In-Space Inspection Technologies
Vision

Workshop Session 1 and 4

JSC/ES2/George Studor
Feb 29, 2012
Motivation

• **Apollo 13** – couldn’t see the damage
  “Houston, we’ve got a problem”
  after the SM was released...
  "There's one whole side of that spacecraft missing“

• **MIR Spectre** damaged by Progress –
  24 minutes to find/plug leak before
  having to shut the hatch.
  [YouTube Video](http://www.youtube.com/watch?v=88XS2G7xRxg)

• **Columbia** – suspected impact to Wing
  Leading Edge, no sensors or good
  inspection options.
  “AF ground cameras see damage 60 sec. before the vehicle broke up over Texas”
In-Space Non Destructive Inspection Technology Workshop

Purpose:
• Assess In-Space NDE technologies and needs - current & future spacecraft.
• Discover & build on needs, R&D & NDE products in other industries and agencies.
• Stimulate partnerships in & outside NASA to move technologies forward cooperatively.
• Facilitate group discussion on challenges and opportunities of mutual benefit.

Focus Areas:
• Miniaturized 3D Penetrating Imagers
• Controllable Snake-arm Inspection systems
• Miniature Free-flying Micro-satellite Inspectors

Agenda:
Feb 29
• Session 1: Vision/Background
• Session 2 & Lunch – End-User Needs
• Session 3 & 4 - Technology Developers(3 Tracks)
Mar 1
• Session 5 & 6 & Lunch – End-User Needs
• Session 7 – One-on-One Sessions with End-User at Individual Tables
  - Sign-up Sheets at Reception Desk
• Session 8 – Forward Planning Sessions - Discussion Groups – Leaders to be assigned

Webex/Telecon Available – send email request to:  i.h.batchelder@nasa.gov
Today’s Situation

• ISS to maintain and extend life to 2025 or 2028?
  – Existing Risks, Challenges and Inefficiencies
  – “Blind” Spots - Crew Time
  – IVA Access - EVA Resources
  – Visiting Vehicles - Unknowns

• New breed of Commercial Crewed Vehicles.
  – Efficiency and Safety
  – Experience with MMOD and Re-Entry Systems
  – Inspection Responsibilities/Capabilities

• New Missions Being Defined
  – Satellite Servicing
  – Human Exploration Destinations beyond low-Earth Orbit

• Technology Demos supporting next gen manned space vehicles.
  – Need for Autonomy - Robotic Inspections
  – Reduced Crew Time - No EVA required
  – Eliminate the Blind Spots - New Technologies
In-Space Inspection
What’s the Problem?

Biggest Risks That Demand Inspections:
- Crew Time for Imagery Support for EVA and Robotic Planning and Operations
- MMOD Impact Damage Inspection
  - Pressurized Modules, Primary Systems, ORUs, Window, Re-entry TPS, etc.
- System Trouble-shooting, Mechanisms like BGA, Leaks and Corrosion

Challenges to Getting Inspections Done:
- Limited Requirements agreed to – we only buy/fly what we can prove we need ahead of time.
- Limited Inspection Tools ready for in-space use on ISS – None planned for stand-alone vehicles.
- Limited Budget to develop/fly new inspection tools
- Limited Crew Time to operate tools/manipulators – planned/emerg.
- Limited Access – internally and externally
- Limited Line-of-Sight Views - ISS cameras don’t cover the entire vehicle, resolution limited
- Limited Resources for EVA – limited resupply of consumables
- Limited Vehicle Communications (IVA & EVA) and Down-link of inspection results
- Limited Life for ISS Components – inspections to understand remaining life
- Limited Crew Training Options – equipment can require too much interpretation
- Limited Ability to Interpret Results In-Space - Dependency on Ground Engineering Support
- Zero-G Limitations on use of both hands, securing/manipulating inspection equipment
- Limited MMOD Shielding in certain areas – configuration upgrades in work, require EVA time
- Increasing MMOD Debris in LEO (Low Earth Orbit)
In-space NDE Inspection System for MMOD Damage

The Problem

MMOD Impact Damage Threat

International Space Station
- Pressurized Modules
- External Systems
- Hi Priority Spares
- COPVS

New Commercial Crewed Spacecraft
- TPS/supporting structure
  - Pressurized Module

Inflatable Module Technology
- Load-bearing Fabric Layer
  - Leaks to Bladder
ISS Impact (IVA Inspection)
What is the damage to the Pressure Wall?

Zarya Impact in 2007

US Lab
Aluminum
Outer
MMOD Shield

Nextel and Kevlar shield Layers

Aluminum Plate sample of MMOD-like damage to outer side of ISS pressurized module.
ISS Module

- Whipple shield for MMOD
- Thermal blanket
- Pressure vessel
International Space Station as a Proving Ground for Future Manned Spacecraft

Current: LEO
- Mostly Crew
- Autonomous Systems

Future: Exo-LEO
- Robotic Auto, Dextrous, Mobile
- Insp Sys/Robotic - Remote Control
- Crew Inspections

Autonomy-driven Inspection Priorities:
1. Mostly Crew
2. None
3. Robotic Manipulator
4. Autonomous Systems

International Participation
- Language/Culture: Unique, Unique, Real-time Translation
- Tools, Cert, Procedures, Trng: Unique/Intense, Common/Intl Sources

Interior Volume Inspection
- Accessibility: US Module Racks Design, No ISS-like racks
- Russian Module Design: Highly packed, but modular
- IVA NDE: Aluminum wall damage/repair, Comp., Inflatable, Multi-func.
Location, Corrosion, SHM/IVHM events/indicators
- Req Prelaunch In-space Inspections

Exterior Inspection
- Windows+EVA+Remote Cameras, Mobile platforms + Modular
- Accepted Risks, Req. Prelaunch In-Space Inspections
Technology Efforts

• **ISS IVA tools** – Videoscope, IR Camera, Russian BAR set

• **ISS Leak Detection & Repair Team** – Ultrasonic Hand-held Leak Locator. Working on contact sensors for module wall inspections

• **NESC NDE TDT and NASA NDE Working Group** – Various Projects

• **NASA SBIR Subtopic:**
  
  X5.03 Spaceflight Structural Sensor Systems and NDE
  

• **Penetrating Inspector Technology Quests:** “In-Space Inspection Sensors Look Through Conductive Material to Target Surface”
  
  – MMOD Impacted Test articles circulated to industry
  
  – DeVenci Challenge – June 2011
  
  – NASA@Work Challenge – July 2011
    
    [https://nasa.innocentive.com/ici/challenge/show/1053](https://nasa.innocentive.com/ici/challenge/show/1053)
  
  – NASA Tech Needs: July 2011
    
    [http://www.techbriefs.com/component/content/article/article/10507](http://www.techbriefs.com/component/content/article/article/10507)

• **National Research Council** assessment of priorities includes:
  
  Smart Habitats (Section 7.4.3), Nanoscale Sensors and Actuators(Section 10.4.1), Autonomous Inspection(Section 12.5.1), TPS Repair(Section 14)

• **Survey of ISS Risks, Challenges and Inefficiencies (not Requirements)**
Example ISS Needs, Risks, Challenges, and Inefficiencies

High MMOD Risks:

- **Highest risk operational components and External Spares (70)**
  - Holes in MLI (often with Alumuminized layers) are the only visual clues
- **Module Leak Location and Repair** – MMOD penetration of pressurized module
- **Thermal Protection Tile/Heatshields** to visiting vehicles
  - Damage could be deeper/more extensive than are visible with cameras
- **Windows** – especially the most vulnerable windows
  - Damage to the outer pane is difficult to quantify
- **Robotic Manipulators - SSRMS/MBS/SPDM**
  - composite boom, avionics, external spares
- **Solar Array Mast** – guide-wires, holes, tears
- **Radiators** - PV and TCS Active Thermal Control
- **Commercial Crew Vehicle Integrity**

MMOD Environments – Models

- **Inspections** to determine actual trends – size, density, direction
MMOD Impacts to ISS (Examples)

- Trailing Umbilical System for Mobile Transporter - 11 Impacts
- S-Band Antenna Support Assembly - 71 Impacts
- EVA Handrail Impacts - sharp edges
- FGB Thermal Blanket
- Node 1 Port Common Berthing Mechanism Cover
MMOD Impacts to ISS (Examples)

MMOD Damage to Windows | P6 Photo-Voltaic Radiator

S-Band Antenna Impact
MMOD Impacts to ISS (Examples)
Radiator Damage from MMOD
MMOD Impacts to ISS (Examples)
Solar Array Mast Guide Wire Damage from MMOD:
Example ISS Needs, Risks, Challenges, and Inefficiencies

Operations - ISS-based External Inspection Optical Cameras:

• Incomplete Viewing from Windows and Robotic Manipulators
  - Fill in Blind-Spots and areas with Insufficient Resolution

• Replace Shuttle fly-around
  - General ISS periodic inspection
  - Public Awareness/Interest for PAO use

• EVA Translation Path Planning to avoid cut gloves from sharp edges
  - Determine which of the 90 potential damage sites to avoid during EVA are actually sharp-edge damage?
  - Determine if more damage has happened prior to each EVA.

• ISS Camera Upgrade Capability:
  - Better resolution, Stereo vision/depth
  - Camera capability and maintainability until end-of-program

• Reduce Robotics tasks for docking/berthing surface Inspections:
  - Inspection of surfaces prior to mating
Example ISS Needs, Risks, Challenges, and Inefficiencies

**Structural Dynamic Measurements** - General assistance with photogrammetry

**Suspected Damage:** Loaded Array Power Generation Degradation - why?
- TARJ, Solar Array mast degradation

**Previous Damage:**
- P1/S1 Radiator Face Sheet damage bulges (related to MMOD?)
- SARJ Grease - port side has cover off - 10’dia rotates in 90 min
- Solar Array Blanket Damage P6 SA Radiator Deploy 2B/4B
- 2B initial deploy lost one string - where? Why?
- SSRMS composite boom - MMOD impact to MLI

**Thermal Imagery:**
- Heat pipe anomalies - S0, Z1 ORUs, MDMs on PMA1
- Avoiding EVAs to obtain good images for troubleshooting

**Quick Response:**
- Module Leak Location and Repair
- SARJ not working – contamination
- FGB Blanket MMOD Impact near Compressor Pump Module
- MMOD impact/High Risk ORUs (Batteries, various elect boxes)
- Avionics: External Antennas, Communication & Power lines
- External Experiments and Payloads: AMS,
Example ISS Needs, Risks, Challenges, and Inefficiencies

Reality May Not Agree with our Perception
US Laboratory

“Just Rotate the Rack and get Easy Access”

Initial Configuration                     Typical Operations

Current Inspection Tools (US)

- IR Camera
- Fiberscope
- Ultrasonic Leak Detector - Locator
Internal Issues for Inspections:

**US Module design** – because of rack design, generally good access (70%) except
- Stowage can be in the way
- Crew time to rotate racks can be 2 hours
- Standoff-areas and end cones
- Some issues (e.g. module leak) could reduce risk (time) with better IVA tools:
  - Improve Ultrasonic Leak Detector adapters
  - Full-length Controllable Stereo View Endoscopes
    - see desired technology functionality chart
  - Access NDE inspection after leak plug has been installed
  - Many system people trouble-shoot without knowing that the on-board inspection tools we do have may be able to help them...

**Russian Modules** – divided responsibility
- Limited Access (70%) panels to remove,
- Module susceptibility to condensation
- Some IVA tools already, but limited access/understanding on US side
Example ISS Needs, Risks, Challenges, and Inefficiencies

ISS External Inspection Challenges

- EVA/Robotics – no time for dedicated surveys
- ISS Fixed Cameras + Windows – limited line-of-sight, resolution issues
- ISS Robotics – Planning joint angles/operations, Moving the manipulator to inspection location, Viewing and resolution still may not be sufficient
- Hole in Thermal Blanket not really indicative of damage underneath… Boeing not worried about holes smaller that 1/8\textsuperscript{th} inch dia.
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In-Space Non Destructive Inspection Workshop
3 Primary Focus Areas

- **Penetrating 3D Sensors:**
  - ISS Pressure Wall (IVA - look from inside – out)
  - TPS tile & backshell substructure (EVA)
  - Metalized MLI blankets that protect numerous systems
  - Composite Pressure Vessels

- **Serpentine Inspection Robots:**
  - Zero-G Derivative of 1-G systems
  - Internal Inspections in poor access situations – behind racks and panels and utility areas
  - External Inspections – MMOD damage holes, exterior Surveys, Satellite Servicing/Phoenix Missions
  - Apply Biomemetics to understand design goals
  - Stimulate other Agency/Industry – Developer – University relationships

- **Free-Flyer Inspection:**
  - Planned (after deployments and prior to starting back to Earth) and Unplanned (Anomalies)
  - Aerospace Aerocube4 Capability + SPHERES Testbed + Mini-Aercam lessons learned
  - Autonomous Inspection Functionality
  - Active “Doghouse” provides cubesat inspector with power, comm, nav, deploy-retrieve
  - Upgradable Camera for use as Robotic manipulator Inspection (Aerocube better than current)
  - Deploy-return in free-flyer mode along line-of-sight path from doghouse
  - On ISS demo - Return to IVA servicing through JEM airlock
In-Space Inspection Sensors Look Through Conductive Material to Target Surface

By George Studor and Ajay Koshti, Johnson Space Center, Houston, TX
Friday, July 01 2011
http://www.techbriefs.com/component/content/article/10507

NASA needs a sensor system to characterize damage from Micro-meteoroid and Orbital Debris (MMOD), corrosion, or to perform configuration verification when there is a conductive surface in between the sensor and the site. The in-space system(s) will need to look from the inside (IVA) out or from the outside (EVA) in for both existing and future to-be-designed vehicles. The ground versions will be very useful for ground inspection purposes in areas of vehicles that are “closed out,” or areas with limited access behind conductive structures. The damage includes, but is not limited to, deformations, penetrations, fractures, cracks, corrosion, and disbonds.

Requirements and Goals:
• Product: 3D image/data after minutes of on-board post-processing, with no down-link required.
• Scan area of $5 \times 5"$.
• Resolution of 1 mm in any dimension, with no practical limit on the time to obtain the image.
• Depth of field must be adjustable based on the need.
• The distance to the object must be adjustable from 1 m to 1 cm.
• Must meet or exceed ANSI/OSHA standards.
• Near real-time feedback of video image and depth of penetration.
• Calibration: must be able to have certified resolution and accuracy via NDE standards.
• Motion compensation is as needed based on handheld or robotic manipulator motion when attempting to provide a still platform in order to obtain the required resolution.
3D Penetrating Imager – July ‘11 NASA Tech Need

MMOD damage to the ISS pressurized module exterior wall
• Sensor needs to look from inside out.
• Time to acquire high res image – up to 20 minutes
• Single-sided, illumination source & sensor on the same side.
• Interior or exterior operations could be two different systems.
• Range - 1 m to 1 cm (goal), physical contact may be allowed.
• Single unit, with few internal or no moving parts (goal).
• The size, weight, and power would be less than
  1 cubic foot, 40 pounds, and 10W (goal)
• It should be portable or handheld
• Min interfaces: power, data processing, displays, controls
  human operator complexity and comm (less wires/wireless).

Aluminum plate MMOD damage (exterior side)

MMOD damage to re-entry tile and substructure
• Sensor needs to look from outside in.
• Low maintenance and costs with minimal or no servicing.
• The materials to see through, and materials containing the
  feature of interest include see-through aluminum, composite,
  thermal protection materials such as low-density silica tile,
  and rubber (RTV to the material and multi-layer insulation).
• Materials are consistent in each layer, but
  different materials may be present in each layer.
• Damage is usually in low- or medium-density material.
• Material doping may be allowed to enhance (NDE) results
  for future vehicles only.

MMOD damage to tile, RTV bond, face plate and honeycomb (side view)
Hypervelocity Impacts to Sample Re-entry Tile Entry Holes and X-ray CT Images
Why Snake-arm Robot?

Internal Inspections:
• Access for inspection can be limited, sometimes not possible.
• Access takes crew time and/or EVA and robotics time.
• Zero-g helps controllable snakes get where we need them to.
• Avoid Hazards – needs to be practical & verifiable before start.
• Coiled snake can have less volume.

External Inspections:
• Holes in MMOD Shields and Thermal blankets
• Getting under shields and blankets from the side
• Spacecraft surveys – uncoil/coil
• Additional Viewing angles for robotic operations(servicing)
What do we need Snake Inspector to do?
Internal Functionality

1. **Stereo vision and articulating head** with lighting, designed in stiffness at various sections along the length
2. **SLAM - Simultaneous Location and Modeling Software** - builds the 3d model as it goes in and subsequently determines position and orientation of all parts very accurately.
3. **Articulating snake robot** - mechanical or piezo-control of the entire snake length - not just the tip as in a typical endoscope. Sensors that sense contact and feed controls to alleviate it.
4. **Snake real-time location** - know/display the location of the entire snake - plot against accurate 3D model built in #1.
5. **Self-following Software** - each segment of the snake knows where and how to turn as it follows the head or backs out of a complex physical path.
6. **Very small size, weight and power and works well Zero-g** (assumed)
7. **Length of at least 2 meters and diameter 3/8" or less** – go through existing penetrations such as the holes for sending fire extinguishing
8. **Minimum crew involvement/training** - easy to use, hands-free, possibly remotely operated from ground.
9. **Ability to change imagers at the end, and/or add sensors/wireless sensors at the tip.**
10. Ability to **grab items at the tip.**
Role of Biomemetics: “Snake-arm” like Monkey’s tail, Elephant’s trunk, Octopus tenacle, Snail’s eye

• Continuous backbone structure with flexibility and control.
  – Joints are coupled – causing complexities.
• Conform around objects without required to touch them.
• Grasp an object with the body.
• Control for balance purposes.
• Exact tip position, orientation and control.
• Full body position, orientation and control.
• Skin with sense of touch/pressure along the entire body.
• Tip with stereo eyes for depth and redundancy.
• Must account for gravity or neutral buoyancy when in water.
PSSC2 STS
AeroCube
Aug '12
10cm cube < 1 kg

SPHERES Test Bed
Magnetic Field Control

NASA Min-Aercam Prototype

Autonomous Inspection Demo
- Survey to identify Potential Damage Sites
- Identify sites that are real damage
- Identify sites for Focused Inspection
- Obtain/Report Focused Inspection results
- Determine remaining uncertainties

AeroCube 4

Cube Sat Test Bed Flight Demo
Commanded Survey Of Upper Stage

AFRL XSS-10 (28Kg)
Survey Delta Upper Stage

Cube Sat Flight Demo Autonomous Survey Of Upper Stage
- Active “Doghouse”
- Retrieve/Download

Studor Free-flying Inspector Vision...
Lessons Learned from Mini-Aercam
Proto-types include Auto Inspect & Doghouse

NASA Tech Demo
FF Inspector

Cube Sat Active “Doghouse”
(A Single Cube Active “PeaPod”)
- Power, Comm, Nav, Thermal
- Sensors Active while mated
- Active Deploy and Retrieve
- Powered Grapple Interface or Installed at OML
Robotic Inspection Crawlers

• Electro-Static Adhesion
  – Outside on Spacecraft Surface
  – Inside on “safe” areas

• Gecko-foot Bio-memetic materials
  – EVA or IVA
  – Passive Temporary Attachment without Velcro
  – Active “Velcro” Attach/Detach

Benefits to InSpace Inspection:
Free up Astronaut hands in Zero-G for inspection
  - provide on-demand, anywhere attachment
  - better use of crew time!
Allows Robot Inspectors to Crawl on surfaces
Reduce Velcro in future spacecraft – fibers contaminate the air