

NPAS

NASA Platform for Autonomous Systems

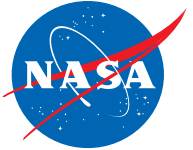
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NASA Stennis Space Center

Subject Matter Expert Series Seminar
Habitats Optimized for Missions of Exploration (HOME)
Space Technology Institute SME Seminar Series

March 4, 2021



NASA SSC Autonomous Systems Laboratory Team
Leadership: Fernando Figueroa, Lauren Underwood, Duane Armstrong, SSC
Mark Walker, Jon Morris, D2K Technologies



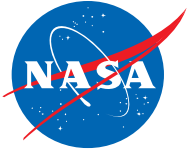
NPAS - NASA Platform for Autonomous Systems

All the tools required to implement hierarchical, distributed, safety critical, autonomous operations in one integrated software platform that's affordable, reusable, & scalable



Project Overview – What is NPAS

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what is NPAS?

NPAS is a platform built with G2

- NPAS technology development extends the inherent capabilities of G2
- NPAS encompasses the tools to simplify the creation of robust knowledge-based autonomous systems
- NPAS is currently in operational use at NASA SSC's High Pressure Gas Facility, a critical piece of test infrastructure used to support SLS, DoD, and commercial propulsion testing

✓ G2 provides foundational tools
✓ NPAS builds upon G2 capabilities to enable autonomous systems

G2 is an expert system framework spun out from MIT

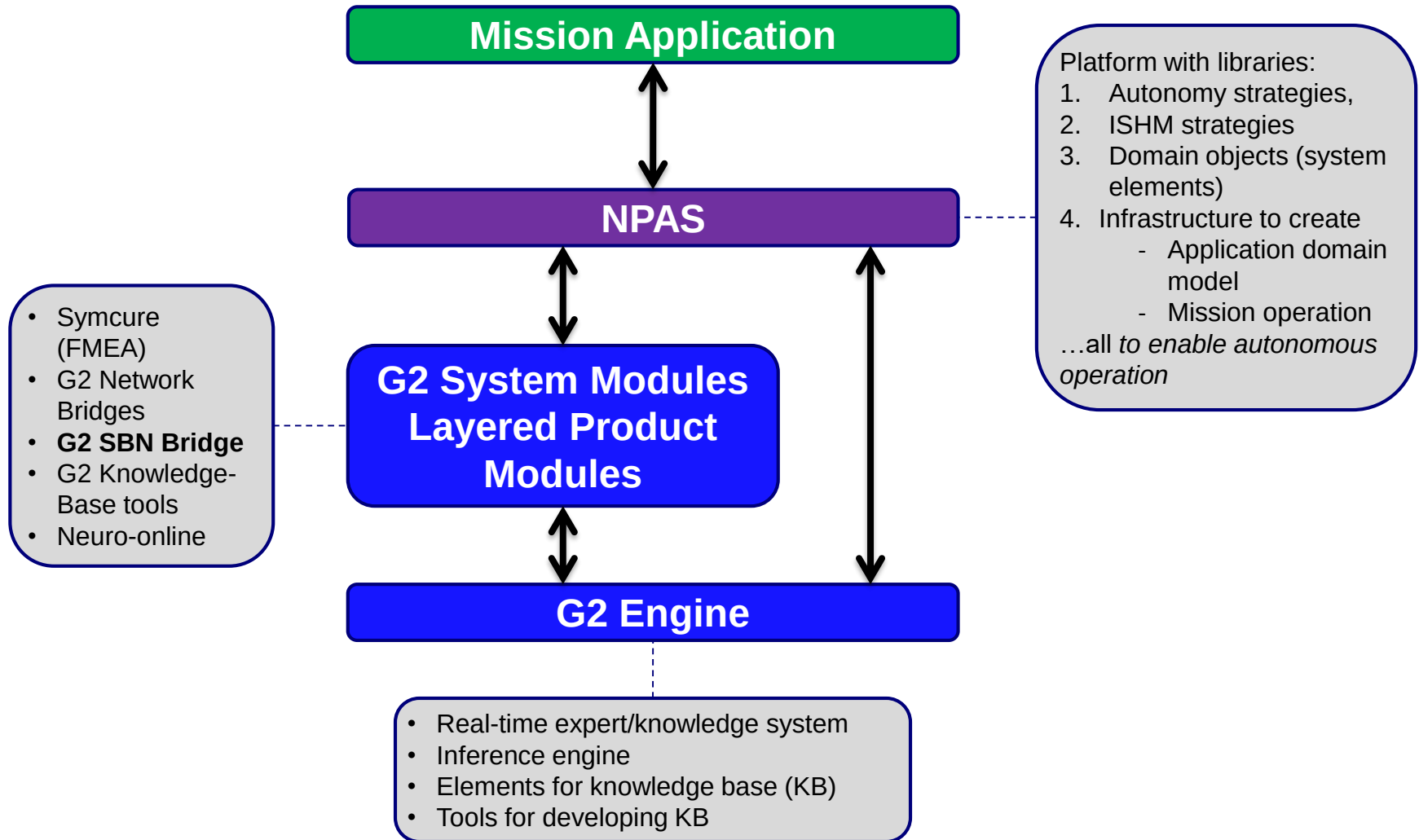
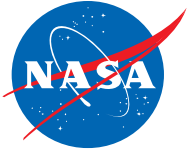
- G2 is a COTS tool for creating intelligent applications
- G2 is used in industry and DoD to control critical systems
- NASA uses G2 to train NASA astronauts to operate ISS payloads (JSC/MSFC)

NPAS provides tools for creating autonomous systems:

1. **ISHM strategies** for integrated system health management, including diagnosis, prognosis, and FMEA
2. **Autonomy strategies** framework based on concepts of operation, redundancy, nominal and off-nominal operation
3. **Domain object libraries** – abundantly reusable software, thus cost effective
4. **Infrastructure** to create **application domain models** and **mission operations that are scalable**

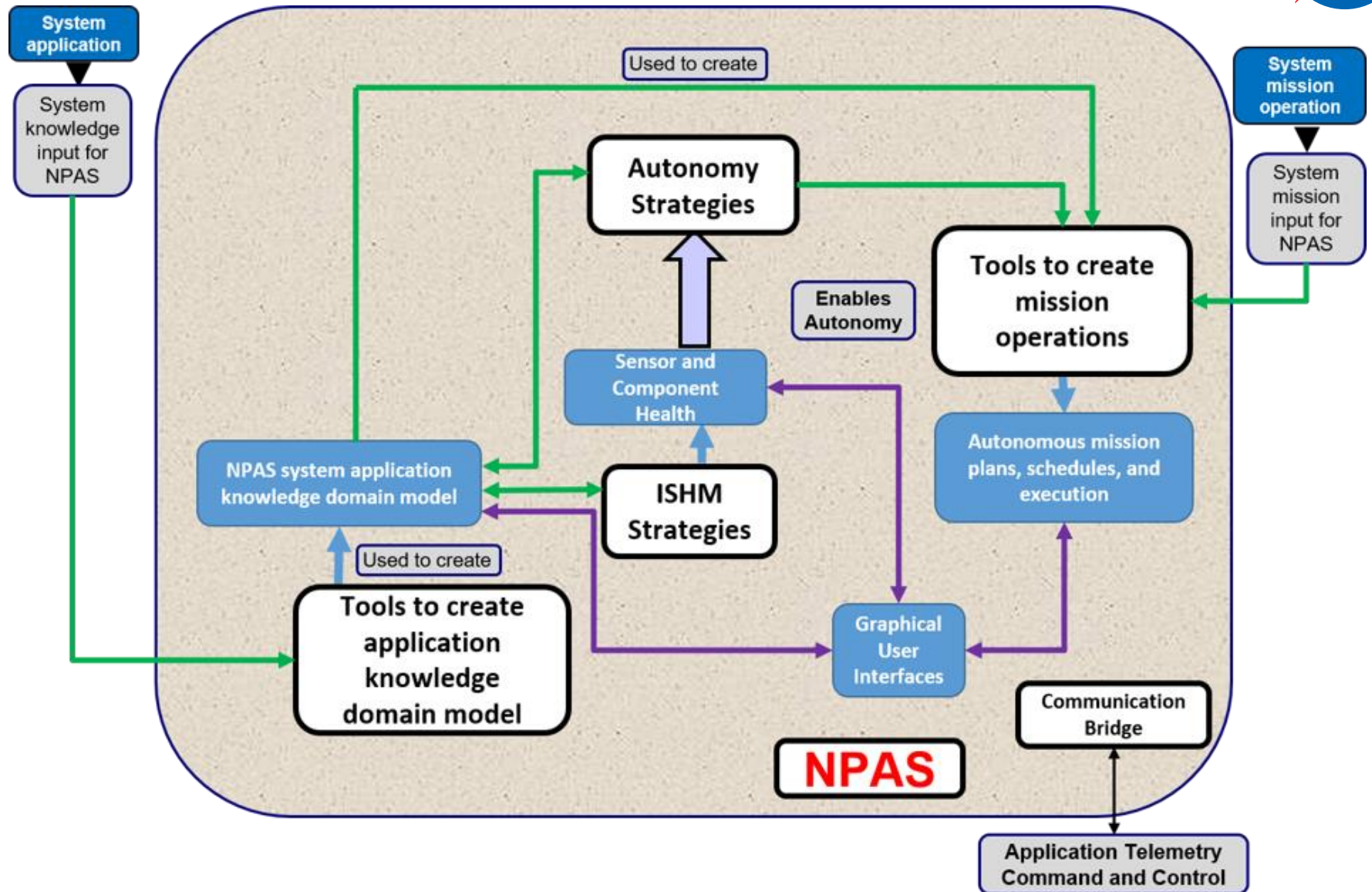
NPAS is an integrated single platform for autonomy with
cost-effective, reusable infrastructure and
provides comprehensive system awareness to operators and users

Architecture for NPAS Implementation

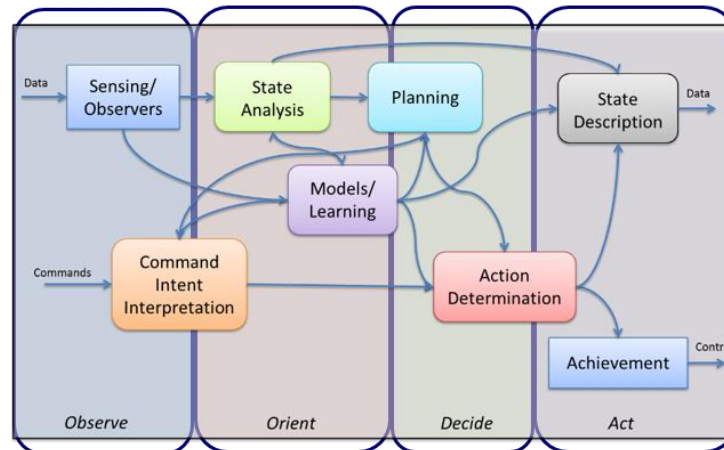
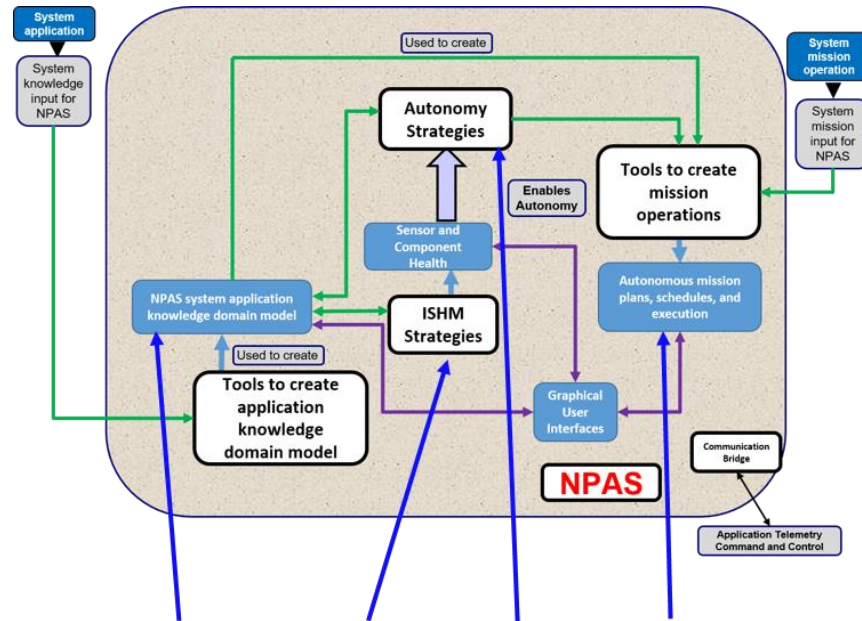
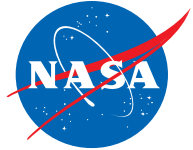


Functional NPAS Architecture

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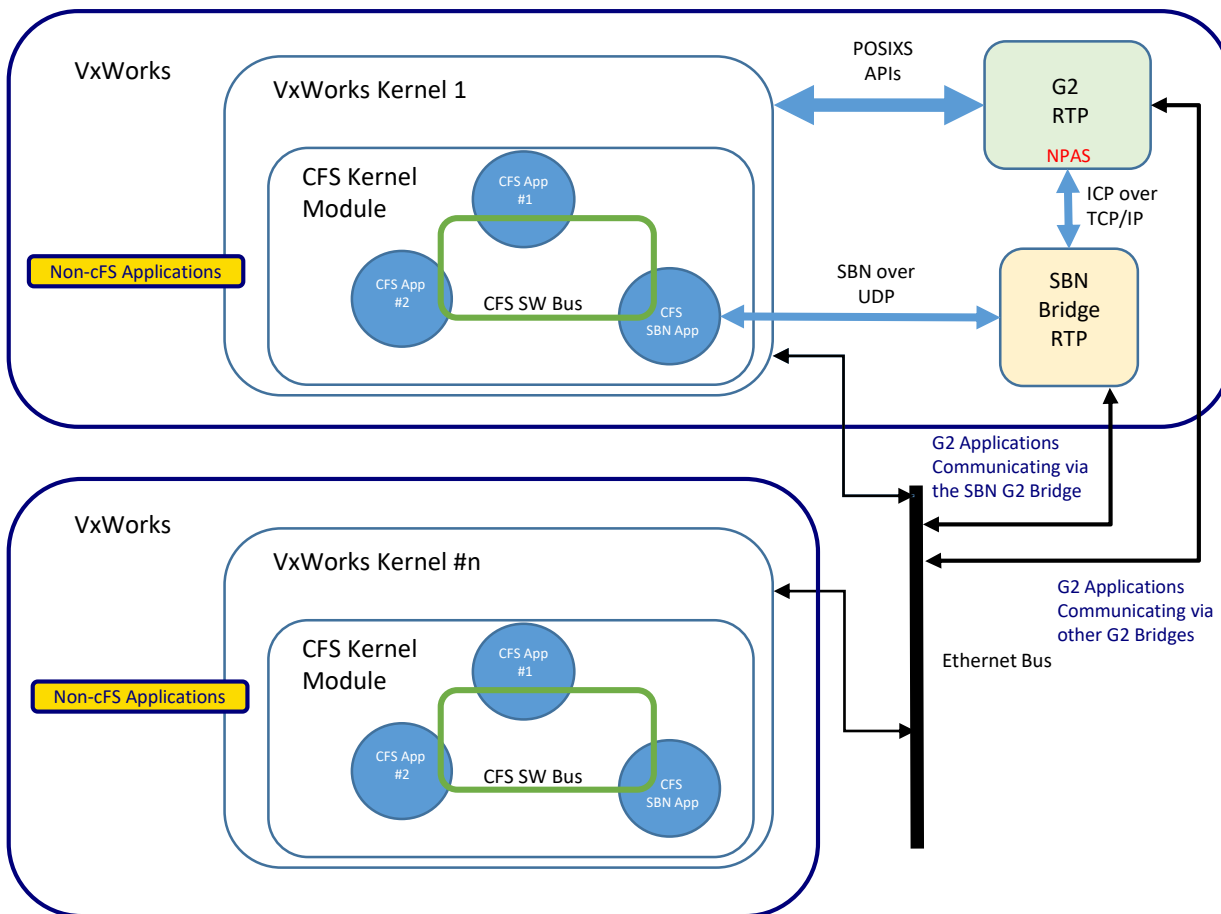


NPAS – Autonomy OODA Loop



G2 SBN Bridge to Integrate with CFS Apps

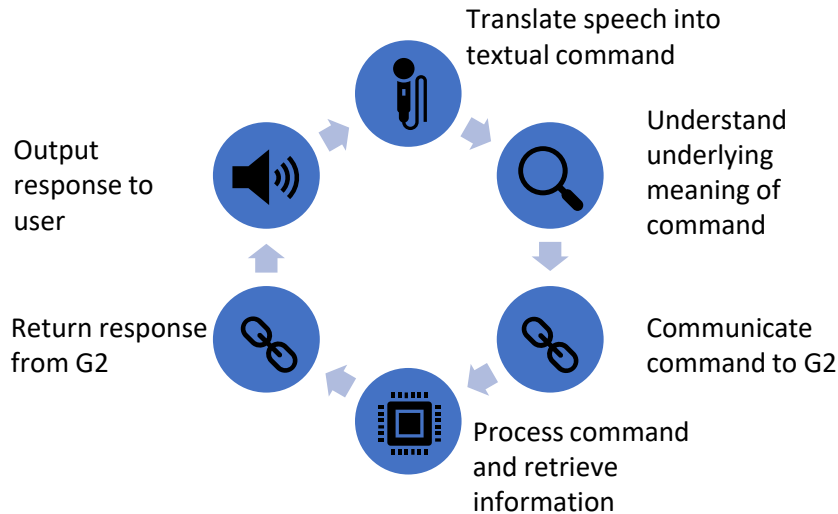
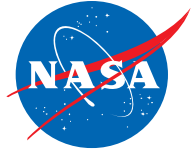
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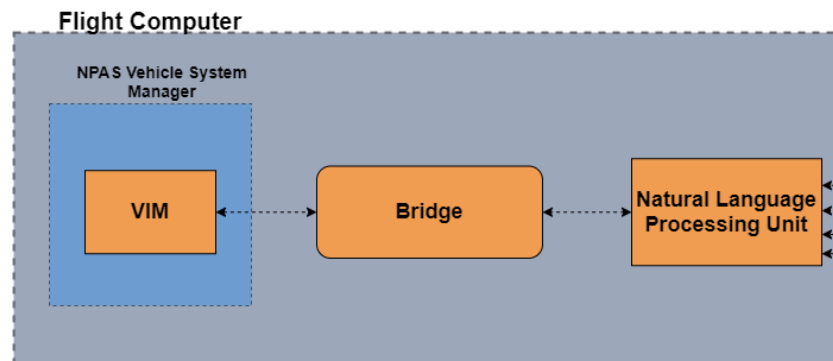
- An integration solution for G2 and CFS over the **Software Bus Network (SBN)** application. This solution involves a custom program (SBN Bridge), which **works as a middleware between G2 and CFS applications** running on the same or any other hardware connected via network.
- The SBN Bridge (product), built as a VxWorks RTP application, allows the NPAS applications (G2 RTP), also built as VxWorks RTPs, to **exchange CCSDS messages with CFS system** (Flight Software Architecture consisting of an OS Abstraction Layer (OSAL), Platform Support Package (PSP), cFE Core, cFSLibraries, and cFS Applications), running in VxWorks kernel space.
- CFS SBN app can route messages that are on the CFS Software Bus (SB) to the SBN Bridge via UDP protocol.
- The SBN Bridge (product) can then process, re-format & route the messages to NPAS applications (G2 RTP) via G2 ICP protocol (TCP/IP).
- This setup/configuration **also allows/enables NPAS applications (G2 RTP) to exchange messages with other CFS systems running in a distributed network**, by using CFS SBN app to route messages from other CFS systems on the distributed network to the SBN Bridge (product).

Autonomy Voice Assistant (AVA) for NPAS Applications

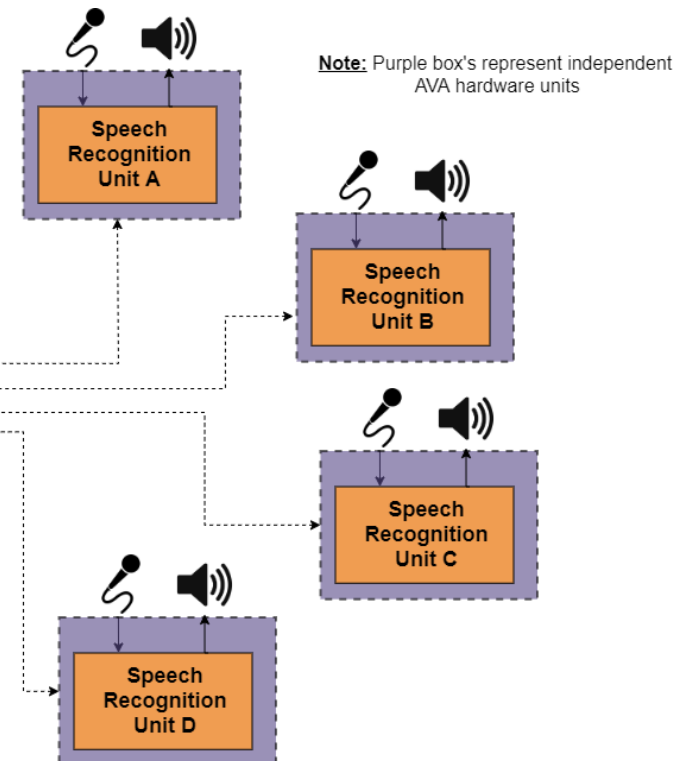
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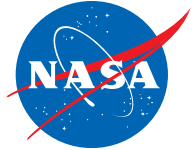


Note: Dotted Lines Represent TCP communication between modules



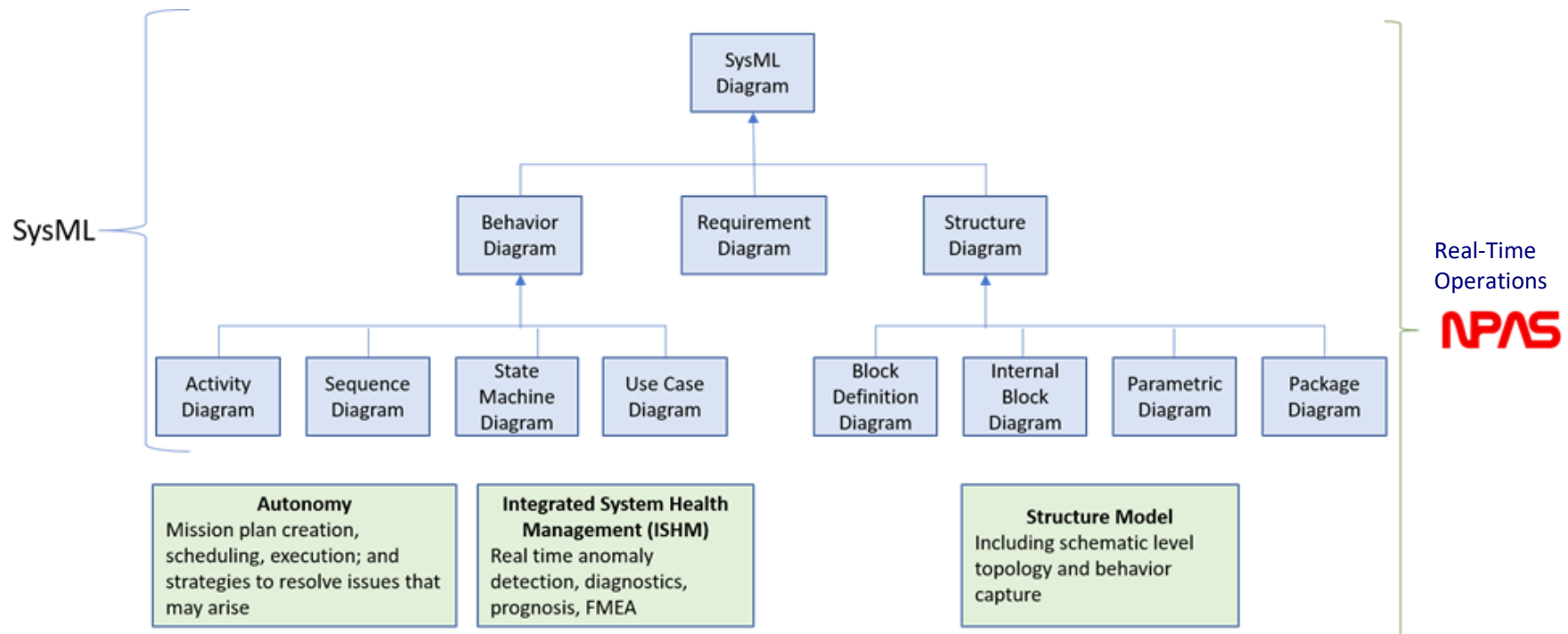
Model-Based Systems Engineering, Real-Time Operations and Autonomy

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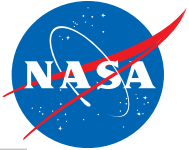


G2/NPAS Model Development

- Includes content associated with all SysML diagrams
- Augments behavior content for ISHM and Autonomy
- Augments detail of structure diagrams by including schematic details
- NPAS uses model in real-time autonomous operations

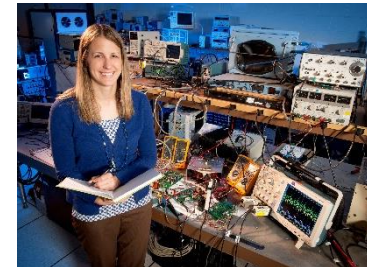
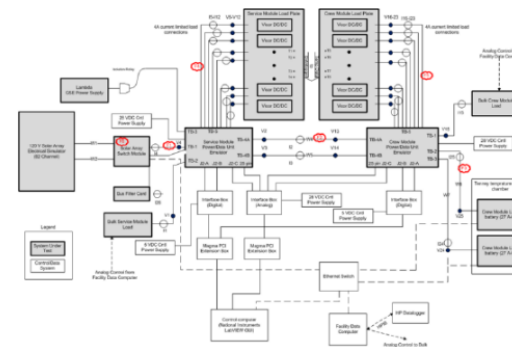
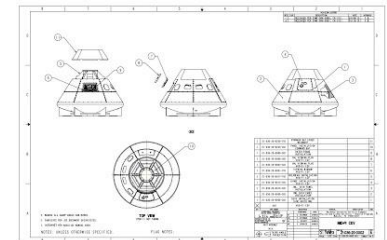
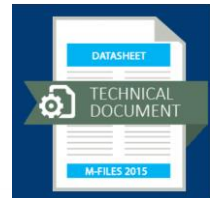
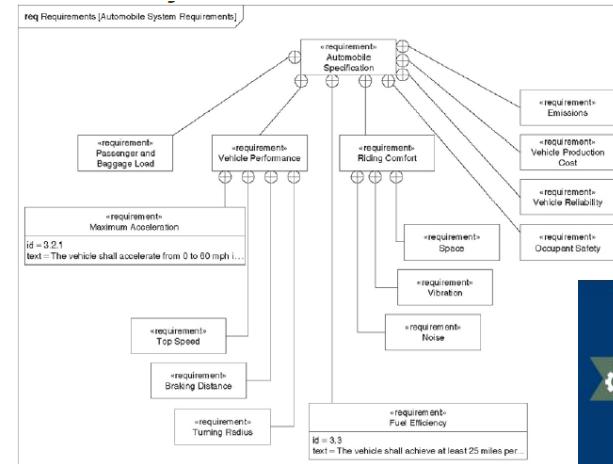


NPAS autonomy knowledge capture



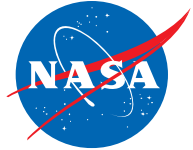
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1. Understand “domain” (**SysML & NPAS**)
 - What does the system do?
 - How does it do it?
 - How is it managed?
 - What are the major subsystems and how do they interface
2. Source of domain knowledge (KB- Knowledge Based) (**SysML & NPAS**)
 - Technical documents, user guides, maintenance trouble shooting manuals, experts
3. Identify general problems (Functional Failure Analysis) (**SysML & NPAS**)
 - Identify and characterize important problems
 - Highlight most frequent faults in the domain
 - Highlight most important problems
4. Describe the domain (System knowledge Model) (**SysML & NPAS**)
 - System configuration
 - Components
 - Dependencies
 - Relationship among other components
 - Models
5. Define performance and abnormalities management (FMEA) – (**NPAS**)
 - Identify lack of performance, abnormal conditions and when actions need to be taken when performance is out of range
6. ISHM – Integrated System Health Monitoring (**NPAS**)
7. Autonomy- creation, scheduling and execution (**NPAS**)
8. Structure Model: Including schematic level topology and behavior capture (**NPAS**)



NPAS - Infrastructure

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Initial Domain Object Library and Knowledge

Health Management

On board reasoning and decision making, using physics models, functional relationships, constraints, and concepts of operation

fluid



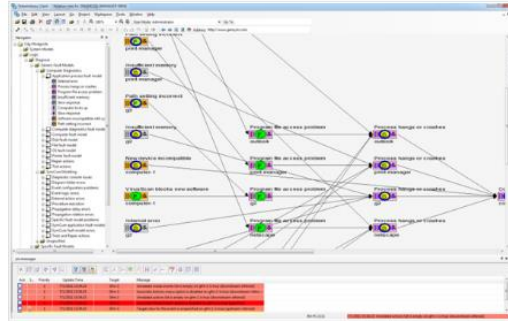
electrical



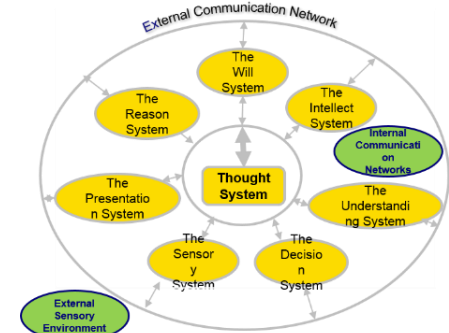
networks



mechanical



FMEA/diagnosis, prognosis, anomaly detection



Processes and event management



OODA loop

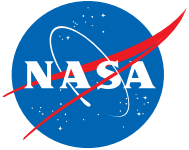
Autonomy

Foundational NPAS Infrastructure

National Aeronautics and Space Administration

Plan, creation, scheduling & execution

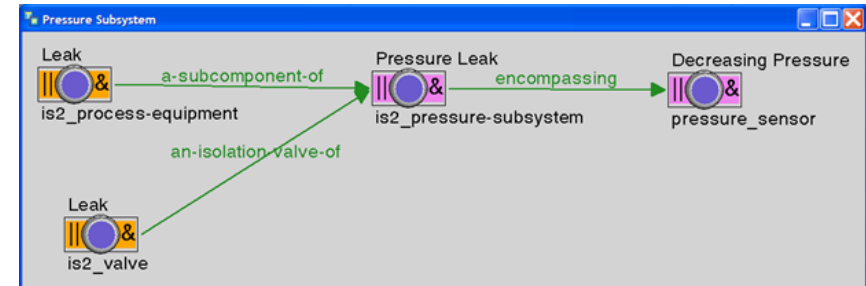
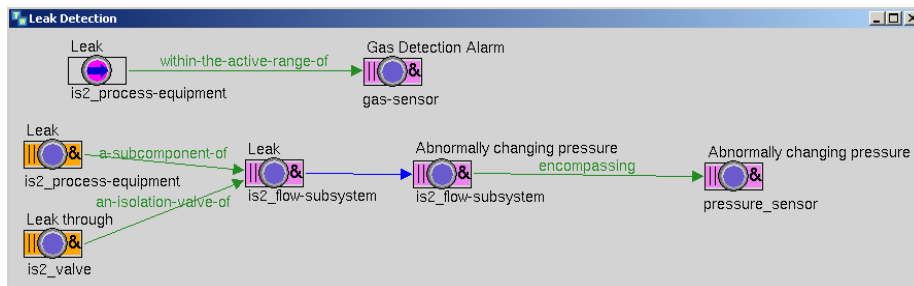
NPAS Failure Modes and Effects Analysis (FMEA)



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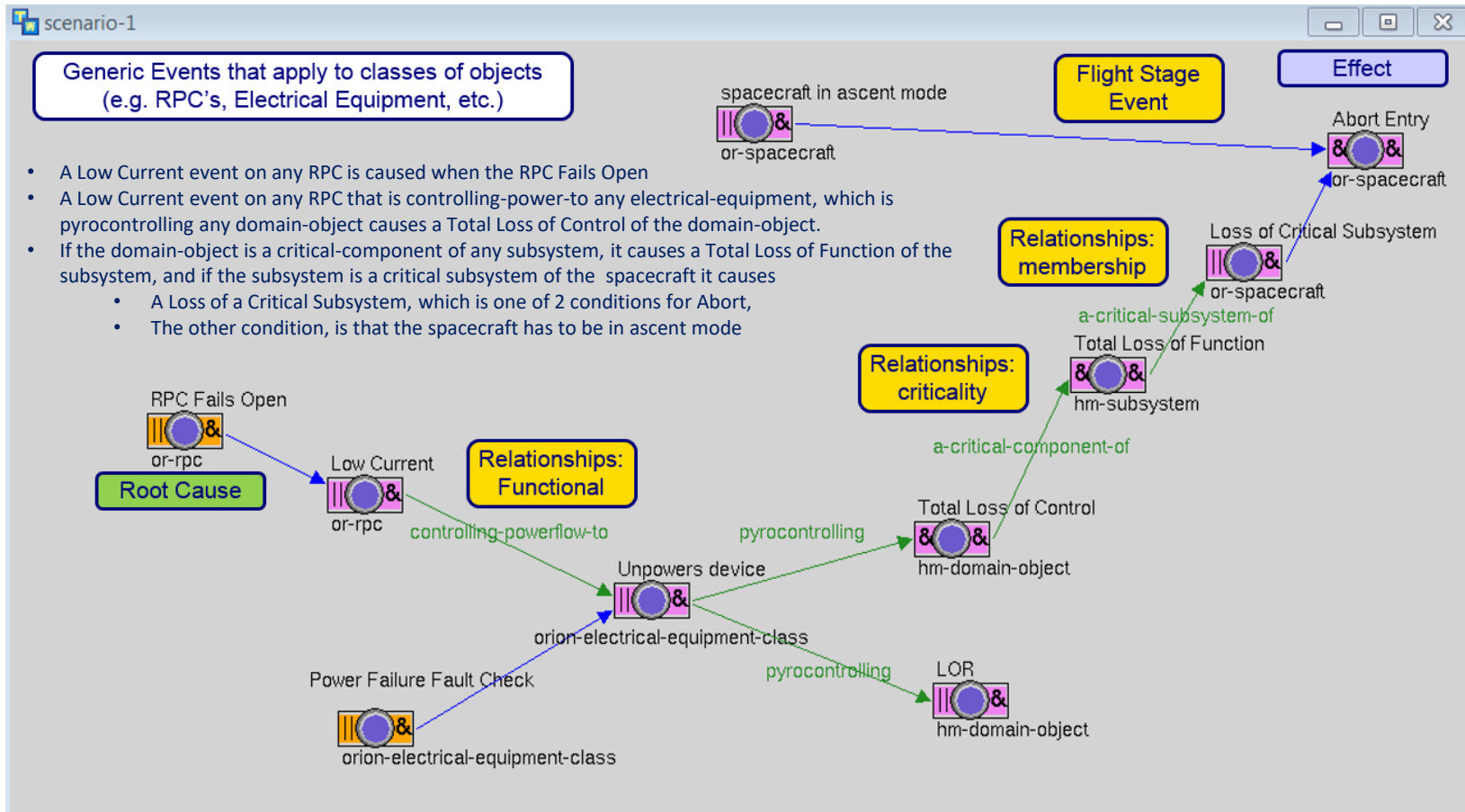
MIL-STD-1629A (NOTICE 2), Military Standard: Procedures for performing a Failure Mode, Effects, and criticality analysis (28 NOV 1984)

ID #	Item-Functional Identification	Function	Failure Modes and Causes	Mission Phase-Operational Mode	Failure Effects			Failure Detection Method
					Local End Effects	Next		
						Higher		
						Level		
	Process Equipment	Fluid feed subsystem	Leak	Sealed subsystem maintaining pressure		Pressure leak	Decreasing pressure measurement	Identify sealed subsystem, and check pressure sensors for decreasing pressure.



Two rich examples of implementation of leak detection root cause trees and encompasses Mil Standard and how FMEAs are defined. Right: leak event and consequences of leak; left: same leak event used for another diagnosis. Root cause trees re-usable/generic, events can be used in multiple root cause trees

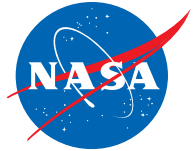
Root Cause Leading to Abort



The system can send an event to any instance represented by a node. Causes and consequences will propagate upstream and downstream to assert status of all events (true, false, suspect).

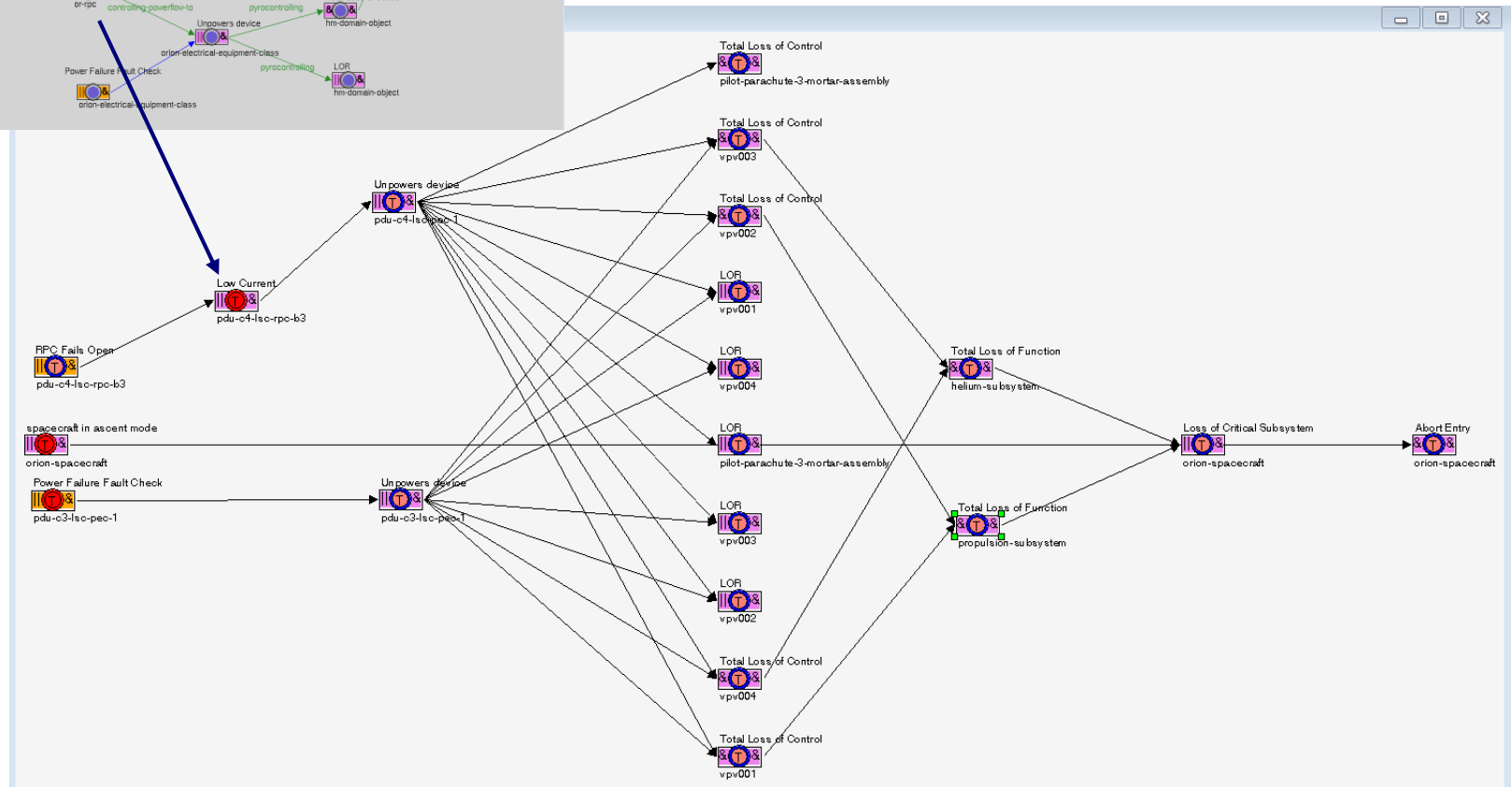
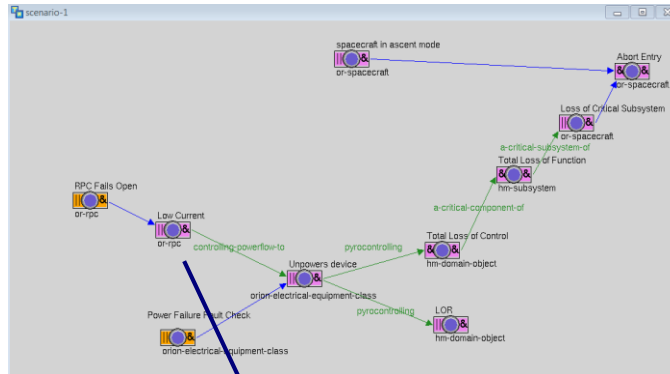
Sample Specific Fault Model automatically generated when a particular RPC fails open

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When RPC (PDU-c4-lsc-rpc-b3) experiences a low current event

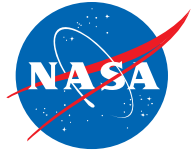
- the full blown specific root cause tree is generated



NPAS includes physics-based models



Example NPAS autonomy strategy: Use replacement for failed sensor



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- Example concepts that NPAS understands
 - Piping section
 - Membership in a piping section
 - Sensor classes/function i.e. thermocouple, pressure sensor
 - Replacement sensor (a kind of redundant sensor-that is in the same piping section as a sensor that has failed)
 - Sensor health (availability)
- Autonomy strategy
 - If a redline sensor becomes unhealthy, look for a replacement sensor; if one exists, continue operations using the replacement sensor
 - If none exist, stop the sequence (if one is being run) and inform the operator (or a sequence for safing the system could be activated)

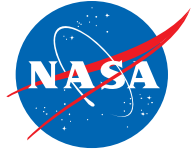
AL Monitors - SELECT STATUS TO MANUALLY ACTIVATE/DEACTIVATE --- SELECT PLAN TO SELECT LOAD PLAN OR SET TO NO PLAN					
	Status	State	Alternate	Plan Assigned - Red/Yellow if Red Line, White if Normal	Triggered
PT501	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Modifi...	7/24/14 4:15:05 p.m.
FT103	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Modifi...	Not Triggered
DP212	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Adv_t...	9/16/14 4:16:43 p.m.
PT199	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Adv_t...	Not Triggered
VFD3-AMPS	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Modifi...	Not Triggered
PT173-PT161	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Modifi...	Not Triggered
SAT_PT161	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Modifi...	9/19/14 12:29:20 p.m.
PT161	Deactivate	HEALTHY	UNKNOWN	C:\ishm-nasa-toolkit\sequence-plans\Automatic Demo Plans\Modifi...	9/16/14 6:39:25 p.m.

Critical sensors monitor showing “alternate” sensor availability should they fail.

Note: This autonomy strategy is “generic”/reusable and applies to any system – no specific coding is needed to apply to another system

NPAS autonomous sequence operations

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NPAS enables quick and easy creation of sequences using menus

- Sequences

- represented in tabular and graphical formats
- verified by simulating conditions that enable actions to be executed
- missions defined by multiple interacting sequences

- Sequence conditions include:

- sensor triggers
- redline triggers
- fluid saturation state
- redline sensor failure
- may include other conditions from health or other algorithm outcomes

- Sequence actions include:

- valve and pump operations
- camera pointing
- execution of special sequences i.e. as shut-down or reverting to a prior step
- can include execution of any activities that responds to system conditions and planning

Sequence

Define saturation redlines timers

Define sensor trigger conditions

Define valve and pump actions

Camera View Definition

Save and load sequences

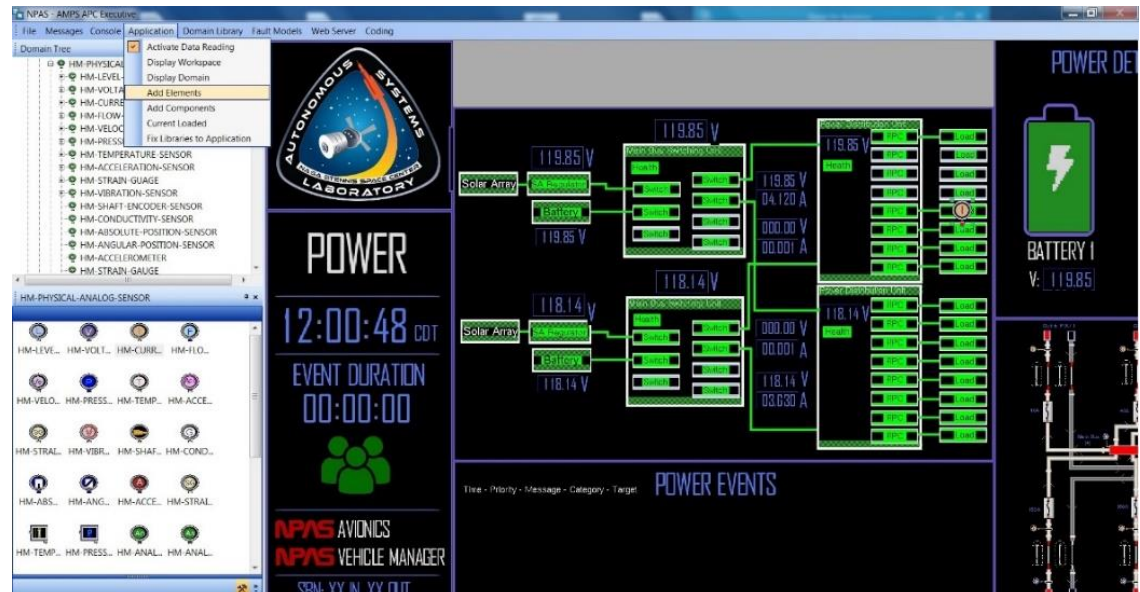
Sequence creation, loading, and execution

.... sequences are fundamental building blocks of plans and activities

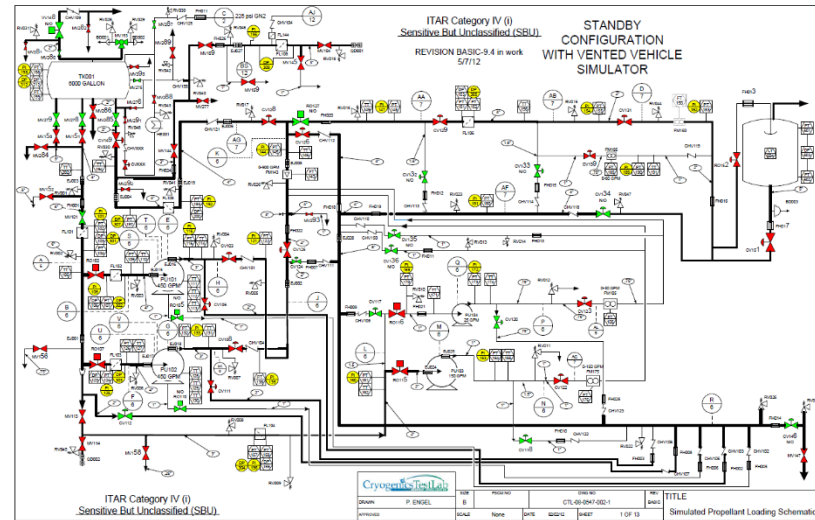
Using NPAS tools/infrastructure

- Create operational mission plans, schedules, and execution
- Core sequences
- Relationships among objects and subsystems relevant to autonomy
- Define i.e. redlines, application specific FMEA, subscriptions to object attributes
- Application specific user interfaces

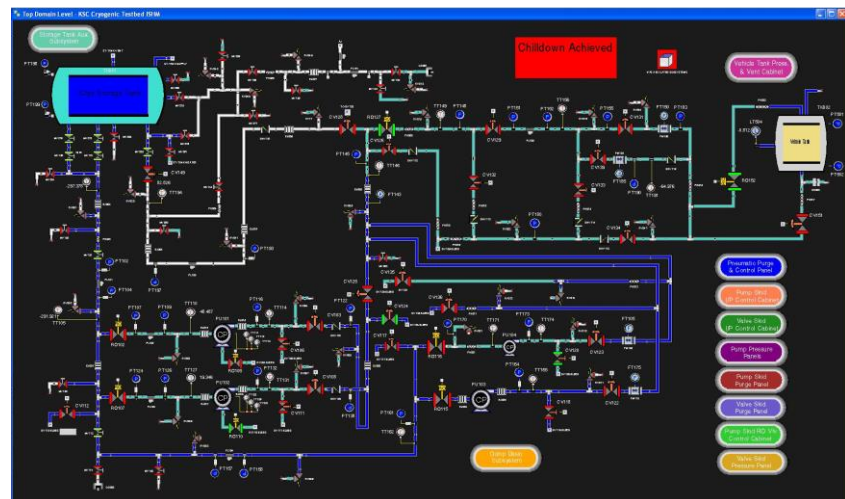
**All capabilities required
for autonomy are
integrated, from data
ingestion through
network bridges, to
scheduling of tasks,
and reasoning with
objects and their
attributes**



- Start with schematics - get schematics
- Use schematics to build application domain
- Build schematic by using NPAS palettes
- Create instance of every object in diagram, and then link them together (use library of palettes)
- This creates the core application knowledge domain – how the knowledge base is formed
- Use this information for reasoning & discovery (NPAS ISHM and Autonomy functions are embedded in NPAS and will apply to the domain from the schematics)

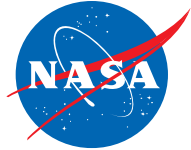


Schematic, KSC Cryogenics Test Laboratory (CTL) – old version



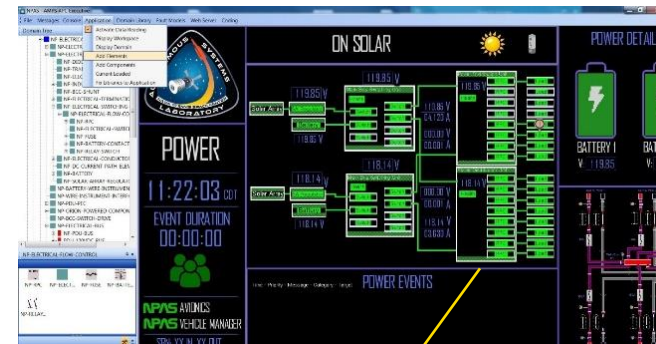
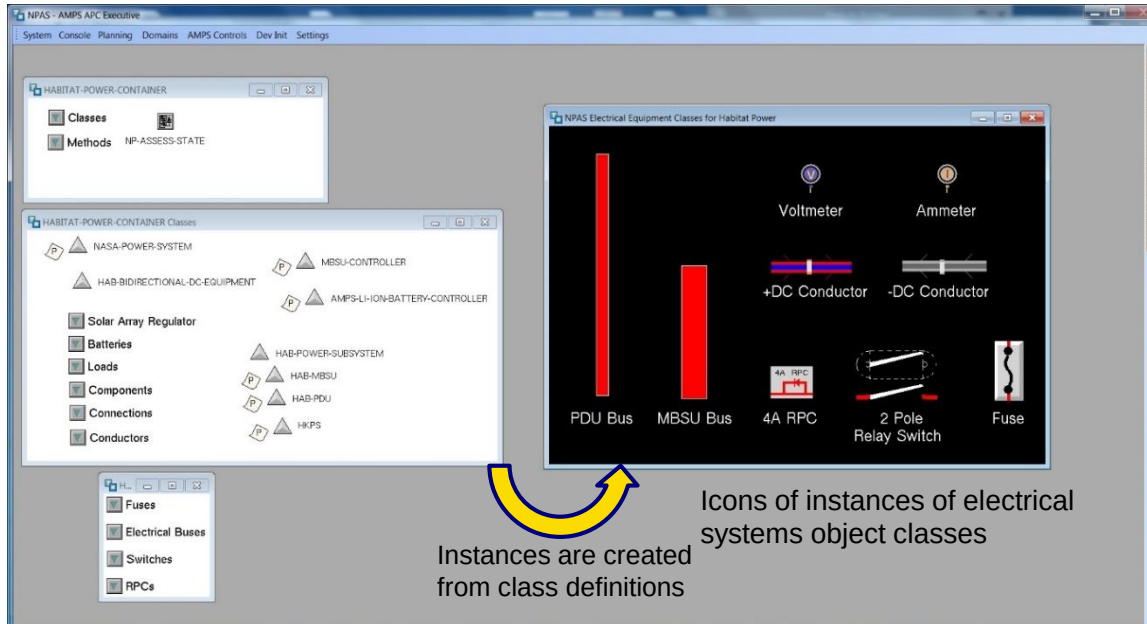
Application domain model, KSC CTL

NPAS palette use: power example



Power equipment classes with sample instance

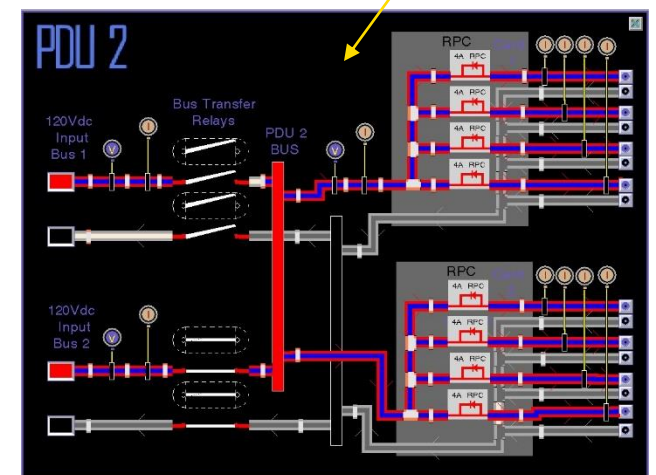
Power UI with palette



Class definitions, used to create an instance

Graphic-oriented environment

- create the model of the application graphically (schematic)
- objects are represented by icons
- objects-representation of some part of the application
 - i.e., tank, valve
 - represented by an icon
 - has a table of attributes (contains the knowledge about the object)
 - Hierarchy of parent and child classes
- objects are placed in workspaces- i.e. like a diagram in SysML
- objects are connected graphically
- pop-up menus for objects (i.e. attribute table)
- actual application objects = instances

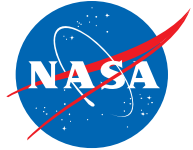


Power system domain model based on schematics

Instances are connected according to schematics to create knowledge domain models

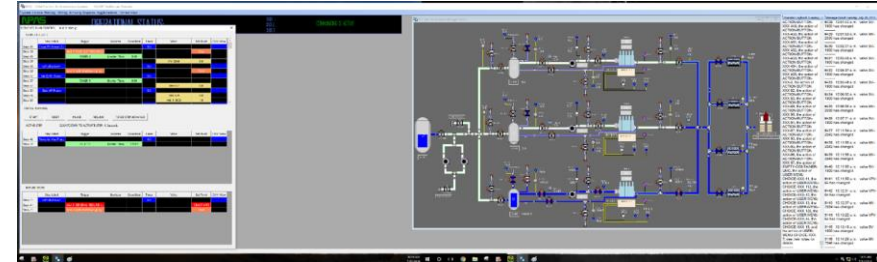
NPAS was used to implement autonomous operations of the nitrogen system at SSC

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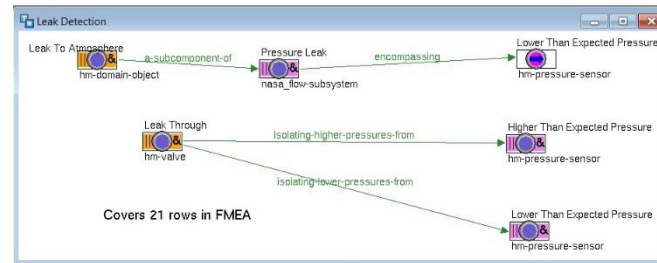


NPAS provide infrastructure to create a digital twin with reusable tools for implementing intelligent, thinking autonomous operation

Sequencer pumping;
site pressure increasing



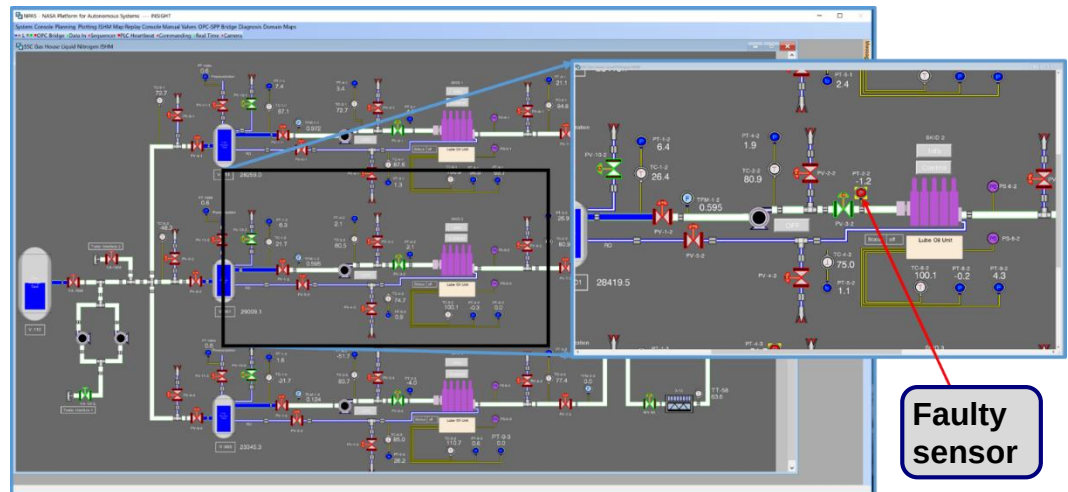
Root cause tree



Domain map

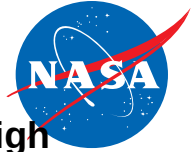


User friendly interface



Faulty sensor

SSC FY18 NPAS Infusion - Project INSIGHT



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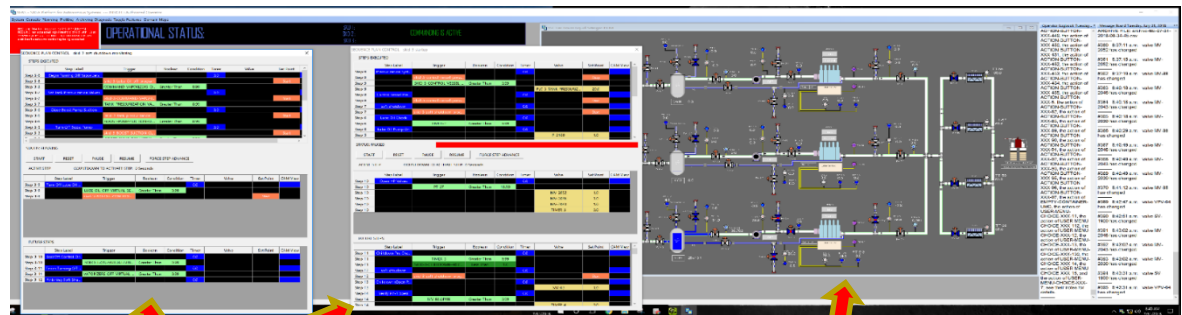
Project INSIGHT (Intelligent Stennis Gas House Technology) Phase 1A – at the SSC's High Pressure Gas Facility (HPGF) – NPAS for INSIGHT for nitrogen (N2) system

- Verified and boarded NPAS for monitoring N2 system
 - **Capable of monitoring and controlling the HPGF N2 skids and existing vaporizers**
 - Monitor PLC activity – including redlines
 - Positioned for validation plan to proceed for SSC authorization to run and operate, with NPAS, the HPGF N2 skids and existing vaporizers
 - Establish software infrastructure to implement autonomous operations for the current & new PLC N2 system software
 - Provides a roadmap to validate and activate an operational autonomous system
 - Release the required NASA documentation
- Phase 1B – complete deployment of NPAS N2 system and create Helium system with leak detection
 - **Project INSIGHT has successfully met implementation challenges, leveraged other related activities to optimize success, and has created the foundation required for implementation of autonomous operation of the HPGF nitrogen system in FY19**

Class C Safety Critical

Checkouts: one of the first steps performed by the system is to verify that the safety shutdown system is operating properly.

The graphic illustrates the redline checkout performed for test TPS-HPGF-01350 on July 31st, 2018, prior to Pump Sequence Operations on Skid 3



- Graphics windows developed with NPAS for Project INSIGHT to illustrate the sequence that is operating in real-time
- Displays both previous sequence steps as well as upcoming steps and expected stimuli

Graphics window developed to mimic existing PLC screens -- minimizes operator training time, maximizes familiarization by existing operators and provides a versatile tool to visualize the system, **in real-time**

AES Major Accomplishments – FY17/FY18

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FY17 Orion Demonstration

EFT-1 Capability Demonstration using NPAS

Pilot study:

- Acquire **EFT-1** system information, telemetry data, **fabricated fault scenarios**
 - Implemented an **intelligent health monitoring capability** including **anomaly detection** and **related diagnostics and consequences (FMEA)**, and show **integrated and comprehensive system awareness**
- **Results:** Demonstrated a reusable integrated monitoring system (including anomaly detection and FMEA capability) for Orion's EFT-1: 1-power system, 2-helium system and 3-parachute system, **in less than 4 man months**

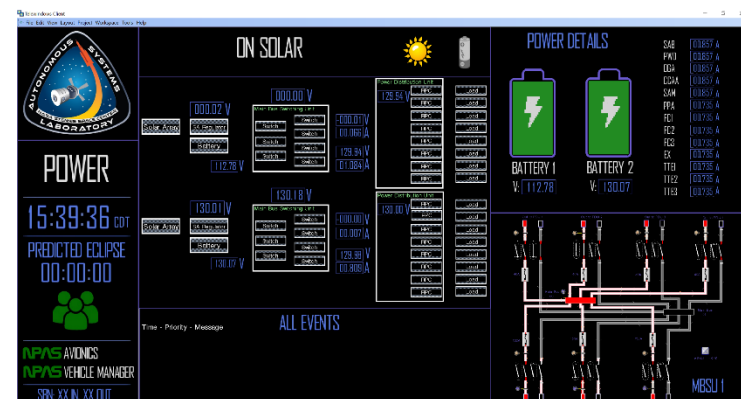
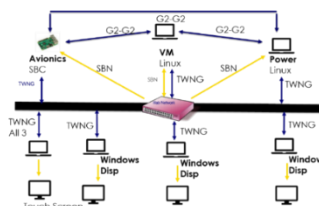
Demonstrate the benefit of using NPAS and an engineering process for rapid capability development and associated significant cost savings



FY18 JSC iPAS Competition

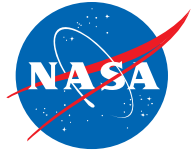
- Demonstrated G2/NPAS autonomous operation functionality
- Demonstrated ability to rapidly implement intelligent hierarchical distributed autonomy architecture
- Integrated into JSC A&S Configuration Management (CM) Core Flight System Command and Data Dictionary (CCDD)

Distributed Hierarchical Autonomy & Integrated System Awareness



AES Major Accomplishments – FY19/FY20

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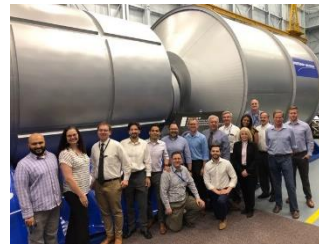


NextSTEP-2 A: Habitation Systems

Northrop Grumman Innovative Systems (NGIS)

NORTHROP GRUMMAN

Developed prototype hierarchical distributed autonomous operation capability, including an **NPAS Vehicle Manager** and **NPAS Electrical Power System**



- ✓ Integrated in Habitation in the Life (HITL) demo
- ✓ Included in NGIS documentation deliverables
- ✓ Enhanced NPAS Vehicle Manager UI created and presented at NGIS's SME stand alone demonstration

Developed a baseline hierarchical distributed autonomous operation capability

NPAS Operational on Flight Processor

SSC Cooperative Agreement Contract with Ignite Technologies

Demonstrated NPAS/G2 functionality on a space qualified processor



gensym

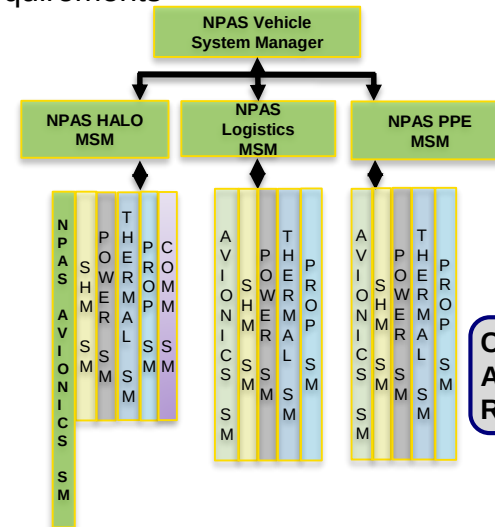


Ignite
TECHNOLOGIES

AiTech SP0-S/RAD 750
3U cPCI Radiation Tolerant Power PC SBC

Gateway Autonomy Architecture Demo

Demonstrated hierarchical distributed autonomy architecture prototype aligned with Gateway Autonomy ConOps, VSM Concept of Operations and Gateway VSM requirements



Conforms to Gateway Autonomy Requirements

Demonstrate G2 SBN Bridge

- ✓ Demonstrate G2-Software Bus Network (SBN) bridge for integration with cFS applications
- ✓ Overall performance testing - bridge functionality behaved as expected

gensym

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TECHNOLOGIES

cFS
core Flight System

Enabled NPAS to communicate with cFS app

AES Technology Infusion – Northrop Grumman, NextSTEP-2



Stennis Space Center

NextSTEP-2, Habitation – NGIS Integration

Northrop Grumman Awarded NASA Contract to Provide First Crew Module for Artemis Program Gateway



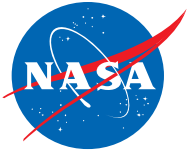
- ✓ Quickly created prototype NPAS Vehicle Manager and NPAS EPS (Electrical Power System), that included hierarchical distributed autonomy
- ✓ Integrated with existing NGIS Station Telemetry Interface
- ✓ Completed in abbreviated time – during government shutdown
- ✓ Able to generate additional UIs in response to customer request
- ✓ All deliverables met within 5 months
- ✓ Positive feedback from HITL astronaut



NPAS VM User Interface

AES Technology Infusion FY20 - NRSAA

Stennis Space Center



Autonomous Avionics Risk Reduction

Objectives:

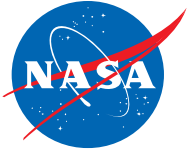
- Autonomous avionics activity to help reduce risk for demonstrating autonomous operations between Gateway and Orion
- Supports efforts to demonstrate a distributed hierarchical autonomy implementation for potential use in Gateway and other elements of the Artemis mission
- Implementing Gateway distributed hierarchical autonomous operations with avionics hardware architecture (network protocols and message definitions) as part of NASA NRSAA with Lockheed Martin



Notional NASA Habitation structure near the Moon

NPAS Summary

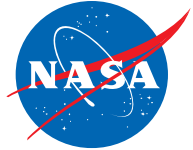
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- ✓ NPAS is an innovative software platform that provides the framework to quickly develop, implement and deploy intelligent/thinking autonomous operations software
 - integrated architecture for creation and analysis of a comprehensive “live” application model, health assessment, diagnostics, anomaly detection (FMEA), autonomous operational strategies, mission planning, scheduling, and execution, as well as network communication for system integration
- ✓ NPAS has reusable core capabilities
 - leverageable - product applicable for other future uses
 - sustainable – modular, knowledge-base resources
 - affordable – **long term cost savings**
 - reduced delivery time
 - **Evolvable/scalable**
- ✓ NPAS is being certified by NASA for boarding software as an operational capability at NASA SSC at the HPGF
- ✓ NPAS is being tested for operation on current and future flight processors
- ✓ NPAS is preparing for FY22 CMMI Appraisal required for Class A human rating software, running on flight processor (SP0-S), in VxWorks OS



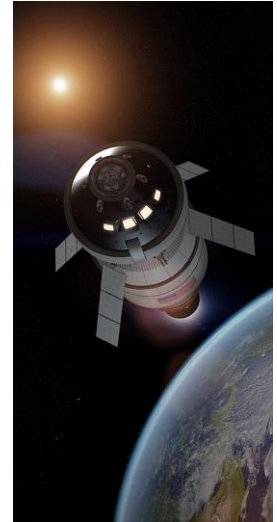
Project Overview – Why NPAS



Why is this project important

- Trusted autonomous systems require
 - ✓ Ability to operate without control from the crew or MCC
 - ✓ Independent reasoning so the need for persistent guidance is eliminated
 - ✓ Intrinsic monitoring of tasks
 - ✓ Rapid notification to crew/operators when necessary
 - ✓ Visibility into decision processes – no black box algorithms

The NPAS project is maturing the technology of autonomous systems in support of Artemis



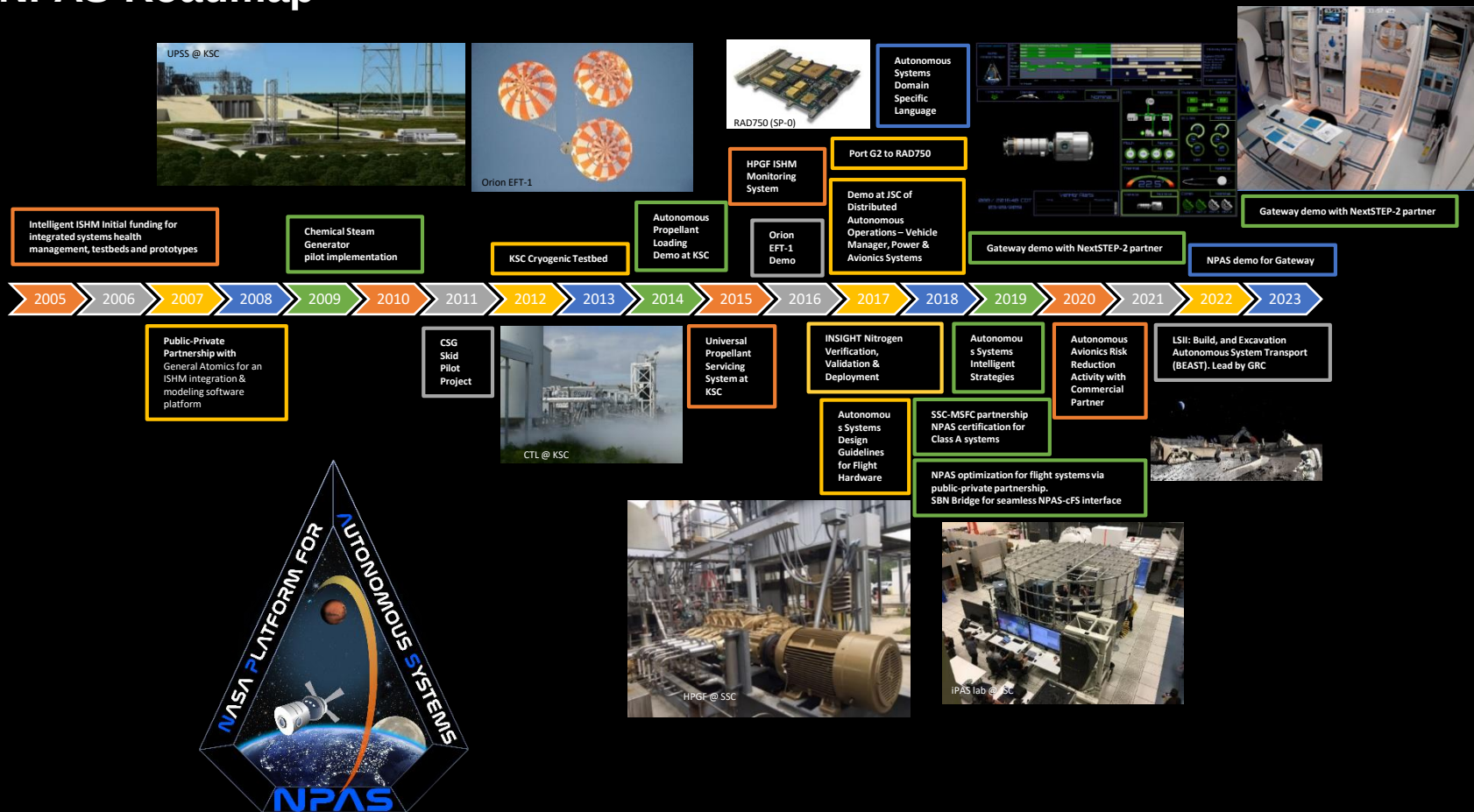
Current Objectives

- Developing the technological framework to transform the paradigm for implementing operational autonomous capabilities, making it easier to define the models required to operate autonomous systems, reducing cost and time to design build test and deploy intelligent distributed hierarchical systems
- Improve the ability to build trusted autonomous systems
- Addressing V&V issues of flight certification for software with AI capability; flight certify NPAS Autonomy Software
- Meeting NASA VSM autonomy requirements and con-ops
- Implementing Gateway avionics hardware architecture (network protocols and message definitions)

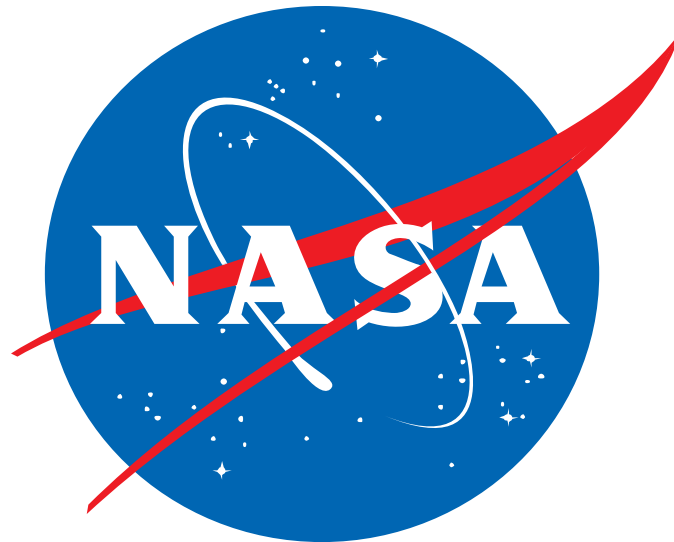
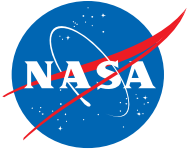


NPAS – NASA Platform for Autonomous Systems

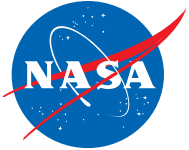
NPAS Roadmap



Contact the Autonomous Systems Lab (ASL) for autonomy engineering/technology and system health management expertise
 Fernando Figueroa: fernando.Figueroa@nasa.gov (228-342-6035)



Brute Force Autonomy vs Thinking Autonomy



Brute Force Minimal or no analysis and decisions by the System	Concept/Model Based (Thinking) Most analysis and decisions by the System
Problems are solved by the expert off-line, and made available to computer code to make the most appropriate choice of solutions (lookup tables).	Problems are solved by the autonomous system that is able to apply generic models of processes taking place in the system, in real time.
Solutions must be found for every possible case defined by every object, every process that involves the object, and every configuration of the system where the object belongs; and for every process that may occur in the system (nominal and off-nominal).	The autonomous system analyses the system behavior at a high level of abstraction, by applying generic models (e.g. physics models or other) that employ definitions and concepts used in the models. Solutions are determined with a relatively small set of models.
Coverage is not comprehensive. It is limited by the thoroughness of the analysis by people.	Coverage is comprehensive for each generic model used. So total comprehensive coverage is feasible, since first principles cover all behaviors.
The autonomous system does not “think” it merely makes use of what has been “thought” by humans.	The autonomous system “thinks” to provide solutions that need not be solved off-line by humans.