NASA Platform for Autonomous Systems (NPAS)

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NASA Platform for Autonomous Systems (NPAS) is a disruptive software platform and processes being developed by SSC Autonomous Systems Laboratory (ASL). Autonomous operations are critical for the success, safety and crew survival of NASA deep space missions beyond low Earth orbit, including Lunar Orbital Platform-Gateway, and for the future of cost-effective ground mission operations. NPAS represents the embodiment of an innovative implementation for "thinking" autonomy in contrast to brute-force autonomy. It also uniquely addresses the requirements and integrates five primary functionalities for autonomous operations including: (1) Integrated System Health Management (ISHM), (2) autonomy, guided by health and system concepts of operations; (3) knowledge models of applications; (4) infrastructure to create, schedule, and execute mission plans; and (5) infrastructure to integrate distributed autonomous applications across networks.

I. Nomenclature

NASA = National Aeronautics and Space Administration
SSC = Stennis Space Center
JSC = Johnson Space Center
NPAS = NASA Platform for Autonomous Systems
iPAS = integrated Power Avionics Software
ISHM = Integrated System Health Management
BFA = Brute Force Autonomy
TA = Thinking Autonomy
DIaK = Data, Information, and Knowledge

II. Introduction

NASA needs autonomous operation software capabilities for safety critical applications that can be affordably and timely qualified and deployed. Autonomy has historically been implemented as "brute-force autonomy (BFA)," as opposed to "thinking autonomy (TA)." BFA consists of considering all possible cases for autonomous decisions and applying those specific strategies to generate solutions offline. Then, cases and solutions are incorporated in the processor for implementing autonomy, and the processor simply chooses the decisions which correspond to each prescribed case. An interpretation of this methodology suggests that the "thinking" is done offline by experts. This method could never be comprehensive, since there will inevitably be cases that are not apparent, imagined and/or just missed, thereby limiting the fundamental degree of autonomy. Thus, brute-force autonomy implementations are specific (hard-coded) to an application, hence they are exorbitantly expensive to develop, maintain, and evolve. For these reasons, BFA has limited capability and reusability, and therefore is not viable for sustained evolution of autonomy, all critical for developing affordable autonomous systems. Thinking autonomy, in contrast, implies that

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the processor for autonomy is able to reason based on concepts and first principles, and applies these principles in real-time to models that support strategies for Integrated System Health Management (ISHM) and autonomous operations.

The future of "true" autonomous systems requires independent thinking and reasoning so that the need for persistent updates is eliminated, unforeseen human oversight is prevented, passive monitoring of the progress of a task when desirable is enabled, and awareness for rapid comprehension and action by operators is made possible. This represents a paradigm shift in the way NASA must develop autonomous operations software for future space and ground systems. Stennis Space Center (SSC) has developed a software platform that enables implementation of "Thinking" Autonomy (NPAS).

This paper describes autonomy capabilities enabled by using NPAS for a broad range of ground and space systems, it also describes NPAS' software architecture and initial implementations. Furthermore, it discusses a path-to-flight for NPAS as part of current efforts in order to support gateway and other NASA activities in the near and mid-term; and to achieve long term exploration objectives.

III. NPAS Description

NASA Platform for Autonomous Systems (NPAS), is a software platform developed by NASA Stennis Space Center (SSC) and continuous to be evolved at the Autonomous Systems Laboratory (ASL). NPAS is used to make systems operate with any desirable degree of autonomy and provides comprehensive health and operational awareness to operators and users, with capability to evolve systematically. NPAS uniquely extends the paradigm of model-based systems engineering (MBSE) beyond static models, into live models for real-time "thinking" autonomous operations that can be rapidly and affordably implemented and evolved.

Autonomous operations are critical technologies required for the success, safety and crew survival of NASA deep space missions beyond low Earth orbit, including Lunar Orbital Platform-Gateway (LOP-G), and for the future of cost-effective ground mission operations. NASA Platform for Autonomous Systems (NPAS) is an innovative software platform and processes that addresses NASA's autonomy needs. NPAS uniquely integrates five primary functionalities for autonomous operations including: (1) Integrated System Health Management (ISHM), (2) autonomy, guided by health and system concepts of operations; (3) knowledge models of applications; (4) infrastructure to create, schedule, and execute mission plans; and (5) infrastructure to integrate distributed autonomous applications across networks.

IV. NPAS Software Architecture

NPAS is architected as modules, and it incorporates tools to help create all elements of an autonomous system. Figure 1 shows the architecture.

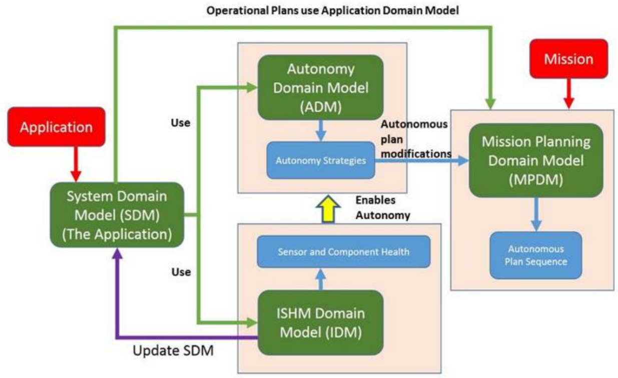


Figure 1. NPAS Software Architecture

A. System Domain Model (SDM)

This is the knowledge model of the system that will be made autonomous. One way to describe it is to say that it is equivalent to a SysML model, but it is an expanded and live/operational SysML model that includes all information that may be needed to apply strategies for ISHM and autonomy; and to plan, schedule, and carry out activities autonomously. The System Domain Model is usually developed from schematics of the system, so as to include all elements upon which reasoning and decision making for autonomy are necessary.

B. ISHM Domain Model (IDM)

- 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:
    - Pipe networks encompassing connected objects
    - Pipe section
    - Object membership of a pipe section
    - Object membership of a flow subsystem
    - Anomalies are detected by applying concepts according to the context for processes taking place

- The NPAS 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) are 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.)

C. Autonomy Domain Model (ADM)

- Strategies to enable autonomy
    - Use of redundancy
    - Determination of potential replacement elements (e.g. sensors)
    - Determination of alternate flow paths
- Uses DIaK from the SDM and condition information from the IDM

D. 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)

V. NPAS Capability

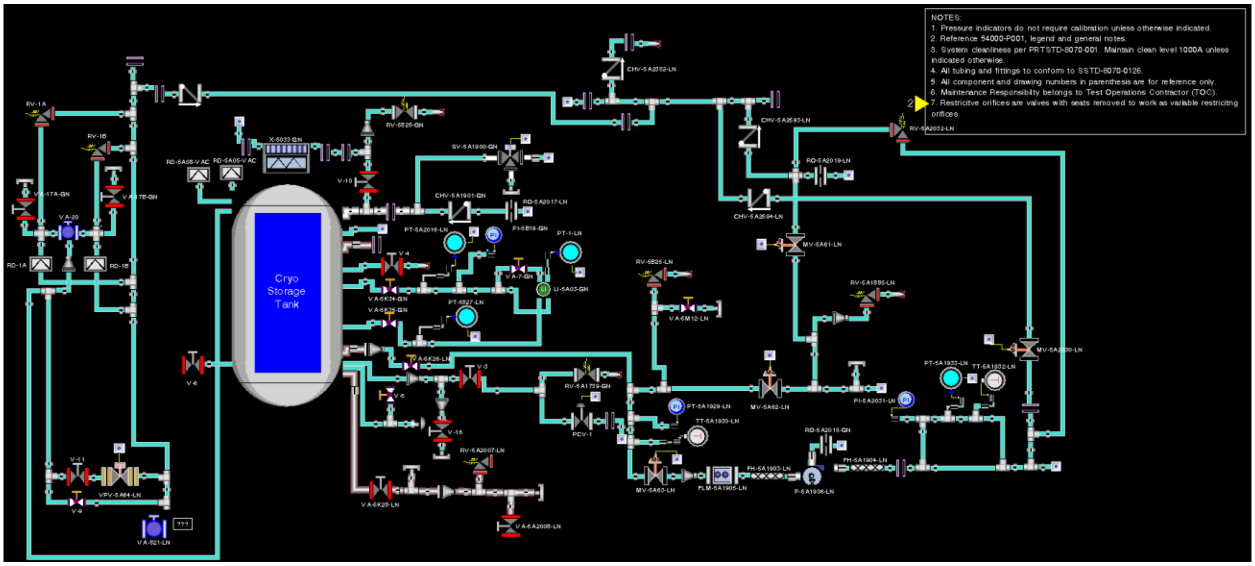
NPAS is used to make systems operate with any desirable degree of autonomy and provide comprehensive system awareness to operators and users.

NPAS integrates these primary functionalities:

1. An Integrated System Health Management (ISHM), that includes anomaly detection, diagnostics and effects (FMEA), prognostics, and comprehensive awareness
2. Autonomy (planning, scheduling and execution), that encompasses strategies for autonomous behavior constrained by health and system Concepts of Operations (i.e. strategies based on redundancy, on alternate actions, on reducing risk, on mitigating failure)
3. Infrastructure to
    - rapidly develop and evolve knowledge models of applications.
    - to create, schedule, and execute mission/operational plans; and sequences
    - to seamlessly integrate distributed NPAS autonomous applications across networks
    - to develop user interfaces that provide integrated awareness and optimal operator access for a desired degree of autonomy.

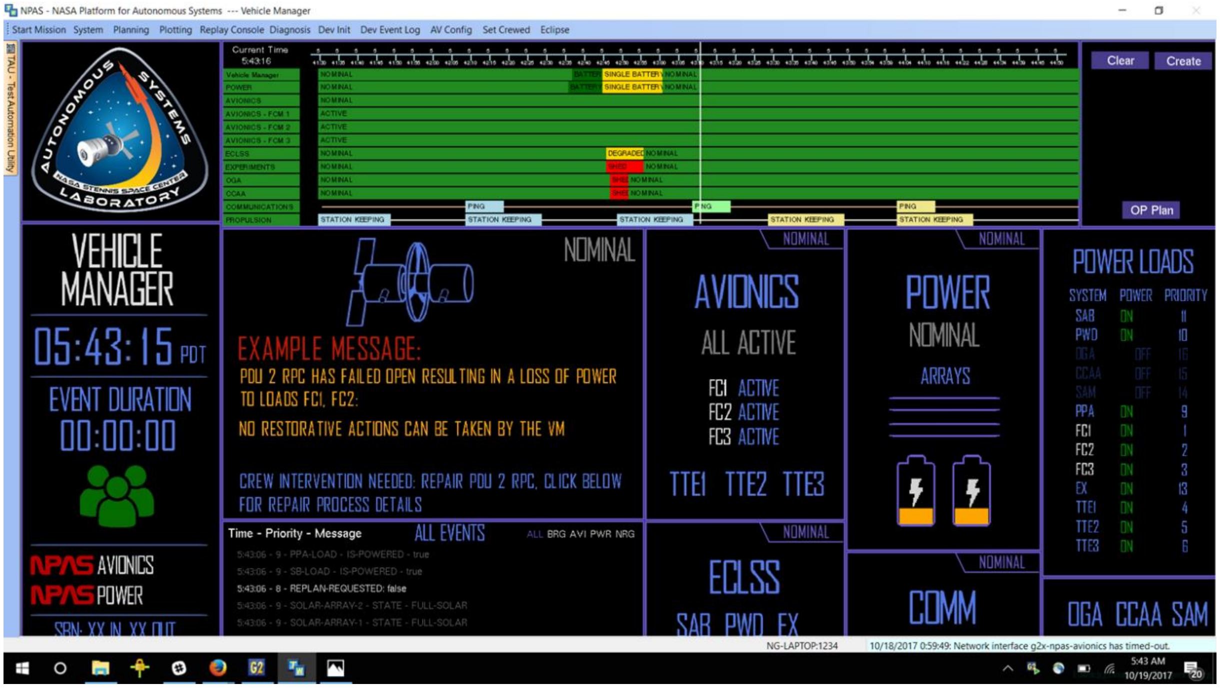
VI. Implementation of Autonomous Systems using NPAS

Autonomous capability implemented using NPAS has been demonstrated successfully for 1) Autonomous Propellant Loading from a storage tank to a flight tank at the Cryogenic Test Bed Laboratory (KSC); 2) a simulated (physics) implementation/demonstration of simultaneous multi-system autonomous propellant loading operations at KSC's UPSS (Universal Propellant Servicing System); 3) an Orion demonstration that used EFT-1 telemetry data to implement an integrated system monitoring, anomaly detection, and FMEA capability for a subset of Orion's EFT-1 systems; 4) a demonstration for deep space autonomous habitat exhibiting hierarchical distributed autonomy encompassing 3 autonomous systems (vehicle manager, power, and avionics), in JSC's A & S Integrated Power Avionics and Software (iPAS) Lab; and 5) is currently being infused for autonomous operations at the Stennis Space Center (SSC) High Pressure Gas Facility - a critical piece of test infrastructure used to support SLS, DoD, and commercial propulsion testing for SLS. This infusion includes certification of NPAS as Class C Safety Critical for autonomous operations. All implementations exemplify the benefit of using NPAS for rapid autonomy development and associated significant cost savings.



NOTES:
1. Pressure indicators do not require calibration unless otherwise indicated.
2. Reference 54000-P001, legend and general notes.
3. System cleanliness per PRTSTD-8070-001. Maintain clean level 1000A unless indicated otherwise.
4. All tubing and fittings to conform to SSTD-8070-0126.
5. All component and drawing numbers in parenthesis are for reference only.
6. Maintenance Responsibilty belongs to Test Operations Contractor (TOC).
7. Restricitve orifices are valves with seats removed to work as variable restricitng orifices.

Figure 2 Life schematics as part of the domain knowledge model of SSC's High Pressure Gas Facility.



EXAMPLE MESSAGE:
PDU 2 RPC HAS FAILED OPEN RESULTING IN A LOSS OF POWER TO LOADS FC1, FC2:
NO RESTORATIVE ACTIONS CAN BE TAKEN BY THE VM

CREW INTERVENTION NEEDED: REPAIR PDU 2 RPC, CLICK BELOW FOR REPAIR PROCESS DETAILS

```
Time - Priority - Message
5:43:06 - 9 - PPA-LOAD - IS-POWERED - true
5:43:06 - 9 - SB-LOAD - IS-POWERED - true
5:43:06 - 8 - REPLAN-REQUESTED: false
5:43:06 - 9 - SOLAR-ARRAY-2 - STATE - FULL-SOLAR
5:43:06 - 9 - SOLAR-ARRAY-1 - STATE - FULL-SOLAR
```

POWER LOADS

SYSTEM	POWER	PRIORITY
SAB	ON	11
PWD	ON	10
OGA	OFF	16
CCAA	OFF	15
SAM	OFF	14
PPA	ON	9
FC1	ON	1
FC2	ON	2
FC3	ON	3
EX	ON	13
TTE1	ON	4
TTE2	ON	5
TTE3	ON	6

```
10/18/2017 0:59:49: Network interface g2x-npas-avionics has timed-out.
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Figure3. Graphical User Interface of a Vehicle Manager as the member of highest hierarchy of an autonomous space habitat module.

VII. NPAS Path-to-Flight

Current efforts are focused on benchmark performance and to advance NPAS on flight-qualified hardware/software platform PowerPC (SP0) running VxWorks, and on ARM-A53 running Linux to create a design guideline that supports other NPAS-based architectures for future missions (e.g., gateway, rovers, and habitat). This will enable the advance of a disruptive autonomous operations software capability for use in safety critical applications that can be affordably and timely qualified and deployed.

VIII. Conclusions and Recommendations

NPAS is a platform that delivers "thinking" autonomous operations capability and leverages a COTS product to address NASA autonomous capability needs. A description of the differences between brute-force autonomy and "thinking" autonomy is shown on Table 1. Without "thinking" autonomy, the technical and cost challenges to achieve the degrees of autonomy that NASA needs for space exploration will be unsurmountable.

IX. Acknowledgements

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