

In-Space Inspection Technologies Vision

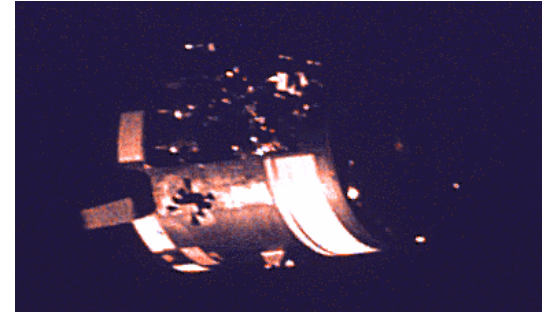
Workshop Session 1 and 4

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.
<http://www.youtube.com/watch?v=88XS2G7xRxg>
- Columbia – suspected impact to Wing
Leading Edge, no sensors or good
inspection options.



Sorry,
No Photo Available

"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

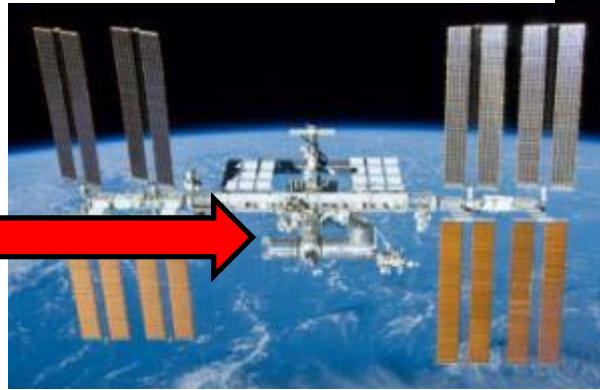
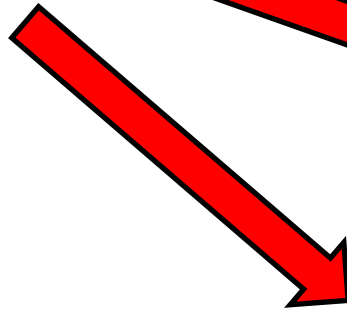
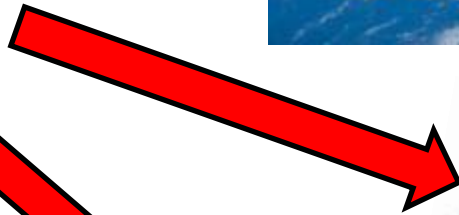
Challenges to Getting Inspections Done:

- 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**



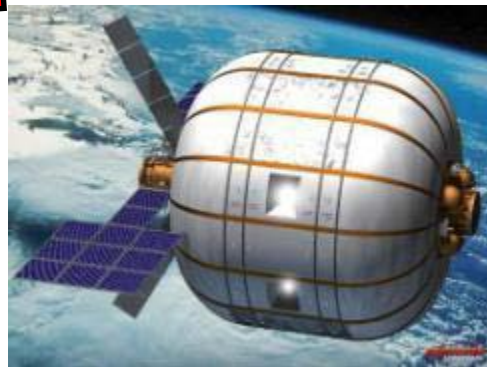
International Space Station

- 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)

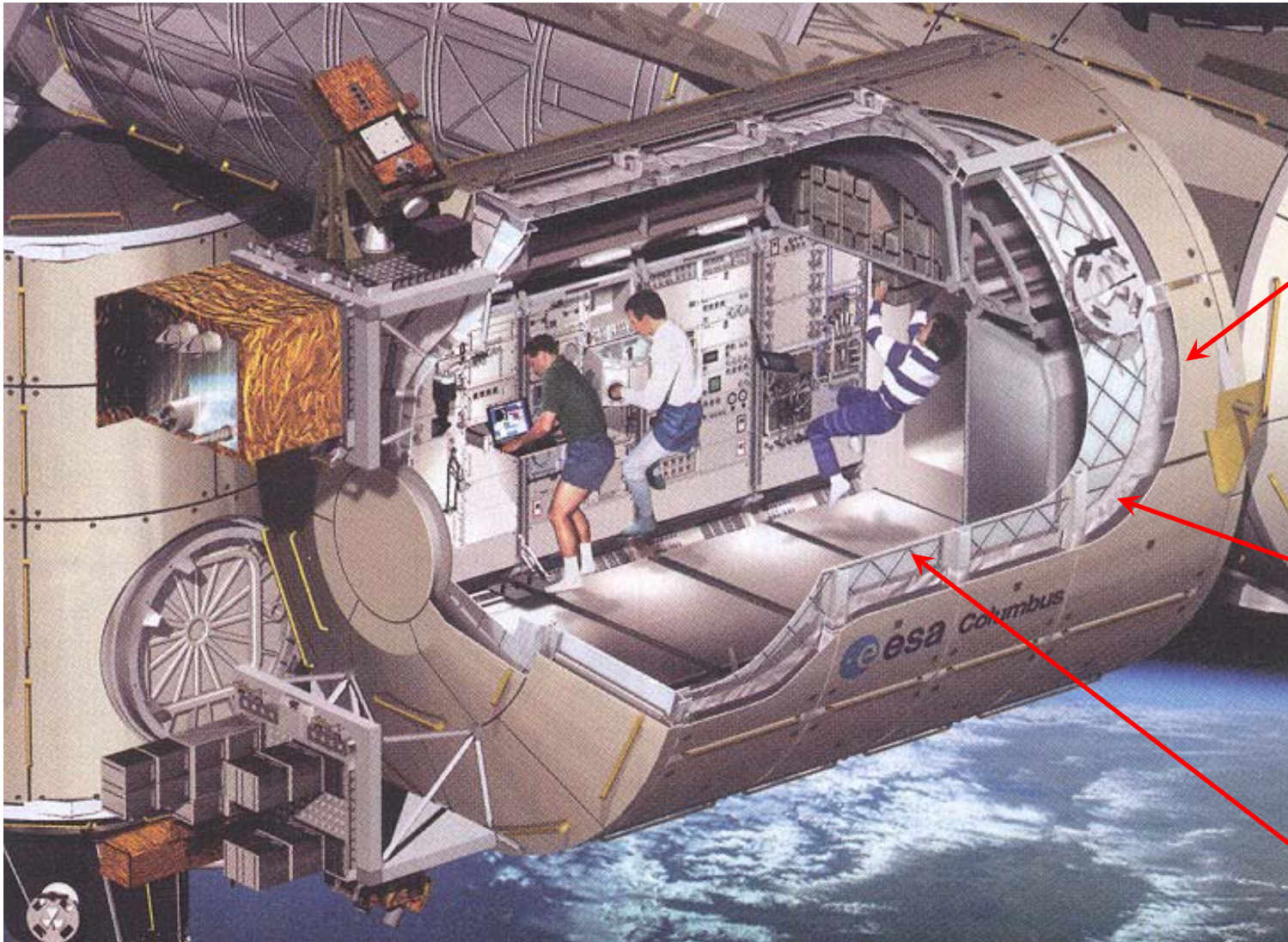
What is the damage to the Pressure Wall?



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

Nextel and Kevlar shield Layers

ISS Module



Whipple shield for MMOD

thermal blanket

Pressure vessel

International Space Station as a Proving Ground for Future Manned Spacecraft

	<u>Current:</u>	<u>Future:</u>
	LEO	Exo-LEO
Autonomy-driven Inspection Priorities:	1 Mostly Crew	Autonomous Systems
	2 None	Robotic Auto, Dextrous, Mobile
	3 Robotic Manipulator	Insp Sys/Robotic - Remote Control
	4 Autonomous Systems	Crew Inspections
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 Russian Module Design	No ISS-like racks Highly packed, but modular
- IVA NDE	Aluminum wall damage/repair Location, Corrosion	Comp., Inflatable, Multi-func. SHM/IVHM events/indicators
		Req Prelaunch In-space Inspections
Exterior Inspection	Windows+EVA+Remote Cameras Accepted Risks	Mobile platforms + Modular 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
 - http://sbir.nasa.gov/SBIR/sbirsttr2010/solicitation/SBIR/TOPIC_X5.html
- **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>
 - NASA Tech Needs: July 2011
 - <http://www.techbriefs.com/component/content/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:

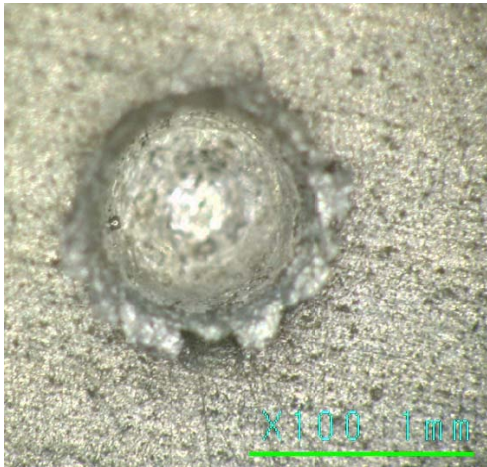
- **Highest risk operational components and External Spares(70)**
 - Holes in MLI (often with Alumuminized layers) are the only visual clues
- **Module Leak Location and Repair** – MMOD penetration of pressurized module
- **Thermal Protection Tile/Heatshields** to visiting vehicles
 - Damage could be 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

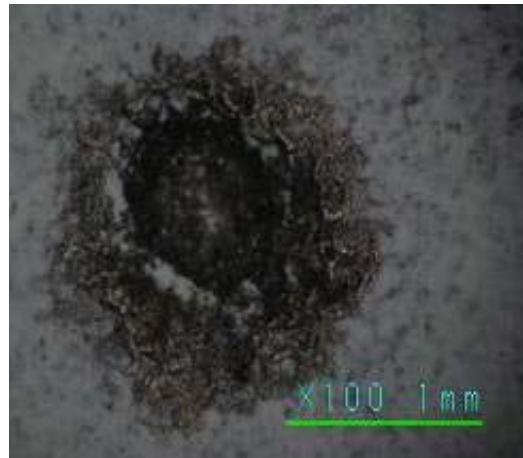
- **Inspections** to determine actual trends – size, density, direction

MMOD Impacts to ISS (Examples)

**Trailing Umbilical System
for Mobile Transporter
- 11 Impacts**



**S-Band Antenna
Support Assembly
- 71 Impacts**



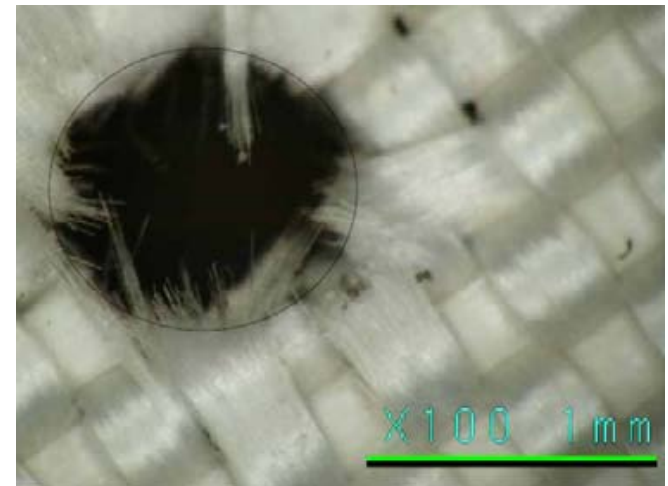
FGB Thermal Blanket



EVA Handrail Impacts - sharp edges



**Node 1 Port
Common Berthing Mechanism Cover**



MMOD Impacts to ISS (Examples)

MMOD Damage to Windows



S-Band Antenna Impact

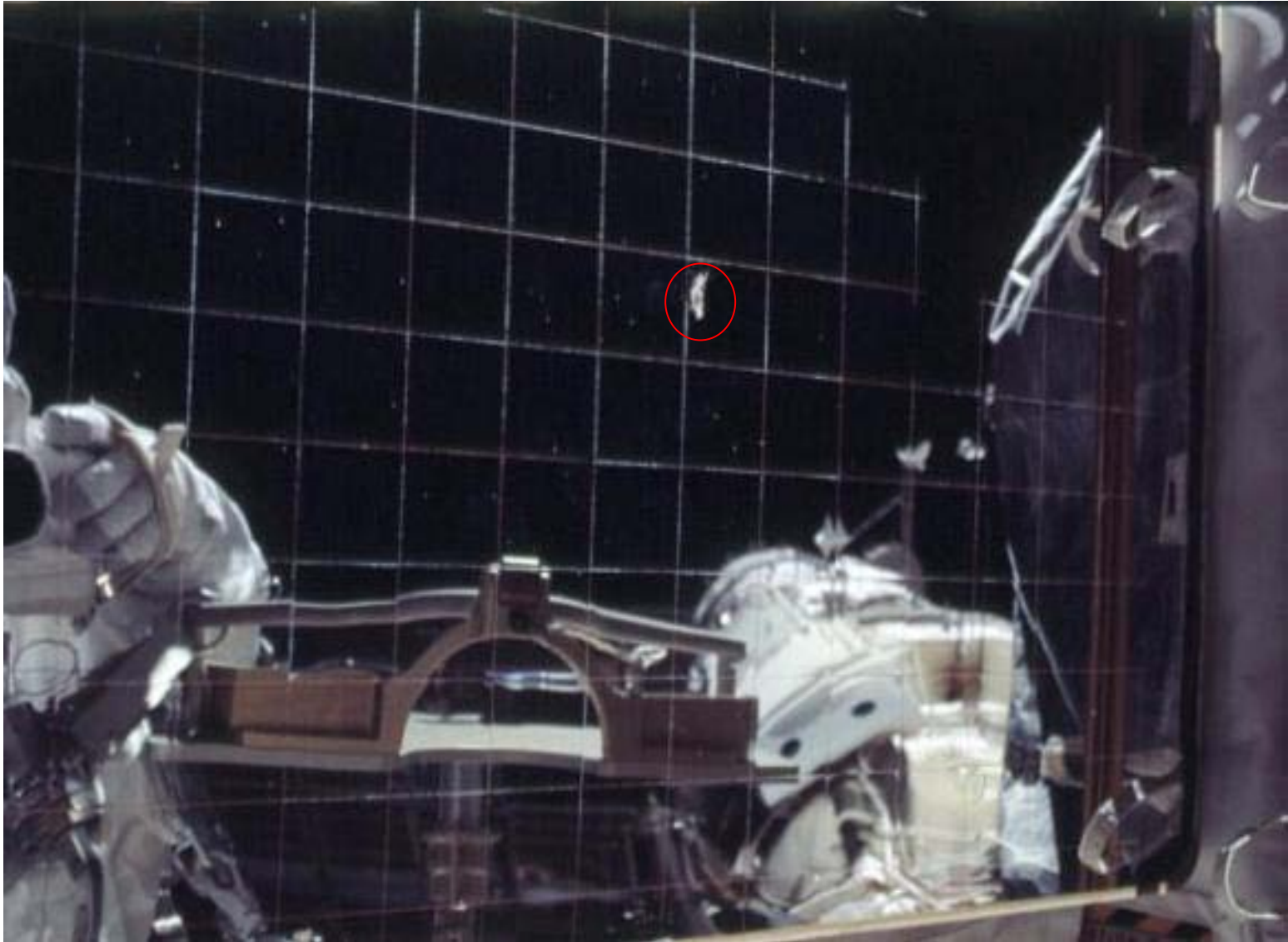


P6 Photo-Voltaic Radiator



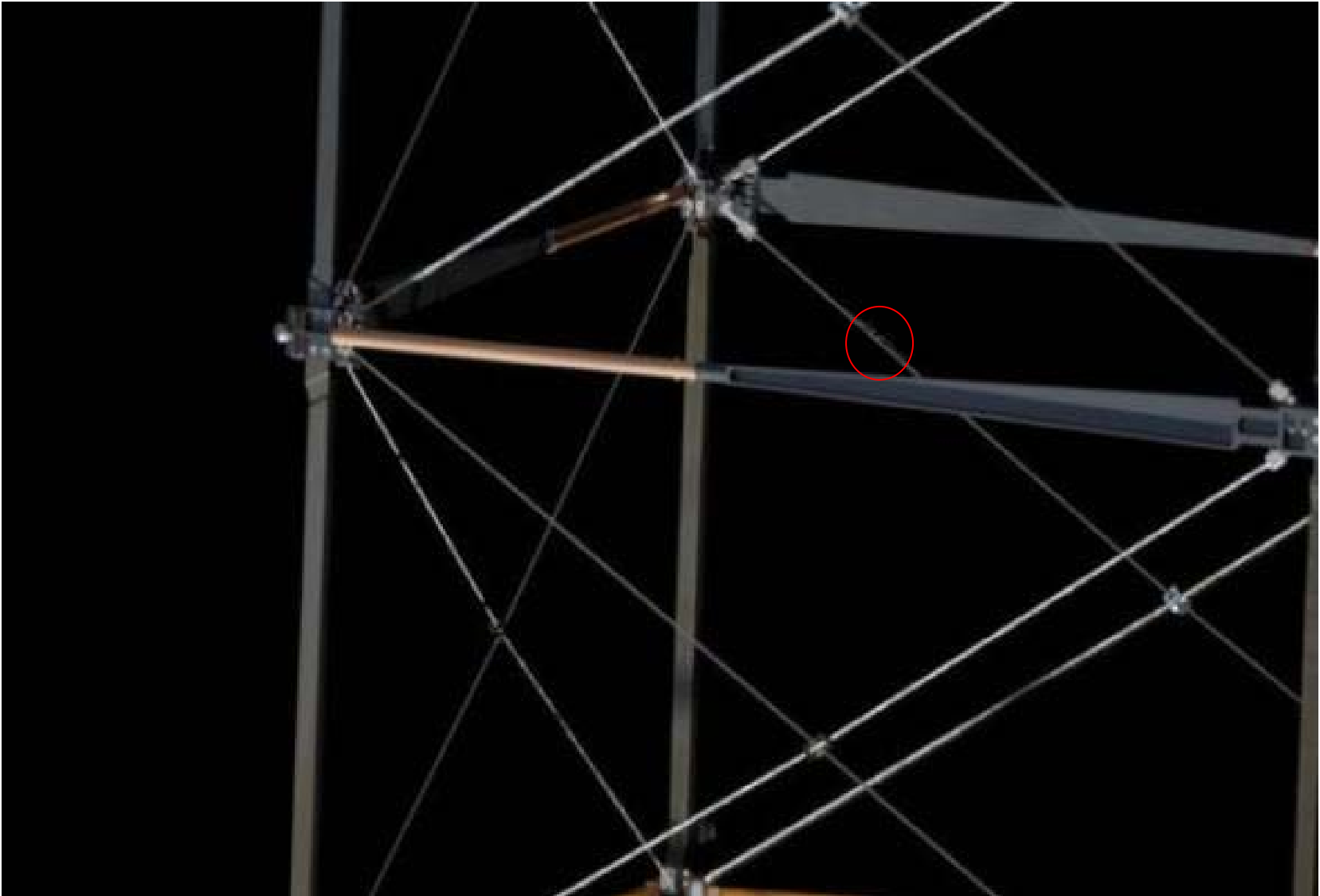
MMOD Impacts to ISS (Examples)

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



Example ISS Needs, Risks, Challenges, and Inefficiencies

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 than $1/8^{\text{th}}$ inch dia.

In-Space Non Destructive Inspection Technology Workshop

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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 Biomimetics 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 × 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.

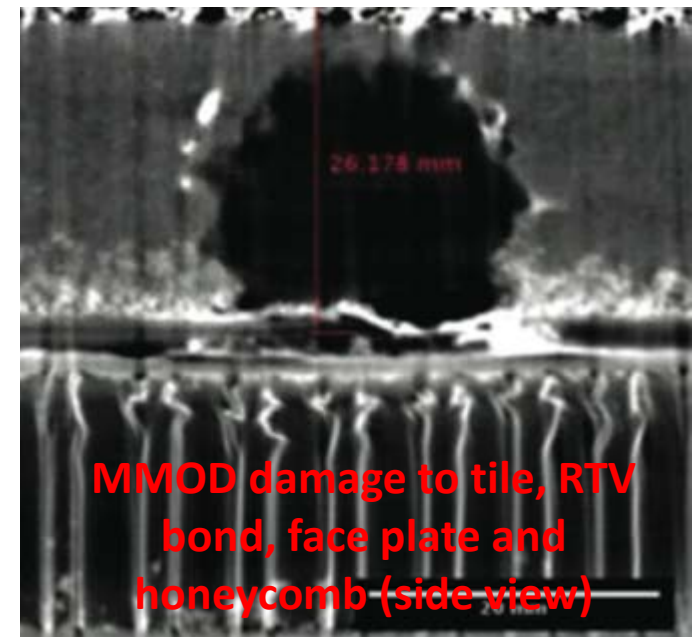
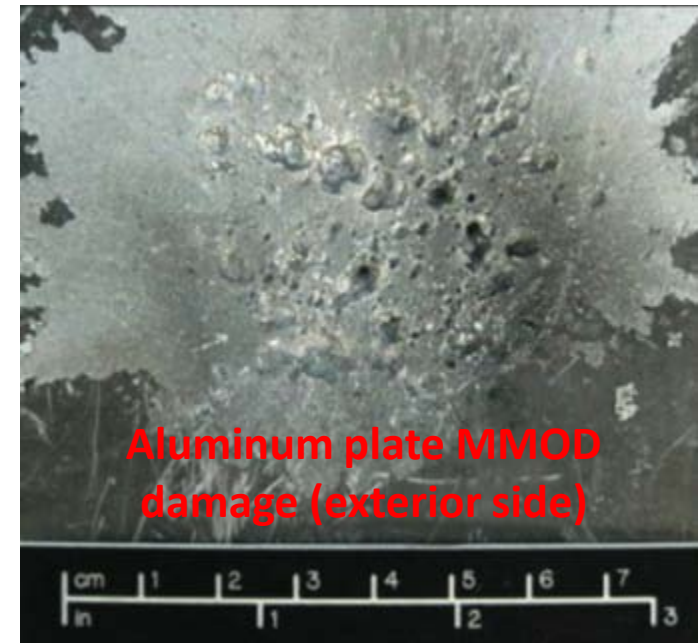
3D Penetrating Imager – July '11 NASA Tech Need

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).

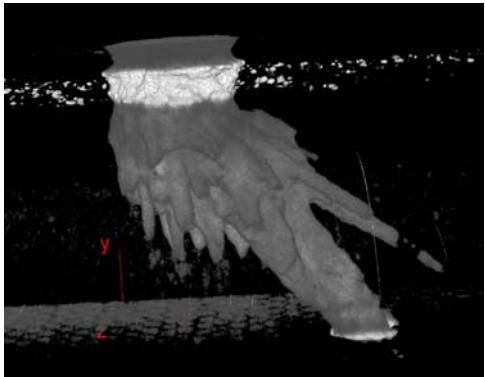
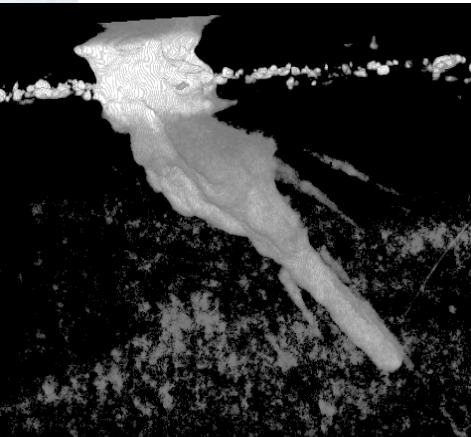
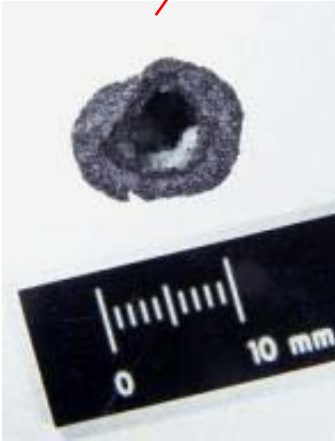
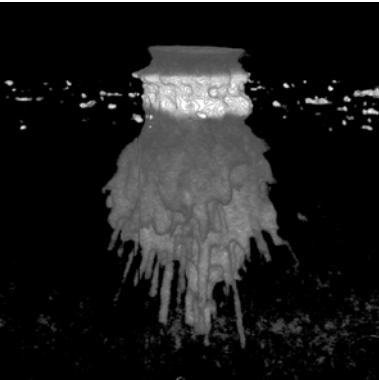
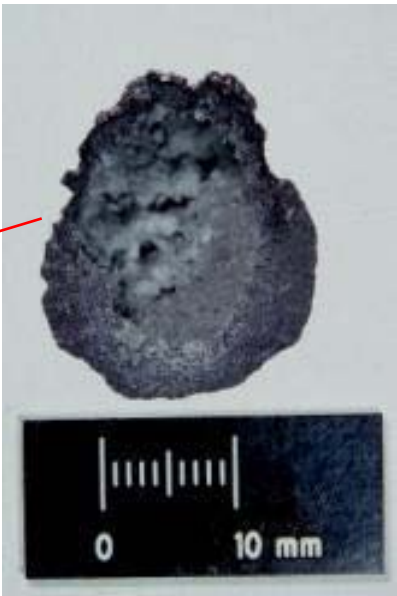
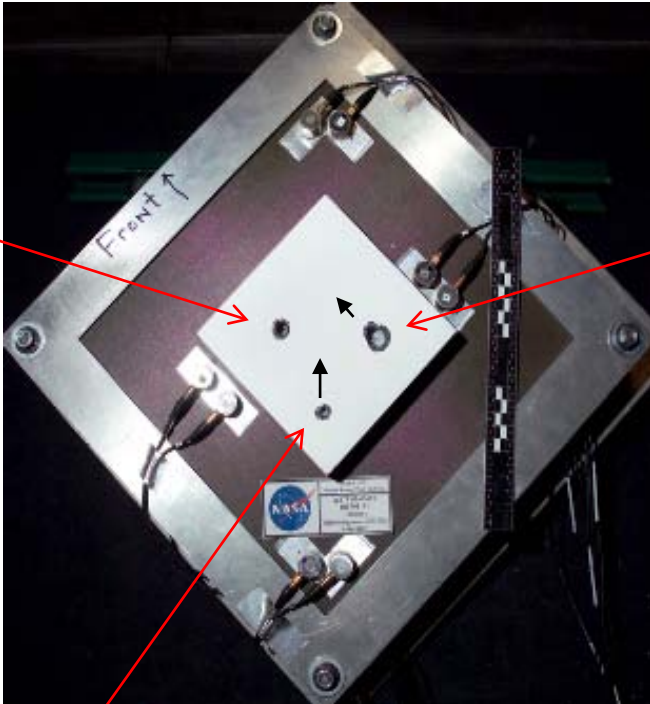
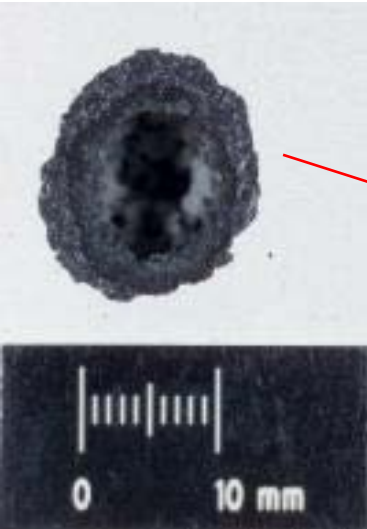
MMOD damage to re-entry tile and substructure

- 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.



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.

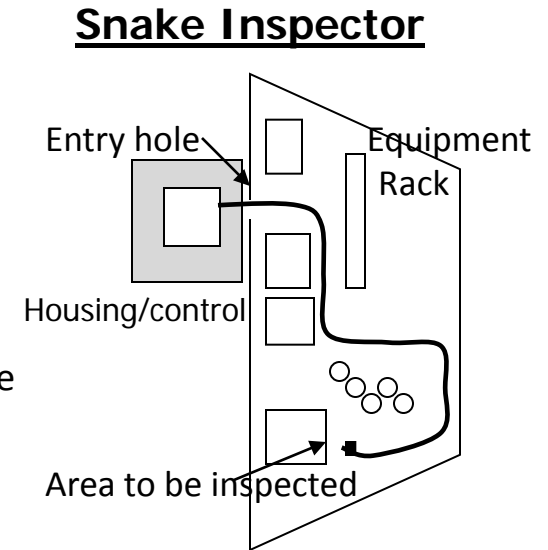
External Inspections:

- 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 Biomimetics: “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.

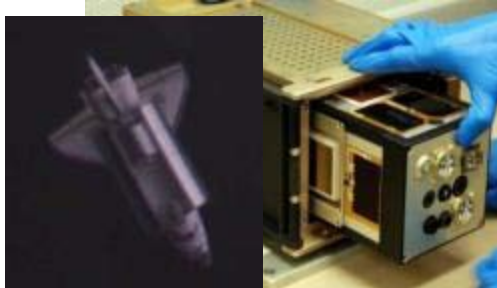
NASA
Mini-Aercam
Prototype



SPHERES Test Bed
Magnetic Field Control



PSSC2 STS-134



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



Studor Free-flying Inspector Vision...

Lessons Learned from Mini-Aercam

Proto-types include Auto Inspect & Doghouse

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 - Jun '12
10cm cube < 1 kg



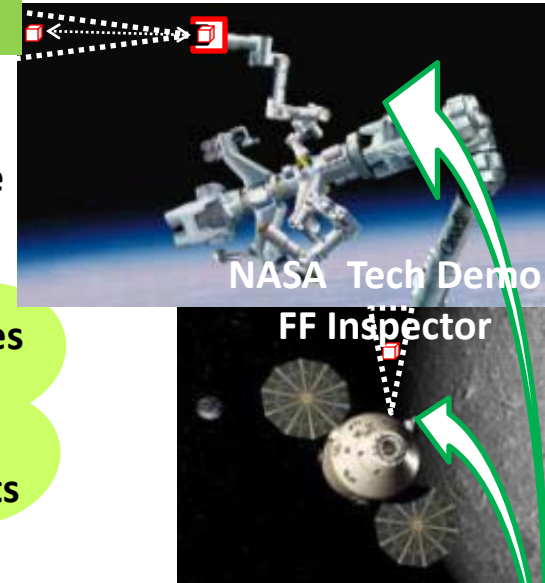
Cube Sat Active "Doghouse"
(A Single Cube Active "PeaPod")

- Power, Comm, Nav, Thermal
- Sensors Active while mated
- Active Deploy and Retrieve
- Powered Grapple Interface or Installed at OML

Cube Sat Flight Demo
Commanded Survey
Of Upper Stage

Cube Sat Flight Demo
Autonomous Survey
Of Upper Stage

Cube Sat Flight Demo
Autonomous Survey
- Active "Doghouse"
- Retrieve/Download



NASA Tech Demo
FF Inspector

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