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

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SSC Gas House Implementation
• 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.
• 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.
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.
Autonomy Software Functional Architecture with Domain Models

Operational Plans use Application Domain Model

Application

System Domain Model (SDM) (The Application)

Use

Autonomy Domain Model (ADM)

Autonomy Strategies

Use

Autonomous plan modifications

Enables Autonomy

Mission Planning Domain Model (MPDM)

Update SDM

Sensor and Component Health

ISHM Domain Model (IDM)

Autonomous Plan Sequence

Mission
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).
• **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

Valve Inconsistency

Gaseous State

Liquid State
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.
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.).
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

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.
• Dlak 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.
In this project, we are only implementing Autonomous Monitoring capability, not Autonomous Control.
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).
Example of System Domain Model Workspace: Top Domain Map
ORION EFT-1 Splashdown
ORION EFT-1 Electrical Power Domain Model

[Image of Electrical Power Domain Map]

Battery -- Unpressured PDU -- Pressured PDU

- Main Parachutes High Speed Camera
- Baro Altimeter 3
- Flight Test Camera 1
- ET PDU MVB DN Control
- ET PDU MVB OFF Control
- OIMU-1
- Coolant Loop 1 Pump A
- Coolant Loop 2 Pump B
- VMC - CCM
- Not Used
- Baseband Processor 1
- Not Used
- Not Used
- S-Band Transponder 1
- Not Used
- MVM - FCM1
- S-Band PAA 1A

Battery -- Unpressured PDU -- Pressured PDU

- Baro Altimeter 2
- GPS LNA 2-1
- GPS LNA 2-2
- Flight Test Camera 2 (TBR)
- Not Used
- VMC - FCM2
- WPU
- OIMU-2
- Coolant Loop 1 Pump A
- VMC - DSM
- Baseband Processor 2
- S-Band Transponder 2
- Not Used
- Not Used
- Not Used
- S-Band PAA 2B
- S-Band PAA 2A
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

Sequence
Define Saturation Redlines Timers
Define Sensor Trigger conditions
Define Valve and Pump Actions

Camera View Definition
Save and Load Sequences

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

Conditions

Actions

Sequence Plan Simulator --- SIMULATOR COMMANING SHOULD SELECTED

<table>
<thead>
<tr>
<th>TT174</th>
<th>-350.000</th>
<th>▼</th>
<th>300</th>
<th>SIM-CV135</th>
<th>SIM VALVE</th>
<th>999.999</th>
</tr>
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<tbody>
<tr>
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<td>▼</td>
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<td>▼</td>
<td>300</td>
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<td>SIM VALVE</td>
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<td>▼</td>
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<td></td>
<td></td>
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<td>SIM VALVE</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>SIM-RO116</td>
<td>SIM VALVE</td>
<td>999.999</td>
</tr>
</tbody>
</table>
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.
• 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

### STEP EXECUTED

<table>
<thead>
<tr>
<th>Step Label</th>
<th>Trigger</th>
<th>Boolean</th>
<th>Condition</th>
<th>Timer</th>
<th>Valve</th>
<th>Set Point</th>
<th>CAM View</th>
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<tbody>
<tr>
<td>Step-2-3</td>
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<td></td>
<td></td>
<td></td>
<td>CV120</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>CV112</td>
<td>100.0</td>
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</tr>
</tbody>
</table>

### STATUS: RESET

- **START**
- **RESET**
- **PAUSE**
- **RESUME**
- **FORCE STEP ADVANCE**
- **SENSOR HEALTH CHECK**

**ACTIVE STEP**

**COUNTDOWN TO ACTIVATE STEP:** 0 Seconds

<table>
<thead>
<tr>
<th>Step Label</th>
<th>Trigger</th>
<th>Boolean</th>
<th>Condition</th>
<th>Timer</th>
<th>Valve</th>
<th>Set Point</th>
<th>CAM View</th>
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<tbody>
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<td></td>
<td>CV120</td>
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<tr>
<td>Step-2-4</td>
<td></td>
<td></td>
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<td></td>
<td>TT162</td>
<td>Less Than</td>
<td>-280.0</td>
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<td>Step-2-4</td>
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<td></td>
<td></td>
<td></td>
<td>CV112</td>
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<td>Step-2-4</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Status</th>
<th>State</th>
<th>Alternate</th>
<th>Plan</th>
<th>Triggered</th>
<th>Lower Limit Active</th>
<th>Lower Limit</th>
<th>Higher Limit Active</th>
<th>Higher Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT-9-CH</td>
<td>HEALTHY</td>
<td>PT-10-CH</td>
<td>Adv_to_Shutdown</td>
<td>Not Triggered</td>
<td>Yes</td>
<td>-100.0</td>
<td>No</td>
<td>0.0</td>
</tr>
<tr>
<td>TT105</td>
<td>HEALTHY</td>
<td>UNKNOWN</td>
<td>emergency1</td>
<td>5/20/15 11:38:25 a.m.</td>
<td>No</td>
<td>0.0</td>
<td>Yes</td>
<td>-200.0</td>
</tr>
<tr>
<td>PT-10-O2</td>
<td>Deactivate</td>
<td>HEALTHY</td>
<td>multiple-test-plan-2</td>
<td>Not Triggered</td>
<td>No</td>
<td>0.0</td>
<td>Yes</td>
<td>25.0</td>
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</tbody>
</table>

### Console

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

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-4-02
TT-1531-02
TT-1532-02
TT-1533-02
TT-2-CH
TT-2-O2
TT-3-CH
TT-3-O2
TT-4-CH
TT-5-CH
TT-5-O2
TT-6504-CH

RELEASED - Printed documents may be obsolete; validate prior to use.
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.).
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.
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.
• 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)