Wireless Applications for Structural Monitoring of Inflatable Habitats

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March 27th 2007
Structural Health Management System (SHMS)

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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
- Inflatable 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

- core
- Inflation tanks
- airlock
- Flexible shell
Multi-Layer Inflatable Shell Overview

- External Thermal Blanket
- Internal Scuff Barrier
- Kevlar Restraint Layer
- MOD Shielding
- Redundant Bladders
Inflatable Advantages

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

  1) **High volume-to-mass ratio** – 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) **High packing efficiency** – Inflatable/deployable structures provide for a more flexible launch manifest, whereby the structure can be designed more efficiently around the launch vehicle.

  3) **Minimal need for on-site construction materials** – With these unique habitats, virtually all of the assembly mechanism is inherent to the structure (although lunar regolith maybe added for more protection)

  4) **Fewer secondary radiation effects** – 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

- **Wireless Leak Monitoring System** (temporarily deployed near hatch)
- **C/E: Ultrasonic Leak Locator/Repair Kit**
- **C/E: Infrared Digital Camera**
- **Impact Area Detection Antennas**
- **Metalized flexible mat for Lunar Dust and Condensation Detection with Millimeter Wave Radar Imager**
- **Wireless Instrumentation Nodes**
- **Wireless Crew & Crew Equipment Network: Audio, Video, Data, Position**
- **RFID Interrogator for Passive Sensors**
- **Wireless Accelerometers and/or AE for Impact Location & Dynamic Models**
- **Wireless Humidity Sensors**
  - Bathroom Floor, plumbing and water tank leaks
- **Passive RFID Tags for Configuration, Location, Sensing: Shell Temps, Impact Shock, Foam Bag Pressures, etc**
- **Multifunctional MLI for EMI and Passive Damage Interrogation**
- **Conductive Material Patterns for damage NDE after MMOD hit using Multispectral imager tool.**
- **Window: Wireless Pressure, Strain, Cover position**
- **Wireless Crew & Crew Equipment Network: Audio, Video, Data, Position**
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)
#3 *Provide Multi-Role Integrated System Functionality*

- 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 notification of impacts and penetrations to the exterior of inflatable habitats, including event time, location, depth of penetration and extent of resulting damage.
Leaks in Bladder

- The SHMS shall detect punctures, tears and leaks in bladder prior to being manned:
  - 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

- 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 (CO2, 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.
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

<table>
<thead>
<tr>
<th>Location</th>
<th>Radiation (no shielding)</th>
<th>Thermal</th>
<th>MM flux (impacts/m²/yr)</th>
<th>Atmosphere</th>
<th>Particulate Abrasion?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar Surface</td>
<td>Total Dose: 25~10000 Rads/yr (~60 Rad/yr + SPEs)</td>
<td>100 to 400K</td>
<td>1 mm: 7×10⁻⁴ 5 mm: 1×10⁻⁶</td>
<td>Hard vacuum</td>
<td>Yes</td>
</tr>
<tr>
<td>Lunar Subsurface</td>
<td>~26 mRad @ ~2m depth (equiv. Earth sea-level)</td>
<td>240 to 260K</td>
<td>N/A</td>
<td>Hard vacuum</td>
<td>Yes</td>
</tr>
<tr>
<td>Martian Surface</td>
<td>Total Dose: 3<del>12 Rads/yr [2.6</del>5.7 Rad/yr + SPEs]</td>
<td>150 to 310K</td>
<td>1 mm: 2×10⁻⁸ 5 mm: 3×10⁻¹⁰</td>
<td>CO₂; 0.1atm</td>
<td>Yes</td>
</tr>
<tr>
<td>Martian Subsurface</td>
<td>Unknown</td>
<td>200 to 240K</td>
<td>N/A</td>
<td>—</td>
<td>Yes</td>
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<tr>
<td>LEO (51° incl.)</td>
<td>Total Dose: 60<del>1000 Rads/yr [50</del>80 Rad/yr + SPEs]</td>
<td>Solar: 1370 W/m²  Planetary IR: 260 W/m²</td>
<td>1 mm: 6×10⁻³ 5 mm: 4×10⁻⁶</td>
<td>Atomic Oxygen</td>
<td>No</td>
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</tbody>
</table>

Sources:
- NASA Mars Transportation Environment TM 210935.
# Functional Requirements vs. Mission Phases

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<td>Detect punctures, tears or leaks in bladders</td>
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<td>Monitor strain around soft/hard material interfaces</td>
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<td>Monitor deployment dynamics and final shape</td>
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<td>Monitor creep in flexible restraint layer</td>
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<td>Detect buckling of inflatable compression members</td>
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<td>Detect cold-flow of membranes</td>
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<td>Monitor thermal dynamics</td>
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<td>Monitor structural static deflection, load and dynamics</td>
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<td>Monitor mechanical functions</td>
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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.

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

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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
  - data communications
    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
  - power requirements
    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:

Pictures:
• NASA Inflatable Structures – grin.hq.nasa.gov, nasa.gov
• Genesis I – bigelow aerospace.com
• TransHab Concept – ocw.mit.edu
• Inflatable Shell Overview – ocw.mit.edu
• Implementation of Wireless SHMS – 2000 AIAA Space Infalatables
• Verification of Folding – ntrs.nasa.gov
• The Future – ntrs.nasa.gov