Human Spaceflight ISHM Technology Development

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Overview of Presentation

- Goals of ISHM for human spaceflight
- Two ISHM tools that are widely used in human spaceflight
  - TEAMS
  - IMS (aka AMISS)
- Two past and current applications of ISHM in human spaceflight
  - AMISS for ISS
  - Ares I-X Ground Diagnostic Prototype
- Current technology development in OCT and AES for 3 testbed domains
  - Habitats
  - Cryogenic fuel loading
  - Extra-Vehicular Activity (EVA) suit batteries

Goals of ISHM for Human Spaceflight

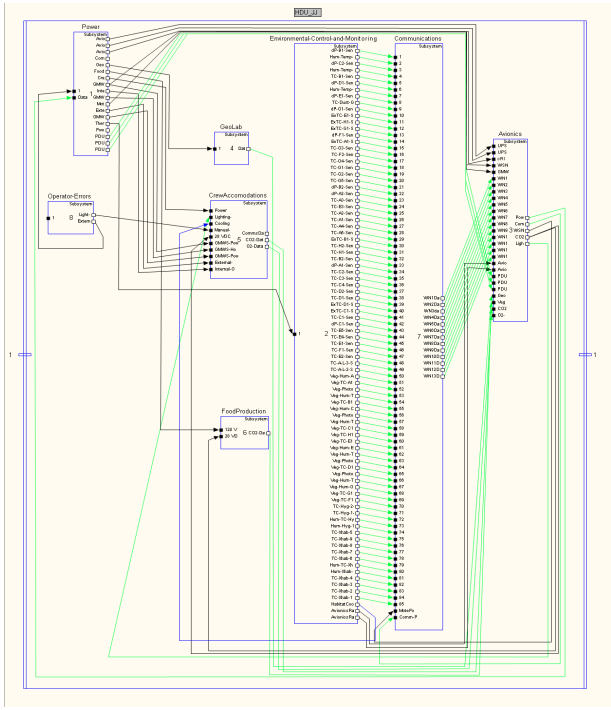
- Increase safety, by detecting problems before they become dangerous
- Increase reliability, by enabling the automatic detection and correction of problems
- Reduce cost, by
  - Detecting and correcting problems before they become expensive
  - Using more automation and less labor to detect and diagnose problems
- Enable missions to distant destinations, where speed-of-light delays make it impossible for flight controllers on Earth to diagnose problems remotely

Functional Fault Modeling in TEAMS

- **Goals**
  - Uncover design issues across subsystem boundaries
  - Assess effectiveness of sensor suite to isolate faults to LRU
  - Provide Diagnostics Model for operations
  - Document failure effect propagation times
- **Approach**
  - Model basic system connectivity, interfaces, interactions, and failure modes
  - Use information from schematics, FMEA, IP&CL, ICD, etc.
  - Implement using COTS tool from Qualtech Systems, Inc. called TEAMS (Testability Engineering and Maintenance System) that was originally developed under ARC SBIR funding
  - Represent propagation of failure effects along physical paths

    (fluid, thermal, electrical, mechanical)
  - Transform failure effects as they propagate to a sensor
  - Sensor data evaluation represented as nodes ('test points')
- **Results**
  - Applied to SLS, Ares I, LADEE, HDU, KSC GO

Habitat Demonstration Unit (HDU)



Functional Model in TEAMS

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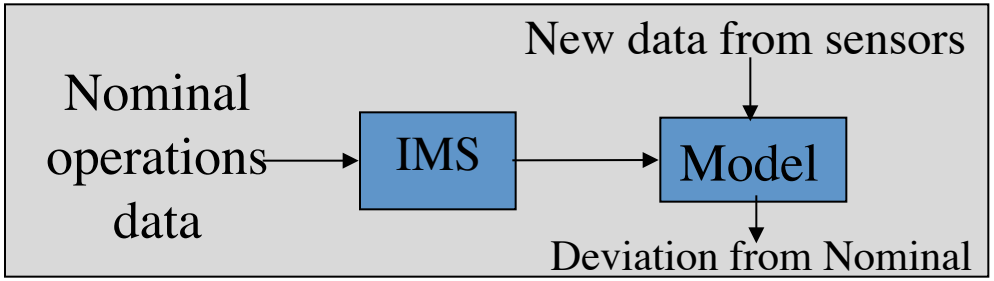
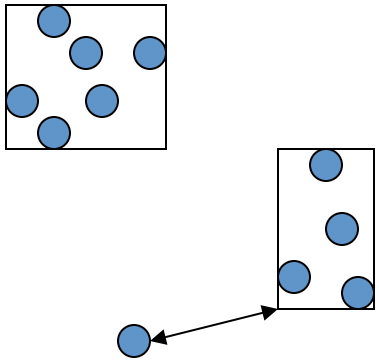
Inductive Monitoring System (IMS)

(aka Anomaly Monitoring Inductive Software System (AMISS))

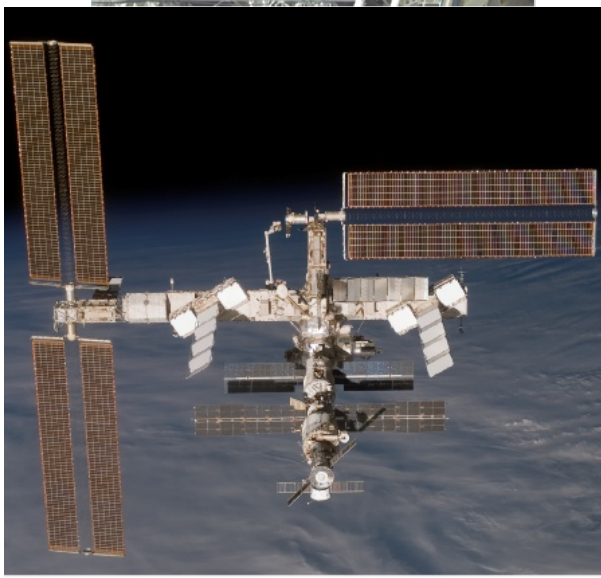




- Data-driven one-class anomaly detection system
- Automatically derives system models from archived or simulated nominal operations data
  - Does not require off-nominal data
  - Does not require knowledge engineers or modelers to capture details of system operations
- Analyzes multiple parameter interactions
  - Automatically extracts system parameter relationships and interactions
  - Detects variations not readily apparent with common individual parameter monitoring practices
- Able to detect subtle anomalies and faults that are not listed in the FMEA
- Monitoring module can detect anomalies whose signatures are not known ahead of time
- On-line monitoring takes as input observations about the physical system (parameter values) & produces "distance from nominal" anomaly score
- Algorithm:
  - clusters the training data
  - uses distance to nearest cluster as anomaly measure
- Developed by Dave Iverson of ARC

IMS for ISS

- Has been running 24/7 at JSC MCC since 2008, monitoring live telemetered sensor data from the ISS
- Has been certified (Level C) for that application
- Monitors:
  - Control Moment Gyroscopes (CMGs)
  - Rate-Gyro Assemblies
  - External Thermal Control System (ETCS)
  - Carbon Dioxide Removal Assembly (CDRA; not deployed yet)



Ares I-X Ground Diagnostic Prototype

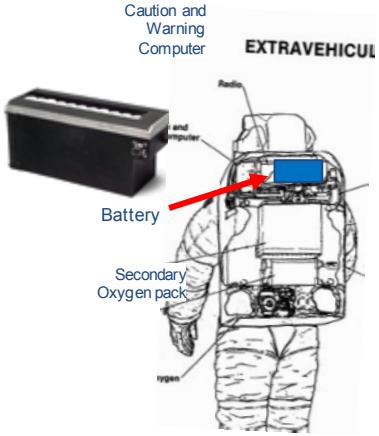
- Ares I-X: the first uninhabited test flight of the Ares I on 10/28/2009
- NASA ARC, KSC, MSFC, and JPL worked together to build a prototype ground diagnostic system
- Was deployed to Hangar AE at KSC, where it monitored live data from the vehicle and the ground support equipment while Ares I-X was in the VAB and while it was on the launch pad
- Combined three data-driven and model-based ISHM algorithms: TEAMS-RT, IMS (aka AMISS), and SHINE
- Focused on diagnosing the first-stage thrust vector control and the ground hydraulics
- Ensured a path to certification
- Kept up with live data from 280 MSIDs using only a PC
- Led by Mark Schwabacher at ARC
- Funded by Ares I, by ETDP, and by KSC Ground Ops

3 Testbed Domains

Habitats

Cryogenic Propellant Loading

EVA Suit Batteries



3 Programs

- OCT Game Changing Development (GCD)
  - TRL 4-6
- HEOMD Advanced Exploration Systems (AES)
  - TRL 5-7
- HEOMD Ground Systems Development and Operations (GSDO) Program
  - TRL 7-10

6 Projects

- OCT GCD Autonomous Systems (AS)
- AES Autonomous Mission Operations (AMO)
- AES Habitation Systems (HS)
- AES Integrated Ground Operations Demonstration Units (IGODU)
- AES Modular Power Systems (AMPS)
- GSDO Advanced Ground Systems Maintenance (AGSM) element

2 of the testbeds are each supported by 3 projects

Programs

Projects

Testbeds

HEOMD AES

OCT GCD

HEOMD GSDO

AMPS

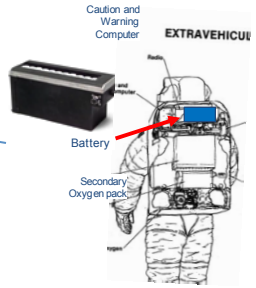
Autonomous Mission Operations

Habitation Systems

Integrated Ground Operations Demonstration Units

Autonomous Systems

Advanced Ground Systems Maintenance



Gen-1 Habitat Demonstration Unit (HDU)

- Tested in Arizona desert in 2010
- Not sealed
- Astronauts lived in it for multiple days

Gen-2 HDU: Deep Space Habitat (DSH)

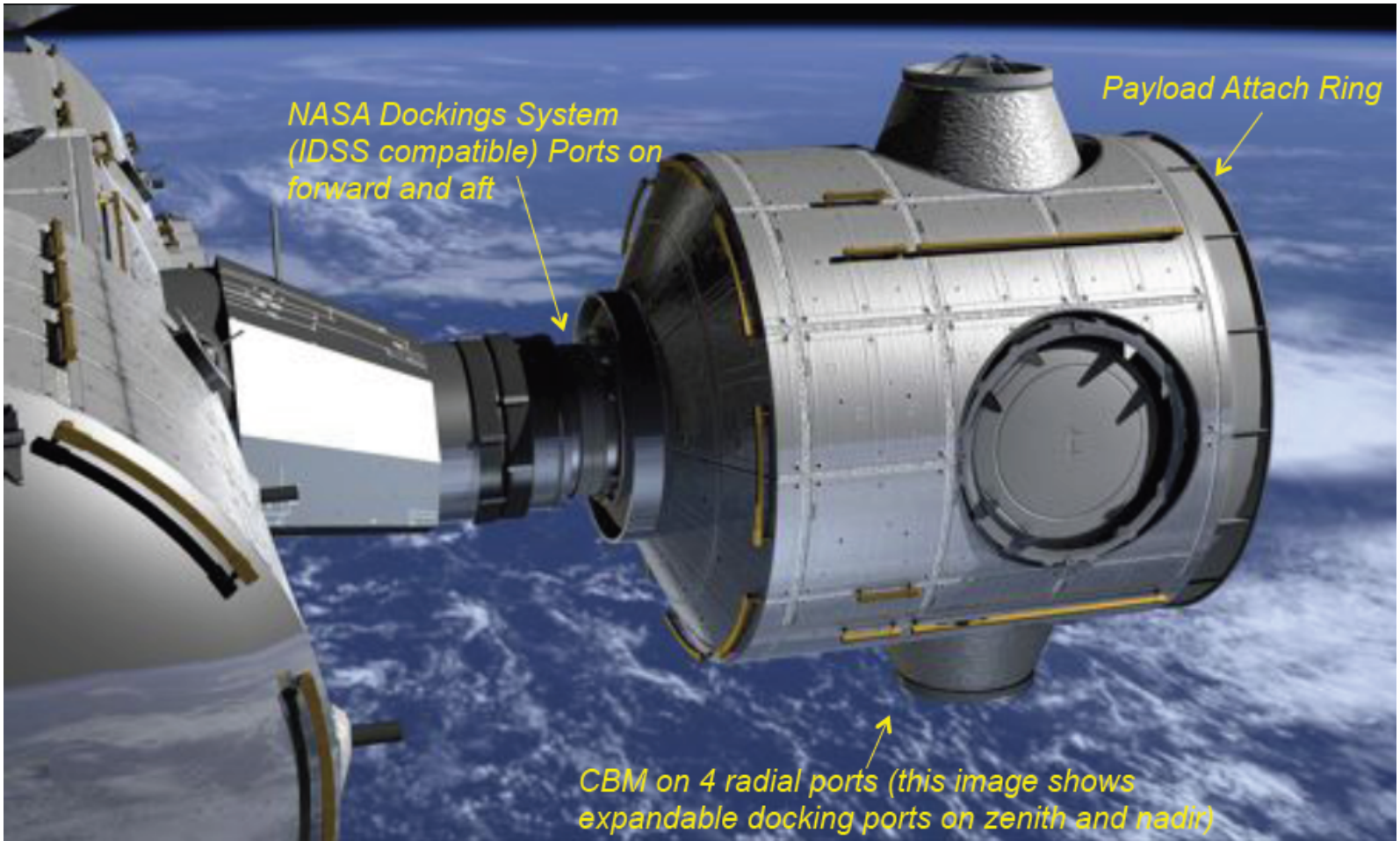
- Tested in Arizona desert in 2011
- Added “X-Hab” inflatable loft and Hygiene Module

Gen-3 DSH

- Will be built inside 20’ Chamber at JSC in FY13-16
- Will be sealed
- Astronauts will live in it for 2 weeks

Gen-4 DSH

- Proposed to be attached to ISS in 2018



Major ISHM technologies being developed for habitats by OCT GCD AS

- Failure Consequence Assessment System (FCAS)
- Interface to planner
- Prognostics for forward-osmosis water recovery system

Failure Consequence Assessment System (FCAS)

- When a real or induced failure occurs in the DSH, the failure will be detected and diagnosed using TEAMS
  - The diagnosis will determine which components have failed.
- FCAS will determine which components have stopped functioning as a result of the components that have failed.
- FCAS will determine the loss of capability resulting from the non-functioning components based on the current environment.
- A procedure to respond to the loss of capability will be automatically selected and displayed.

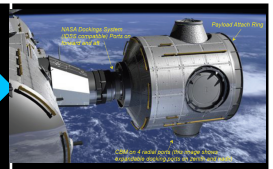
Integration of ISHM with automated planner

- Will be used in cases where no predetermined procedure exists to recover from the loss of capability (determined by FCAS).
- The loss of capability will be communicated to an automated planning system, which will either automatically or semi-automatically replan the rest of the mission to:
  - repair the components that are broken, and/or
  - accomplish as many mission objectives as possible given the loss of capability (if some broken components can't be fixed).

ISHM for Habitats 10-year Roadmap

Gen-2 DSH

Gen-3 DSH in 20' Chamber at JSC



Gen-4 DSH at ISS

Water recovery testbed at ARC

Task						
	Model includes power & comm. Capabilities include Anomaly Detection (IMS), Fault detection, diagnostics (TEAMS), and procedure execution.	Added capabilities include FCAS and interface to planner.	Model includes power, comm, water recovery. Capabilities include Anomaly Detection, Fault detection, diagnostics, prognostics, procedure execution.	Model adds CO_2 scrubber. Added capabilities include FCAS.	Model adds trash processor. Added capabilities include interface to planner.	Model includes power, comm, water recovery, CO_2 scrubber. Capabilities include Anomaly Detection, Fault detection, diagnostics, prognostics, procedure execution, FCAS, interface to planner.
	Capabilities include Fault detection and diagnostics.	Added capabilities include prognostics.				
FY	12	13	14	15	16-17	18-21
TRL	4	5	6	6	7	8

Cryogenic Propellant Loading

Goals of ISHM (and Automation) for Cryo

- Reduce operations and maintenance cost
- Increase availability of ground systems to support launch operations
- Prepare for future in-space cryo loading

Objectives of ISHM for Cryo

- Demonstrate autonomous cryogenic (LN2) loading operations at the Cryogenic Test bed Facility with recovery from selected failure modes
- Develop prognostics capability for selected complex failure modes
- Demonstrate tank health/diagnostics using physics models and simulation

IMS for cryo

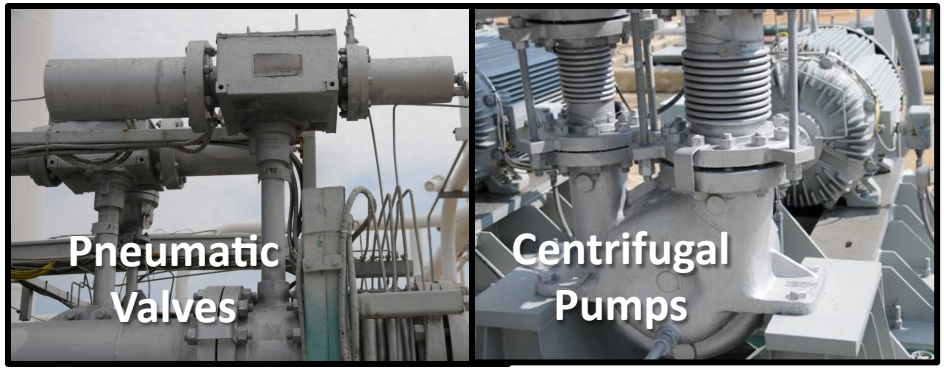
- STS-119 launch attempt #1 (3/11/09) was scrubbed due to LH2 leakage exceeding specification at the Ground Umbilical Carrier Plate (GUCP)
- Real time monitoring subsequently deployed in KSC LCC for STS-134 (Endeavour) fueling operations in Spring 2011

Current Work in ISHM for Cryo

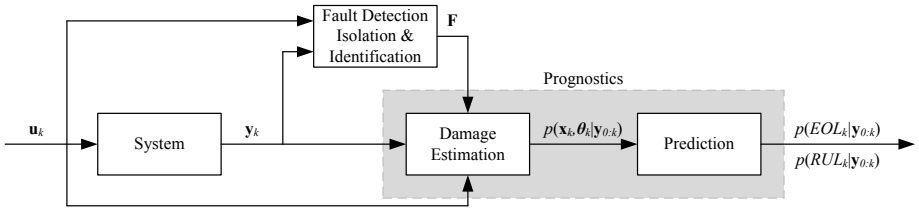
- IMS
- TEAMS
- Hybrid Diagnosis Engine (HyDE)
- G2
- Knowledge-based Autonomous Test Engineer (KATE)
- Prognostics
- Physics-based models

Prognostics for Cryo

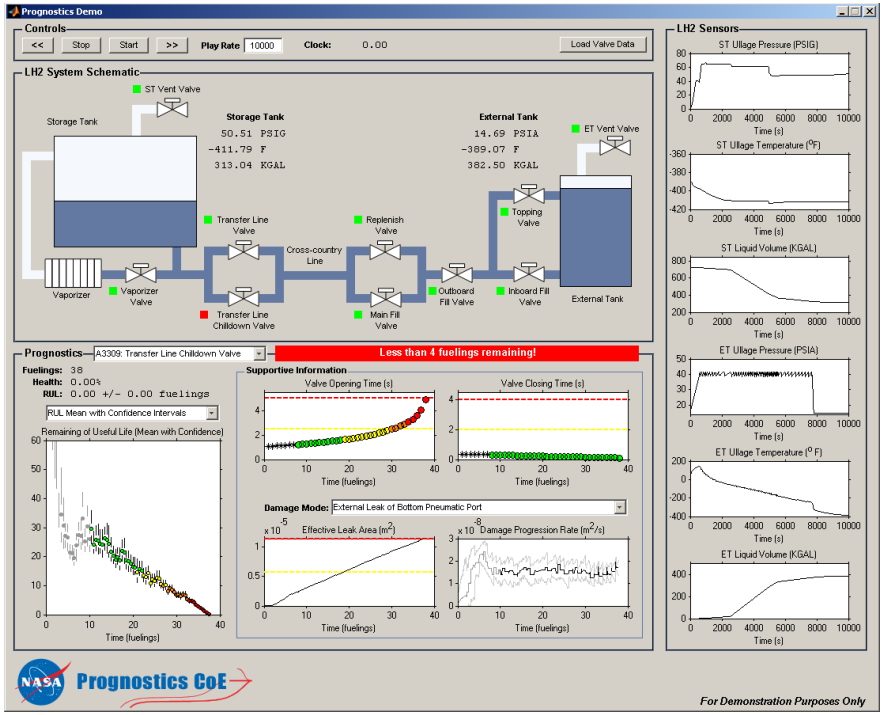
Problem: Develop fault prognostics algorithms that determine end of life (EOL) and remaining useful life (RUL) of components in a propellant loading system, namely, pneumatic valves and centrifugal pumps.



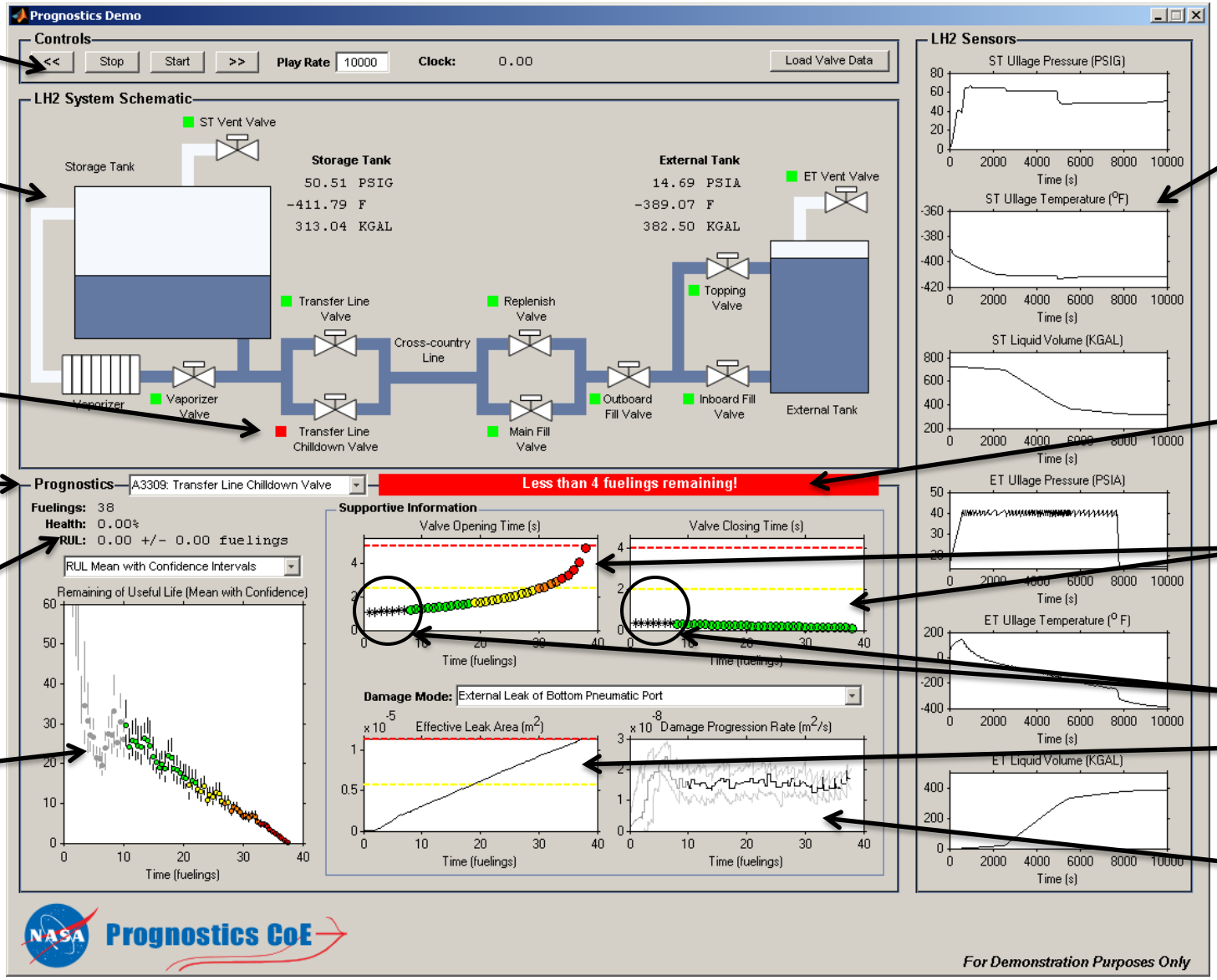
Approach: Apply model-based prognostics architecture, in which physics-based models are constructed that capture nominal component behavior and the underlying damage progression mechanisms. Combines Bayesian state estimation algorithms with model-based prediction algorithms.



Results: Performed comprehensive simulation-based validation experiments investigating the effects of sensor noise, the available sensors, sampling rate, and model granularity. Pneumatic valve prognostics technology demonstrated using historical valve degradation data from the Space Shuttle liquid hydrogen refueling system.



Prognostics for Cryo Interface



Demo Controls

Integrated Schematic

Valve Health Indicator

Prognostics Interface

Cycle count, overall health, RUL with confidence bounds

Prognostics Plots (EOL, RUL, etc.)

System Plots

Prognostics Summary

Valve Timing

Real Data

Fault Estimation

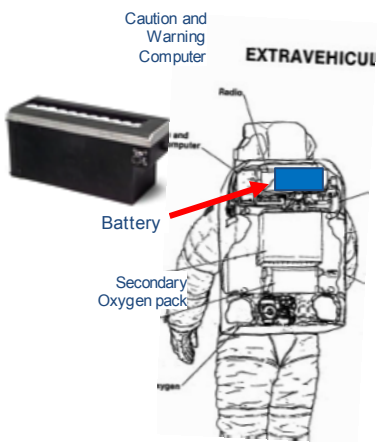
Wear Rate Estimation

Battery Prognostics for EVA Suits

- AES Modular Power Systems (AMPS)
  - Infuse and demonstrate batteries (and other power modules) for exploration ground system demonstrations

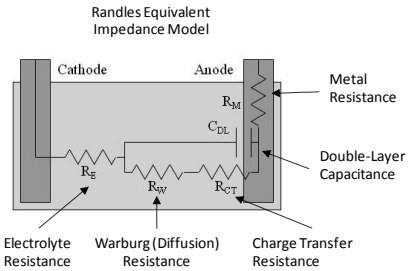
Problem

- Prediction of end-of-charge and end-of-life based on current state estimation and estimated future usage to answer
  - Can the current mission be completed?
    - Given the health of the battery, is there enough charge left for anticipated load profile (within allowable uncertainty bounds)?
    - Dominant metrics: state of charge (SOC), state of health (SOH)
  - Can future missions be completed?
    - Given the health of the battery, at what point can typical future missions not be met?
    - Dominant metrics: end of life (EOL) or remaining useful life (RUL), state of health (SOH)
- Target application:
  - Extra Vehicular Activity (EVA) battery for astronaut suits

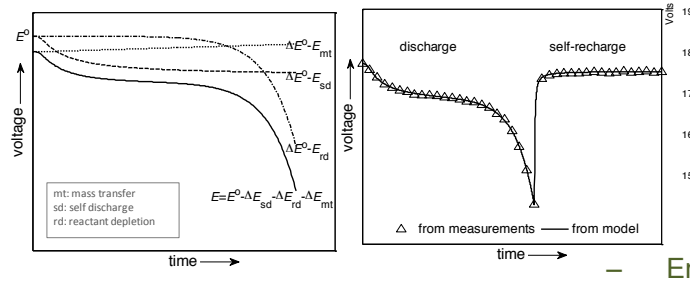


Approach

- Model relevant electrochemical phenomenon in the battery



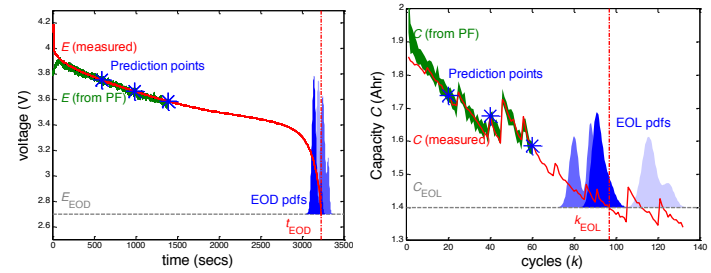
- Modeling State of Charge (SOC)
  - SOC model expressed as a sum of 3 sub-processes – mass transfer, self discharge and reactant depletion
- Modeling State of Life (SOL)
  - Model self-recharge at rest and capacity loss due to Coulombic efficiency



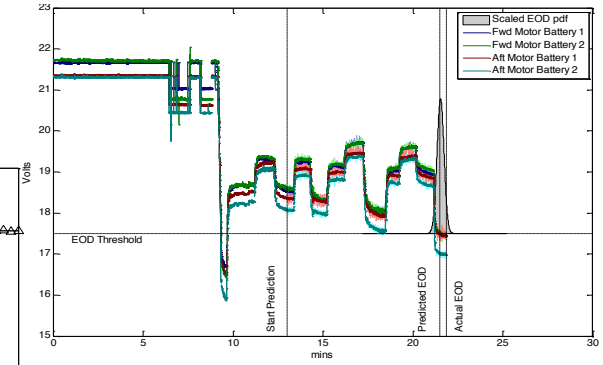
- Conduct lab experiments to collect data and validate degradation and fault models
  - Learn base model from training data
  - Let the PF framework fine tune the model during the tracking phase
  - Use tuned model to predict RUL until EOD and EOL is reached

Results

- Both SOC and SOL are accurately predicted under constant operational loads



- Predictions for realistic load profiles were validated in related application domain



- Enhance models to account for environmental (temperature and pressure) conditions
- Develop models for faults in batteries
  - Internal shorts, overcharge, deep discharge
- Extend models from cell level to pack and battery levels
- Test and validate for other applications and different battery chemistries

Conclusions

- OCT and AES are developing ISHM technology in the following areas
  - Anomaly detection
  - Diagnostics
  - Prognostics
  - Failure Consequence Assessment
  - Interface to automated planning
  - Physics-based modeling
- These technologies are being tested using three testbed domains (habs, cryo, and batteries), but are also applicable to many other systems (launch vehicles, robotic spacecraft, aircraft, etc.).