

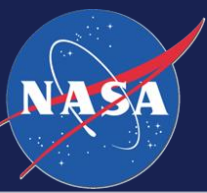
# Implementations Using NASA's Autonomous Operation Mission Development Suite (AO-MDS)

- Nitrogen System: High Pressure Gas Facility, NASA Stennis Space Center, MS
- Pilot Health Management of the ORION Capsule (EFT-1) Power and ECLSS subsystems

**Fernando Figueroa**  
**NASA Stennis Space Center**

**G2 Users Group Conference**  
**September 27-29, 2016**

**Gaylord Palms Resort and Convention Center**  
**Orlando, FL**



# Development Contributors

## **Nitrogen System: High Pressure Gas Facility (Gas House), Stennis Space Center.**

Fernando Figueroa, NASA Stennis Space Center.

Mark Walker, D2K Technologies.

Tommy Wagner, D2K Technologies.

Neal Gross, D2K Technologies.

Bjorn Regalado Reyes, NASA Intern.

Luke Miller, NASA Intern.

Ashley Edsall, NASA Intern.

Esteban Duran, NASA Intern.

Stephanie Rocha, NASA Intern.

Addison Howenstine, NASA Intern.

Phillip Bakker, NASA Intern.

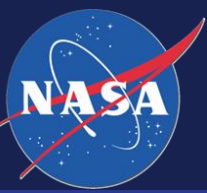
## **Pilot Health Management of the ORION Capsule (EFT-1) Power and ECLSS subsystems**

Fernando Figueroa, NASA Stennis Space Center.

John (Jay) Gurecki, NASA Kennedy Space Center.

Mark Walker, D2K Technologies.

Kim Wilkins, General Atomics.



# Acknowledgement

Funding for this work was provided by the NASA's Advanced Exploration Systems (AES) of the Human Exploration and Operations Mission Directorate, NASA Space Technology Mission Directorate, NASA Rocket Propulsion Test Organization, and NASA Education (supporting Interns).

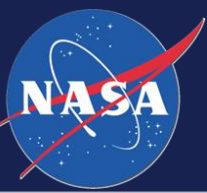
## SSC Gas House Implementation





# Introduction

- **Autonomous Operationm (AO) refers to control actions of a system that take place without intervention from humans.**
- **AO denotes control actions that respond to events that are unexpected, and enable the system to continue on a path to achieve an original objective or alternate objectives.**
- **AO incorporates concepts such as adaptation, mitigation, and re-planning in space and time.**



# Paradigm for Autonomy

- **Autonomy is a capability that is not absolute. There are degrees of autonomy, ranging from low levels to high levels, but there is no maximum level (how many autonomy strategies are implemented?).**
- **It is an evolutionary capability that can handle increasing degrees of complexity for reasoning and decision making.**
- **It must know the condition of the system elements and their ability to carry out the task. Integrated System Health Management (ISHM) then becomes an enabler for autonomy.**



# Autonomy Strategies

- **Strategies for autonomy guide the decision making process. What to do when an element cannot be used? There must be a strategy to replace the function of that element in the current plan.**
- **Autonomy is scripted to apply strategies, but it is more powerful and affordable when scripted at a high level of abstraction, that is, at a more generic KNOWLEDGE level. Where concepts are used instead of just data and information. Strategies scripted at low levels is specific in space, time, process, application, etc. It leads to high complexity, high cost, and low autonomy capability.**

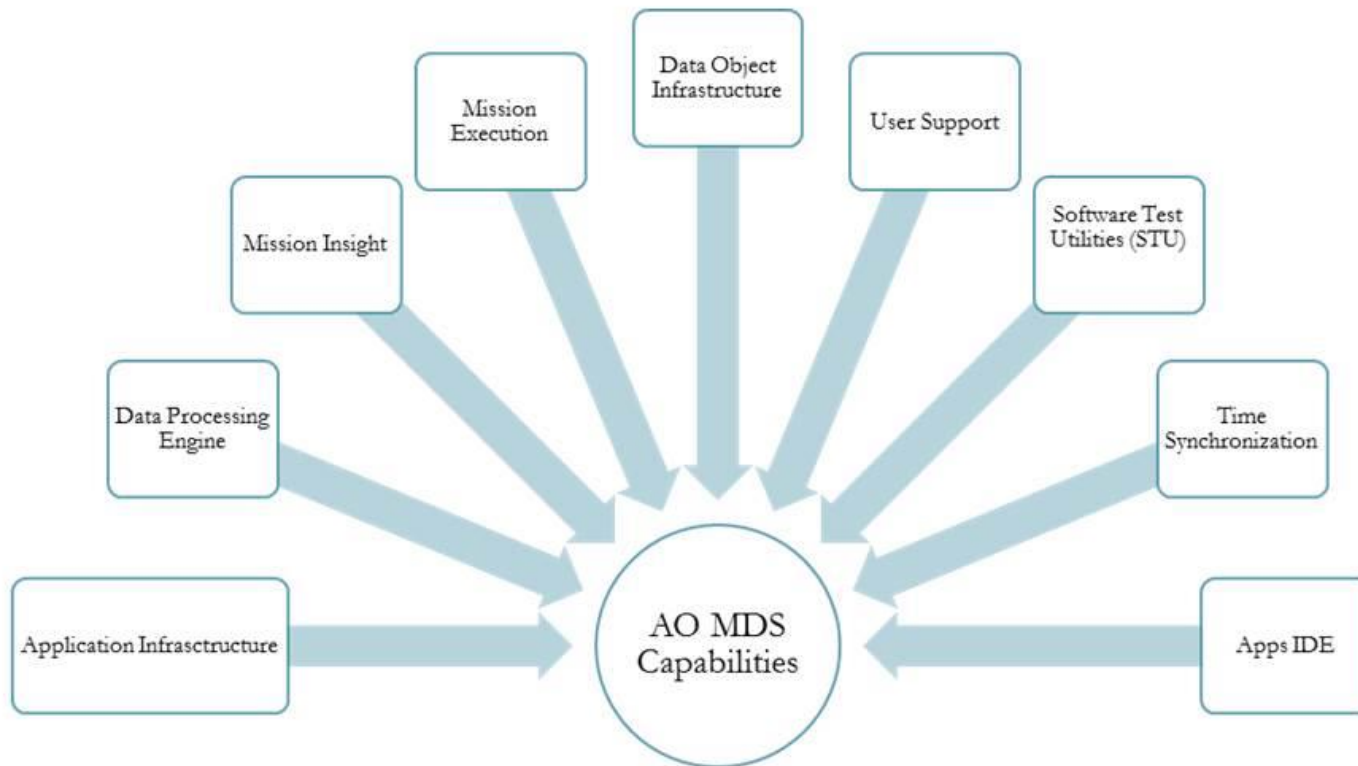


# Autonomous Operation System (AOS)

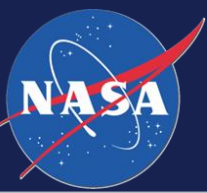
- **The Autonomous Operation System (AOS) was developed using the G2 software environment and the G2 NASA ISHM Toolkit, which has evolved into the G2 NASA AO-MDS.**
- **The capability is built based on knowledge and information domain models that provide context, to apply models and concepts for autonomous execution of a mission.**
- **The AO-MDS is an operational platform to implement autonomous operation of systems (currently focused on fluid and electrical).**
- **The AO-MDS is designed to evolve systematically to achieve higher levels of autonomy and inherently supports scalability.**



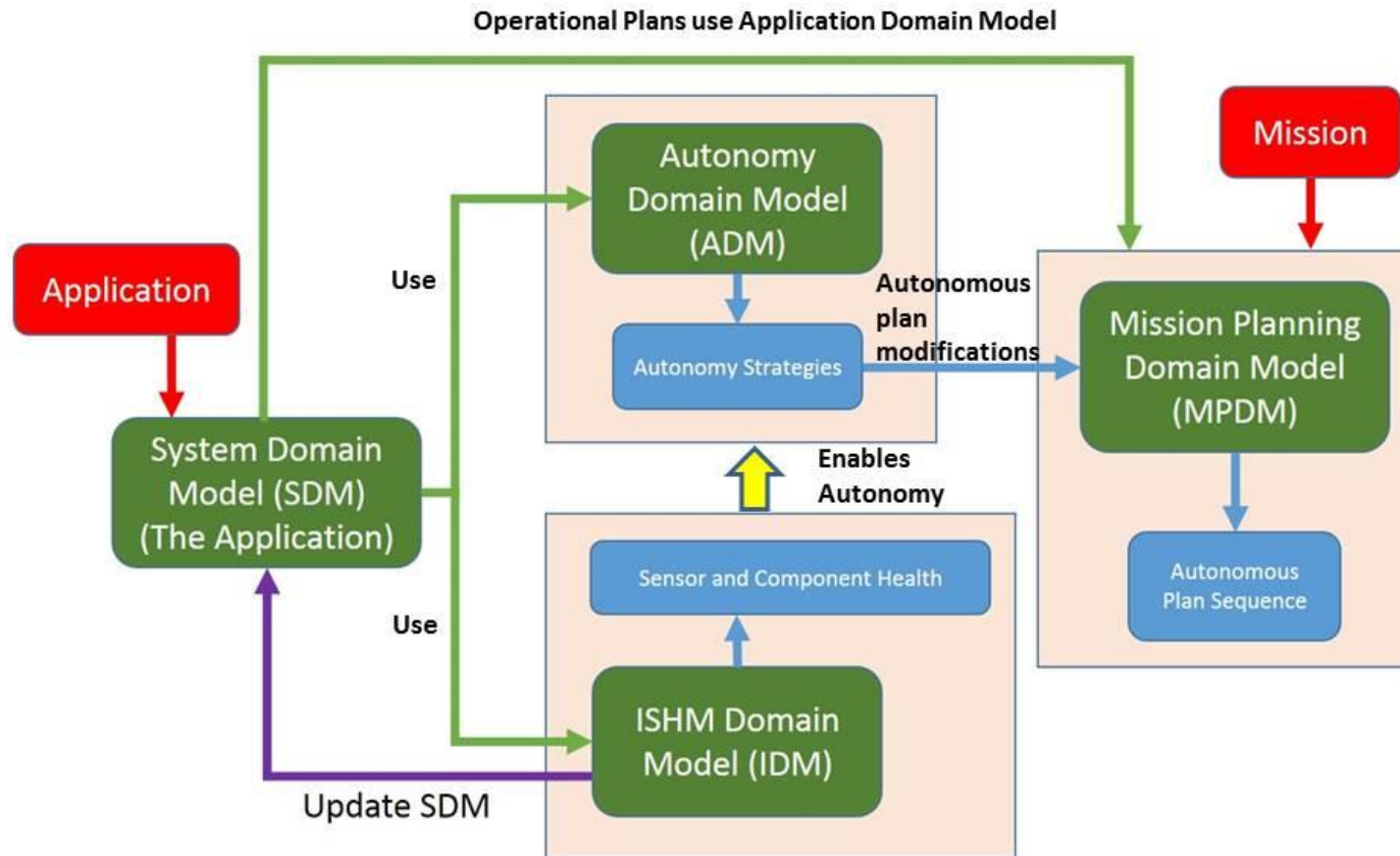
# AO-MDS Capabilities

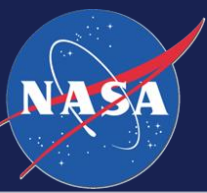






# Autonomy Software Functional Architecture with Domain Models





# Domain Models for Autonomy Summary

- **The System Domain Model** is specific to each application, and can be quickly developed using a library of objects. It incorporates application specific data and information.
- **The Mission Planning Domain Model** is specific to each mission, and mission plans can be quickly developed with user interfaces that enable access to the System Domain Model, and Autonomy Domain Model.
- **The ISHM Domain Model** is generic and enables ISHM functionality for the System Domain Model (anomaly detection, diagnostics, integrated awareness, etc.).
- **The Autonomy Domain Model** is generic and enables Autonomy strategies to be applied by the plans to achieve the mission (Mission Planning Domain Model).

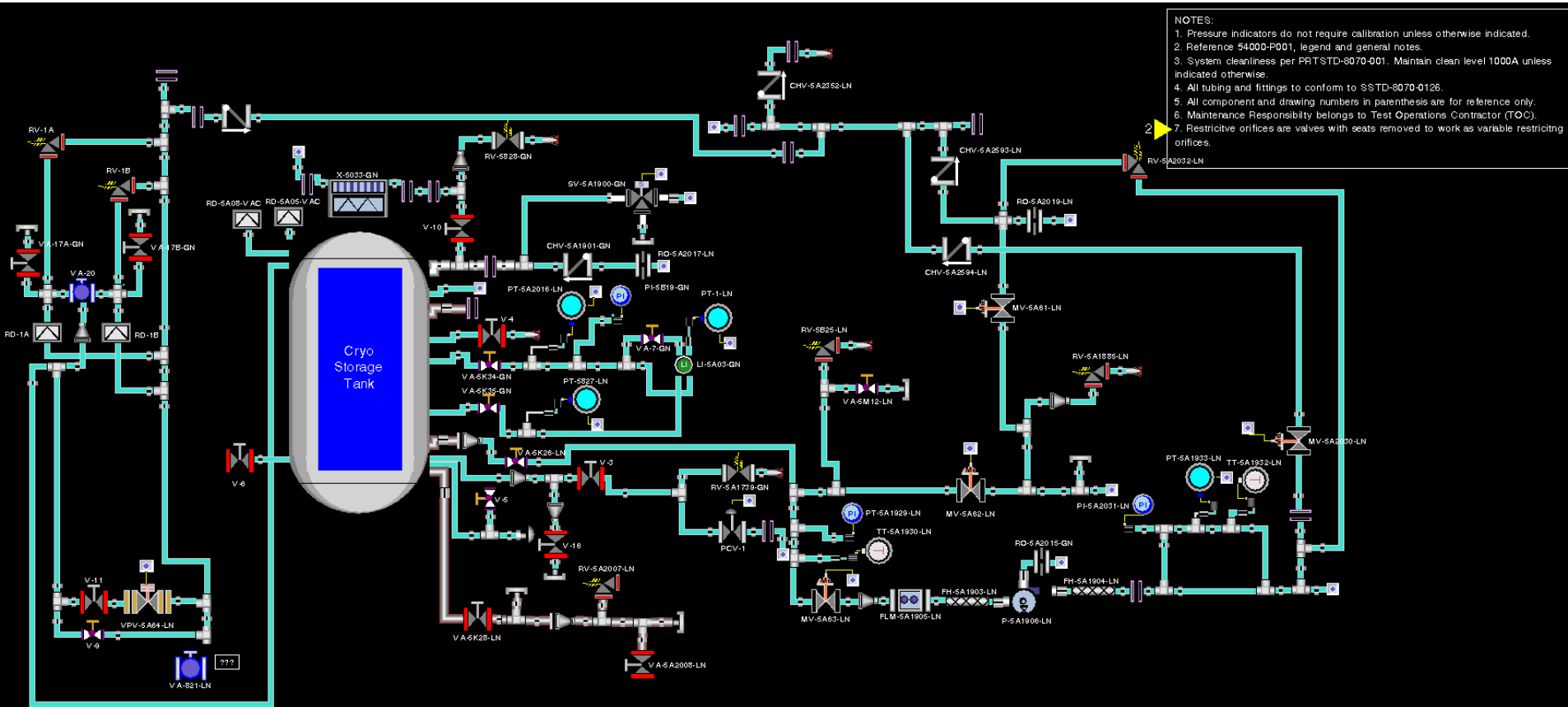


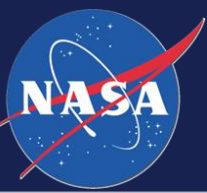
# Domain Models for Autonomy

- **System Domain Model (SDM)**
  - This is the application domain model.
  - Encompasses all elements in the system, generally created from design diagrams (e.g. piping and Instrumentation diagrams or P&IDs).
  - Encapsulates Data, Information, and Knowledge particular to the application.
  - Generally, each schematic sheet corresponds to a workspace of the SDM.
  - Other workspaces are created as user interfaces to provide integrated awareness and control action/operational-visualization capabilities. These workspaces are generally called control screens or ISHM screens. Control and awareness can be combined in a screen if desired.

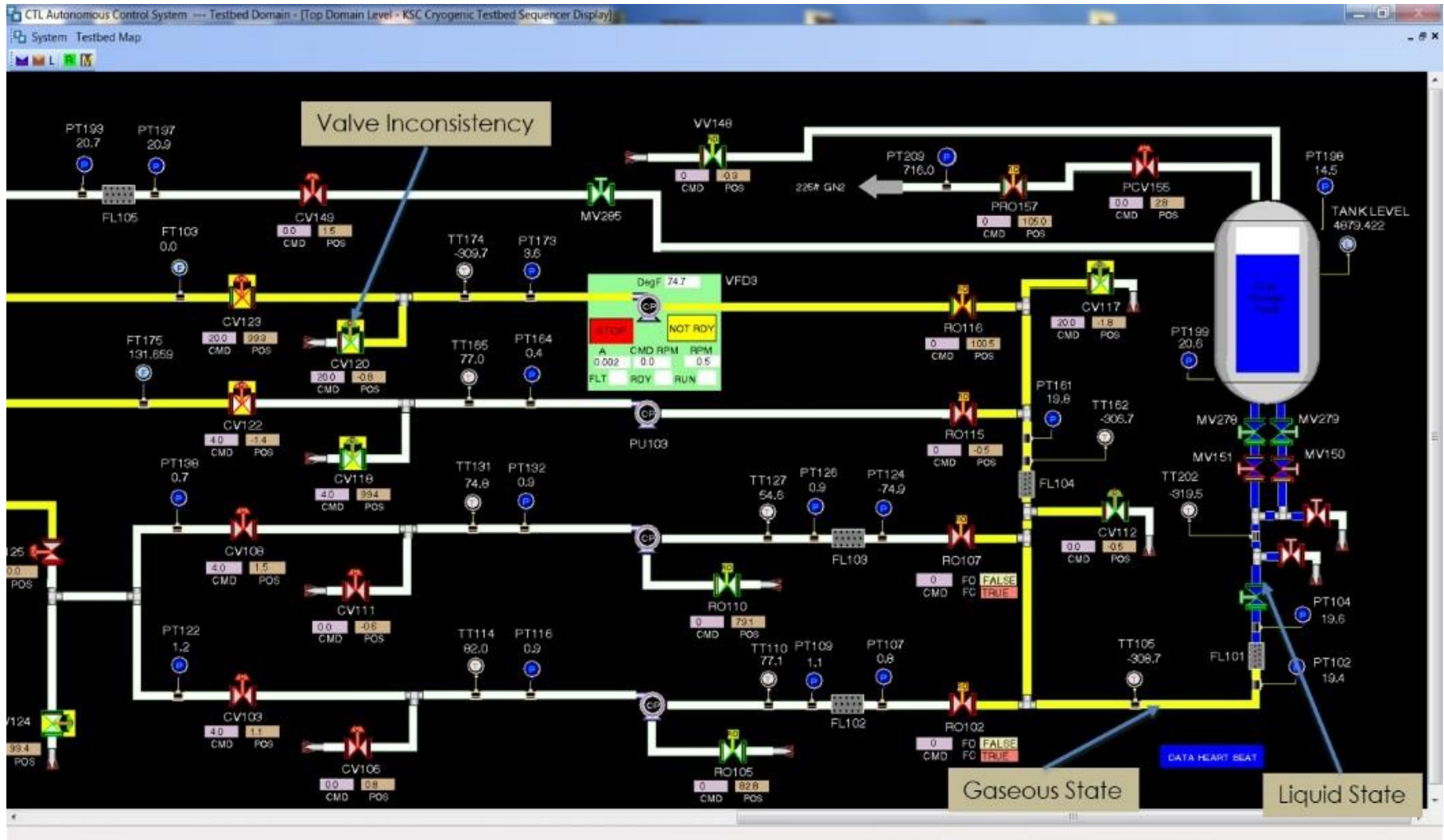


# Example of System Domain Model Workspace





# Example of a Control/Operational-Visualization Workspace





# Domain Models for Autonomy

- **ISHM Domain Model.**
  - Encapsulates knowledge to achieve ISHM functionality (anomaly detection, diagnostics - FMEA, prognostics, user interfaces for integrated awareness.
  - Uses the SDM and updates ISHM parameters in the SDM objects (e.g. health status of a sensor) to be consistent with the current condition of its elements.
  - Incorporates concepts for reasoning and decision making. Most concepts are generic and physics-based. Example concepts include:
    - Concept of pipe networks encompassing connected objects.
    - Concept of a pipe section.
    - Concept of object membership of a pipe section.
    - Concept of object membership of a flow subsystem.



# Domain Models for Autonomy

## ISHM Domain Model (continue).

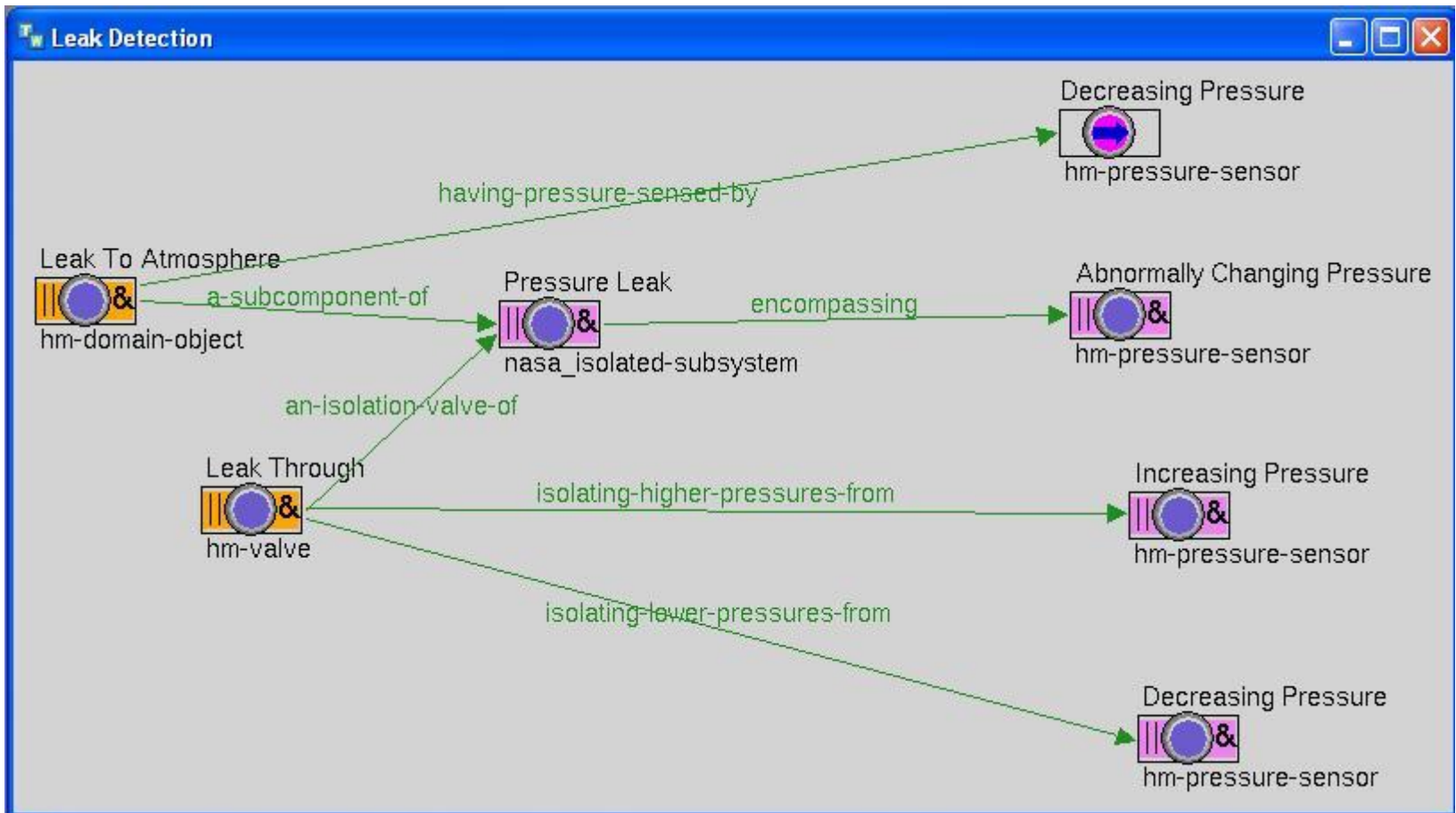
- Anomalies are detected by applying concepts according to the context for processes taking place. The AO-MDS applies generic (physics based concepts) to any system.
  - For example, concepts of physics of flow subsystems from a source of a commodity (e.g. storage tank) to a sink (flight tank) is used for the following purposes.
    - Check for leaks on isolated subsystems (zero flow).
    - Reflect flow measurements from flow sensors to other objects along a flow subsystem.
    - Reflect pressure measurements to predict pressures across valves and apply local models for prediction and anomaly detection.
    - Apply local physics models for anomaly detection and prediction on any element that is member of the flow subsystem (sensors, valves, etc.).



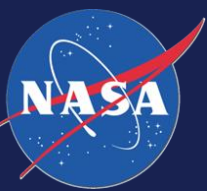
# Domain Models for Autonomy

## ISHM Domain Model (continue).

- Diagnostics is done by implementing root-cause-trees that reflect FMEA cases. Most are generic and thus are reused in all applications.

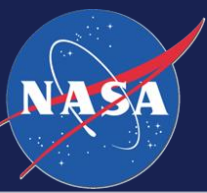






# Domain Models for Autonomy (Continued)

- **Autonomy Domain Model (ADM)**
  - Strategies to enable autonomy.
    - Determination of potential replacement elements (e.g. sensors).
    - Determination of alternate flow paths.
  - Uses DLaK from the SDM and condition information from the IDM.
- **Mission Planning Domain Model (MPDM)**
  - Creation of mission plans to achieve an objective.
  - Real time and autonomous modification of mission plans guided by strategies from the ADM and information from the SDM.
    - For example, if a redline sensor fails, based on availability of a replacement sensor and the current step in a plan, use a proper strategy (from the ADM) to forge toward achieving the mission (the proper strategy may be to use a replacement sensor if available, or to run a plan to place the system in a safe configuration and state).



# Creation of Mission Plans: User interface to create a plan for a mission

Create/Modify Sequence Plan - Suction Line Chilldown 07192013 1055EST

Current Sequence Plan

	Trigger	Boolean	Condition	Timer	Parameter	SetPoint	CAM
Step-1				0.0			
Step-1					RO116	100.0	
Step-1					CV117	25.0	
Step-1					CV112	10.0	
Step-2	TT105	Less Than	-280.0				
Step-2				5.0			
Step-2					CV112	0.0	
Step-3	TT162	Less Than	-280.0				
Step-3				5.0			
Step-3					CV117	0.0	

Create Saturation Condition   Red Line Activate/Deactivate   Timer

Create Condition

TT174   Less Than   95.5   Add Step Condition

CURRENT CONDITIONS

	Trigger	Boolean	Condition
Step-8	TT174	Less Than	300.0

SELECT CONDITION TO DELETE

TT174

Create Camera View

Add Device View

CHV109

View: Unknown

Delete View

SET VALVE/PUMP SETPOINTS

PCV155   10.0    Open   Create Valve/Pump Setpoint

Closed

Variable

CURRENT SETPOINTS

	Valve/Pump	Setpoint
--	------------	----------

SELECT SETPOINT TO DELETE

Save Plan   Save Current Plan

Load Plan   Show Graphical Plan

Delete Step

Step-8

Sequence

Define Saturation Redlines Timers

Define Sensor Trigger conditions

Define Valve and Pump Actions

Camera View Definition

Save and Load Sequences

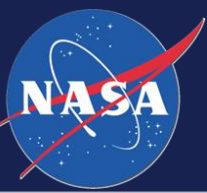


# Reusability

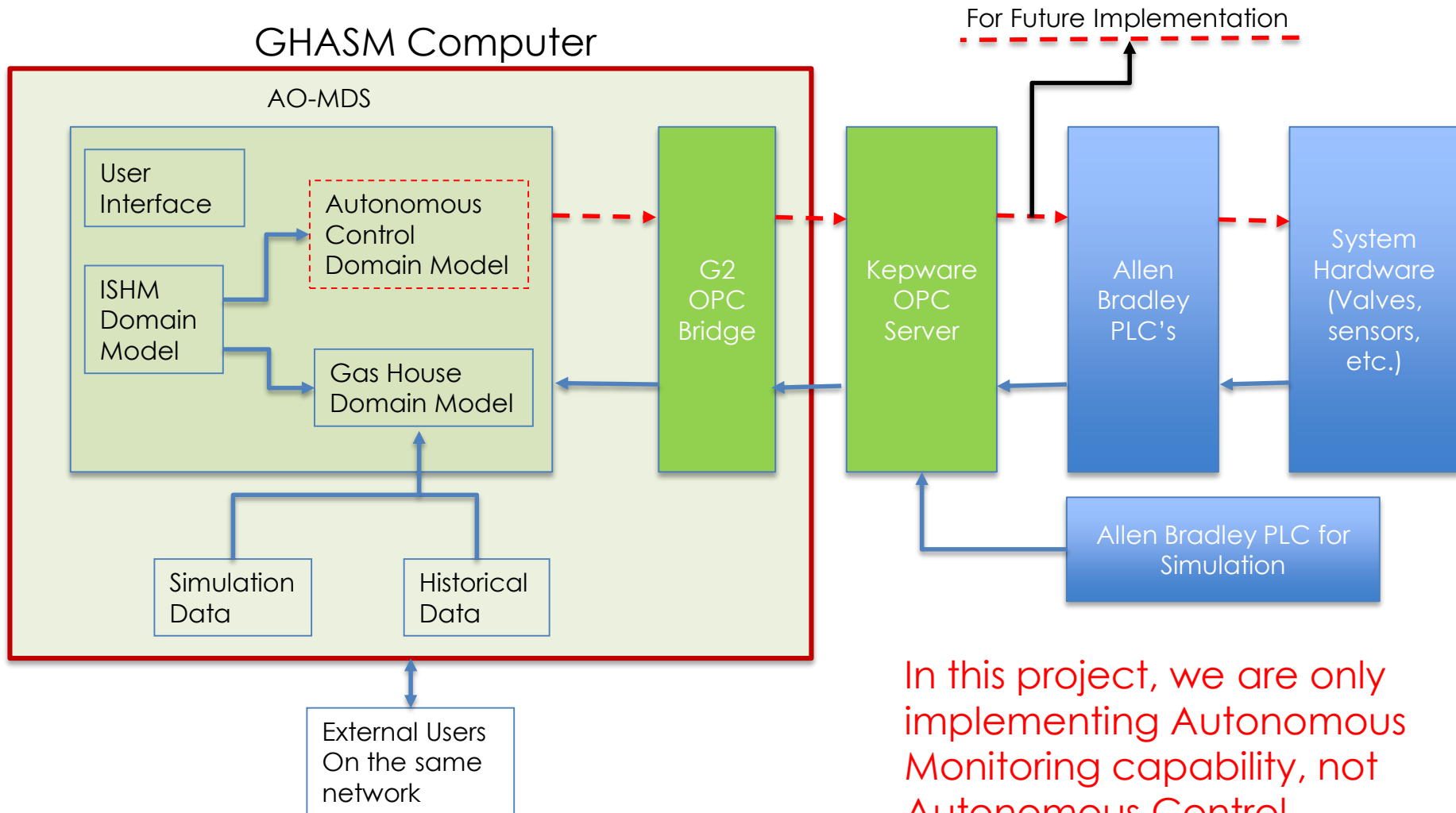
- **Code in the IDM and the ADM is fully reusable.**
- **DiAK to implement autonomy has a substantial portion of re-usable code in the SDM and MPDM.**
- **Strategies for health management and autonomy can be applied to many classes of systems.**
- **The reason is that these strategies are founded in engineering principles that apply to classes of systems.**
- **For example a leak detection strategy monitors isolated subsystems (subsystems isolated by valves that are closed), and detects if pressures are not steady. This is a special case of a flow system with zero flow and can apply to fluid and electrical systems.**



# Implementation Process



# GHASM Software Architecture



In this project, we are only implementing Autonomous Monitoring capability, not Autonomous Control.



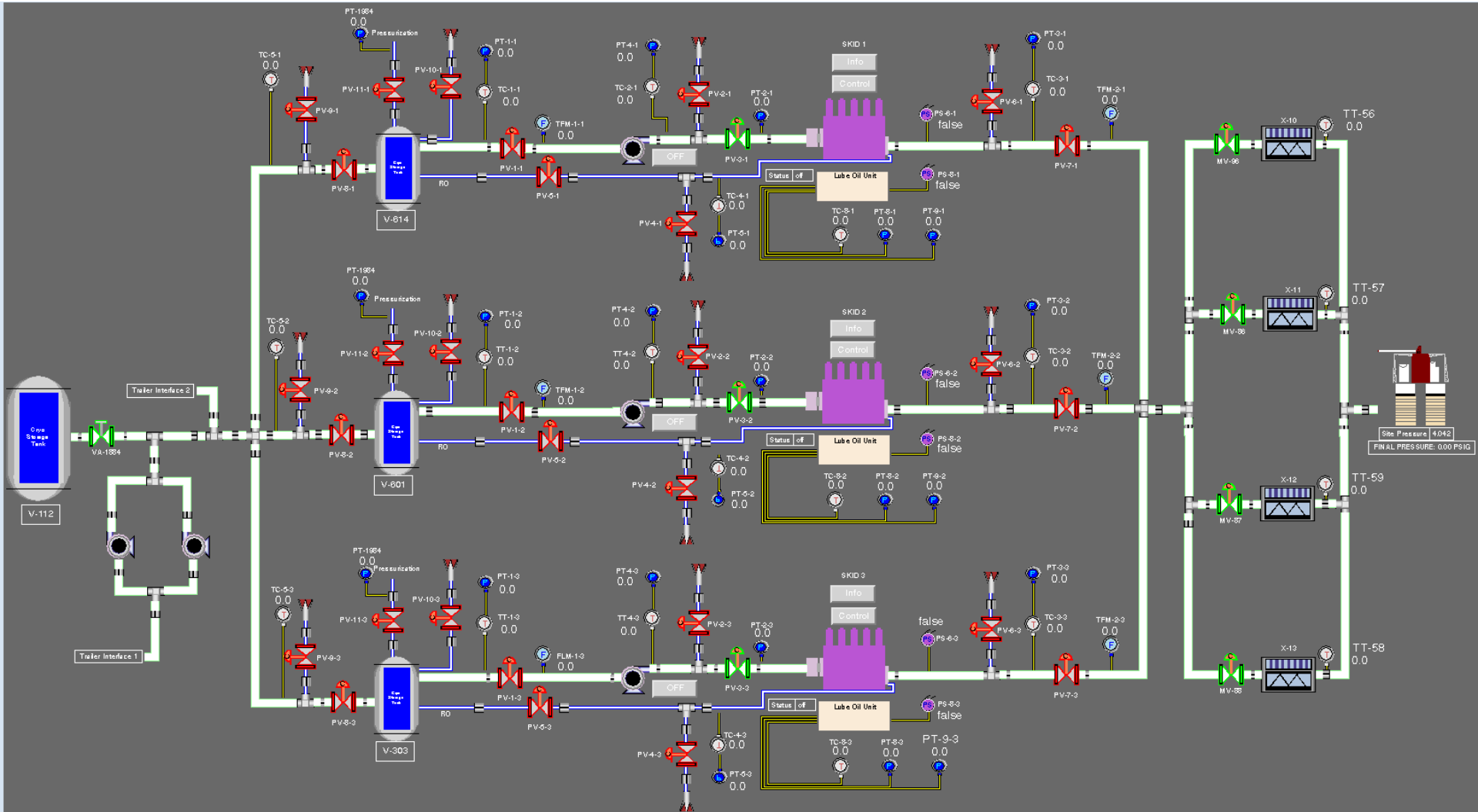
# Implementation of AO Capability

- **Create the System Domain Model by re-creating the schematic sheets in the AO-MDS. This results in a knowledge-base that includes data and information about each element of the system (sensors, components, etc.). Each schematic sheet corresponds to a “Workspace” in the AO-MDS ( a schematic workspace).**
  - Schematic workspaces can be navigated by selecting icons in the main workspace, or by clicking on ports on pipes, or other elements that are continued in other workspaces (as indicated in the schematic sheets). In this manner, schematic workspaces become knowledge representations of the system, and not just drawings. These workspaces can be used to quickly navigate to any element, and to do typical knowledge-base inquiries (e.g. list all pressure sensors attached to pipe x, or go to sensor x).

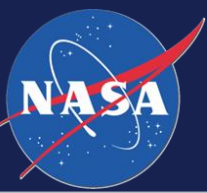




# Nitrogen System Control Screen

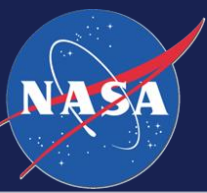






# ORION EFT-1 Capsule





# ORION EFT-1 Completed



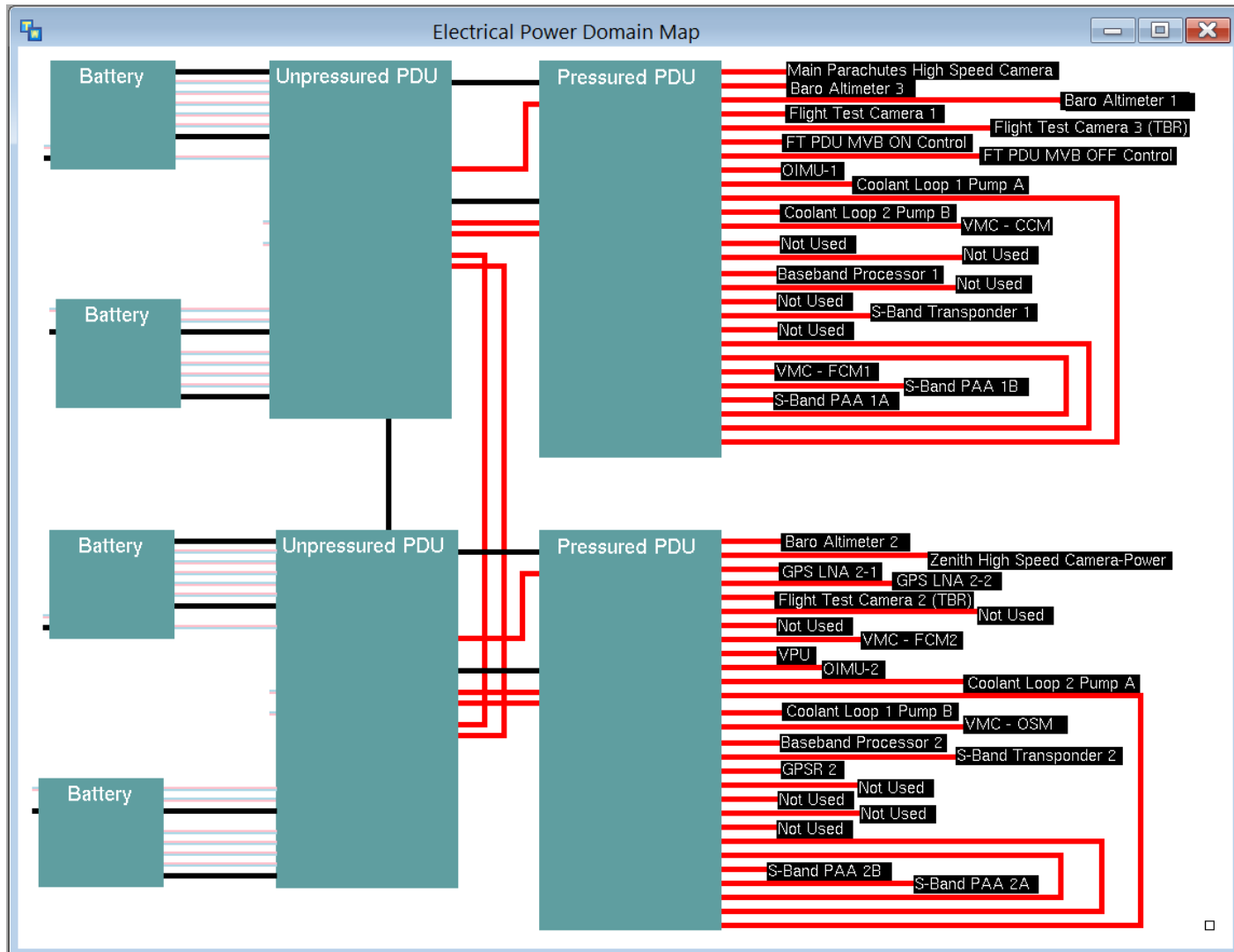


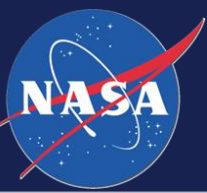
# ORION EFT-1 Splashdown





# ORION EFT-1 Electrical Power Domain Model





# Implementation of AO Capability

- **Create the Mission Planning Domain Model (MPDM) by creating the sequences that must be run to achieve the mission objectives.**
  - Each plan is created using a menu-based user interface that is intuitive. A plan is a series of steps.
  - For each step, conditions (temperature sensor  $A > x$ ) and actions (Open Valve  $V$  10%) are defined; such that when the conditions are met, the actions are executed.
  - Actions may include sending commands to external resources such as camera systems to point in a particular direction.
  - Timers can be used to check if values are stable over a period of time as a condition to move forward with the plan.



# Autonomous Operation Sequence Creation

Create/Modify Sequence Plan - Suction Line Chilldown 07192013 1055EST

Current Sequence Plan

	Trigger	Boolean	Condition	Timer	Parameter	SetPoint	CAM
Step-1				0.0			
Step-1					RO116	100.0	
Step-1					CV117	25.0	
Step-1					CV112	10.0	
Step-2	TT105	Less Than	-280.0				
Step-2				5.0			
Step-2					CV112	0.0	
Step-3	TT162	Less Than	-280.0				
Step-3				5.0			
Step-3					CV117	0.0	

Create Saturation Condition   Red Line Activate/Deactivate   Timer

Create Condition

TT174   Less Than   95.5   Add Step Condition

CURRENT CONDITIONS

	Trigger	Boolean	Condition
Step-8	TT174	Less Than	300.0

SELECT CONDITION TO DELETE

TT174

Create Camera View

Add Device View

CHV109

View: Unknown

Delete View

SET VALVE/PUMP SETPOINTS

PCV155   10.0    Open    Closed    Variable   Create Valve/Pump Setpoint

CURRENT SETPOINTS

	Valve/Pump	Setpoint
--	------------	----------

SELECT SETPOINT TO DELETE

Save Plan   Save Current Plan

Load Plan   Show Graphical Plan

Delete Step

Step-8

Sequence

Define Saturation Redlines Timers

Define Sensor Trigger conditions

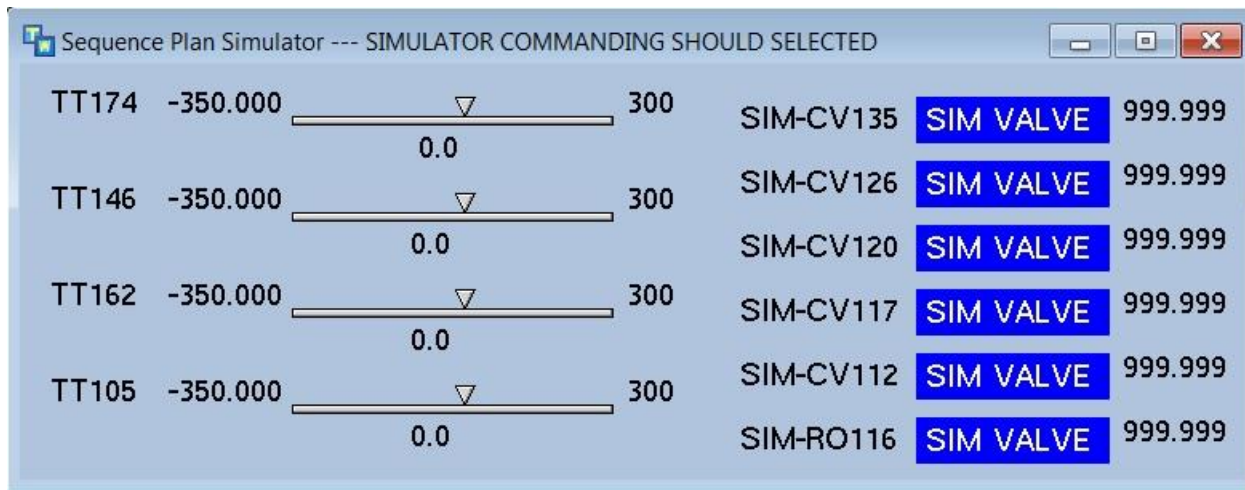
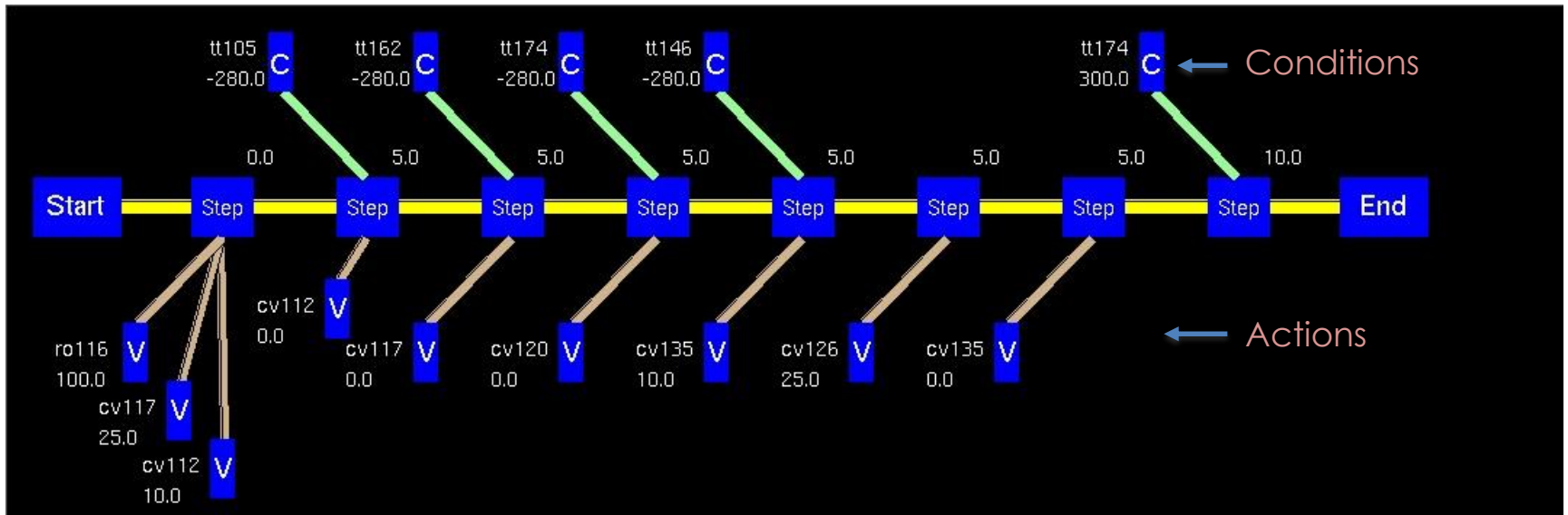
Define Valve and Pump Actions

Camera View Definition

Save and Load Sequences



# Autonomous Operation Sequence Simulation





# Implementation of AO Capability

- **Redlines and monitors** can be activated and de-activated in any step. In this manner, redline/monitor triggers are interpreted and acted upon during relevant activities. The SDM can include virtual sensors defined to detect critical events during a specific part of an operation (e.g. a critical valve failure during tank replenish). These virtual sensors can be defined as redline sensors and start appropriate action when triggered.
- **Programs can be started and ended** as actions of a step (e.g. a program to maintain level of commodity in a tank).
- **A mission, such as loading of the flight tanks, may have multiple sequences that run simultaneously** (liquid oxygen loading, liquid methane loading, actuation supply pressure, power management, etc.). Moreover, The mission plans can address objects from any System Domain Model.





# Autonomous Operation: Monitor/Redline Creation

**Data Monitor Configuration** [X]

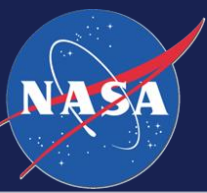
PT-8-O2  
 PT-9-CH  
 PT-9-O2  
 SAT\_PT161  
 SAT\_TT162  
 **TT105**  
 TT110  
 TT111  
 TT112  
 TT113  
 TT114  
 TT127  
 TT128  
 TT129  
 TT130  
 TT131  
 TT146  
 TT149  
 TT156  
 TT162  
 TT165  
 TT174  
 TT191  
 TT194  
 TT-1-CH  
 TT-1-O2  
 TT-1X10-O2

Start Hours: 0 Start Minutes: 0 Start Seconds: 0 Red Line:   
End Hours: 0 End Minutes: 0 End Seconds: 0  
No Time Limit:  Limits Color: blue  
STEP: None Found Line Color: green

**Maximum Value**  
Enabled:  Setting: -200  
Condition: lower threshold

**Minimum Value**  
Enabled:  Settings: 0  
Condition: Enter Low Red Line Condition Here.

Save Changes Delete Next Create Current Monitor: 0  
Monitor Name: tt105-lower-threshold Total Monitors: 0



# Implementation of AO Capability

- **Execute the Mission Plans in the Mission Planning Domain Model (MPDM) to achieve the mission objectives.**
  - Multiple plans that encompass a mission can be run simultaneously. Each have a user interface showing executed steps, current step, and remaining steps.
  - Interactions among systems (e.g. liquid oxygen and methane) are incorporated in the plans by addressing conditions, redlines, programs, secondary sequences, etc. that reflect how these systems interact.
  - Autonomy is achieved when plans use autonomy strategies and resources provided by the Autonomy Domain Model (ADM). For example, availability of replacement sensors for failed ones, analysis to ascertain available resources and their quality (power supply, pressure supply, etc.).



# Autonomous Operation Sequence Execution

SEQUENCE PLAN CONTROL - Simple\_RL\_Nominal\_Short\_CVCond\_wTimer\_wPump\_v3

## STEPS EXECUTED

	Step Label	Trigger	Boolean	Condition	Timer	Valve	Set Point	CAM View
Step-2-3						CV120	75.0	
Step-2-3	1030				13.0			
Step-2-3		TT174	Less Than	-125.0				
Step-2-3		CV112.POSITION	Greater Than	20.0				
Step-2-3		CV117.POSITION	Greater Than	95.0				
Step-2-3		RO116.POSITION	Greater Than	95.0				
Step-2-2						CV117	100.0	
Step-2-2						CV112	25.0	
Step-2-2						RO116	100.0	
Step-2-2						TIMER-1	0.0	
Step-2-2	1020				12.0			
Step-2-2		PT199	Greater Than	9.5				

STATUS: RESET

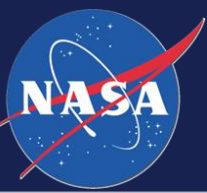
ACTIVE STEP      COUNTDOWN TO ACTIVATE STEP: 0 Seconds

	Step Label	Trigger	Boolean	Condition	Timer	Valve	Set Point	CAM View
Step-2-4		CV120.POSITION	Less Than	80.0				
Step-2-4		TT162	Less Than	-280.0				
Step-2-4						LC155	15.0	
Step-2-4						CV112	0.0	
Step-2-4	1040				0.0			



# Integrated System Awareness

- **Integrated Awareness. Beyond the plan execution and simulation windows, the following items provide additional awareness about the system.**
  - Monitor/Reline window: showing all monitors/redlines, their active/inactive status, the action to take place when triggered, availability of replacement sensor, and whether a replacement sensor is in use in place of the original sensor.
  - A console that displays health management and execution events, e.g. sensor failures, valve anomalies, results of component health checks prior to execution of plans, etc. These events are also logged into a file, indicating the time when they occurred.



# Autonomous Operation: Monitors and Console

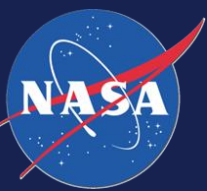
ALL Monitors - Click STATUS to manually ACTIVATE/DEACTIVATE --- Click PLAN to SELECT PLAN or set to NO PLAN

	Status	State	Alternate	Plan	Triggered	Lower Limit Active	Lower Limit	Higher Limit Active	Higher Limit
PT-9-CH	Activated	HEALTHY	PT-10-CH	Adv_to_Shutdown	Not Triggered	Yes	-100.0	No	0.0
TT105	Triggered	HEALTHY	UNKNOWN	emergency1	5/20/15 11:38:26 a.m.	No	0.0	Yes	-200.0
PT-10-O2	Deactivate	HEALTHY	UNKNOWN	multiple-test-plan-2	Not Triggered	No	0.0	Yes	25.0

Console

Options Delete Msgs  Active  Log

Time	Message
5/20/15 11:39:11 ...	Logging to c:\ishm-nasa-toolkit\log\5M-20D-11-39-log.txt
5/20/15 11:38:26 ...	All sequence plan sensors are healthy
5/20/15 11:38:26 ...	All sequence plan sensors are healthy
5/20/15 11:38:26 ...	RED Line Monitor tt105-lower-threshold triggered by TT105 has exceeded high thres

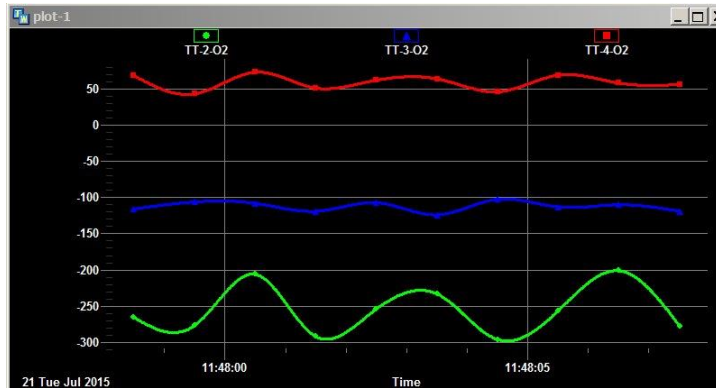


# Autonomous Operations: Real-Time Plotting

- **The AO-MDS supports real-time plotting of sensor readings, valve commands and position feedback, valve indicator values, etc.**
- **Multiple plots can be defined and shown at any time.**
  - Plots can be placed anywhere on the user interface screens.
- **Each plot may contain multiple signals and scales.**
- **Max/Min values of scales can be defined manually and modified in real-time.**
- **The number of samples to be shown in each plot can be defined manually in real-time (time window).**
- **Plots can show the operational stages of a plan along with the data (e.g. Chill-down Stage or Slow Fill Stage). This provides context to the data displayed.**



# Autonomous Operation: Real-Time Plotting



Create/Modify/Delete Plot

Select Plot: plot1

Create New Plot plot1

Delete Plot Modify Plot

Select Plan: No Plan

From Phase: All Data

To Phase: All Data

Start Hours 0 Start Minutes 0 Start Seconds 0 Total Points 10  Auto Scaling  1 Scale  2 Scales  3 Scales

Axis 1 MAX 100 Axis 2 MAX 100 Axis 3 MAX 100

Axis 1 MIN -330 Axis 2 MIN -330 Axis 3 MIN -330

Current Plot Sensors, Select Sensor to Remove

- TT-2-02
- TT-3-02
- TT-4-02

Select Sensor to add to Plot

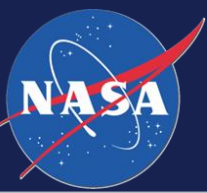
- TT-1531-02
- TT-1532-02
- TT-1533-02
- TT-2-CH
- TT-2-02
- TT-3-CH
- TT-3-02
- TT-4-CH
- TT-4-02**
- TT-5-CH
- TT-5-02
- TT-6504-CH



# User Interfaces

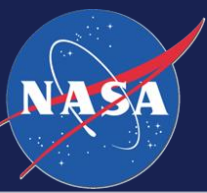
- **AO-MDS includes the ability to quickly create user interfaces that suit specific needs for an application and mission.**
- **User interfaces provide visibility to desired events and information; and enable manual control activities according to Con-Ops and/or exploring details of information presented (anomalies, redlines triggered, etc.).**





# Evolution

- **AO-MDS encompasses a software architecture and tools that embody inherently systematic evolution of autonomy, as well as systematic and natural scalability to implement autonomy in large systems of systems (e.g. space stations, planetary settlements, etc.).**
- **For example, any time there is a new strategy to determine that a sensor is faulty, one is able to implement that strategy and make it part of the existing knowledge base of the domain model in a systematic manner, without affecting existing code. And the new strategy is integrated immediately.**



# Conclusions

- **AO-MDS addresses all aspects of implementation of autonomous operations. Moreover, it enables degrees of autonomy as defined in concepts of operations of system applications.**
- **AO-MDS enables scripting of concept/model based autonomous operations strategies, in contrast with brute-force scripting of all possible combinations of strategies to deal with all combinations of unplanned scenarios.**
- **AO-MDS embodies GUI's and tools that enable implementation of autonomy by non-G2 programmers.**



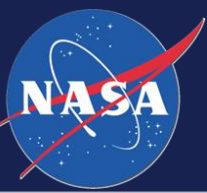
# Backup Slides



# Autonomous Control Sequence Capability

## Sequence Creation, loading, and execution

- a. Sequences can be seen as mission plans.
- b. The system enables quick and easy creation of sequences with menus.
- c. Sequences are represented in tabular and graphical formats.
- d. Sequences can be verified by simulating conditions that enable actions to be executed.
- e. Sequences can be saved and loaded as needed.
- f. Sequence conditions include:
  - Sensor triggers.
  - Redline triggers.
  - Fluid saturation state.
  - Redline sensor failure
  - May include other conditions from health or other algorithm outcomes.
- g. Sequence actions include:
  - Valve and pump operations.
  - Camera pointing.
  - Execution of special sequences such as shut-down or reverting to a prior step.
  - May include execution of any sequence that responds to system conditions and planning.



# CTL System Description

- **HM-PIPE: 2168 (Pipe elements)**
- **HM-PRESSURE-SENSOR: 62 (Pressure Sensors)**
- **HM-TEMPERATURE-SENSOR: 22 (Temperature Sensors)**
- **HM-VALVE: 286 (Valves)**
- **HM-ELECTRICAL-CONNECTION: 100 (Electrical Connections)**