Learning Agents for Autonomous Space Asset Management (LAASAM)

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ABSTRACT

Current and future space systems will continue to grow in complexity and capabilities, creating a formidable challenge to monitor, maintain, and utilize these systems and manage their growing network of space and related ground-based assets. Integrated System Health Management (ISHM), and in particular, Condition-Based System Health Management (CBHM), is the ability to manage and maintain a system using dynamic real-time data to prioritize, optimize, maintain, and allocate resources. CBHM entails the maintenance of systems and equipment based on an assessment of current and projected conditions (situational and health related conditions). A complete, modern CBHM system comprises a number of functional capabilities: sensing and data acquisition; signal processing; conditioning and health assessment; diagnostics and prognostics; and decision reasoning.

In addition, an intelligent Human System Interface (HSI) is required to provide the user/analyst with relevant context-sensitive information, the system condition, and its effect on overall situational awareness of space (and related) assets. Colorado Engineering, Inc. (CEI) and Raytheon are investigating and designing an Intelligent Information Agent Architecture that will provide a complete range of CBHM and HSI functionality from data collection through recommendations for specific actions. The research leverages CEI's expertise with provisioning management network architectures and Raytheon's extensive experience with learning agents to define a system to autonomously manage a complex network of current and future space-based assets to optimize their utilization.

1. OVERVIEW

Colorado Engineering, Inc. (CEI) and Raytheon have been investigating an intelligent information agent architecture called PENLPE (Polymorphic, Evolving, Neural Learning and Processing Environment) that provides a complete range of CBHM and HSI functionality from data collection through recommendations for, and implementations of, specific actions. The research leveraged CEI's expertise with provisioning management network architectures to define a system employing PENLPE to autonomously manage a complex network of current and future space-based assets to optimize their utilization. The effort builds upon and combines the intelligent information agent inputs of Raytheon with a Learning Agent-Based Provisioning Management (LABPM) architecture, developed by CEI, resulting in a condition-based health management architecture enhancing situational awareness of space-based assets and their supporting ground control system: LAASAM (Learning Agents for Autonomous Space Asset Management).

The high level objective of the LAASAM program was to research and develop a system capable of autonomously managing a complex network of space-based assets to enhance situational awareness. The research required to meet this objective is driven by the need to:

1. Define and develop Intelligent Information Agent (I^2A) technology capable of realizing CBHM functions for a wide range of ground and space-based assets; and
2. Define and develop a network architecture encapsulating the I^2A technology that will support CBHM-oriented data collection, processing, and system management for both current and future space platforms. The architecture, named LAASAM, will support autonomous as well as man-in-the-loop operation.

The research encompassed the design of a condition-based health management architecture for enhanced situational awareness (SA) in both space-based assets and the supporting ground control system. Ultimately, the LAASAM system architecture must be able to support CBHM as illustrated in Fig. 1

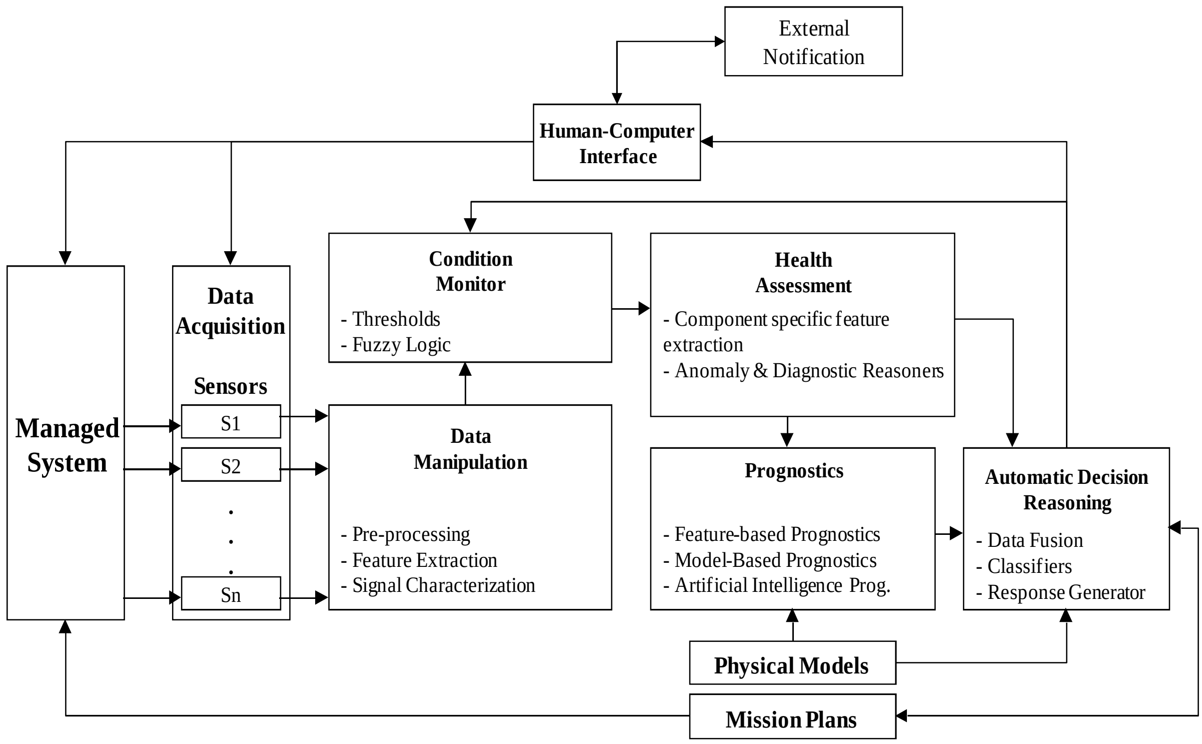

Fig. 1. An Architecture is Needed to Implement CBHM Functionality

2. ARCHITECTURE

The LAASAM architecture (Fig. 2) focuses on the use of I^2A technology designed to address the requirements of condition based health management of space and ground based assets. I^2A specifications under LAASAM are derived from components of PENLPE, a general purpose and distributed I^2A-based architecture from Raytheon, and LABPM, a centralized agent-based asset management system from Colorado Engineering. LABPM's centralized model defines a single entry and exit point to the system. PENLPE, on the other hand, allows for a distributed model that provides for multiple, as-needed entry and exit points while providing reasoning and inference capabilities missing from LABPM. However, PENLPE does not define the infrastructure that allows for dynamic growth of the system while LABPM is built around a dynamically changing agent environment. Therefore, a combination of both architectures is required to achieve LAASAM. Portions of the architecture focus on the supporting framework provided by LABPM while the majority focuses on I^2A features found in PENLPE.

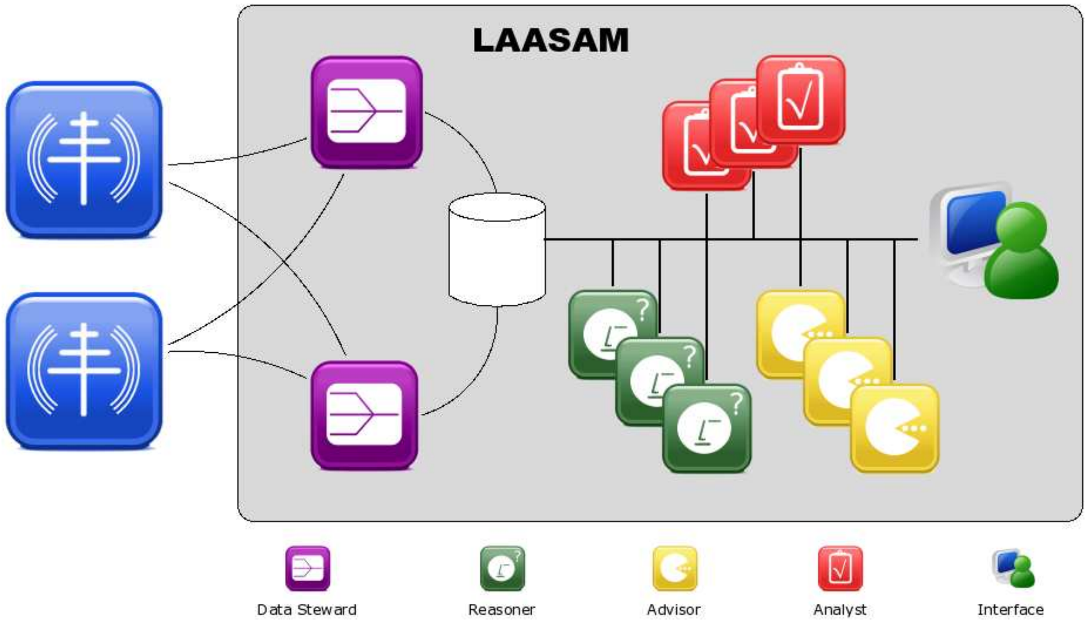

Fig. 2. LAASAM Provides Agent-Based Asset Management for Enhanced SSA

LAASAM represents significant advancement in the field of Space Asset Management by providing cognitive abilities similar to human reasoning. The LAASAM architecture provides the following high level features:

- An Intelligence Network: mechanisms for gathering information, learning, inferring, and providing decision support to situational analysts;
- Answer Extraction: mechanisms for posing hypotheses about situations and providing answers;
- Situation Analysis: mechanisms for finding situations that require active investigation and provide actionable intelligence.

These features define the core of LAASAM and are realized by PENPLE I^2A technology. PENLPE provides the intelligence within the LAASAM system through an implementation of an artificial prefrontal cortex, associated memories and data management, defined and derived strategies, reasoning, analysis and inference. PENLPE defines agent functions that range from data collection through providing recommendations for specific actions. Agents take on roles within the system, implemented through dynamically changing services and functional nodes, in support of system defined goals.

All three of LAASAM's high level features are enhanced by evolutionary processes embedded within the PENLPE architecture and implemented utilizing functional distribution capabilities provided by LABPM. LAASAM agents acquire, remove and modify functional nodes at birth and during operation in order to evolve based on conditions of their environment and rules associated with both agent and system goals.

LAASAM is based on the idea that agents carry personalities. A personality is a collection of state information that describes the agent. Personalities can be cloned and distributed. A single agent may give up its personality to another agent which then assumes the responsibilities of the former. Alternatively, an agent may be cloned where the clone acquires a copy of the original agent's personality. In either case, the new agent is no longer tied to the same conditions or environment from which the personality of the original agent was acquired. The new agent therefore evolves under its own conditions and environment. The mobile nature of personalities, or state mobility, allows agents to evolve on a self-determining basis. The LABPM architecture provides the infrastructure on which state mobility will be implemented.

LAASAM operates on a collection of co-located host systems that support Java clients connected through a secure network. Authentication and authorization capabilities are provided through interface agents, providing secure access to agents within the network. Policy management for the distribution of units of code and state to agents within the LAASAM collection is also handled through interface agents that provide User Interface (UI) capabilities.

The initial use-case helping frame LAASAM is the GPS OCX system in development by Raytheon. GPS OCX is being implemented on a collection of IBM blade servers running a Linux-based operating system. LAASAM, via its flexible Java implementation, can support this deployment configuration as well as installations based on Windows platforms.

In summary, the LAASAM architecture significantly enhances the analyst's ability to make timely, effective decisions and take action to protect, and maximize the utility of, Space Assets. LAASAM provides context for space related events and can alert analysts to potential space-based threats. LAASAM's unique Intelligent Software Agent (ISA) technology establishes a foundation for assigning attribution to hostile activity and for analyzing emerging activities through the application of advanced data-agnostic acquisition and reasoning agents (Fig. 3).

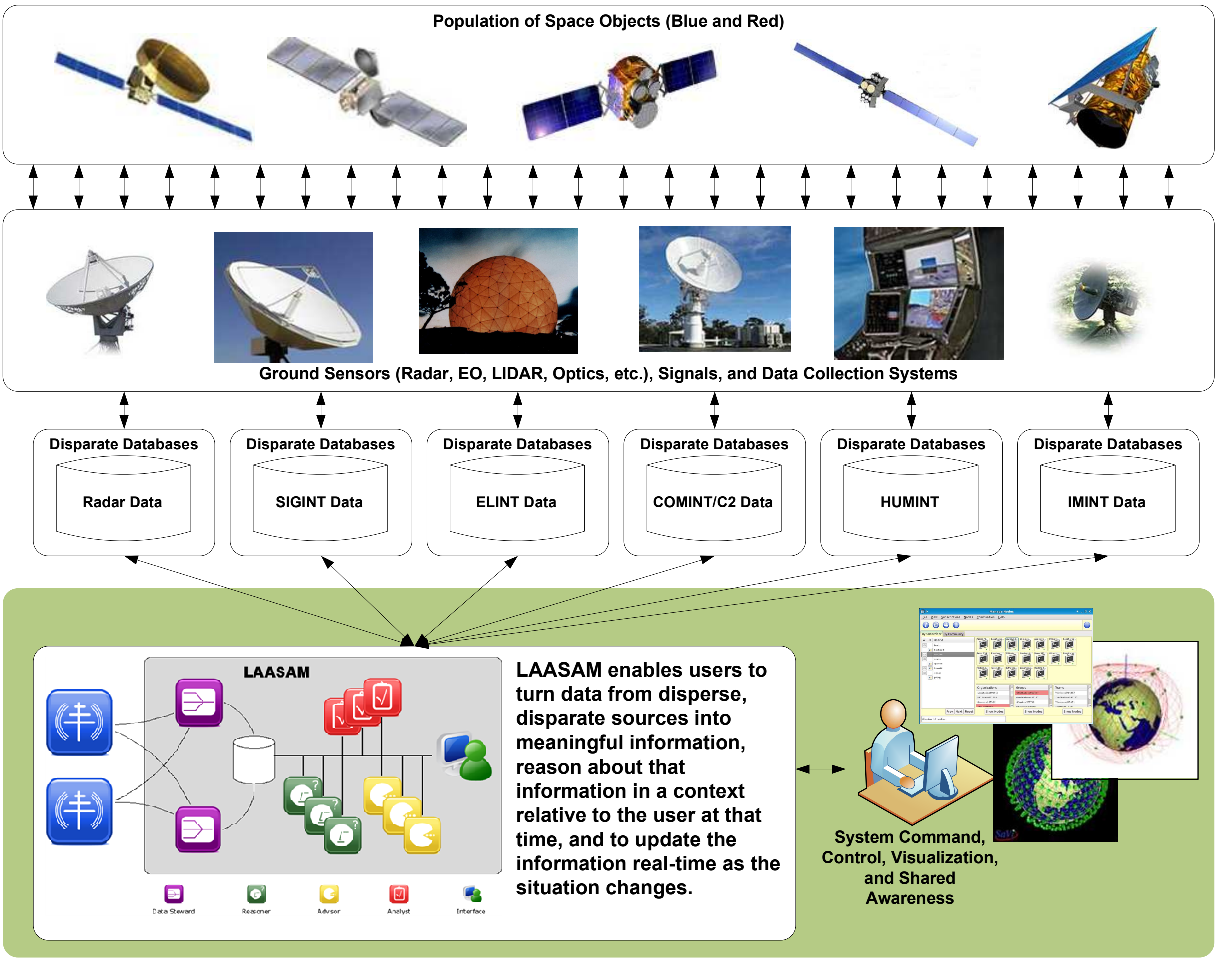

Fig. 3. LAASAM Can Consume Data from a Variety of Sources and Reason About that Information in Context to Enhance Space Situational Awareness

3. PENLPE OVERVIEW

PENLPE (Fig. 4) is based on intelligent information agents that implement an artificial prefrontal cortex through the use of distributed, extensible, and dynamically changing, learning-based services (Fig. 5). Multiple agent types exist within PENLPE, each with a mandatory collection of services. Each service, in turn, is a collection of one or more functional nodes (Fig. 6). The functional nodes provide the dynamic functional aspect of PENLPE, allowing changes to services on an as-needed basis.

PENLPE defines an agent type specifically responsible for handling incoming data. The extensibility that LAASAM provides to PENLPE allows these data acquisition agents to be updated to support new sources and data types on the fly, without affecting an in-service implementation. PENLPE also defines agent types for handling user input and display output. These agents act as entry and exit points to the system for human interaction.

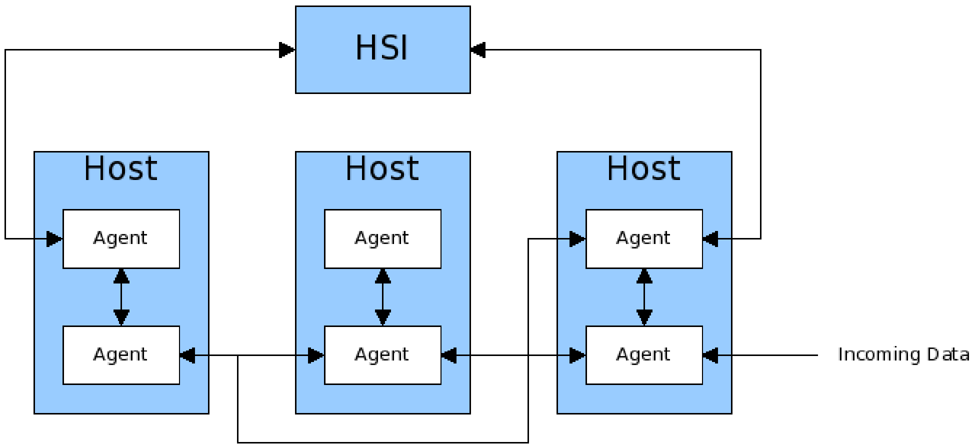

Fig. 4. PENLPE Agents Interact to Provide Reasoning, Analysis, and Inference to Assist Users in Decision Making and Taking Action

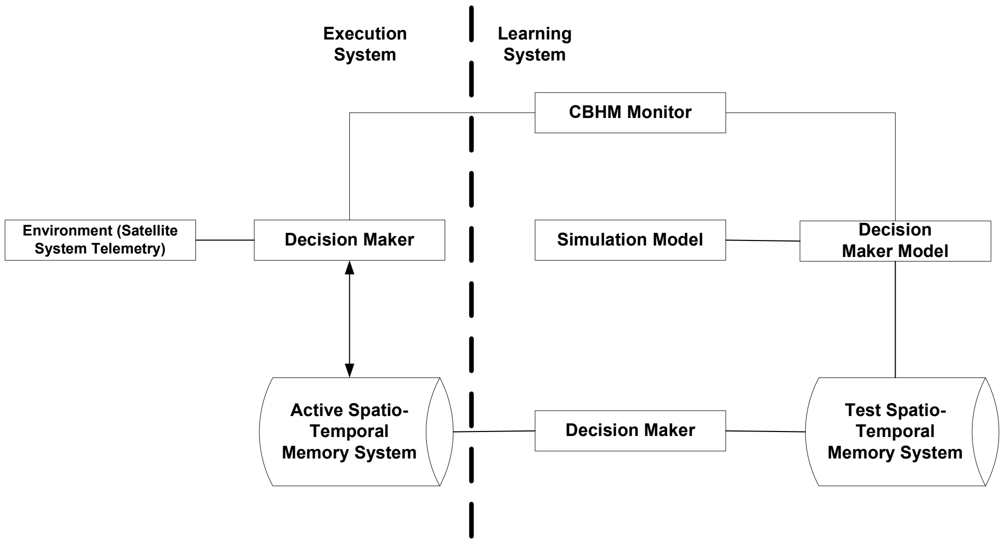

Fig. 5. The PENLPE Learning Environment Provides the Ability to Learn about Individual Assets, Enabling Comprehensive and More Accurate CBHM Diagnostics, Prognostics, and SSA

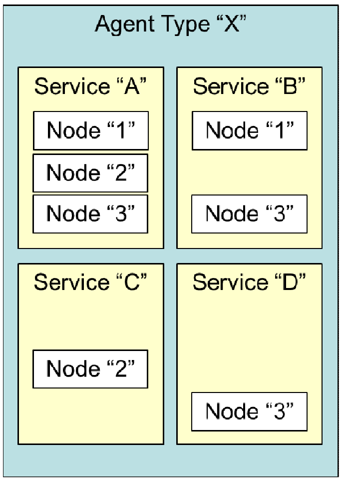

Fig. 6. Agent/Service/Node Hierarchy for Dynamic Functionality

LAASAM contains a mediator that takes information from the different PENLPE agents and facilitates the formation of agent coalitions that are used to solve problems and analyze data/information within the CBHM context. The mediator provides cognitive intelligence for the LAASAM system and allows for rapid analysis, reasoning, and reporting capabilities. The mediator facilitates information, analysis, and memory integration and allows faster accommodation and delivery of knowledge and knowledge characteristics across the system for enhanced Space Situational Awareness (SSA).

Agents communicate with one another to exchange data and metadata. If an agent becomes overwhelmed with processing duties, its mediator can transfer that agent's personality to a mediator on another host. That mediator will clone the agent, apply the personality and launch an agent clone which takes up the same responsibilities as the original agent. The mediator of the original agent is also free to clone that agent locally, without transferring the personality to another host. This allows a single host to run as many agents of a specific type required for a given task.

Various agents provide reasoning, analytical, and fuzzy inference based services. These services utilize defined and derived rules applied to inbound data, physical models and mission plans within LAASAM’s framework of agents to provide health assessment, prognostics and decision reasoning. The I^2A components of PENLPE allow the system to assist users and act on their behalf. This includes finding and filtering information, automating tasks, finding and fixing problems, automated pattern recognition and classification, and making predictions on future system health.

In summary, PENLPE consists of components within agents responsible for the following items: planning, reasoning, learning, memory, perception, attention and domain knowledge.

4. PENLPE AGENTS

The primary software component of LAASAM is the agent. Each ISA provides different cognitive capabilities that, together, form a cognitive ecosystem within LAASAM allowing inter-agent cooperation, collaboration, and communication (Fig. 7).

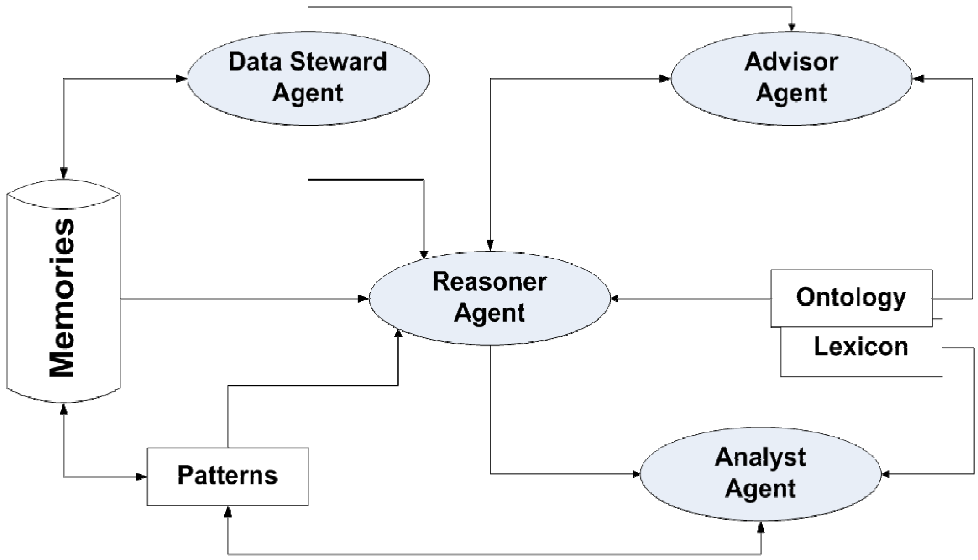

Fig. 7. Cognitive Ecosystem Formed by Collection of LAASAM Agents

An agent is a self-contained software unit comprised of one or more services (Fig. 8). A mandatory set of services define an agent type while additional services can be added to extend that type. The combination of services defines the agent's capabilities.

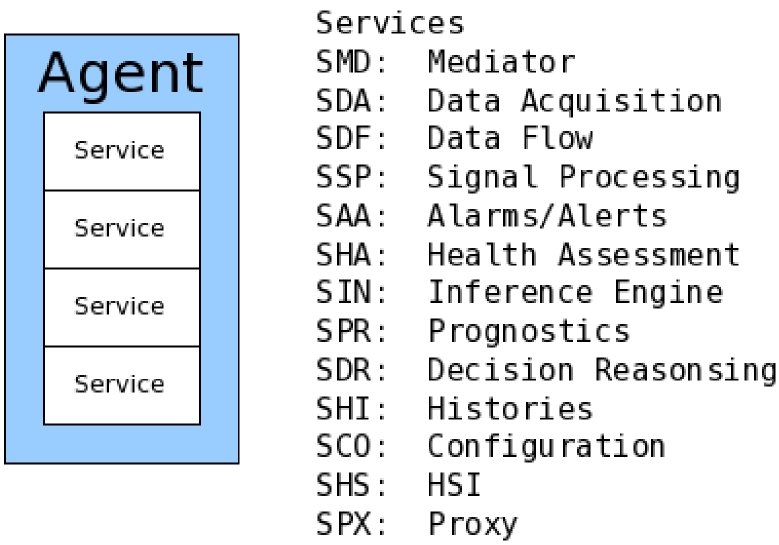

Fig. 8. Agents Provide One or More Services

There are five defined agent types within the LAASAM architecture:

1. **Data Steward (“ADS”- Agent Data Steward)**: acquires raw data from a variety of sources including sensors, networks, and libraries of existing use-case data; its primary function is to prepare incoming data for use by other agents; this agent type generates and maintains the system metadata required to find and extract data/information from heterogeneous sources;
2. **Advisor (“AAD”- Agent Advisor)**: disseminates the right information to the right place at the right time; it provides capabilities that allow collaborative question asking and information sharing by agents and end-users; it provides features that support federated search and possibilistic queries to find relevant information; Advisors generate and maintain topical maps required to find relative information fragments, memories, and “expert” information agents;

3. **Reasoner (“ARE”- Agent Reasoner)**: integrates with Data Stewards and Advisors and utilizes ontologies and lexicons from the latter to automate development of domain-specific encyclopedias; it provides a mixed source information and question answering system used to develop an understanding of questions and answers and their domains; Reasoners analyze questions and relevant source information to provide answers and to develop cognitive ontology rules for CBHM;
4. **Analyst (“AAN”- Agent Analyst)**: fed by Reasoners, analyst agents use Advisor ontologies and lexicons to expand upon questions and answers and learn from collected information;
5. **Interface (“AIN”- Agent Interface)**: assesses the correctness of major decisions and adjusts the decision processes of Advisor agents; Interface agents also accommodate human-in-the-loop structures.

LAASAM is a distributed architecture. This means agents act independently but in coordination in order to achieve system-wide goals. The use of negotiated roles provides a hierarchical management structure that realizes this coordination. Any agent type may take on a special role of mediator. A mediator is the first agent started on a single host computer. It has special duties related to short and long term memory within that host and among the agents that will, over time, run on that host.

Mediation relies on an initial Reasoner Agent launched by every host within the network. This agent checks to see if an agent mediator is present on that host. If not, the Reasoner Agent assumes the role of the mediator for that host. All mediator agents, one from each host, negotiate to determine which mediator will act as the System Mediator. The System Mediator is responsible for managing the goal-orientation of the overall system, which implies the ownership of the highest level, long term memory. Once mediation is established, each mediator is free to launch additional agents to perform required tasks. The System Mediator maintains its role for the lifespan of the LAASAM system.

LAASAM agents are not mobile on their own, but components within them are. An agent may acquire and remove pluggable modules, known as nodes, within their various services. The host mediator maintains the collection of available nodes, and agents use the host mediator as their node repository. Interface agents provide the means of distribution of new nodes to host mediators. Agents also have mobile personalities. A personality is the collective state of the agent. This state collection can be passed as tokens to host mediators, which in turn can distribute them amongst themselves. A host mediator can use a state token to create a clone of an agent which may or may not assume the responsibilities of the original agent. Each of the agent types have a set of required services that define their types. Non-mandatory services within an agent can be added or removed over the life of the agent. However, such changes are infrequent and discouraged. The internal workings of services actually provide the dynamic software aspect of agents through the use of dynamically loadable functional nodes.

5. PENLPE SERVICES

Agents within LAASAM consist of a collection of services (Fig. 9).

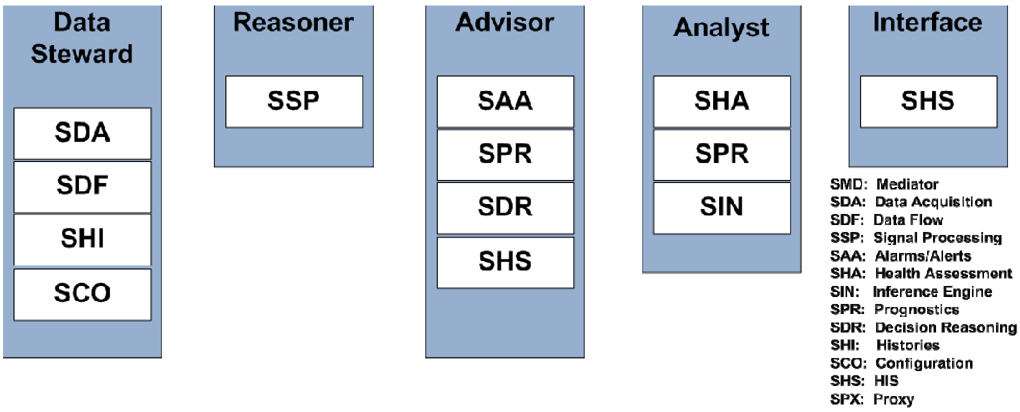

Fig. 9. Mandatory Services Each Agent Must Contain to be Defined as a Specific Agent Type

Services are modularized to allow building new agents with new purposes. Services available under LAASAM include mediation, data acquisition, data flow, signal processing, alarms/alerts, health assessment, inference engine, prognostics, decision reasoning, histories, configuration, human system interface (HSI), and proxy. Each service is comprised of one or more nodes. It is the collection of nodes (
Fig. **10**) that define the functionality of the service.

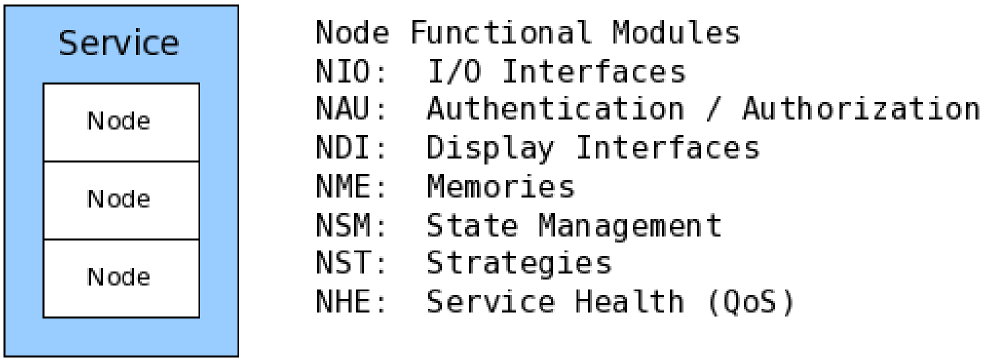

Fig. 10. Services are Dynamic Features within Agents and Consist of Nodes

6. PENLPE NODES

A service is an abstract concept within LAASAM. Internally, a service is an empty shell. It gets its functional capabilities from dynamically loadable LAASAM nodes. Nodes provide the core functionality of LAASAM, from state management to inter-agent communication to computational modules that implement the AI components of PENLPE. Other nodes are dedicated to authentication / authorization and configuration management.

Nodes are functional modules. A family of nodes is defined as a "plugin." The nodes listed in
Fig. **10** are defined within the LAASAM architecture and combined to create and support a variety of services; Fig. 11 illustrates example services and the nodes utilized within them.

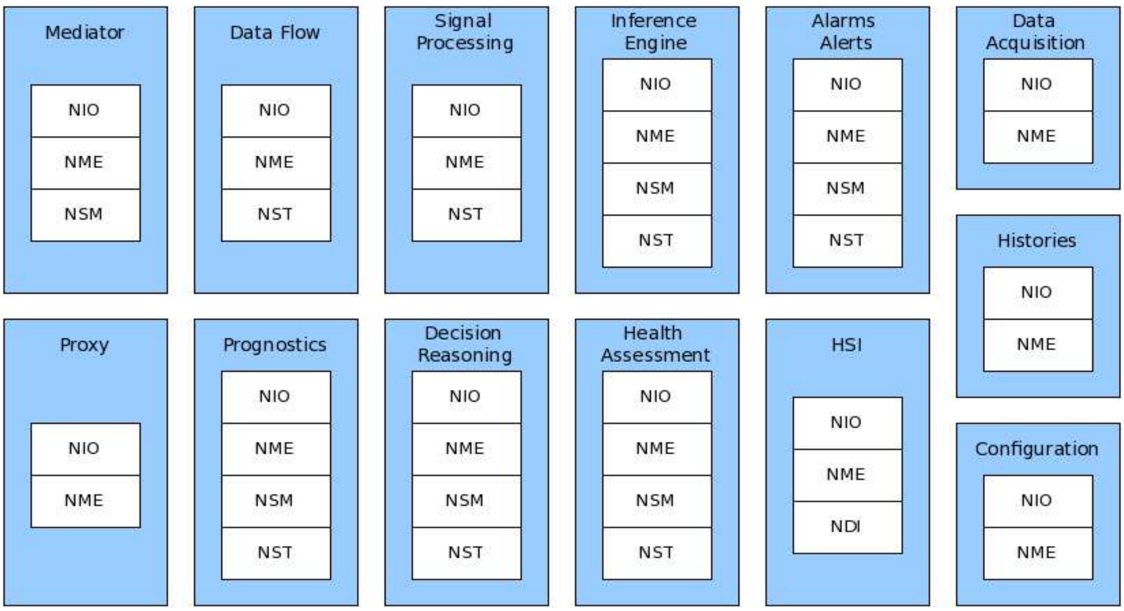

Fig. 11. Nodes Provide Core Computational Features via Plugin Interfaces (Example Services Shown for Illustration)

7. CONCLUSION

The thrust of the research (and therefore LAASAM) is to realize a CBHM architecture for enhanced SA in both space-based and the supporting ground control system assets. The CEI team has been researching the application of LAASAM to address the CBHM needs of GPS OCX. For effective CBHM, prognostics must play a major role in autonomous systems in order to provide improved system stability and protect against failure of mission critical assets. Early prognostic initiatives were often driven by in-field failures that resulted in critical safety and/or high-cost impacts. Diagnostic and prognostic system developers found it necessary to analyze and describe the benefits associated with reducing in-field failures and their positive impact on system utilization, quality-of-service / reliability, effectiveness, safety, and reducing overall lifecycle costs. Such efforts have led to many complex system designs, like GPS OCX and other space and ground-based systems, needing to consider integrated health management technologies that can support the system throughout its lifetime. A "designed-in" approach to CBHM starts with the design itself and acts as the process for system validation. The CBHM approach ideally involves synergistic deployments of component health monitoring technologies as well as integrated reasoning capabilities for the interpretation of fault-detect outputs. The technology, however, should also be data agnostic and able to consume other available streams such as geo and spatial information and activity-based data. In addition, integrated CBHM involves the introduction of learning technologies to support the continuous improvement in support of reasoning capabilities. Effective CBHM requires organizing these elements into a maintenance and logistics architecture that governs integration and interoperation within the system, between its on-board elements and their ground-based support functions, and between the health management system and external maintenance and operations functions. In short, the CBHM capability described here enhances SSA and operational management of the assets and overall system. A core component of this CBHM strategy is based on the ability to (1) accurately predict the onset of impending faults/failures or remaining useful life of critical components and (2) quickly and efficiently isolate the root cause of failures once failure effects have been observed. The approach can not only identify problems that are caused by asset component failures, but it can also highlight when system issues are caused by external forces (e.g., attacks on individual or multiple assets such as satellites). Maximizing system availability and minimizing downtime through more efficient troubleshooting efforts is the primary objective. The CEI team has architected LAASAM to support such CBHM system implementations; the application of LAASAM agents to the CBHM process is illustrated in Fig. 12.

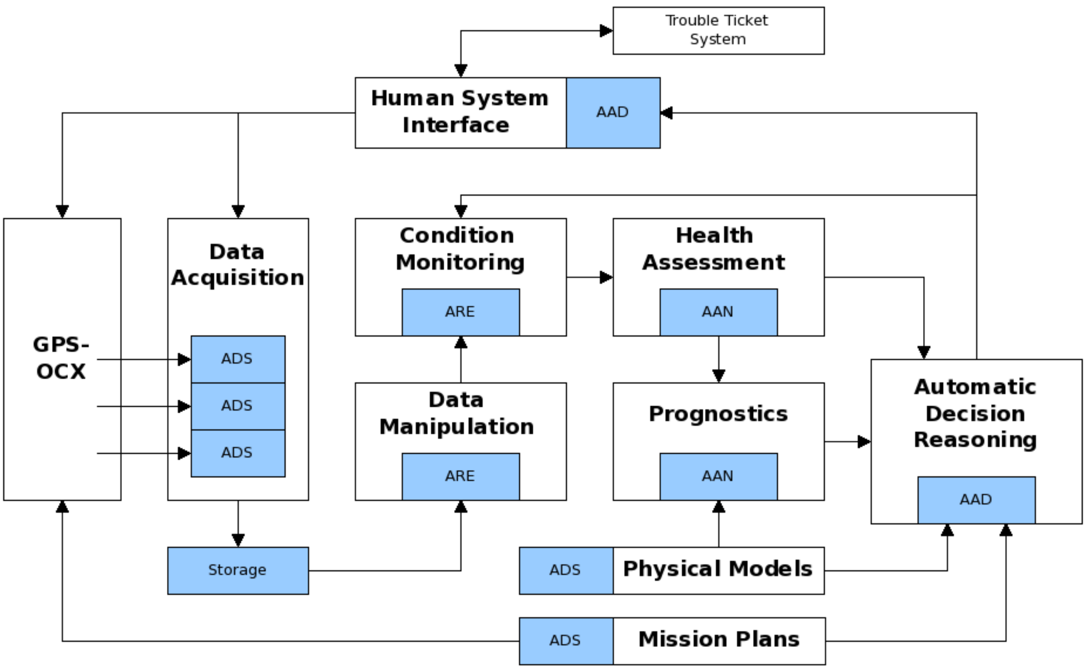

Fig. 12. LAASAM Applied to Realize CBHM Functionality