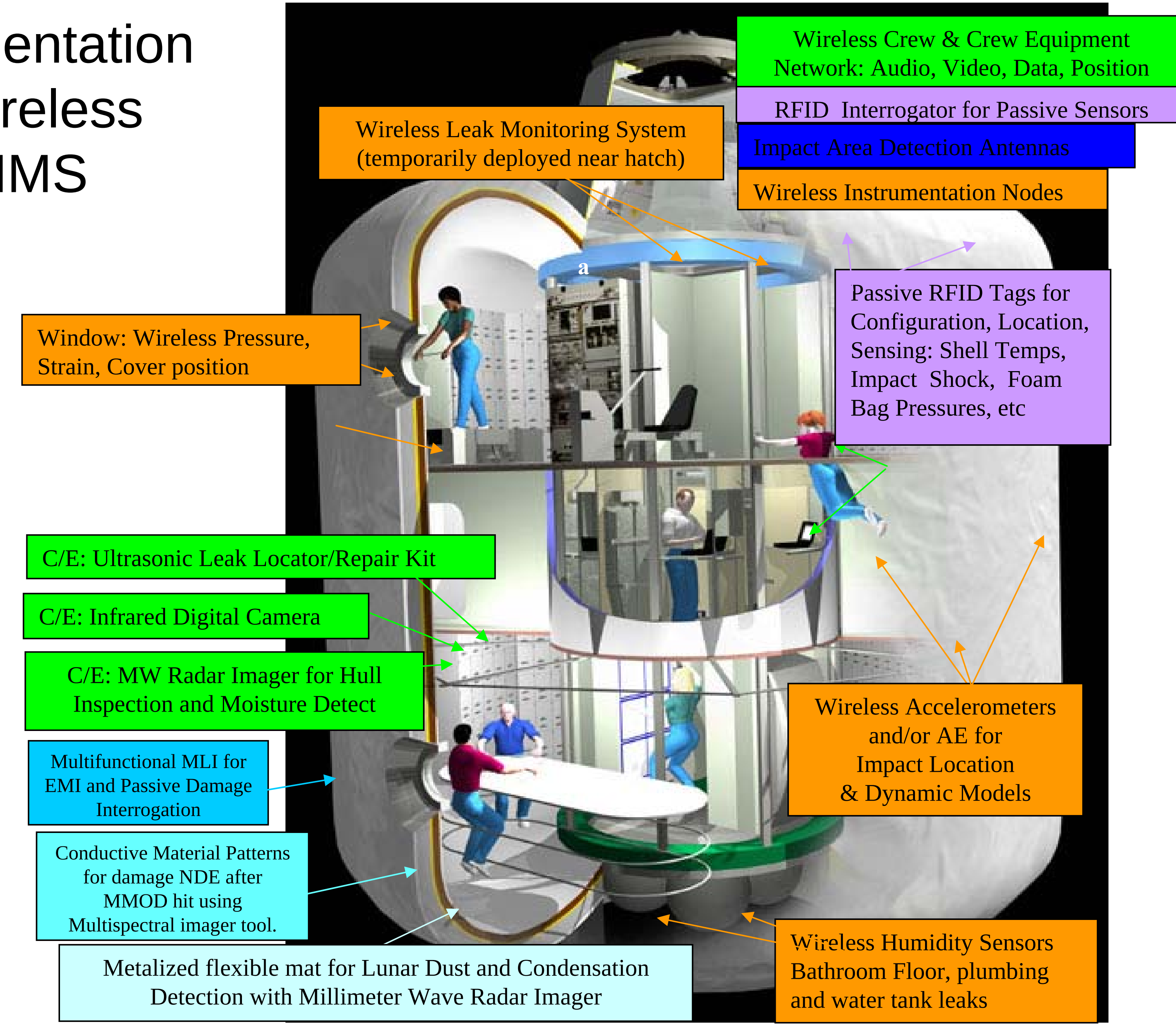
a) MMOD Detection

b) Leak Detection

c) Verification Atmospheric Conditions

d) Identify Condensation on inside surface of bladder

Implementation of Wireless SHMS



2.0 SHMS Requirements

2.1 Objectives

Structural Health Monitoring Objectives

#1 ***Increase Crew Safety***

- Provide autonomous, continuous, ongoing monitoring of habitat structural integrity (includes unmanned period – assures safe ingress)
- Identify, locate and scope damage, failures and degradations
- Alert the crew in real time to issues requiring immediate attention
- Facilitate Repairs (provide location of leaking bladder or seal)
- Monitor hidden and inaccessible regions of the structure (provide warning of “dead” air pockets, smoke or condensation)
- Allow accurate estimates of any impacts on habitat lifetime (example: record MMOD impacts, location and resulting damage)
- Self-rectify or mitigate problems where possible (return to normal ops)

Structural Health Monitoring Objectives

#2 ***Reduce Life-Cycle Cost***

- Facilitate pre-launch integration and test
  (provide sensors to measure leakage and correct folding of shell)

- Reduce unnecessary inspection and preventive maintenance
  (monitor vibrations in motors as an indicator of wear)

- Decrease crew monitoring and housekeeping time

- Provide real-world validation of models and assumptions
  (correlate thermal and loads models)

- Ensure an acceptable level of reliability and maintainability

- Allow instrumentation decisions to occur later in design cycle
  (minimizes re-planning yet maintain flexibility to swap out or upgrade later)

Structural Health Monitoring Objectives

#3 ***<u>Provide Multi-Role Integrated System Functionality</u>***

- Increase system efficiency with a flexible and modular sensor and data acquisition system design approach (minimize volume, mass and effect on inflatable materials)
- Minimize impact on other habitat systems (SHMS should not tax vehicle software, data storage and power)
- Share hardware and data across multiple systems (generic parameters such as temperature, pressure and humidity can be shared with other subsystems)
- Sensor suite aids in Non Destructive Evaluation (NDE) by making damage visible to inspection equipment
- Module walls assist life support with thermal control, provide radiation and MMOD protection and can provide a surface for mounting solar cells, while potentially healing itself (self-sealing bladder)

2.2 Functional Requirements

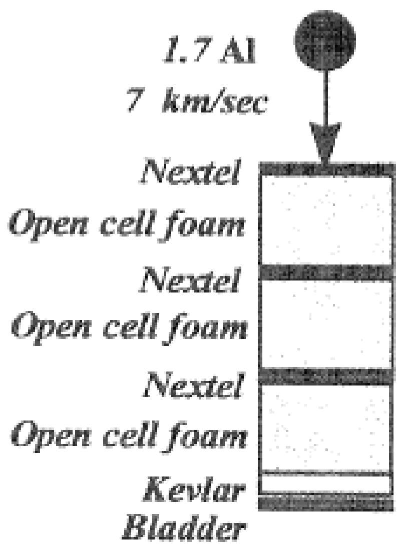
SHMS Functional Requirements

Inflatable/Deployable Failure mode Detection

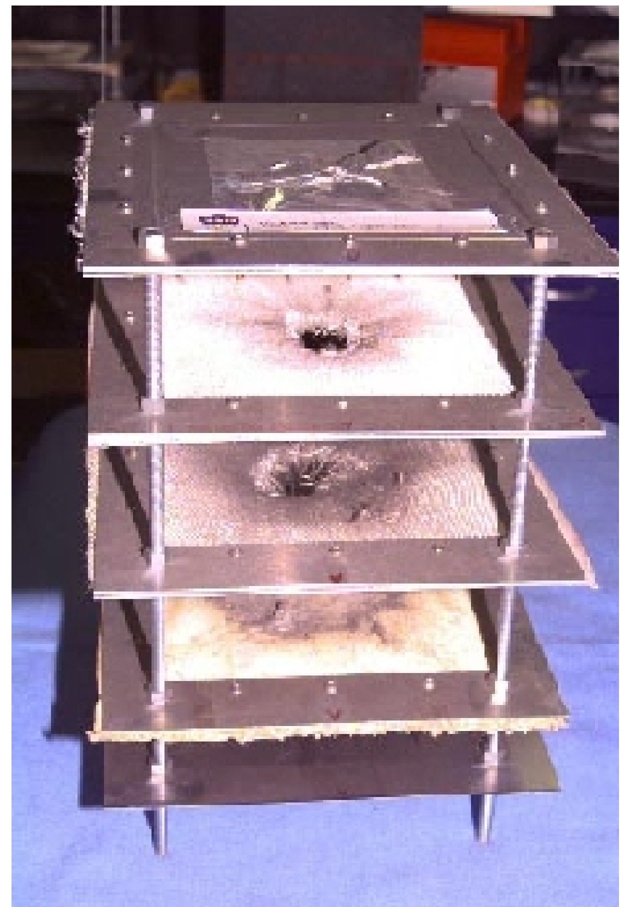
- Detect Impacts from Outside (chart follows)
- Detect Punctures, Tears, and Leaks in Bladders (chart follows)
- Monitor Strain around Soft and Hard Material Interfaces
- Monitor Deployment Dynamics and Final Shape
- Monitor Creep in Flexible Restraint Layer
- Detect Buckling of Inflatable Compression Members
- Monitor Window Seals

Impact Detection

- The SHMS shall provide real-time monitoring and notifcation of impacts and penetrations to the exterior of inflatable habitats, including event time, location, depth of penetration and extent of resulting damage



TransHab Orbital Debris Shield



Leaks in Bladder

- The SHMS shall detect punctures, tears and leaks in bladder

<u>prior to being manned:</u>

- damage can occur during ground assembly or transportation
- on-orbit (post deployment) identify leak magnitude and location in order to determine probable cause of damage
- identify magnitude and location of damage prior to crew entry in order to facilitate timely repairs

<u>manned:</u>

- damage can occur from inside due to sharp objects
- determine rate of leakage and time for repair or evacuation
- locate leak in seals that are cycled (hatches)
- locate leak in windows

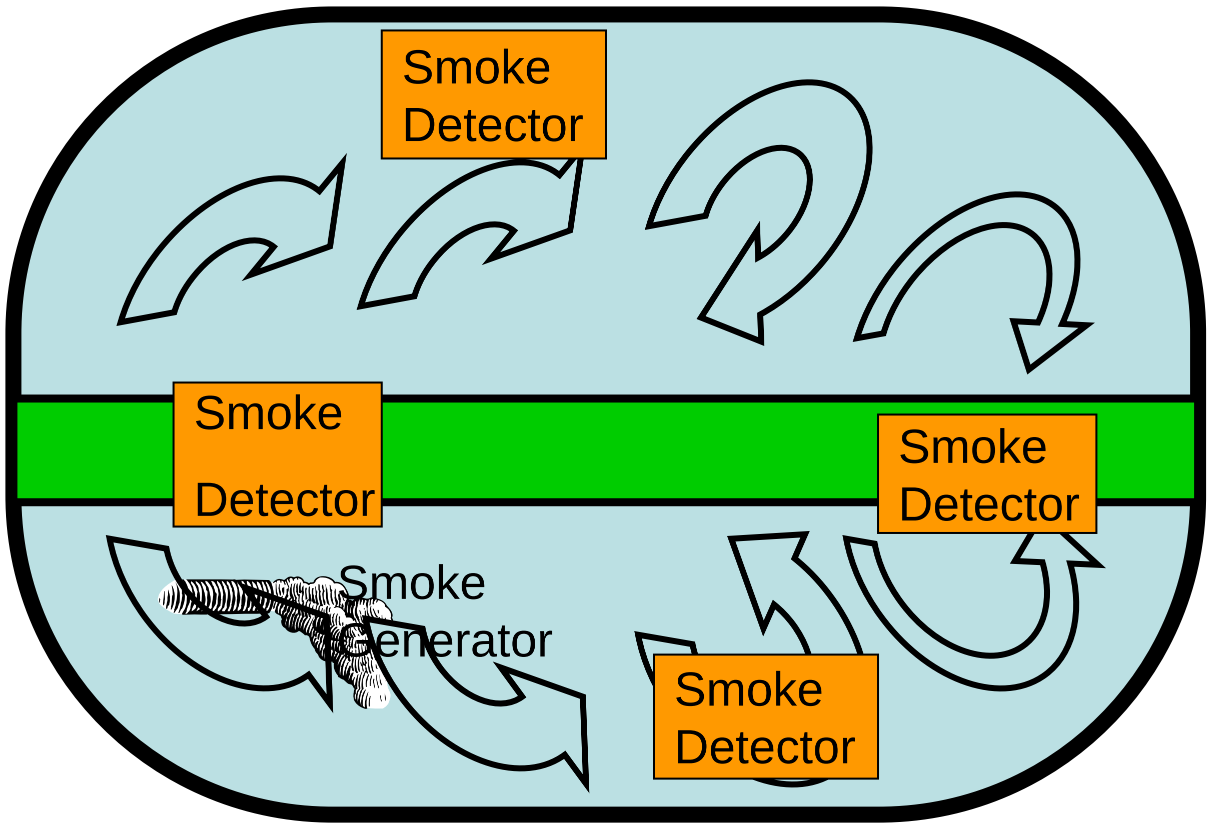
SHM Function Requirements (cont.)

- Other failure mode detection
  - Detect delamination and cracks
  - Detect materials and manufacturing defects
  - Monitor materials for changes and degradation
  - Detect Condensation

- Extended Functions
  - Monitor Thermal and Radiation Conditions
  - Monitor Structural Deflection, load and dynamics
  - Monitor Mechanical Functions
  - Monitor Atmosphere (CO_2, smoke)
  - Validate pre-flight readiness

Monitor Atmosphere

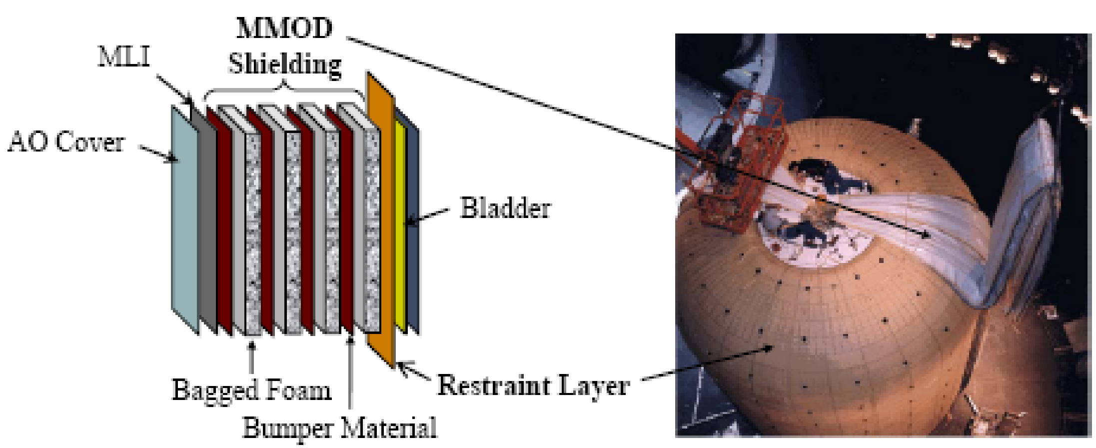
- Provide sensors for monitoring condensation, CO2 and smoke



Verification of Folding

- Folding of shell around core is done per design requirements for venting, chaffing and deployment.

- Need verification that layers of shell are in correct orientation and configuration after folding procedures



1998
TransHab
JSC Engineering Unit

2.3 General Requirements

SHM General Requirements

- Criticality (Crit 1 – loss of crew or mission, Crit 2 – loss of mission)
- Environmental Requirements (chart following page)
  - radiation, thermal, MMOD, atmosphere, particulates, other
- Mission Phase Applicability (chart following)
- Architectural Requirements
  - flexibility and modularity (ability to modify or expand existing system)
  - wireless communications
  - Embedded distributed sensors
  - robustness and redundancy
  - dual-role transducers
  - self-heal damage
  - sharing and optimization of hardware across systems
  - compatibility with the overall system, including integrate command, control and communications architecture

Table 1-2. Sample External Conditions

	Radiation (no shielding)	Thermal	MM flux (impacts/m^2/yr)	Atmosphere	Particulate Abrasion?
Lunar Surface	Total Dose: 25~10000 Rads/yr (~60 Rad/yr + SPEs)	100 to 400K	1 mm: 7×10^{-4} 5 mm: 1×10^{-6}	Hard vacuum	Yes
Lunar Subsurface	~26 mRad @ ~2m depth (equiv. Earth sea-level)	240 to 260K	N/A	Hard vacuum	Yes
Martian Surface	Total Dose: 3~12 Rads/yr [2.6~5.7 Rad/yr + SPEs]	150 to 310K	1 mm: 2×10^{-8} 5 mm: 3×10^{-10}	CO_2; 0.1atm	Yes
Martian Subsurface	Unknown	200 to 240K	N/A	—	Yes
LEO (51° incl.)	Total Dose: 60~1000 Rads/yr [50~80 Rad/yr + SPEs]	Solar: 1370 W/m^2 Planetary IR: 260 W/m^2	1 mm: 6×10^{-3} 5 mm: 4×10^{-6}	Atomic Oxygen	No

Sources:

Lunar Base Handbook, Peter Eckart.

Space Environment, Tribble, Princeton Univ Press, 1995.

Natural Environment for Space Station Design, Revision A. NASA SSP-30425/A, June 1989.

NASA TP 3300, Mars Surface Radiation Exposure for Solar Maximum Conditions and 1989 Solar Proton Events, 1993.

NASA Mars Transportation Environment TM 210935.

NASA Technical Paper 3300, Lisa C. Simonsen & John E. Nealy.

Functional Requirements vs. Mission Phases

Functional Requirement	Manufacturing	Test	Integration	Checkout & Qual.	Packaging	Installation	Launch/Ascent	LEO	Transit	Descent & Landing	Relocation	Deployment	Initial Operations	Long-term Operations	Upgrades	EOL Extension
Detect impacts and penetrations													√	√	√	√
Detect punctures, tears or leaks in bladders	√	√	√	√	√	√						√	√	√	√	√
Monitor strain around soft/hard material interfaces		√	√	√	√							√	√	√	√	√
Monitor deployment dynamics and final shape			√	√	√	√						√	√	√	√	√
Monitor creep in flexible restraint layer				√	√	√						√	√	√	√	√
Detect buckling of inflatable compression members												√	√	√	√	√
Detect cold-flow of membranes													√	√	√	√
Detect delamination and cracks	√	√	√	√								√	√	√	√	√
Detect materials and manufacturing defects	√	√	√	√								√	√	√	√	√
Monitor materials for changes and degradation													√	√	√	√
Detect condensation			√	√	√	√	√	√	√	√	√	√	√	√	√	√
Monitor thermal dynamics		√	√	√			√	√	√	√	√	√	√	√	√	√
Monitor structural static deflection, load and dynamics			√	√	√	√	√	√	√	√	√	√	√	√	√	√
Monitor mechanical functions			√	√					√	√	√	√	√	√	√	√

3.0 Implementation

SHMS Implementation

Structural Component Types – Most inflatable design concepts include both flexible and rigid elements and a wide range of materials. The following table lists most of the structures expected to be encountered in the next decade. Each has its own unique design parameters and health monitoring requirements. Different sensor and monitoring solutions will be optimal for each.

Component	Description
Outer Layers	For orbital or space-borne habitats. provide AO protection. For surface habitats provide abrasion resistance and, possibly, thermal management.
MMOD Shield	Typically either a soft or rigid multilayer coating of significant thickness (>10 cm). Number of layers depends on the environment, e.g., lunar surface requires less protection than LEO.
Thermal Insulation	Typically several layers of multi-layer insulation (MLI).
Restraint Layers	Provide mechanical support for the inner bladder(s) and define the shape of the habitat.
Bladders	Low-permeability membranes that form a gas barrier to contain the breathable atmosphere inside the habitat. Some designs have multiple bladders for redundancy.
Bleed Cloths	Used between bladders in multilayer bladder designs.
Scuff Layers	Protect the inside of the bladder from damage due to crew activity.
Rigid Components	Include window assemblies, airlocks, bulkheads, structural beams & columns, rigid shell sections.

SHMS Implementation

<u>Structural Component Types</u> – Most inflatable design concepts include both flexible and rigid elements and a wide range of materials. The following table lists most of the structures expected to be encountered in the next decade. Each has its own unique design parameters and health monitoring requirements. Different sensor and monitoring solutions will be optimal for each.

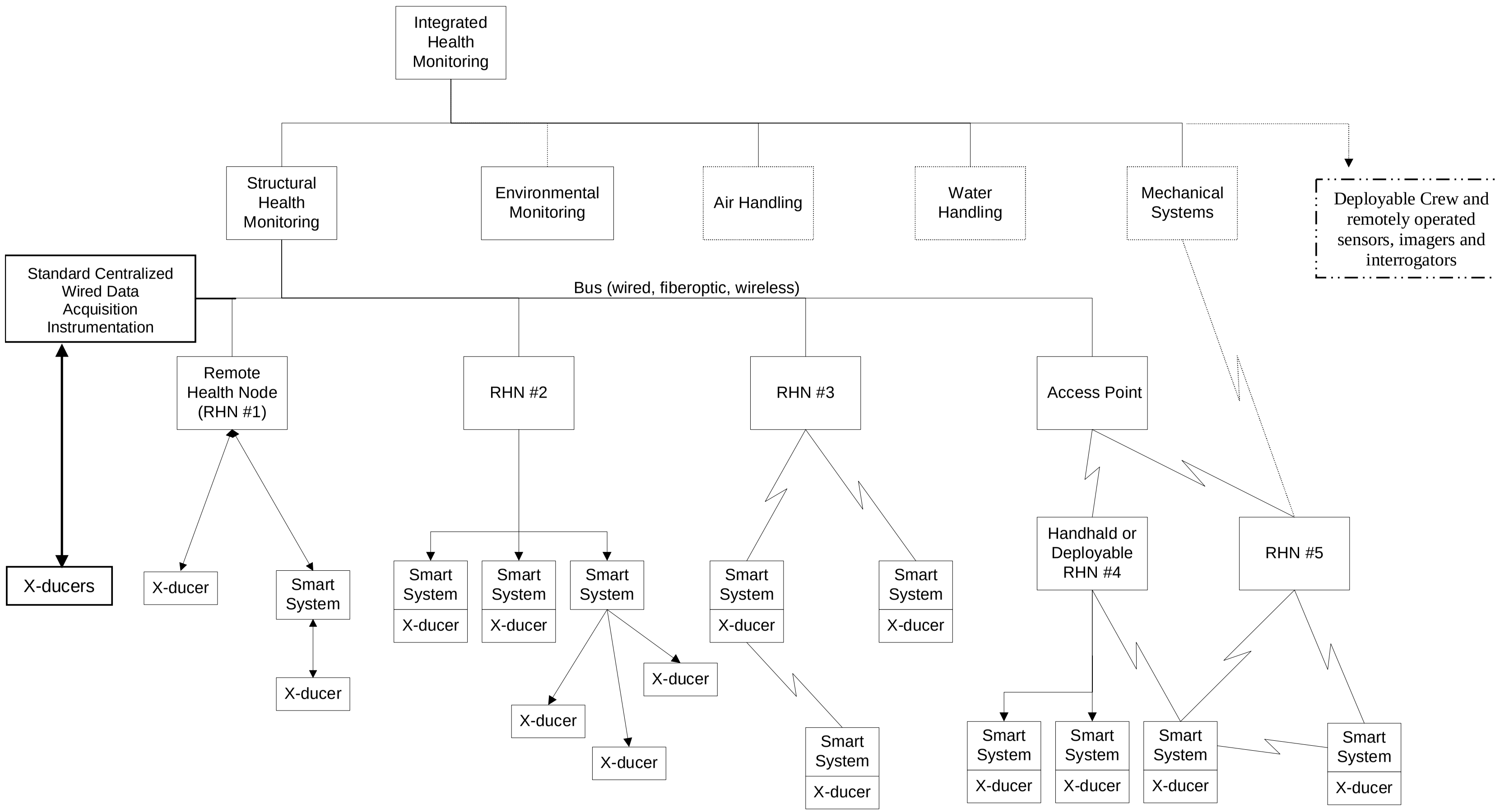
Component	Description
Outer Layers	For orbital or space-borne habitats this layer provides AO protection. For surface habitats it provides abrasion resistance and possibly thermal management.
MMOD Shield	This is typically either a soft or rigid multilayer coating of significant thickness (>10 cm). The number of layers depends on the environment: the lunar surface requires less protection than LEO.
Thermal Insulation	Typically several layers of multi-layer insulation (MLI).
Restraint Layers	This provides mechanical support for the inner bladder(s) and defines the shape of the habitat.
Bladders	The low-permeability membrane that forms a gas barrier to contain the breathable atmosphere inside the habitat. Some designs have multiple bladders for redundancy.
Bleed Cloths	Used between bladders in multilayer bladder designs.
Scuff Layers	Protects the inside of the bladder from damage due to crew activity.
Rigid Components	Includes window assemblies, airlocks, bulkheads, structural beams & columns, rigid shells sections

SHMS Implementation

System Architecture (figure following page)

- Unique Challenges for Inflatable/Deployable Structures
  - Large flexible regions of multiple layers
  - providing power and obtaining data from a large number of widely spaced sensors
  - flexible sensors that must match their respective substrates to minimize strain
- The Balance between Centralization and Decentralization
- Distributed Sensing
- Initial Data Acquisition and Networking Architecture
- Sensors and Actuators
  - individually wired into an electrical system
  - Multiplexed through analog switches
  - Interfaced via radio frequency interrogation (RFID)
- Data Acquisition

Conceptual SHMS Architecture



Conceptual Hybrid SHMS Architecture for Future Space Habitats

(Centralized and Decentralized)

(Wired and Wireless)

(Standard Sensors and Smart Systems)

SHMS Implementation

System Architecture (cont)

- Data Processing and Storage
  - Data-dependent Acquisition or Transmission
    - a) time based
    - b) primary data channel
    - c) Auxiliary data channels
    - d) On-demand
  - Data reduction and Sensor Fusion
  - Time synchronization (absolute and relative)
  - Notification and Reporting
  - Integration and Synergy with Other Habitat
  - Smart Systems

SHMS Implementation

- Data processing and storage
  - <u>data communications</u>
    - a) wired network sensors/actuators
    - b) power line communications
    - c) wireless networked sensors/actuators
      - Advantages of wireless:
        - 1) safety and reliability
        - 2) life-cycle costs
        - 3) performance
  - <u>power requirements</u>
    - traditional power distribution
      - low-voltage power
      - local energy storage
      - wires or existing metallic structure or layers within habitat shell
    - non-rechargeable batteries – Beta-voltaic
    - scavenging concepts
      - thermal differentials or solar sources
      - remote power distribution – RF or laser sources
      - instantaneous power - impact

4.0 Summary

SHMS Summary

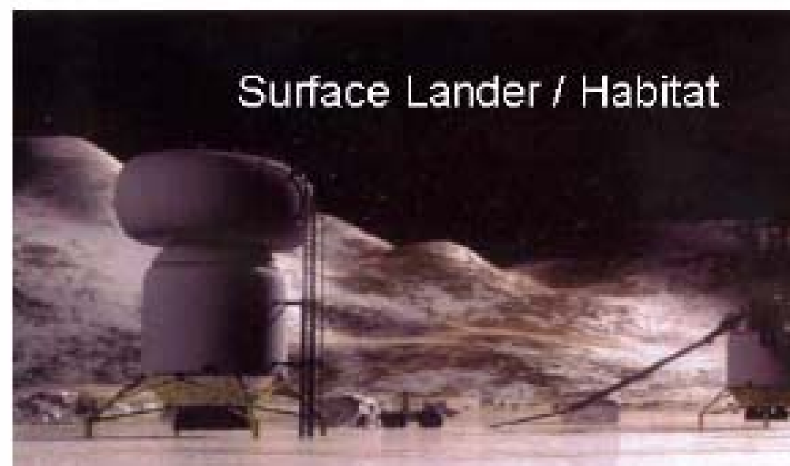
- Inflatable Structures offer significant advantages for crew habitats
- However they present unique challenges to implementing a Structural Health Monitoring System (SHMS)
  - large flexible structures of multiple layers
  - powering and obtaining data from large number of sensors
  - flexible materials are more sensitive to inclusion of sensors
- Wireless Systems using ultra-low-power and no-power sensors alleviates these problems
- NASA is leading effort to define high level SHMS objectives and requirements
- Commercial developers of inflatable structures are likely to implement SHMS on flight vehicles in the near term

The Future


Space Station Module


Space Station


Transit Module


Surface Lander / Habitat

5.0 Contributors

Contributors

Text and Tables:

"Structural Health System Technologies for Inflatable/Deployable Space Vehicles", Sept.24, 2006, Chapter 1 – "Introductions and Needs Analysis"; Erik J. Brandon, Max Vozoff, Tony Paris (JPL), George Studor (JSC), et.al.

Pictures:

- *NASA Inflatable Structures* – grin.hq.nasa.gov, nasa.gov
- *Genesis I* – bigelowaerospace.com
- *TransHab Concept* – ocw.mit.edu
- *Inflatable Shell Overview* – ocw.mit.edu
- *Implementation of Wireless SHMS* – 2000 AIAA Space Infalatables
- *Impact Detection* – AIAA Space Architecture 2002, hitf.jsc.nasa.gov
- *Verification of Folding* – ntrs.nasa.gov
- *The Future* – ntrs.nasa.gov