AFRL’s Integrated Systems Health Management Roadmap

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Outline

- Motivation
- AFRL ISHM Roadmap
- Future Direction
Military Need

- Operationally Responsive Spacelift ensures the Air Force has the capability to rapidly put payloads into orbit and maneuver spacecraft to any point in earthcentered space.
- The AF Strategic Master Plan shows a Vision End State including:
  - Launch Operations for Satellite Operations and Counter Space
  - Robust and Responsive Spacelift
  - Regeneration and Augmentation of Satellite Constellations
  - Reposition, Recover, and Service on-Orbit Assets
  - Terrestrial Point-to-Terrestrial-Point Transport Through Space
  - Sortie Military Missions
Space Access Technology Goals
- Incremental Steps to Future Vision -

**Near Term**
- Rapid turn 48 hrs
- 3X lower ops cost
- Vehicle reliability 0.995
- All Wx availability 90%
- 250 Sortie Airframe
- 100 Sortie Propulsion & Systems

**Mid Term**
- Rapid turn 24 hrs
- 10X lower ops cost
- Vehicle reliability 0.999
- All Wx availability 95%
- 500 Sortie Airframe
- 250 Sortie Propulsion & Systems

**Far Term**
- Rapid turn 4 hrs
- 100X lower ops cost
- Vehicle reliability 0.9998
- All Wx availability 98%
- 1,000 Sortie Airframe
- 500 Sortie Propulsion & Systems

BASELINE
EELV, Shuttle, Aircraft Ops
Space Access Technology Goals
- Incremental Steps to Future Vision -

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**BASELINE**
EELV, Shuttle, Aircraft Ops
Any system that collects, processes, and manages health data to assess the current condition of an aerospace vehicle and determine its ability to perform a given mission.
## ISHM for RLVs Roadmap

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### Technology Readiness Level
- **Transition Point (TAD)**
- **Sub-Products**
  - $\S1$ Spiral

| Program Area | FY04 | FY05 | FY06 | FY07 | FY08 | FY09 | FY10 | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 |
|--------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 6.1 / SBIR Program |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 6.2 Program |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Integrated 6.3 Experiment/Demo Leveraged Program |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Other Funding |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Funded Transition Partial Funded Unfunded |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |

### Sub-Products
- $\S1$ Spiral

**6.3 Program**
- Program Focus: Other Funding
- Program Briefing: Partial Funded
- Program Duration: Unfunded

**Integrated 6.3 Experiment/Demo Leveraged Program**
- Program Focus: Other Funding
- Program Briefing: Partial Funded
- Program Duration: Unfunded
Determined critical focus area for mechanically attached TPS to meet quick turnaround goals

Downselected technology to reduce turnaround time for a next generation space vehicle

Techniques developed:
- Delamination using AE and PZT system
- De-bond using active PZT system
- Bolt loosening detection using AE
- Impact detection using AE
- Crack growth using AE and PZT
• Determined critical area (mechanically attached TPS) to focus on to meet quick turnaround goals for a next generation space vehicle and downselected technology to attack that problem

• Effective bolt/panel loosening damage detection method established for use in operational environment

• Fed the ISHM Architecture program
Integrated System Health Management Architecture Design

- **DACHM**: Data Acquisition Control & Health Management
- **VMS**: Vehicle Management System
- **IMS**: Information Management System
- **OCC**: Operations Control Center

**Diagram Highlight:****

1. **IMS** performs vehicle-wide coordination: orient, decide.
2. **VMS** schedules actions.
3. **DACHM** observes events and initiates action commands.

**Key Components:**
- **Message Handler**
- **Controller**
- **Observe Manager**
- **Self Check**
- **Configuration Control**
- **Orient Reasoner**
- **Decision Maker**

**Flow:**
- Sensors -> DACHM -> VMS (message scheduling) -> OCC (command execution)
Benefits of ISHM Architecture

Operation Control Center Reasoning:
- Fleet wide statistics
- Condition Based Maintenance
- Mission Decision Validation

VMS Flight Control → IMS Reasoning

Vehicle Level Reasoning:
- Multi subsystem capability
- Ambiguity Resolution
- Mission decision
- Damage Assessment

Engine DACHMs → Structure DACHMs

Subsystem Level Reasoning:
- Multi sensor data fusion
- Subsystem Capability
- Anomaly Detection
- Sensor Validation

Minimize False Positives, Validation at All Levels, Provides Corroboration
System Health Capability Reasoner Design

Observe Locally
- Sensor Networks
  - Subsystem DAC&HM
    - Forward Inference
      - Observe
      - Diagnostics
      - Component States

Orient & Decide Globally
- Information Management System (IMS)
  - System Health Capability Reasoner
    - Orient Constraints:
      - Subsystems
      - Mission Phase
      - Time to Criticality
  - Orient Database:
    - Domain Knowledge
    - Terminal Situations
    - Feasible Actions
    - Procedural Rules
  - Autonomy?
    - Ground Decision
    - On-board Decision
  - Recommended List of Actions

Act Promptly
- Vehicle Management System (VMS)
  - Execute Action Steps

Mission Operations Center
- Decide
  - Recommended List of Actions
**ISHM for FAST Operations and Control Center**

**ISHM Ground Functions:**
- OCC Reasoner Module I/F with Air Vehicle to provide vehicle status
- Landing & Pre-launch Checkout
- Validates repaired LRU

**Description:** ISHM is an active ground system during both flight & ground ops. As an OCC module, it provides subsystem status for display, gathers data to improve on-board algorithms, and relays maintenance information for vehicle repair. ISHM validates components during horizontal processing & performs pre-launch calibration & vehicle checkout.

**CONOPS:**
In-flight – on-board IMS sends vehicle health assessment, configuration status, events, and maintenance messages to OCC and receives commands back. On-Ground – Reasoner provides status of each system being monitored by OCC. Participates in maintenance & checkout.
ISHM for FAST Structures Experiment

Description: SHM instrumentation to detect micro-cracking, delamination, and leaks in composite propellant tank, impacts and damage to TPS, and strain on structural attachments. Utilizes PZT sensors & SMART Layer strips - sensors/wiring in one, to minimize weight and volume and maximize coverage and detection.

SHM Anomalies:
- TPS Impact & Damage Assessment
- Temperature under TPS
- Strain on Tank/Wing Attachments
- Tank Delamination/Cracking & Leaks

Stats:
- Sensors per DACHM: 16-256
- No. DACHMs: 2 for TPS (1 fore/1 aft), and 1 for tank and attachments
- Events: health status, detections with severity, sensor failure, calibration, TPS bolt loosening scan results
- No. samples per sensor: 100–400
- Processing speed: 50 ms – 500 ms
- Impact Sensor: 800 bytes at 25 KHz
- Bolt Sensor: 2* 8000 bytes at 40 MHz

CONOPS:
In-flight – detects faults and assesses damage for tanks, attachments, & TPS, reports to IMS, maintenance messages sent to OCC => Ground Ops
On-Ground – remove & replace damaged TPS, re-scan to insure complete repair, re-calibrate sensors
### ISHM for FAST Propulsion System

**Engine Anomalies:**
- Fuel icing
- Foreign Object Debris (FOD)
- Stuck Thrust Control Valve
- Damaged bearing
- O-ring leak
- ...

**Stats:**
- Sensors per DACHM: <64
- No. DACHMs: 1 per engine
- Events: health status, self-checks, anomaly detections – with severity & time to criticality, sensor failure, sensor calibration results
- Sample rates: 300 - 8000 Hz
- Data rate: 42KBytes/sec

**Description:** Propulsion DACHMs acquire data from the engine sensors, digitize, condition, and validate all engine health and performance sensor signals. Engine Health Management (EHM) employs algorithms that determine engine status, detects faults, and determines corrective actions, consistent with OODA cycles. Interfaces to VMS & IMS.

**CONOPS:**
- In-flight – assesses health status, detects faults, takes action if autonomy authorized, reports to IMS, maintenance messages sent to OCC => Ground Ops
- On-Ground – remove & replace or perform pinpoint repair, utilize IMS to re-validate engine and perform self-check
ISHM for FAST Flight Control System

Anomalies:
- Aerodynamic surface effectors
- Upper/lower position limits
- Stuck/Free
- Rate limit
- Power and hinge moment limits
- RCS Stuck on/off
- Avionics - reconfiguration

Stats:
- No. DACHMs: x for Flt Actuators, x for RCS, 1 for Vehicle Avionics
- Events: health status, anomaly detections, sensor failure, calibration
- Sensors: TBD
- Processing: TBD

Description:
Integrated Adaptive Guidance & Control (IAG&C) responsible for Reconfiguration, Trajectory reshaping calculation, Footprint calculation, and Autonomous trajectory changes. IMS sends VMS/IAG&C vehicle health status, vehicle capabilities (effectors, RCS jets, propulsion, thermal, structure) & mitigations.

CONOPS:
In-flight – assesses status and detects faults for RCS, Flight Actuators, Avionics which are reported to IMS, maintenance messages sent to OCC => Ground Ops
On-Ground – repairs directed to specific LRU problems, re-calibrate sensors, checkout to validate unit is operational
FAST ISHM Integration
Flight Controls ISHM

- Determine current health capability of the flight control system through onboard, real-time analysis of sensor information
- Utilize diagnostic techniques to compute an estimation of current health capability
- Provide system health capability reasoner current flight control capability to enable determination of system health capability
- Ensure system integrity
Structural Health Capability Reasoner
Structural Health Capability Reasoner

- Determine the current capability of an aircraft’s structure through the onboard, real-time analysis of sensor information
- Utilize physics-based models and active & passive techniques to compute an estimation of current capability
- Provide system health capability reasoner current structural capability to enable determination of system health capability
# ISHM Integrated Subsystems Demonstration

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## Technology Readiness Level

- 1: Spiral
- 2: Transition Point (TAD)
- 3: Leveraged Program
- 4: Funded Transition
- 5: Partial Funded
- 6: Unfunded

**Programs**
- 6.1 / SBIR Program
- 6.2 Program
- 6.3 Program
- Integrated 6.3 Experiment/Demo
- Other Funding

**Sub-Products**
- SOV Structural Health Monitoring
- IPHM
- ISHM Architecture Design
- Cntl of M-Mission UAV Systems
- SOVOCS
- Engine Diagnostics
- Engine Fault and Anomaly Resolution / Detection
- Flight Controls ISHM
- RLV ISHM Arch Dev & Sub-Systems Integrated Exp
- Reusable Space Access Extended Flight Test
- AG&C/ISHM Validation
- AG&C/ISHM Integration
- Full Env AG&C Valid/SOV
- Full Env AG&C Int
- Fast Integrated Demo

**FY Years**
- FY04
- FY05
- FY06
- FY07
- FY08
- FY09
- FY10
- FY11
- FY12
- FY13
- FY14
- FY15
- FY16
- FY17
- FY18
- FY19
- FY20
ISHM Simulation for FAST RFS

LEGEND:
- VMS Network
- IMS Network
- FTS Cmd. - Flight Term.
## Integrated Systems Health Management (ISHM)

### Program Overview

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<thead>
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### Key Activities

- **Engine Diagnostics**: Engine Fault and Anomaly Resolution / Detection
- **RPA Test Bed for Robust Decision Making**: RPA Payload Health Mgmt.
- **Signal Processing & Decision Fusion Methods for SHM**: RPA Test Bed for Robust Decision Making

### Technology Readiness Levels

- **Transition Point (TAD)**: 5
- **Technology Readiness Level**: 4, 5, 6

### Sub-Products

- **Spiral Sub-Products**

### Funding Information

- **6.1 / SBIR Program**: Leveraged Program
- **6.2 Program**: Funded Transition
- **6.3 Program**: Partial Funded
- **Other Funding**: Unfunded
## State Awareness & Real-time Response

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<th>Goals</th>
<th>Now</th>
<th>Next</th>
<th>Future</th>
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| **Failure Driven Reconfiguration:** Flight control actuator state driving adaptive guidance and control (AG&C) for autonomous space access vehicles  
- Finite set of failed control actuator states (e.g. stuck, floating, reduced bandwidth)  
- Inner-loop controllability and outer-loop trajectory planning adaptation under flight control health constraints  
- Defined requirements for complete system adaptation | **Degradation Driven Adaptation:** Self state awareness of major subsystems driving AG&C and cooperation/teaming  
- Real-time determination of system capability for engine, power, flight control, and structural subsystems  
- System capability assessment driving AG&C  
- System capability assessment feeding cooperative/collaborative control  
- Uncertainty of self state awareness assessments quantified | **Performance Driven Optimization:** Comprehensive self state awareness driving efficient, effective operations and maintenance  
- Fleet management based on individual systems’ self state awareness  
- In situ characterization of and response to emergent behavior/unexpected states  
- Characterization of each system’s unique response to environment  
- Prognosis feeding real-time response  
- Self state awareness feeding inner-loop control |

### Key Questions to be Answered

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<th>Now</th>
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<th>Future</th>
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<td>1. Are there sufficient control effectors to compensate for effector failures?</td>
<td>1. Is there sufficient cost-benefit for utilizing self state awareness for AG&amp;C, cooperation/teaming, or condition-based maintenance?</td>
<td>1. How will comprehensive state awareness impact mission and fleet capabilities?</td>
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<td>2. Can the algorithms be verified for real-time performance through simulated ground tests, supplemented by limited flight demonstrations?</td>
<td>2. What degree of self state awareness and AG&amp;C is appropriate for a given application?</td>
<td>2. How will in situ characterization be verified?</td>
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<td>4. Can the algorithms be verified for real-time performance through simulated ground tests, supplemented by limited flight demonstrations?</td>
<td>4. How will system reliability be impacted by added fault mitigation capability and resulting complexity?</td>
<td>4. How far can current and predicted system states be extrapolated to mission impacts and how should uncertainties be accommodated?</td>
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<td>5. What system state information is required for complete system adaptation by an autonomous space access vehicle?</td>
<td>5. To what extent can degradation be reliably incorporated into adaptation?</td>
<td>5. What is the cost-risk for V&amp;V’ing the resulting system?</td>
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### Future Research is Focused on Investigating Common Theories For ISHM

- How will comprehensive state awareness of each system impact mission and fleet capabilities?
- How will in situ characterization be verified?
- Can prognosis be reliably incorporated into adaptation?
- How far can current and predicted system states be extrapolated to mission impacts and how should uncertainties be accommodated?