Integrated System for Health Management and Autonomous Control (ISHM-AC) for Cryogenic Operations on the Simulated Propellant Loading System

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Autonomous control systems represent a technological barrier from manual and automated operated control systems in an industry wide application. An increase in energy-efficient storage, transfer and use of cryogens and cryogenic propellants on Earth and in space has been observed in space related industries between NASA, government and commercial programs. An increase in efficiency of cryogenic systems demands an increase in the capabilities of the control and monitoring system that manages them. As new technologies are developed for cryogenic systems, complexity and capability increases. The increase in complexities are a natural drive to develop better and more capable health monitoring and control system management. Current research and development efforts lead the Cryogenics Test Laboratory at the Kennedy Space Center to improve its automated control and health monitoring system from a Programmable Logic Control (PLC) based-only system to a fully Integrated System for Health Management (ISHM) - Autonomous Control (AC) capable of performing autonomous operations on a cryogenic propellant transfer system. This ISHM-AC system has been developed and tested by controlling a complete simulated propellant transfer operation. The capabilities and test results of this fully integrated autonomous system for cryogenics propellant transfer operation will be presented in this paper.

I. Introduction

TEchnology development of intelligent software systems that increases the capabilities of a hardware component on fielded applications is a dynamic field constantly being explored by industry and goverment agencies. The ability to enhance the capabilities of health manangement and prognostics provided by intelligent systems have been embraced by a wide variety of industrial applications. The space program have been using health management to improve relialability under real time flight environment for the space shuttle main engines (Ref. 1-2). As part of NASA's vision aimed at exploring far and beyond, improvements to ground support systems for future vehicles must be addressed. One of the main areas being encouraged by the NASA Advance Exploration Systems (AES) program is the technology infusion of intelligent system in space related applications. In order to validate the application of real time intelligent systems into a operational hardware, a testbed is needed to increate the Techonology Readiness Level of intelligent system. Several platforms for testing rocket engines can be found at NASA Stennis Space Center

(Ref. 3-4) and NASA Johnson Space Center (Ref. 5-6). The Cryogenic Test Laboratory at NASA Kennedy Space Center has developed the Simulated Propellant Loading System (SPLS) with the purpose of testing new technologies aimed to improve integrated ground support systems for cryogenic propellant loading operations (Ref. 7). The test capabilities of this test platform allows for health monitoring intelligent system to evolve their state of the art into autonomous systems by developing integrated command and control features. This command and control capabilities combined with an integrated system of health monitoring (ISHM) enhances the use of intelligent systems on space applications. This control functionality enhancement provides the system with the power of self-govern, making the system an autonomous control system (Ref. 8). The integration of automated control and health monitoring capabilities provides a system capable of performing autonomous control operations.

The Cryogenic Test Laboratory at NASA Kennedy Space Center has taken the task of exploring the automated control and health monitoring concepts to develop autonomous control operations on SPLS. The development, testing validation efforts resulted on the autonomous control opertation tool known as the Integrated System for Health Management and Autonomous Control (ISHM-AC). Managing a simulated cryogenic propellant transfer operations by controlling the SPLS under laboratory conditions allowed this technology to increase its maturity level to be used on real cryogenic propellant transfer operations. The development and application of the ISHM-AC for Cryogenic Operations on the Simulated Propellant Loading System is presented in this paper.

II. Project Overview

The Integrated Ground Operations Demonstration Unit (IGODU) project is intended to demonstrate the ability to quickly develop a control system that can provide autonomous control of cryogenic tanking operations using a Commercial-Off-The-Shelf (COTS) software product called G2 (Gensym Corporation) augmented with a layer for ISHM called ISHM Toolkit (Ref. 9).

To accomplish this, the ISHM-AC capability for an Autonomous Propellant Loading (APL) system will be developed. This ISHM-AC capability will provide information on the health of every element of the system, such as sensors, actuators, pipes, pumps, tanks, valves, etc. It will also include Autonomous Control (AC) that executes control sequences after evaluating conditions, including health conditions of system elements involved in sequence executions. The scope of this software project involves the programmatic integration of autonomous sequence control, hardware component commanding and health monitoring in one application. The objective of this software will be for the ISHM-AC system to perform monitoring, health management and limited non-hazardous cryogenic system commanding of the SPLS cryogenic hardware system located at the Cryogenics Test Laboratory (CTL). A demonstration of these capabilities will be achieved through the use of a test sequencer that will perform autonomous control of Liquid Nitrogen (LN2) cryogenic tank loading and de-tanking operations against the actual cryogenics hardware. Additionally in the CTL, alongside and independent of the ISHM-AC software, an Allen Bradley (Programmable Logic Controller (PLC) software suite is available as a backup to monitor PLC tag telemetry common to both.

III. Software Design Description

Some of the main modules that constitute the ISHM-AC are the following: Top Level, Engine, Sequencer, NASA Library, Bridge, Domain Object Libraries, Redline Monitoring, OPC Bridge, Real Time Engine, Redundacy Model, Sensor Model, Autonomous Engine and other supporting modules. Each module is saved as a Knowledge Base (KB) file (a G2 specific format); the KB file format is a proprietary binary file that is created, modified, and used by the G2 COTS tool. KBs contain logical sets of related information.

Each module developed in G2 contains all or some combination of the following: rules, methods, procedures, Graphical User Interfaces (GUIs), objects, class definitions and workspaces. Rules, procedures, and methods set up the behavioral functionality of objects in the real-time environment. Procedures and methods are named objects that execute a sequence of actions including, but not limited to, calling other methods, procedures, and setting parameters. Each method is associated with a given class and procedures are not associated with classes. GUIs allow the user to interact with the system. Objects represent physical components in the system, within the application. Class definitions define the attributes of objects and the associated methods. Workspaces are where objects exist within the application and they contain the application objects representing physical components and their connections.

The high level architecture of ISHM-AC is illustrated in **Figure 1**. This architecture includes the deployed application for the Integrated Ground Operations Demonstration Unit (IGODU) project composed of the SPLS.

A. ISHM-AC Software Components

1. Top Level

The Top Level module is responsible for the management of the integrated development environment (IDE), initialization of application software components, management of launching procedures to initiate the execution of the AOS module hierarchy, and the functionality for creating and closing the telewindows connection that is required for running G2.

2. Sequencer

The Sequencer is the module responsible for executing sequential commands that can be scripted to represent an operation. Steps execute commands when conditions of state and health are met; and alternate plans may be selected autonomously to achieve the final objectives of a plan, in spite of unforeseen anomalies.

3. Domain Object Libraries

This module contains the domain object elements used to build domain maps. A domain map is a user interface to the application domain model consisting of every element of the system represented as an object. Domain objects are connected according to schematics, and incorporate data, information, and knowledge about the system.

In addition to the domain map, a subcategory of this map is the control map. This map uses information available on the domain map to monitor telemetry obtained from the instrumentation of hardware. The control map is capable of executing command and control of command-supported elements in the system which includes valves and setpoints. In addition, the control map provides the user with a visual interface to monitor the progress of a cryogenic propellant transfer operation.

4. Real Time Engine

The Engine module is the driver used to execute the rules and procedures necessary to run the application. This module manages data, transferred from external raw signal and stored to domain object elements, which presents the knowledge of the external system. In addition, it executes procedures necessary to interact with real-time data recorded on the systems, processes the end-user operational control map, executes redline monitoring, the plotting features, and proper mapping between communication elements and domain object elements.

5. Redline Monitoring

Redline monitors are limit threshold values referenced with a sensor or a combinations of sensors. The redline elements perform monitoring activities across the system. The triggering of the redline monitors produce alerts and execute safing plans. Redlines can pause a main sequence and execute an advance to shutdown safing plan to protect the system from undesirable conditions.

6. OPC Bridge

This module is responsible for establishing communication protocols with external interfaces. The OPC Bridge manages Space Packet Protocol (SPP) data transfer (incoming and outgoing) using the G2 Gateway Standard Interface (GSI) by interfacing objects to an external tool called the AOS Bridge. These objects create an interaction with any external system that can manage telemetry in the specified format. In this case, this module contains all the GSI data object elements involved in a specific application. Data object elements can be divided into telemetry and command elements.

7. NASA Library

This module is responsible for the integrated system for health management (ISHM). ISHM is fundamentally linked to the management of data, information, and knowledge (DIaK) with the purposeful objective of determining the health of a system (Ref. 10). Within this module a machine state analysis is performed over the command and telemetry of the elements, such as valves and sensors, to determine health. In addition, several physics localized models are being managed under this module to determine saturation conditions of cryogenic commodity, valve state assessment, valve consistency, health assessment and failure modes. This module is constantly assessing the conditions of the system to determine an appropriate response. This module can determine instrumentation-only failure according to several parameters and sensors, as well as mechanical failures.

8. Sensor Based Reasoning Model

Metadata for compoment specifications are used to build a sensor model that exhibits the operational capabilities of the sensor during nominal operations. These operational capabilities are bound by limits of the design on the sensor component. This model performs synchronous monitoring of sensor-native-telemetry data to ensure the operational use of the sensor, based on its specifications. If the sensor violates its operational specifications, it is deemed inoperable.

9. Alternate Sensor Redundancy Model

This module is responsible for performing recursive operations across piping sections and flow subsystems model results provided by NASA Library models to execute a redundancy model. Piping sections are statically determined at initialization of the system. Flow subsystems are dynamically determined as the cryogenic flow progresses across the system, by opening/closing bounding elements (valves) across piping sections. The purpose of this model is to determine if a replacement sensor, due to an off-nominal behavior of primary sensors, is being used under nominal operations. A sensor deemed inoperable, based on the sensor model, is an input received by the reduncancy model. The redundancy model performs recursive operations to find a suitable replacement for the inoperable sensors. Some of the factors that determine a replacement sensor are: type, proximity, same piping section, and functionality assessment of the replacement sensor. The model finds a sensor of the same type in nearby sections of piping. Some of the characteristics of the same piping sections are similar pressure, temperature, and flow rate. Similarly, sensors in adjacent piping sections might experience the same physical conditions. In the case where a alternate sensor is unavailable on the same piping sections, other factors are considered for selecting alternate sensors on adjacent piping sections.

10. Autonomous Engine

This module is the integrator engine between redundancy model, sensor model, redline monitoring and sequencer. This engine considers the use of the replacement sensor, in nominal and safety critical operations, being performed by the sequencer and redline monitoring. During nominal operations, the autonomous engine is assessing the health of the sensors while monitoring the use of the sensors for nominal tasks. Redline monitoring and sequencer execution are considered nominal tasks. A reaction upon health, by the autonomous engine, implies that a sensor being used during a nominal task has become inoperable. The autonomous engine reacts to the health state of the sensor to mitigate the off-nominal behavior, with the purpose of ensuring continuity of nominal operations. Mitigation procedures include finding a replacement sensor or safing the system if there are no available alternatives.

B. Application Software Components

1. Domain Maps

Domain maps are the central location for the knowledge of the application, supplying information to all the application software components. They serve as the user interface to the application domain model, and consistof every element of the system represented as an object. Domain objects are connected according to schematics, and incorporate data, information, and knowledge about the system.

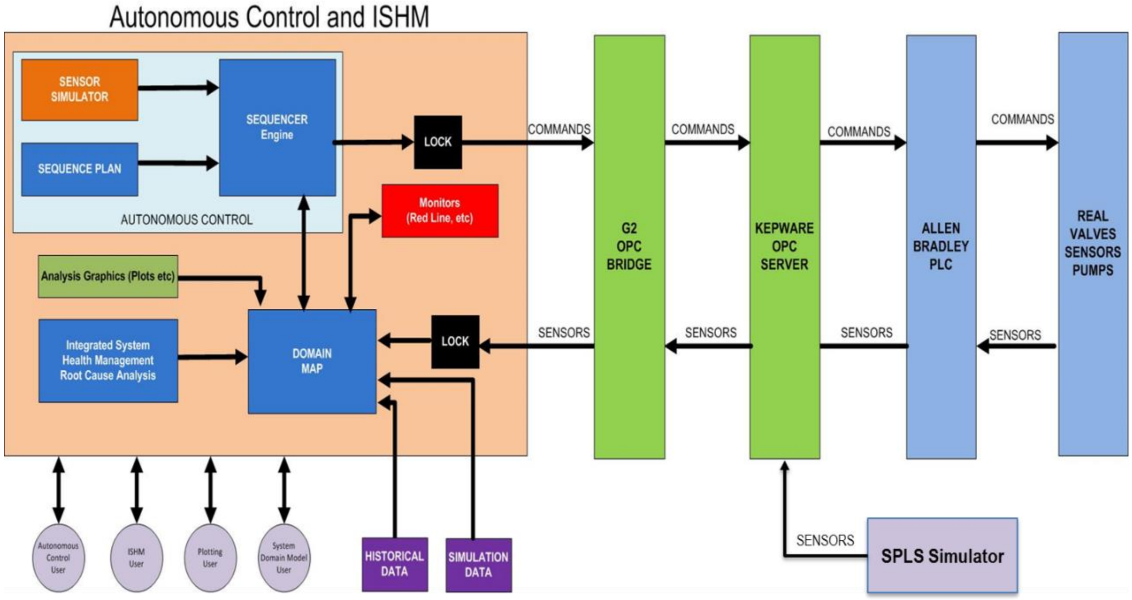


Figure 1. ISHM-AC Software Architecture

2. Control Maps

These maps use information, available on the domain maps, to monitor telemetry obtained from the instrumentation of hardware. The control map is capable of executing command and control of command-supported elements in the system, which includes valves and setpoints. The control map also provides a user interface to monitor the progress of a cryogenic propellant transfer operation.

3. Application Models

These models can be instantiated and used within specific applications. Generic models from the NASA Library are applied to the domain map representation to produce piping section object models; flow subsystem object models; saturation condition of cryogenic commodity according to application specific sensor pair (pressure and temperature); leak detection; valve state assessment on application valves and others.

4. Redlines

Redline monitor generic capability, along with user inputs, can determine undesirable conditions of the system in which mitigation actions need to be taken to protect the system, once a threshold violation is triggered.

5. Sequencer Plans

These plans are derived using the Sequencer generic capability to provide a set of scripted, sequential commands focused on nominal and off-nominal operations. Off-nominal plans associated with redline triggering are considered safing plans, since they provide a mitigation sequence that returns the system into a safe configuration once an undesired condition is met. Control algorithms are provided by the sequencer, to employ the use of sequential commanding in a parallel execution, for specialized needs, required by the application.

IV. Autonomous Operations

ISHM-AC allows the developer to create an application that closely represents the external hardware for command and control operations. The tools within ISHM-AC allow for a domain map representation using generic libraries for components and models used for modeling the real system. These utilities allow for the creation of the application software components, needed to deploy an application, for hardware operations. Several engines are tasked to execute the application software component in an integrated manner. This coordinated execution of all the ISHM-AC Software Components represent the true nature of the autonomous operations.

A. Nominal Operations

During nominal operations, the workflow of the autonomous engine behaves as seen in **Error! Reference source not found.**. During this operation, there are several parallel modules executing their functionalities on the domain map.

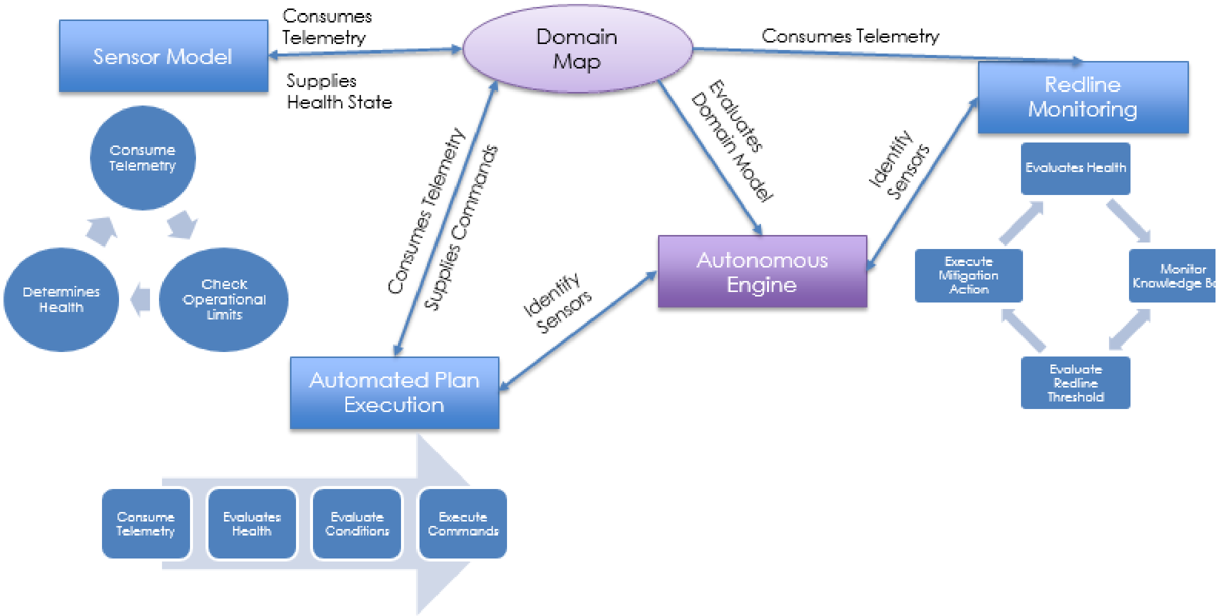


Figure 2. Nominal Autonomous Operations

1. Automated Plan Execution

The Sequencer uses telemetry from the application software domain object elements to execute the automated script for commands. This process is known as Automated Plan Execution. During the execution of the script, in a nominal plan, conditions are evaluated prior to command execution. The command execution is supplied to the domain object elements and communication is provided to the external hardware components to execute the command. This module also evaluates the health of the sensors in each step. For nominal operations, the health of the sensors are on a fully functional state.

2. Redline Monitoring

In a parallel effort, Redline Monitoring evaluates domain object element. The nominal state is compared to the previously specified threshold for a redline. Nominal states of domain objects do not trigger any redline conditions and no further action is taken.

3. Sensor Based Reasoning Model

This model evaluates, in a synchronous manner, the nominal design parameters of sensors, and determines the health conditions. This module contains technical specifications of the sensors regarding its electrical signature. The telemetry signature, during operations, is compared to the specifications of the sensor and a determination of an off-nominal condition is made. This model is capable of determining off-nominal conditions, based on the behavior of application-specific parameters.

4. Autonomous Engine

In a parallel effort, the Autonomous Engine ingests sensor data and evaluates components in piping sections. During nominal operations, the model executes a search algorithm within the piping sections. If a sensor is being used by the Redline Monitor and/or Sequences, the Autnonomous Engine selects a redundant sensor, to be used as an alternate, if an off-nominal condition occurs. This module integrates health management with automated plan execution to mitigate failure modes and ensure continuation of operations..

B. Off-Nominal Operations

During off-nominal operations, the workflow of the autonomous engine behaves as seen on Figure 3**Error! Reference source not found.**. During this operation, several parallel modules execute their functionalities on the domain map.

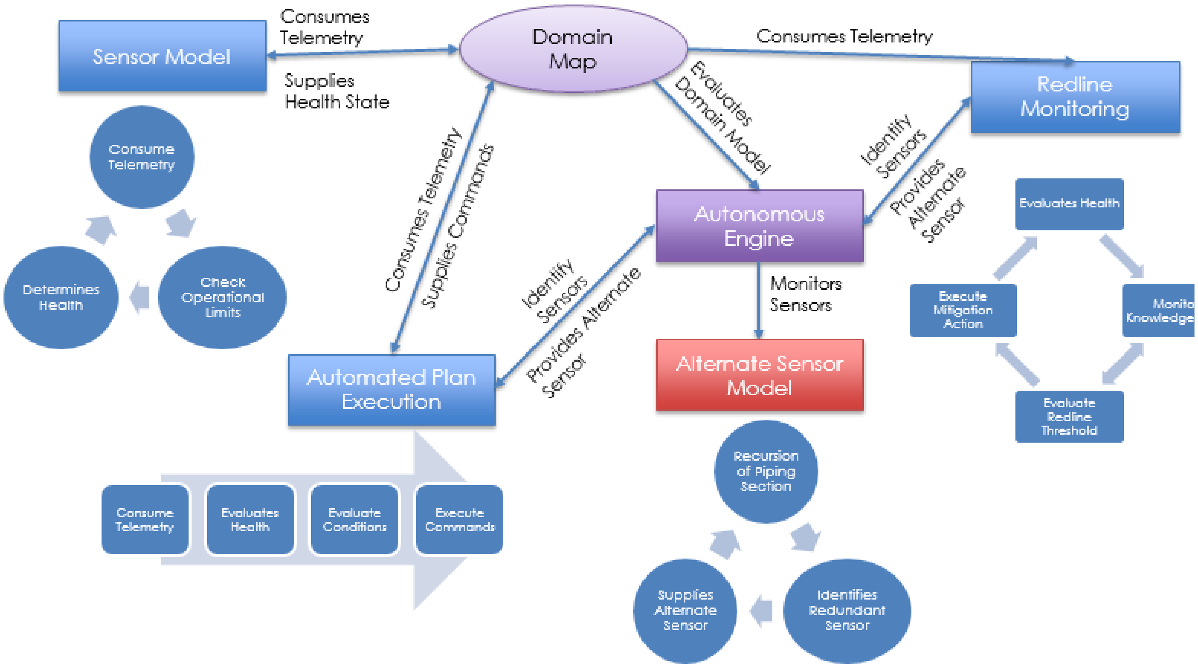


Figure 3. Off-Nominal Autonomous Operations

1. Sensor Based Reasoning Model

During off-nominal operations the Sensor Based Reasoning Model identifies anomalies in the electrical signal of the sensor. The signal is evaluated against an operable threshold. Once the threshold limit is exceeded, the sensor is deemed inoperable. A flag is set on the sensor domain representation. This domain representation is monitored by several customers of the domain map.

2. Automated Plan Execution

During off-nominal operations, the Sequencer consumes the data from the domain map. During automated plan execution, all sensors involved in the sequential script are evalutated for health. A flag on a sensor, identified to be used during the scripted plan execution, produces a request from the Sequencer to the Autonomous Engine. The Sequencer needs a fully functional sensor to perform its operation. If a sensor is deemed inoperable, according to its health state, the Sequencer requests an alternate sensor from the Autonomous Engine. The Autonomous engine provides either an alternate sensor or a signal that indicates no alternate sensor found.

- Alternate Sensor Found: The Sequencer uses the alternate sensor found as a replacement for the flagged sensor. The signal of the alternate sensor is used to perform scripting, ensuring continuation of operations.
- No Alternate Sensor Found: The Sequencer uses the provided signal to pause current operations. The operator can decide to terminate the operation, by executing a safing plan, bypass the use of the sensor under question to continue operations, or provide any mitigations for the interruption of the operations.

3. Redline Monitoring

In a parallel effort, the Redline Monitoring evaluates telemetry from the domain object. In this case, the telemetry signal obtained reflects an undesirable condition. This condition is compared to the redline monitor threshold values. Once the redline condition is triggered, mitigation actions will take place. The first action is to stop the execution of any nominal plan. The second action is to initiate a parallel process that executes a mitigation safing plan, associated with the triggered redline. This action is dependent on a reliable sensor that is in a fully functional state.

The Redline Monitoring, uses the Autonomous Engine to identify any sensor anomalies, prior to use of the sensor as the redline monitors. During monitoring operations, all sensors involved are evalutated for health. A flag on a sensor, identified to be used during monitoring operations, produces a request from the Redline Monitoring to the Autonomous Engine. The Redline Monitoring needs a fully functional sensor in order to perform its operation. If a sensor is deemed to be inoperable, according to its health state, the Redline Monitoring requests an alternate sensor from the Autonomous Engine. The Automous engine provides either an alternate sensor or a signal that indicates no alternate sensor found.

- Alternate Sensor Found: The Redline Monitoring uses the alternate sensor found as a replacement for the flaggedsensor. The signal of the alternate sensor is used to performmonitoring operations. If a redline needs to be triggered, due to a violation of an established threshold, the Redline Monitoring uses the alternate sensor to perform this operation, and executes a mitigation plan associated with the off-nominal signal.
- No Alternate Sensor Found: The Sequencer uses the provided signal from the Redline Monitoring to execute the mitigation plan associated with the off-nominal condition. A lack of visibility of a redline monitor sensor becomes a safety concern for the operation and an automated safe mitigation procedure is executed without operator intervention.

4. Autonomous Engine

During the execution of an operational plan or redline monitoring operation, the Autonomous Engine functionality is requested by the Sequencer and the Redline Monitoring. Once invoked, the Autonomous Engine uses the Alternate Sensor Model to perform recursive operations over the piping system of the sensors in question. This model determines if a redundant sensor exists to provide an alternate reading of the operation being performed by the sensor in question. Once an reduntant sensor is identified, the autonomous engine evaluates the health of the alternate sensor. If the alternate sensor is fully operational, the name of the sensor is provided to the customer of the Autonomous Engine to continue operations. Sensors within the same piping sections are evaluated for proximity and similar measured physic phenomena. If an alternate sensor is not found, a signal is returned to the customer of the Autnomous Engine.

V. Additional Health Monitoring Operations

In addition to the Autonomous Operations, several functionalities of the NASA Library Models are employed to detect anomonalies in the system.

A. Nominal Operations

1. Phase Detection Model

During nominal operations, a phase detection model monitors a saturation-pair sensor to determine the thermodynamic phase of the cryogenic commodity. Data from the National Institute of Standards and Technology (NIST) is used to compare the correlation of temperature and pressure against the saturation table of the commodity being used. This data is used to provide awareness to the operation and track the development of the commodity as it travels across the pipeline.

2. Flow Subsystem Model

During operations, the dynamic behavior of the cryogenic propellant distribution, across the transfer line, is being tracked by the flow subsystem model. This model is a listener of the valves across the pipeline. Once a valve opens, the model identifies a new path for the cryogenic commodity to travel. In conjuction with the phase detection model, the flow subsystem identifies the new path and provides the control map and awareness of the trajectory of the commodity across the transfer line. For display purposes, the pipeline is colorized with the phase of the cryogenic commodity.

B. Off-Nominal Operations

1. Leak Detection Model

The data rate of change between piping sections is tracked by a sensor rate determination model. In the case of a leak detection model, it uses sensor rate of change data to compare adjacent, distinct piping sections. In this case, piping sections are divided by a bounding element (a valve) and pressure sensors are located on both sides of the piping sections. A difference in the rate of change of the pressure between these two piping sections provides insight into leaks in the system.

2. Valve Inconsistency Model

Monitoring operations on valves are triggered by change of states in valves. This model compares the command of a valve with the response of its positions sensors. An inconsistency in the valve is identified if the valve sensor telemetry is inconsistent with the command. There are analog and discrete position sensors in valves across the transfer line. These sensors are represented as follows:

- Open indicator: This open indicator is a limit switch that turns on or off once the valve stem travels up or down, respectively. Open indicator equals 1.0 when the valve is open and 0.0 when the valve is closed.
- Closed indicator: This closed indicator is a limit switch that turns on or off once the valve stem travels down or up, respectively. Closed indicator equals 1.0 when the valve is closed and 0.0 when the valve is open.
- Position Indicator: This indicator is an analog sensor that provides telemetry values from 0.0% to 100.0%. A closed position is represented by a value of 0.0%. An open position is represented by a value of 100.0%. A value of 5% is added to the open and closed position, to capture the tolerance of the valve and sensor installation.

Deviation from the default values of these indicators as compared with the commands, represent an inconsistency with the valve. Once an inconsistency is observed, the operator is notified. During operations this event triggers a need for maintainance actions on the valve, for calibration purposes.

VI. Application

A. Application Description

The SPLS resides at NASA KSC Cryogenic Test Laboratory. It is composed of several subsystems, designed to simulate real cryogenic propellant transfer systems for flight vechicles. Some of the main components are:

1. Propellant Transfer Lines

The SPLS (see ***Figure 4***) consists of a storage tank, a simulator tank, and four distinct “skids” (Pump Skid, Valve Control Skid, Vehicle Interface Skid, and the Variable Frequency Drive (VFD) Skid). All cryogenic components within the SPLS are liquid nitrogen (LN2) cryogenic rated. All gaseous nitrogen (GN2) gas components are rated for the anticipated temperatures, system tests, and operating pressures.

- The Pump Skid is supplied by a LN2 line. The cryogenic pump, currently in use, is delivering LN2 from storage tank to simulated vehicle tank. There are chilldown/drain valves provided for each pipe section and shutoff valves on the upstream and downstream of the pump. The discharge of the pump is directed to the Valve Control Skid.

- The Valve Control Skid LN2 line from the pump plumbed into supply line. Downstream of the 1.5inch feed, the 4inch line contains a tee; one leg continues to the Vehicle Interface skid, the remaining leg returns to the storage tank. Thus, flow from the 4 inch line can be directed to any or all of three locations when the pumps are running: to the simulated vehicle tank, back to the storage tank, or to the dump/drain line.

- The Vehicle Interface Skid has a 4 inch line, with additional valves, to supply the vehicle tank or to return LN2 to the drain/vent line.

- The VFD skid has equipment to control the pump speed and rate of LN2 flow from the Storage tank. The VFD equipment also monitors the pump speed and motor condition.

As part of the development of SPLS, a generic transfer line was developed to support simulated propellant transfer between storage and vehicle tanks with liquid nitrogen as the simulated propellant commodity. The mobile launcher area contains a main solenoid and control valves which provides flow control of simulated propellant incoming from the cross country line. The vehicle interphase area contains the control valves for main and replenish flow into the vehicle tank. The simulated vehicle tank represents a section of the test bed dedicated to support various vehicle tank technologies, including composite tanks, single stage tanks, and multiple-stage vehicle tanks. This section also contains pressure, temperature and level sensors, a vent line to relieve control, simulated vehicle pressure, and tank boil off gas.

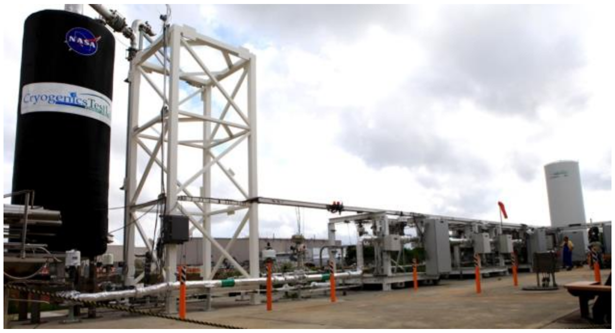


Figure 4. Simulated Propellant Loading System

B. Storage Tank

The storage area is composed of a main liquid nitrogen supply tank, which provides the simulated propellant (see Figure 4). This tank is well instrumented with temperature, pressure and a liquid level transducer to provide telemetry of the tank during any phase of the cryogenic test. The SPLS is equipped with a pneumatic system that provides control of the valve supply pressure, storage and vehicle tanks ullage pressurant gas, purging system, and pump system.

C. Single Stage Vehicle Tank

The single stage vehicle tank area is a vehicle simulator tank. The tank is designed for liquid nitrogen temperature. The cylindrical side (barrel) of the tank is fairly unobstructed and ports are concentrated on the upper and lower domes.

D. Instrumentation

The SPLS is composed of several sensing technologies for health monitoring, research, and innovation purposes. Currently, pressure (PT) and temperature transducers (TT) are being used to monitor testing operations for the SPLS.

These sensors are used to monitor the propellant thermodynamic state, maximum allowable working pressure, and flow conditions for pump operations. In addition, these sensors are used as trigger points to advance the propellant transfer phases in the system. Capacitance probes (LT) and silicone diode (ECO) transducer technologies have been used to measure liquid levels in the simulated vehicle tank and storage tank.

As part of the valve monitoring and control system, the SPLS is composed of remotely and manually operated valves for flow control. The remote operated (RO) and control valves (CV) are monitored via discrete or analog position sensors (POS), to indicate the state of the valve, during the various phases of a simulated propellant transfer process. Solenoid valves (SV) are another type of valve which are remotly operated, and do not contain a position sensor.

E. Data Acquisition, Command and Control System

A programmable logic controller (PLC) has been configured and integrated to command, control and health monitor the SPLS loading sequence operations. This control system includes a command and control human-machine interface (HMI) panel that reflects temperatures, pressures, liquid levels and position sensors. The control system has the capability of commanding and controlling valves by manual signal input and/or by executing a pre-programmed sequence of steps initiated by feedback data. A proportional-integral-derivative (PID) control loop feedback mechanism, incorporated into the control system, is used to control commands to valves with position indicators to achieve a desired commanded state. The SPLS control system is also capable of executing automated, pre-programmed, sequences to control the cryogenic loading operations. The PLC also manages the control of several auxiliary sub-systems and provides a real-time monitoring of all sensors of the SPLS.

VII. ISHM-AC Application Development System

In order to successfully demonstrate the capabilities of ISHM-AC, several hardware and software components are used for testing different phases of the development. By testing the software in different phases, the ISHM-AC will accomplish a validation and verification process.

The ISHM-AC for SPLS is composed of a main computer for software development, with four monitors for displaying data, visualization, domain maps and programmable code. In this computer system, the main application for controlling, commanding and monitoring the cryogenics propellant transfer for ISHM-AC is being developed. Within its local configuration, the knowledge of the system is being created by transferring mechanical, electrical and communication maps into a domain map system. This domain map system receives data for the outside systems (PLC, SPLS Simulator, and Kepware OPC Server) and feeds different subsystems (health management, automated sequencer control, etc.).

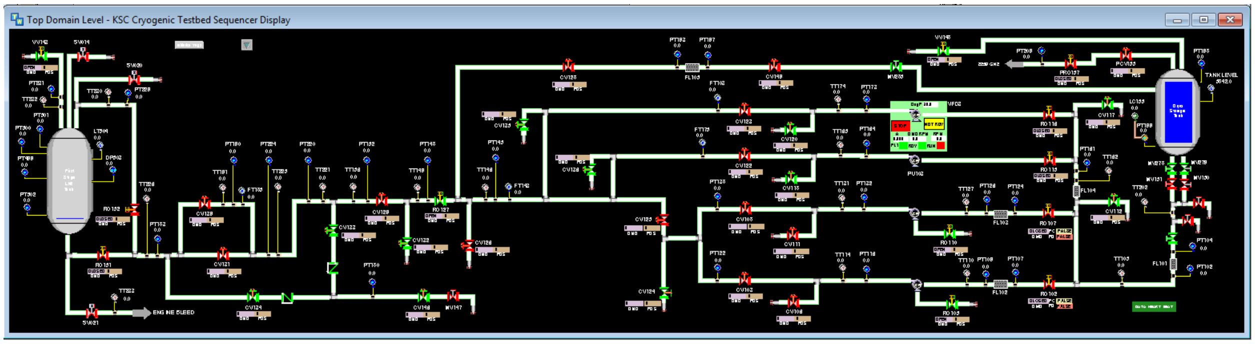
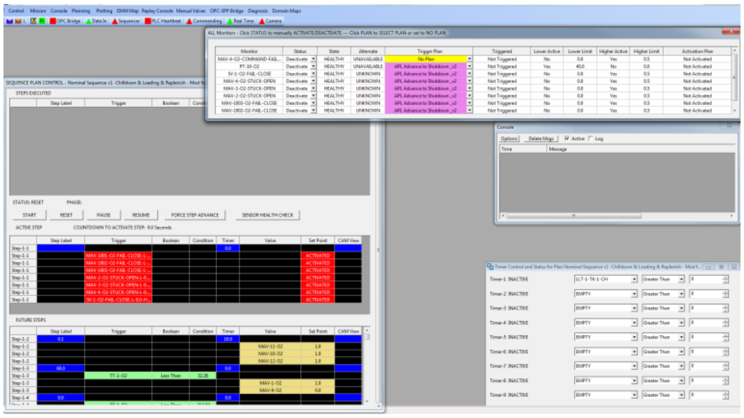


Figure 5. SPLS Control Map

The development of several subsystems within the ISHM-AC SPLS includes a visual representation of the domain map for commanding and control (see Figure 5), an automatic sequencer controller (see Figure 6), health management subsystems and plotting features.



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

Monitor	Status	State	Alternate	Trigger Plan	Triggered	Lower Active	Lower Limit	Higher Active	Higher Limit	Activation Plan
MAV-4-O2-COMMAND-FAIL...	Deactivate	HEALTHY	UNAVAILABLE	No Plan	Not Triggered	No	0.0	Yes	0.5	Not Activated
PT-10-O2	Deactivate	HEALTHY	UNAVAILABLE	APL Advance to Shutdown _v2	Not Triggered	Yes	40.0	No	0.0	Not Activated
SV-1-O2-FAIL-CLOSE	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown _v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-4-O2-STUCK-OPEN	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown _v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-3-O2-STUCK-OPEN	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown _v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-2-O2-STUCK-OPEN	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown _v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-1803-O2-FAIL-CLOSE	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown _v2	Not Triggered	No	0.0	Yes	0.5	Not Activated
MAV-1802-O2-FAIL-CLOSE	Deactivate	HEALTHY	UNKNOWN	APL Advance to Shutdown _v2	Not Triggered	No	0.0	Yes	0.5	Not Activated

SEQUENCE PLAN CONTROL - Nominal Sequence v1 -Chilldown & Loading & Replenish - Mod f

STEPS EXECUTED

Step Label	Trigger	Boolean	Cond

STATUS: RESET PHASE:

ACTIVE STEP COUNTDOWN TO ACTIVATE STEP: 0.0 Seconds

	Step Label	Trigger	Boolean	Condition	Timer	Valve	Set Point	CAM View
Step-1-1					0.0			
Step-1-1		MAV-1801-O2-FAIL-CLOSE-L-...					ACTIVATED	
Step-1-1		MAV-1802-O2-FAIL-CLOSE-L-...					ACTIVATED	
Step-1-1		MAV-1803-O2-FAIL-CLOSE-L-...					ACTIVATED	
Step-1-1		MAV-2-O2-STUCK-OPEN-L-0...					ACTIVATED	
Step-1-1		MAV-3-O2-STUCK-OPEN-L-0...					ACTIVATED	
Step-1-1		MAV-4-O2-STUCK-OPEN-L-0...					ACTIVATED	
Step-1-1		SV-1-O2-FAIL-CLOSE-L-0.0-H...					ACTIVATED	

FUTURE STEPS

	Step Label	Trigger	Boolean	Condition	Timer	Valve	Set Point	CAM View
Step-1-2	0.1				18.0			
Step-1-2						MAV-11-O2	1.0	
Step-1-2						MAV-10-O2	1.0	
Step-1-2						MAV-12-O2	1.0	
Step-1-3	60.0				0.0			
Step-1-3		TT-1-O2	Less Than	32.26				
Step-1-3						MAV-1-O2	1.0	
Step-1-3						MAV-9-O2	0.0	
Step-1-4	0.0				0.0			

Console

☑ Active ☐ Log

Time	Message

Timer Control and Status for Plan Nominal Sequence v1 -Chilldown & Loading & Replenish - Mod f...

Timer-1 INACTIVE	LLT-1-TK-1-CH	Greater Than	0
Timer-2 INACTIVE	EMPTY	Greater Than	0
Timer-3 INACTIVE	EMPTY	Greater Than	0
Timer-4 INACTIVE	EMPTY	Greater Than	0
Timer-5 INACTIVE	EMPTY	Greater Than	0
Timer-6 INACTIVE	EMPTY	Greater Than	0
Timer-7 INACTIVE	EMPTY	Greater Than	0
Timer-8 INACTIVE	EMPTY	Greater Than	0
Timer-9 INACTIVE	EMPTY	Greater Than	0

Figure 6. Automatic Sequencer Controller, Redline Monitoring, Timers, Console and Operations Display

VIII. Test Results

When testing the SPLS developed application, using the ISHM-AC, real hardware was used. Several strategies for propellant loading transfer were explored to develop a nominal and off-nominal plan for cryogenic propellant transfer. A more detailed explanation of the testing capabilities of the SPLS can be found at [XXX]. In this paper, the testing and demostrations are compared with repeatability sequences already validated. The testing capabilities of the SPLS allows the ISHM-AC to control propellant loading operations similar to the SPLS Command and Control system. The use of ISHM-AC for command and control extends the capabilities of the SPLS Command and Control system to allow for autonomous operations. Testing results of ISHM-AC are compared with previously obtained data from [].

A. Nominal Operation Test Case

1. Chilldown

During the chilldown phase, liquid nitrogen is used to decrease the temperature of the system to a cryogenic nitrogen temperature range (-321 °F). During this phase, liquid nitrogen is transferred from the storage tank to the vehicle interface valve. Boil-off gas generated during the cool down process is relieved through valves that are redirected to the exhaust line on the system (“Dump Area”). During the suction line chilldown, the main block valve of the storage tank is opened, allowing cryogenic liquid to flow across the suction line. A comparison of test data is shown on *Figure 7*. The ISHM-AC autonomous operations in comparison with the SPLS command and control system shows similar trends during the chilldown phase of the test. Variations in test results were due to a higher initial atmospheric temperature on the different days the tests were performed. Behaviors in temperature decrease rate and final temperature states were found to be similar in both tests.

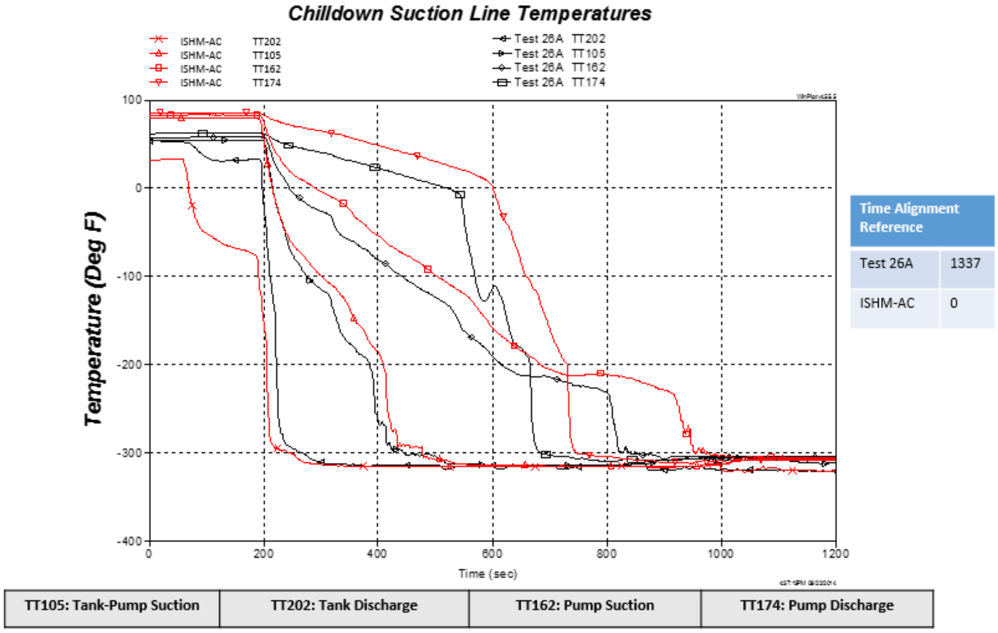


Figure 7. Chilldown Temperature: ISHM-AC vs. SPLS Command and Control System Test.

2. Pump Operations: Fast Fill to Replenish Phase

During this phase, the cryogenic pump speed is increased to produce a flow rate of 90 GPM. The flow provided, produced a faster increase rate of LN2 liquid level in the simulated vehicle tank. A steady increase in tank liquid level (%) was observed by LT504 in Figure 8. Test results show that the ISHM-AC is capable of producing similar results as compared to the conventional command and control system use on SPLS.

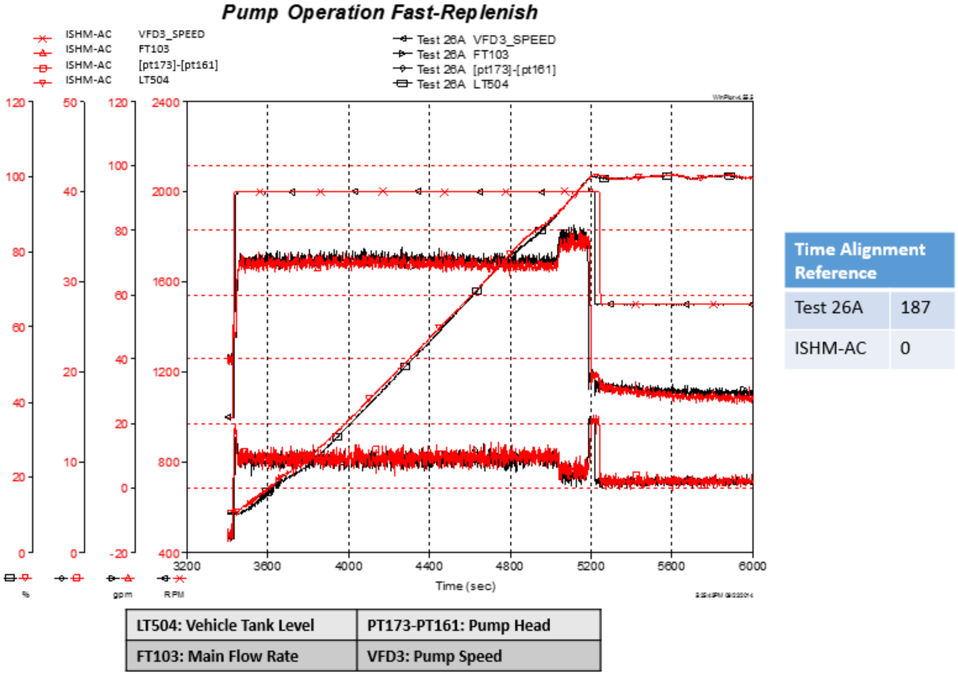


Figure 8. Pump Operations: Fast Fill to Replenish for ISHM-AC SPLS Test

3. Replenish

During this phase, a maximum tank fill level is achieved by the cryogenic commodity and a replenish algorithm is enabled (see Figure 9). This replenish algorithm monitors the tank level and commands an exhaust valve (CV134) to either allow flow commodity into the tank (if tank level falls below a minimum threshold) or prevent an overfill on the vehicle tank. If the vehicle tank liquid level LT504 falls below 99.5%, then the exhaust valve CV134 closes to 5% to allow more commodity into the tank. If the vehicle tank liquid level LT504 rises above 100.5%, then the exhaust valve CV134 opens to 20% to exhaust commodity into the atmosphere. Test results shows that the ISHM-AC is capable of performing a control algorithm for flight ready conditions on a simulated vehicle tank. Small deviations in tests are caused by variations in boil-off rates, due to differences in ambient temperature, on the days the tests were performed.

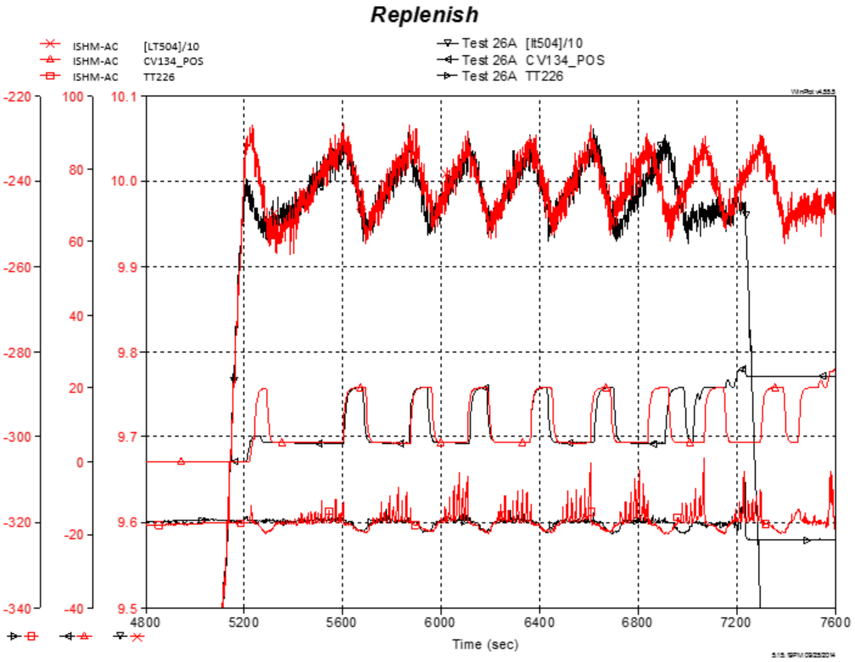


Figure 9. Replenish Phase

B. Off-Nominal Operation Test Case

The off-nominal operation consists of introducing failure to trigger the autonomous engine to perform safing operations, as well as mitigation operations. In addition, several health monitoring related, off-nominal conditions will be introduced to demonstrate the health monitoring capabilities of the ISHM-AC. These tests will consist of a nominal loading operation, followed by the insertion of preplanned anomalies. Common failure modes using a loading sequence, utilizing fully autonomous sequencing, have been identified. As part of the off-nominal case scenarios, instrumentation failure only consists of pressure sensors being used by the Sequencer and Redline Monitoring.

1. Sequencer Sensor Failure – Alternate Sensor Available

During the chilldown phase, cryogenic commodity is transferred from the storage tank to the vehicle tank. Several bleed valves are used to relieve the system of warm gas. The operation of bleed valves are constrained by pressure conditions along the pipeline. Pressure transducer PT220 is located at the Valve Control Skid. This pressure transducer is used to progress the scripted sequence plan designed for the simulated propellant transfer operation. During the execution of the automated plan, PT220 is disconnected from the control panel to simulate a failure in this sensor. The outcome of this event is a sensor current reading below manufacturer's specification (0 mA) as compared with the current reading for the nominal operation (4-20 mA). The Sensor Based Model identifies the failure and notifies the domain map object by flagging the sensor as inoperable. The updated health state of this sensor allows the customers of the domain map to evaluate the use and mitigation actions for this event.

For this failure, the Sequencer identifies that the pre-planned sequence plan is dependent on this sensor to perform the full propellant transfer operation. The Sequencer requests that the Autonomous Engine identify an alternate sensor to perform the required operation. This evaluation and request happens in real-time, while the chilldown phase is in progress. The Autonomous Engine invokes the Alternate Sensor model and a reduntant sensor PT190 is found to be used as an alternate for this operation. In this case, the availability of an fully functional alternate sensor allows the sequence plan to progress, once the pressure required for PT220 reaches 8 psig, as shown in Figure 10. The continuation of the operation can be observed by noticing a command being sent to CV131_CMD and a position sensor CV131_POS follows the specified command. The commanding of this valve, during this phase of the operations, is only possible if nominal conditions have been idenfied in the sequence of steps for this operation. The use of an alternate sensor allows for a nominal operation to continue as a result of an off-nominal event mitigation.

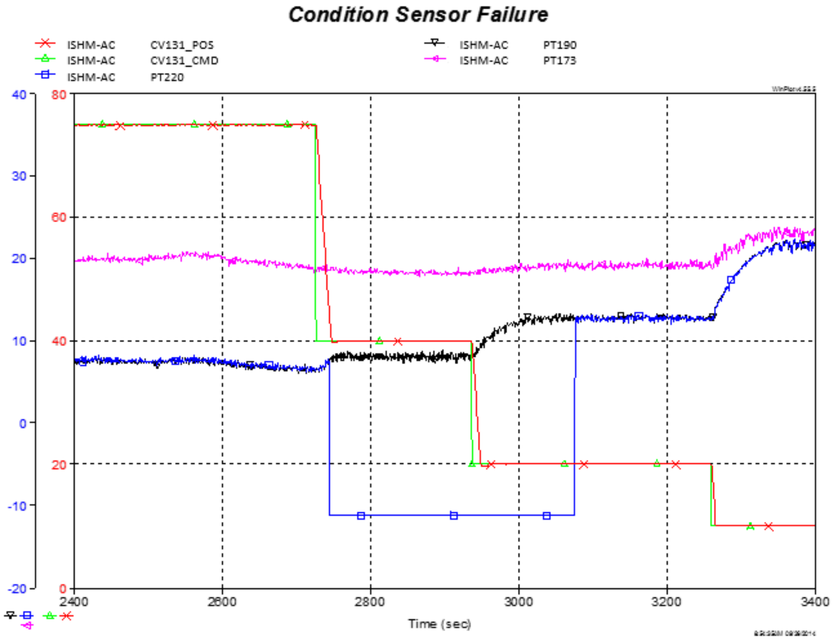


Figure 10. Sequencer Condition Sensor Failure: Alternate Found

2. Redline Monitoring Sensor Failure – Alternate Sensor Available

During execution of the propellant transfer operations, subsystems are constantly being monitored by the Redline Monitoring to prevent component failures. During the chilldown phase, the simulated vehicle tank is being cooled down by receiving liquid nitrogen through the pipeline. The vehicle tank is constantly being monitored for its maximum allowable working pressure (MAWP). That is the operational limit of this vehicle tank. There are several sensors across the ullage of the tank that provide the required pressure readings to monitor the MAWP. The pressure sensor PT501 is set to be a redline monitor for the MAWP of 26 psig. In order to properly monitor this pressure, the domain object element representing this sensor must indicate a fully functional state.

During this failure mode, as with PT220 failure injection, the pressure sensor PT501 is disconnected from the control panel to simulate a failure in this sensor. The outcome of this event is a sensor current reading below manufacturer’s specification (0 mA) as compared with the current reading for the nominal operation (4-20 mA). The Sensor Based Model identifies the failure and notifies the domain map object by flagging the sensor as inoperable. The updated health state of this sensor allows the customers of the domain map to evaluate the use and mitigation actions for this event. In this case, the Redline Monitoring identifies that the sensor in question is currently being used to monitor the MAWP of the vehicle tank. The Redline Monitoring requests that the Autonomous Engine offer an alternate sensor to perform the required operation. The Autonomous Engine invoked the Alternate Sensor model and a reduntant sensor PT500 is found to be used as an alternate for this monitoring operation. In this case, the availability of an fully functional alternate sensor allows the Redline Monitoring to continue monitoring activities on the vehicle tank as shown in Figure 11.

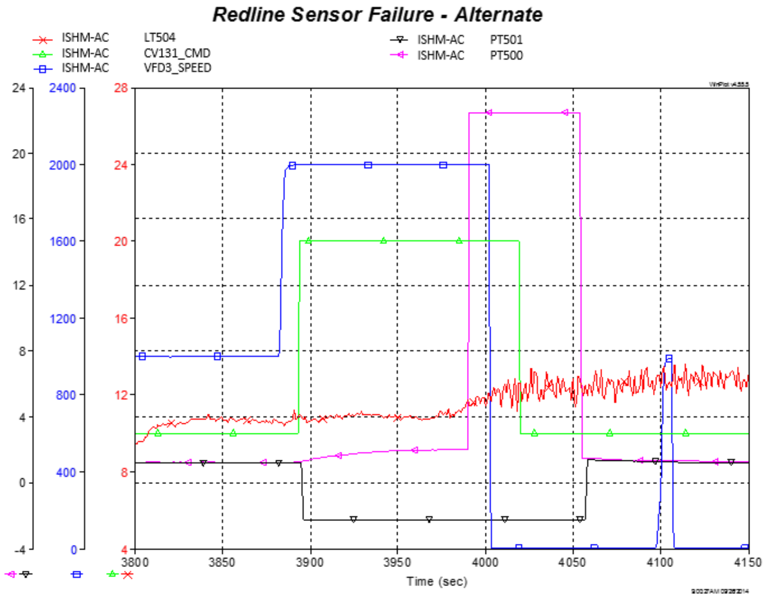


Figure 11. Redline Sensor Failure: Alternate Found

The continuation of the operation can be observed by noticing a command being sent to the pump speed VFD3_SPEED, that shows a constant value, even if PT501 is showing negative values. In order to test that a redline threshold can be triggered using the alternate sensor PT500, a value of 26 psig is forced into the telemetry signal of this sensor. This event triggers a violation of the redline monitor and a mitigation action is executed. One of the actions, after a redline violation in this category, is to shut down the pump to prevent any additional pressurization on the vechicle tank. This figure shows the pump speed VFD3_SPEED going down to zero after the pressure reached 26 psig. The use of an alternate sensor allows for nominal monitoring operations to continue and a safing plan to be executed according to redline monitoring conditions.

3. Redline Monitoring Sensor Failure – No Alternate Sensor Available

There are sensors on the SPLS that do not have a redundant sensor that can be used as alternate sensor by the Autonomous Engine. This is the case for the DP212 sensor which monitors the ullage pressure on the storage tank. During this failure mode, the selected sensor is used to monitor MAWP for the storage tank. Redline monitor sensors are constantly monitoring nominal conditions on the storage tank and have an associated safing plan in case a redline violation occurs. During nominal operations, the vehicle tank is filled with liquid nitrogen provided from the storage tank. The cryogenic pump allows for rapid commodity transfer between both tanks. During this operation, a failure is inserted by disconnecting the sensor DP212 from the control panel. Similar to previous failures, the Sensor Based Reasoning Model updates the domain map with the state flag and the Autonomous Engine is requested for an alternate sensor. In this case, the Autonomous Engine returns a signature indicating that no alternate sensor was found. As a safing strategy, the integrated autonomous control system has been programed to shutdown the nominal operations due to a lack of visibility on a redline monitor sensor. This allows for a mitigation procedure that puts the hardware system in a safe state. Figure 12 shows a shutdown of the pump VFD3_SPEED as part of the shutdown safing plan being executed when DP212 indicates a reading outside of its fully functional range.

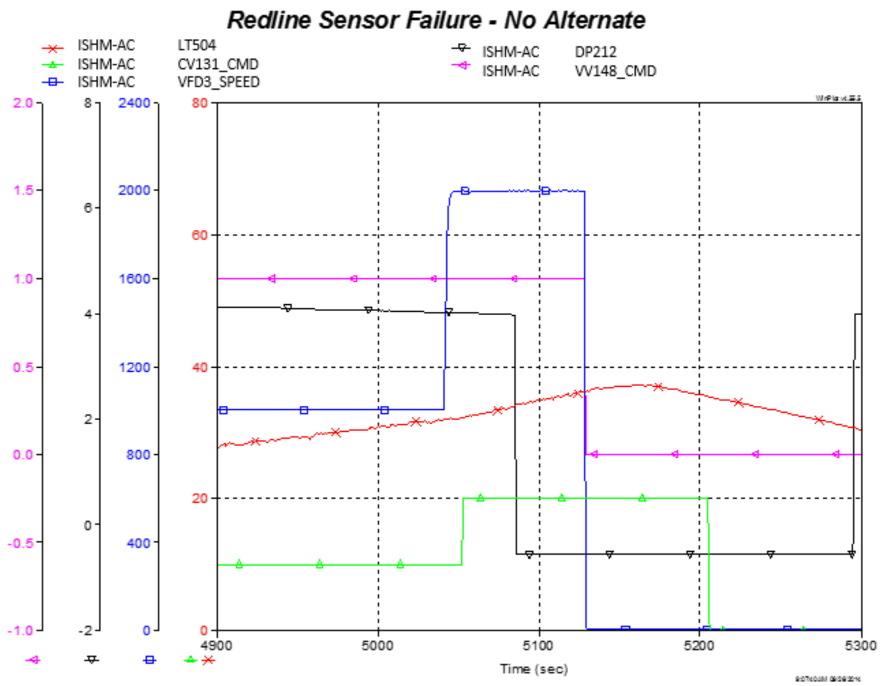


Figure 12. Redline Sensor Failute - No Alternate Sensor Found

IX. Conclusions

The ISHM-AC has proven to provide fully autonomous control software capabilities to an experimental test bed used for improving software and hardware technologies. The integration of automated control with ISHM to command and control cryogenic propellant loading operations, under a safe environment, has been achieved with the aid of SPLS. The use of SPLS against ISHM-AC has made it possible to increase the NASA Technology Readiness Level (TRL) from a analytical and experimental proof-of-concept (Level 3) to validation in laboratory environments (Level 4). Current efforts are aimed to increase the TRL to produce a product in a relevant environment (Level 5) by evolving the ISHM-AC into a autonomous software that can command and control a GSE aimed for cryogenic propellants (LOX and LCH4) servicing under the APL project.

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