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Monitoring Agents for Assisting NASA Engineers with Shuttle Ground Processing

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Abstract. The Spaceport Processing Systems Branch at NASA Kennedy Space Center has designed, developed, and deployed a rule-based agent to monitor the Space Shuttle's ground processing telemetry stream. The NASA Engineering Shuttle Telemetry Agent increases situational awareness for system and hardware engineers during ground processing of the Shuttle's subsystems. The agent provides autonomous monitoring of the telemetry stream and automatically alerts system engineers when user defined conditions are satisfied. Efficiency and safety are improved through increased automation.

Sandia National Labs' Java Expert System Shell is employed as the agent's rule engine. The shell's predicate logic lends itself well to capturing the heuristics and specifying the engineering rules within this domain. The declarative paradigm of the rule-based agent yields a highly modular and scalable design spanning multiple subsystems of the Shuttle. Several hundred monitoring rules have been written thus far with corresponding notifications sent to Shuttle engineers. This chapter discusses the rule-based telemetry agent used for Space Shuttle ground processing. We present the problem domain along with design and development considerations such as information modeling, knowledge capture, and the deployment of the product. We also present ongoing work with other condition monitoring agents.

Keywords. Agent, monitoring, rule-based expert system

Introduction

1. Background

NASA Kennedy Space Center (KSC) is responsible for pre-launch ground checkout of the Space Shuttle. The Launch Processing System (LPS) at KSC provides facilities for NASA Shuttle system engineers, contractors, and test conductors to command, control,

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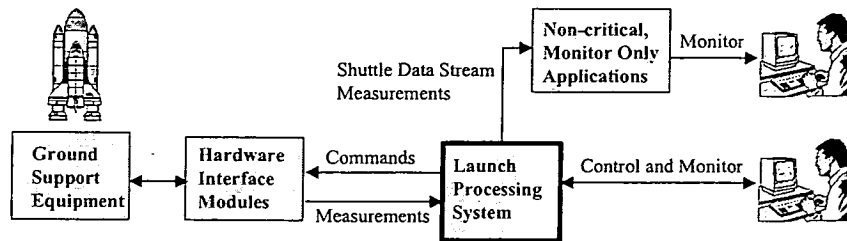


Figure 1. Ground Control and Monitoring at NASA KSC

and monitor space vehicle systems from the start of Shuttle interface testing through various phases including terminal countdown, launch, abort, safing, and scrub turnaround.

LPS continually monitors the Shuttle and its ground equipment including environmental controls and hardware that loads propellants. Consoles with vehicle responsibilities communicate information directly to and from the Shuttle computer systems. Consoles with ground support equipment responsibility communicate information to and from the hardware interface modules which are connected to the numerous ground support systems. See Figure 1. Each module is capable of interfacing to approximately 240 sensors or controls. Overall, some 50,000 temperatures, pressures, flow rates, liquid levels, turbine speeds, voltages, currents, valve positions, switch positions, and many other parameters must be controlled and monitored.

Using LPS, NASA Shuttle engineers and contractors at KSC are responsible for certifying that ground checkout of the Space Shuttle has been performed according to program specifications. The Operations and Maintenance Requirements and Specifications Document[2] lists those procedures. For over 25 years, engineers have used LPS to verify Space Shuttle flight readiness and to control launch countdown. LPS has performed superbly well. Recently, much of the LPS hardware was upgraded assuring its continuance for many more years. However, the system architecture was not changed and software remains basically the same. As a result, the level of situational awareness has not increased proportionally to what would otherwise be possible with more modern software technologies.

After the Shuttle Columbia disaster on February 1, 2003, the Columbia Accident Investigation Board[3] proposed recommendations to improve safety from both an organizational and technical perspective. The Board indicated the need to "[adopt] and maintain a Shuttle flight schedule that is consistent with available resources." Also, both management and engineering support staff must maintain an awareness of anomalies and those must not be lost "as engineering risk analyses [move] through the process." Given two tragic losses of a crew and Shuttle, today NASA engineers have an even greater pressure to be more vigilant in identifying problems. At KSC, ground processing of the Shuttle is performed by thousands of employees, both contractors and civil servants. Anomalies must be detected and reported to prevent problems with Shuttle subsystems, countdown, and launch. The aging LPS hardware has limited

resources and precludes the level of automation and notification warranted by this domain.

Contractors at KSC are responsible for the day to day operations, checkout, and maintenance of the Shuttle. They are the primary users of LPS. NASA Shuttle engineers are civil service employees who oversee the contractors. Given the limitations and resource scarcity of LPS, NASA Shuttle engineers needed a tool to provide more insight and situational awareness and oversee the work performed by contractors. An increased insight could help detect anomalies that might otherwise go unnoticed, whether by process error, software or hardware failures in the monitoring equipment, or many other possible causes. A tool was needed to complement LPS that could autonomously and continuously monitor Shuttle telemetry data and automatically alert NASA Shuttle engineers when predefined criteria have been met. In the latter half of 2003, a software tool was proposed to provide better insight into Shuttle ground processing and increase the level of situational awareness. This tool is known as the NASA Engineering Shuttle Telemetry Agent (NESTA).

1.1. Objectives

Data processed by LPS is distributed on a local area network. As shown in Figure 1, the distributed data is known as the Shuttle Data Stream (SDS)[4] and contains real-time vehicle ground processing data. It is used by monitor-only applications. The primary objective of NESTA is to provide full time autonomous monitoring of the SDS and to automatically alert NASA engineers in near real-time when pre-defined criteria have been met. Types of monitoring criteria include expected operational events or milestones (e.g. vehicle power up, start of launch countdown test, etc.) as well as unexpected events or failures (e.g. large difference between redundant sensor values). NESTA allows Shuttle engineers to work on other tasks while minimizing the risk of losing awareness of real-time Shuttle processing data and events.

NESTA acts as a software agent for the NASA engineer. For this discussion, an agent is defined as rule-based, autonomous software that reacts to its environment and communicates results to a human, a NASA engineer in this usage. Agents have been extensively researched[5][6]. Agent standards[7] and frameworks[8][9] have also been developed.

The primary objectives for NESTA include:

- Allow a NASA engineer to specify rules to be applied to measurements published in the SDS.
- Generate near real-time notifications and alerts in the form of emails or wireless pages. Notifications may include a text message and measurement values, and may be sent to multiple users when the rule's premises are satisfied.
- Monitor up to four separate SDS sources. This includes four control rooms used for checkout and launch of the Shuttle and its components.
- Process multiple types and subtypes of measurements including discretely (i.e. boolean measurements), analogs (i.e. floating point measurements), and digital patterns (i.e. integer measurements).
- Allow users to create and modify multiple monitoring requests without restarting NESTA.

1.2. Why an AI Solution

NESTA leverages various AI technologies within a rule-based paradigm including forward chaining, fast pattern matching, declarative programming, predicate logic, and more. AI was a natural fit for monitoring the SDS since pattern recognition and analysis are the primary needs. Although pattern identification could be achieved by employing regular expression libraries within various procedural and object oriented languages, those paradigms are not specifically intended for this type of application and have less efficient matching algorithms. The pattern matching algorithms of rule-based expert system shells are highly specialized and tuned. Also, AI, particularly rule-based languages, lends itself better to this domain since pattern recognition wrapped within a premise-action construct closely mirrors the level of abstraction at which the domain experts work.

The type of data signatures sought by Shuttle engineers requires the derivation of rules that are of the same granularity as those typically used in rule-based languages. Fortunately, Shuttle engineers were already accustomed to representing knowledge at a fine grained level. The engineers are adept at either constructing the rules themselves or expressing the knowledge in pseudo code that lends itself well for translation directly into declarative rules. Many of the rules are either standalone or work in conjunction with several other rules. This suggests a highly modular system with a rule being a suitably sized working block.

1.3. Other Attempted Solutions

NESTA is a peripheral advisory tool to the real time control system within LPS. There were three previous projects that attempted to upgrade LPS in the last 15 years. Even though those efforts had significantly greater objectives that spanned well beyond just advisory applications, they were advertised to include many of the capabilities that NESTA provides and much more. Approximately half a billion dollars was spent on those efforts and upwards of 600 people worked on the most recent of those upgrade attempts. There were various technical and political hurdles that initially impeded and then ultimately doomed those full scale replacements of LPS.

NESTA's infusion of state-of-the-art AI technologies and engineering within the legacy launch system, LPS, is particularly notable given the number and size of the preceding attempts to modernize the ground control system at KSC. Those fallen projects, despite having much grander objectives, had little to no spin-offs within the LPS community. In contrast, NESTA is becoming accepted and internalized by members of the launch team and appears to be on its way as a widely used tool. From a business vantage point, NESTA's greatest asset is its development and marketing as a value added product. That is helping pave its path to acceptance.

2. Application Description

2.1. System Components and How They Interact

Figure 2 shows the context diagram for NESTA. The agent process is represented in the middle circle. It communicates with various sources and data stores. A

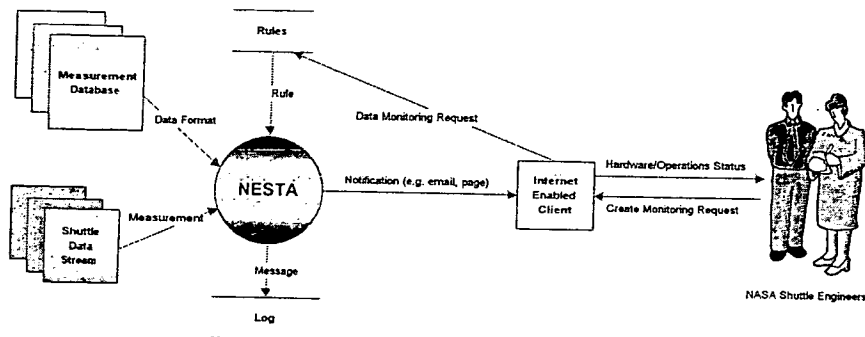


Figure 2. NESTA Context Diagram

measurement database is used to decode the SDS into usable measurements. The SDS source broadcasts measurements as data packets over local area networks. NESTA monitors this stream for data patterns specified by the Shuttle engineers. If a pattern is matched, a notification is sent as an email or wireless page. The Rules data store represents the Jess scripts and knowledge base that defines the rules for the monitoring criteria. All messages and relevant agent activities are also locally logged.

2.2. Languages and AI Tools Used in Application

The Java Expert System Shell (Jess)[10] was selected as the rule engine. Jess was developed and supported by another government agency, Sandia National Labs. As such, our development team and customer have full usage of the tool via government licensing without any fees. This includes access to all the Jess source code.

Jess' forward chaining reasoning system was modeled after production systems such as CLIPS[11] and OPS5[12]. It contains highly efficient and sophisticated pattern matching based on the Rete algorithm[13]. This enables its inference engine to process many rules and data rapidly. The engine repeatedly processes through a match-select-act cycle. As a production system, its consequents can be actions. A conflict resolution strategy determines the precedence of rule firings.

Several hundred monitoring rules have been written thus far for monitoring Shuttle ground telemetry. Jess' predicate logic lends itself to capturing and specifying the heuristics and engineering rules of this spaceport domain. The declarative paradigm of this rule-based agent also makes it highly modular and scalable to span multiple subsystems of the Shuttle. Jess also includes a fourth generation scripting language and interactive command line which are very conducive for prototyping and testing.

Jess is written entirely in Java and has access to the full Java application programming interface from the scripting language. It provides standard control flow constructs and supports variables, strings, objects, and function calls. Jess automatically converts between its own types and Java types insulating the developer from manually performing the conversions. Its use as a Java library made Jess' selection more appealing since Java supports multiple platforms with its "write once, run anywhere" paradigm. Beyond that, the need for NESTA to support web enabled clients also made Java a natural fit given its origins and strong support for developing Internet based applications.

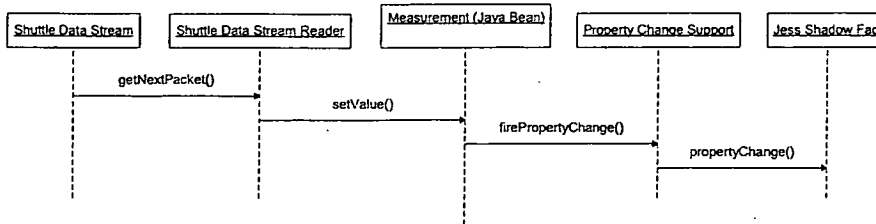


Figure 3. Sequence Diagram Illustrating Update to Jess Working Memory from Shuttle Data Stream

2.3. Design

Java classes were developed to parse and decode the data stream and represent measurements as facts in Jess' working memory. To interface Jess' rule engine with the SDS, each data measurement is modeled and implemented as a Java bean[14]. Java beans provide a component architecture to enable easier integration of applications. A property change notification mechanism is supported that allows one object to become a registered listener of another object. The listener object will then automatically receive changes from the source object. This is also known as a publish-subscribe or observer pattern[15]. Within Jess, each Java bean corresponds to what is known as a shadow fact. A Jess shadow fact is a mirror image of a Java bean, such as a pressure measurement, within Jess' working memory. All shadow facts are registered listeners of their Java bean counterparts. Thus, whenever a measurement changes in the data stream, a property change event is automatically generated for the given measurement and its sibling shadow fact is updated in Jess' working memory. Figure 3 illustrates this path.

After a shadow fact is updated, the Jess pattern matcher will determine if the premises of any rules match the new or modified facts. Rules are compared to working memory to identify premises that are matched by the data in working memory. For NESTA, this data represents measurements from the SDS and rules represent data monitoring criteria submitted by NASA Shuttle and system engineers. Rules with matching premises are activated and placed onto an agenda. Next, the agenda is ordered according to Jess' default conflict resolution strategy. The highest priority rule is then fired and executed. This match-select-act cycle repeats until no more rules are available to fire. An action handler class was developed and is used to build and send the notification message to the Shuttle engineer whenever a rule fires.

2.4. Knowledge Capture and Representation

Figure 4 shows the knowledge acquisition workflow for creating or modifying a rule to monitor specific measurements on the Shuttle data stream. The Shuttle engineer must specify who is responsible for the rule, the contents of the email notifications, the rule's firing conditions (i.e. antecedent, left hand side), and rearming conditions. That is, some rules may need to have a "one shot" behavior and only fire once when activated the first time. Other rules may need to be re-armed after a given time period or when

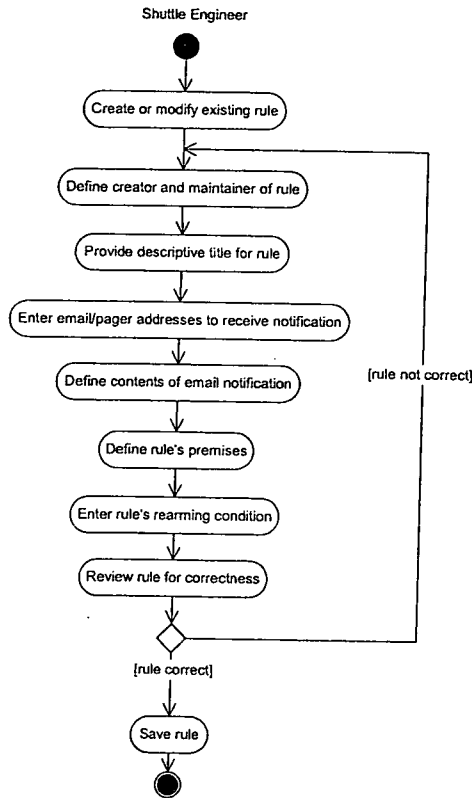


Figure 4. NESTA Knowledge Acquisition Workflow

certain types of conditions are met.

The current version of NESTA does not have a graphical user interface capturing this workflow, but all of the steps are effectively provided within script files. Those files are editable with a plain text editor by the end users. Hundreds of rules have been produced by the customer.

As the rule database grew, patterns of rules began to emerge. Patterns in software design and modeling have been extensively investigated and reported[15]. Analogous to those design patterns, the development team and customer began recognizing knowledge patterns for this domain and developed rules following these structures. Some patterns include:

- *One shot*: Rule fires once regardless of how many times facts cause the premise to reactivate.
- *Recurring*: Rule fires each time the premise reactivates.
- *Timed*: Rule fires every X minutes as premise remains true.

- *Queued*: Multiple rules will fire but notifications are sent to a queue that gets flushed based on a user configurable amount of time or maximum number of firings. One composite notification is sent when the queue is flushed. That composite notification contains what would have otherwise been multiple emails or wireless pages.

Some sample rules in English prose include:

- *Notify Shuttle Engineer when measurement V79S4126E1 or V79S4132E1 or V79S4138E1 or V79S4143E1 equal ON*. Indicates that Flight Control Power (ASA 1-4) has been activated.
- *Notify Shuttle Engineer when measurement V90Q8001C1 equals 801*. Indicates that a Shuttle is in orbit and is preparing to initiate the on-orbit flight control checkout activity.
- *Notify Shuttle Engineer every 60 minutes with current values of Flight Control launch countdown measurement list when measurement NMAJORTEST equals 7*. Indicates launch countdown test is occurring. While in launch countdown test, send a current value email containing a list of Flight Control measurements every hour.
- *Notify Shuttle Engineer when FD N79IV019D Bit masked 0x0001 equals 1*. Indicates that an LPS command and control program has stopped due to a failure and is waiting on the operator for action.

This is an actual NESTA rule written in the Jess scripting language:

```
(defrule vehicle-pwr-on-rule
  "Orbiter electrical power is up."

  (recipient-list (recipient-list-name vehicle-pwr-on-rule))

  ?notPowered <- (vehicle-not-powered)

  (DigitalPatternFd (fdName "NORBTAILNO") )

  (AnalogFd (fdName "V76V0100A1") (valid TRUE) (value ?val1))
  (AnalogFd (fdName "V76V0200A1") (valid TRUE) (value ?val2))
  (AnalogFd (fdName "V76V0300A1") (valid TRUE) (value ?val3))
  (test
    (and
      (> ?val1 26.0)
      (> ?val2 26.0)
      (> ?val3 26.0)
    )
  )
)

=>

(retract ?notPowered)
(assert (vehicle-powered))
(notifyActionHandler nil nil)
)
```

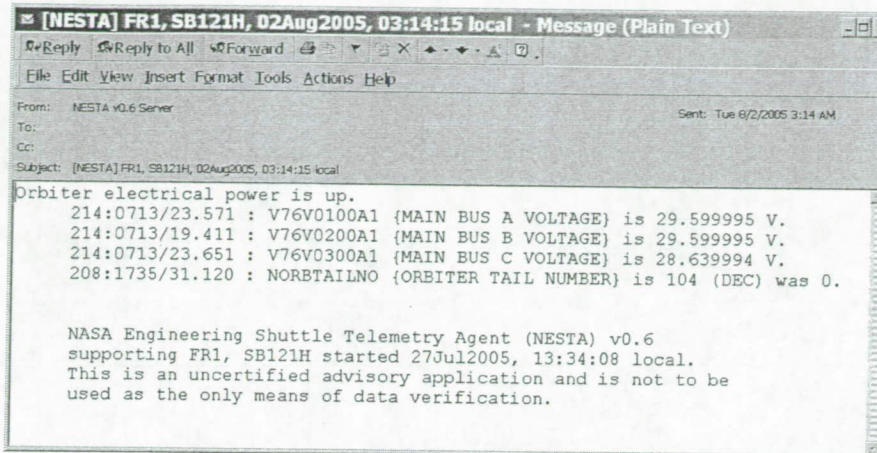


Figure 5. Email Generated by NESTA

For this rule, if all three analog bus voltage measurements, V76V0100A1, V76V0200A1, and V76V0300A1, concurrently exceed 26 volts, the Shuttle Orbiter is considered to be powered on. Another indicator, SOIADATAV, is used to assure the validity of the incoming data. Finally, another measurement, NORBTAILNO, is located on the rule's left hand side. In our terminology, we call this an informational measurement as its specific value has no bearing on whether the rule fires, but it is necessary to include it on the rules left hand side so that it becomes part of Jess' activation object and then its value is included in the notification. The action handler parses the fields in the activation object and builds an email with all of the measurements' values that were listed on the left hand side of the rule. The `notifyActionHandler` call has two arguments that allow for the notification to be queued. This particular example does not use queuing and simply passes `nil` arguments in the call. Queuing is discussed later in the chapter.

Figure 5 shows an email that was generated for the preceding rule. As illustrated, the exact values of all three bus voltages are listed along with the informational measurement showing which of the three Orbiters was powered up. In this case, 103 refers to Discovery. The informational measurement proves useful in not only allowing the Orbiter reference to be included in the email, but it does not bind the rule to a particular Orbiter. That is, NASA Shuttle engineers are interested in any Orbiter that may become powered up. The rule's pattern matching provides that level of genericity in a very straight forward representation. Of course, the engineer may be interested in being notified only about a specific Orbiter. This would require a simple modification to the rule. One additional slot would be referenced in the `DigitalPatternFd` template narrowing the focus to a particular Orbiter. Thus, minor modifications to the rule demonstrate the rich behavior available to the Shuttle engineer and show the semantic power of pattern matching.

2.5. Hardware and Software Environment

The NESTA application resides on a Dell 1.7 GHz Pentium server. The server includes the necessary user and support files such as the facts scripts, rules scripts, measurement database, logs, and more. Currently, the server executes on a Microsoft Windows 2000 operating system. However, since Java was used exclusively along with its virtual machine, the ability to execute software on other types of servers is readily available. Again, this was a primary driver in the selection of Java and Jess so as to not be bound to a particular hardware platform or operating system. Customers receive notification on standard email clients including Windows workstations, wireless pagers, personal digital assistants, cell phones, and more.

2.6. Performance Requirements and Testing

2.6.1. Performance Characteristics of Shuttle Data Stream

At application startup, NESTA connects to a datastream selected by the user. The datastream includes all measurements at their respective change rates. No data changes will be missing from this stream. For this discussion, only the FIFO stream will be presented as it is the stream of choice for the NESTA customer.

The datastream averages 5 to 10 packets per second and peaks around 50 packets per second at launch. Each SDS data packet can hold up to 360 measurement changes before rolling over to another packet. This calculates to an average of 1,800 changes per second for the FIFO stream nominally, and 18,000 changes per second peak at launch. During peak data loads, the SDS is throttled at the source and does not maintain true real time updates. It may lag up to 1 minute or so, but all measurement changes are buffered and none is ever dropped from the data stream. Throttling of the data typically begins at T+1 second, that is, just after launch. Even though it is the hypothetical peak limit, 18,000 changes per second is the performance load that NESTA is expected to meet to avoid missing a measurement change. This is referring strictly to updating 18,000 facts per second and not indicating how many rules might fire. In fact, only a small percentage of those facts is expected to result in a small percentage of the total rules to fire at any given time, even during the peak launch data rates.

The measurement data in the stream is refreshed every three minutes regardless as to whether or not it has changed. Since the stream is based on User Datagram Protocol (UDP), this results in an unreliable datagram packet service. When a packet is dropped on the network, all measurements are marked invalid and the measurements change back to valid one by one as refresh data is received until the completion of a three minute refresh cycle.

2.6.2. Performance Testing

Performance testing occurred on an Intel Pentium 4, 1.7 GHz desktop workstation with 768 MB of RAM running Microsoft Windows XP Professional. The SDS reader class in NESTA parses the data stream and updates facts in Jess' working memory. To test the reader class, 12 high speed analog measurements were selected and instantiated as shadow facts. In the range of 18,000 (nominal) to 36,000 (peak at launch) data changes occurred every second in the test-enhanced data stream and were processed by the SDS

reader class. This included various types of measurements such as discretized and analogs. 12,000 analog data changes per second were being processed into current values and updated in Jess' working memory by a property change event handler.

Rules were written for 6 of the high speed analog measurements. The other 6 measurements were still relevant to stress the SDS reader class and updating of facts. 5 of the 6 rules fired once every minute. The 6th rule fired once for every single measurement change (1,000 per sec) for two full seconds sustained out of every minute. Thus, a total of 2005 rules fired every minute, with 2000 of them firing within a 2 second period. Analog measurements have considerably more processing overhead than the discrete measurements so it was not possible to sustain thousands of rules containing analogs to fire every second without causing CPU starvation. However, the "fair test" was considered to have only a very small percentage of the measurements that are in the stream actually causing rules to fire. It was considered fair to have short bursts of high rate rule firings but not long term sustained high rate rule firings. NESTA is not intended for users to write rules to notify them via email hundreds or thousands of times each second for a long and sustained period of time.

To summarize, NESTA sustained the above scenario for many cycles on the test-enhanced playback file without CPU starvation and without reporting any packet losses. The CPU utilization on the development workstation was about 90% prior to launch and higher than that after T-0. It was heavily loaded, but NESTA maintained the pace. NESTA performed well considering that the data stream was stuffed with between 1 and 2 times the hypothetical peak load of measurement changes for the performance test. The "long pole" in the process appeared to be the number of rules that actually fired every second sustained. However, even under launch conditions when a heavy data change load exists, there is not expected to be many thousands of rules firing every second. Even several hundred rules firing per minute is considered unrealistically high, but this performance test suggests NESTA could readily handle that load.

3. Development and Deployment

3.1. Application Use and Payoff

At the time of writing of this chapter, the customer had used NESTA for over a year. Hundreds of rules have been written. Along with that, hundreds of NESTA notifications have been generated for multiple NASA engineers. These users have received both emails and wireless pages at KSC and other remote sites. Since the customer is a NASA engineer responsible for oversight of contractors, the notifications act as an extra set of eyes that further assure the quality of government oversight.

To better understand NESTA's payoff, the responsibilities of NASA Shuttle Engineers must be examined. They include:

- Understanding their system and supporting equipment.
- Knowing how their systems are tested and processed.
- Being aware of when their systems are activated, tested, or in use.
- Analyzing performance and data retrievals from any use of a system.
- Being ready to answer questions about their systems such as

- When was it tested?
- How did testing proceed?
- How did the data look?
- Is it ready to fly?

NESTA has helped Shuttle Engineers meet these responsibilities in varying degrees. Below are three success stories documenting some of the benefits NESTA has provided.

3.1.1. Success Story – Increased Situational Awareness

In one usage, a Shuttle avionics system was powered up over a weekend. The NASA Shuttle Engineer, being responsible for that system, would not have been aware that the system was powered up except for receiving a NESTA notification. In this case, the avionics user was not part of the Shuttle Engineer's immediate organization. Thus, the Shuttle Engineer did not receive any communiqués regarding the system's weekend usage. Due to NESTA, the Shuttle Engineer was better prepared to address questions about his system's usage were they to arise. This has not been an uncommon occurrence. Shuttle Engineers utilizing NESTA began realizing that some of their systems were being utilized much more than previously thought. Situational awareness increased markedly.

3.1.2. Success Story – Increased Efficiency

Some ground operations span 24 hours and include dozens of asynchronous events that are broadcast on the data stream. For example, checkout of flight control hardware in the Orbiter Processing Facility occurred 4 to 6 times within the last year. The checkout included long hydraulic operations, powering up different parts of avionics, pressurizing/depressurizing the Orbiter, and other work. During a recent flow, the NESTA notifications gave exact times of events of interest to the Shuttle Engineer. That allowed the Shuttle Engineer to quickly identify timelines of these lengthy operations. Effectively, a virtual roadmap identifying significant events was automatically generated and that saved an hour of labor. More efficient data retrievals resulted.

3.1.3. Success Story – Customer Testimonial

Below are excerpts of an email received from a NESTA customer in April 2005. The testimonial details how NESTA notified a NASA engineer of a hardware inspection that was not previously known to be occurring. That notification provided an increased awareness and might have prevented a further delay in testing of Shuttle components.

"NESTA earned its keep this weekend and I wanted to share the story with you.

The Shuttle program has a very large test called S0008 - Shuttle Integrated Test. After the Orbiter is mated to the ET[external tank] and SRB[solid rocket booster] stack, S0008 is the first big power ON testing which performs numerous tasks mostly concerned with the integrated Shuttle vehicle. For example, the interaction between the Orbiter's avionics and the SRB's electro-hydraulic thrust vector control actuators.

Due to significant technical problems with ET attach point pyros and the ET attach point electrical connections (the 'monoballs'), the schedule for S0008 fell completely apart. What started as a 42 hour test operation has now consumed the entire weekend and will probably not be finished anytime soon.

One of our NASA engineers came in for third shift Sunday to cover the testing. One important NASA function during this time period was star tracker light shade inspection. What happens in this test is that the star trackers are powered ON, the star tracker doors are opened, and then [the contractor] and NASA engineers inspect the inside of the star tracker - a cavity called a light shade which is a large cone coated with a black non-reflective coating and several baffles. The design of the light shade is to eliminate any and all extraneous light sources and reflections except for the star in view which the star tracker is trying to get a fix on. The inspection is made to make sure there is no foreign object debris. For example, a flake of paper could cause a reflection and lead to an erroneous star tracker star fix. If debris is found, special equipment is available to vacuum out the inside of the light shade. After this procedure, the star tracker is powered OFF and the star tracker door is closed for the last time at KSC.

Now here's where NESTA payed off. During this third shift operation yesterday, [the contractor] and NASA were all on center waiting on the word from the S0008 test conductors to perform the star tracker light shade inspection. For whatever reason, our NASA engineer was never notified when the checkout was to begin. [The contractor] began the checkout without attempting to notify NASA. The first indication the NASA engineer had was when NESTA sent an email to the engineer announcing that the star tracker was powered ON. At this point, the NASA engineer contacted the test conductor and directed him to keep the doors open until he could witness the internal cavity inspection. Without NESTA, NASA would have missed the star tracker inspection. And this would have led to an uncomfortable discussion about whether the test would have to be repeated or whether NASA could rely solely on the eyes of the [contractor] engineers."

3.2. Phased Approach to Implementation and Delivery

Multiple releases of NESTA have been delivered to the customer. The development team has four members each working approximately sixty percent of his time on the project. The team works very closely with the customer. Generally, the team meets with the customer at least once per week and has multiple other correspondences via email and phone.

The initial NESTA release required six months. Thereafter, a release occurred approximately every month. Prior to adopting Java and Jess, some preliminary performance testing was completed to verify that the Java language and Jess rule engine were fast enough to handle the Shuttle data stream rates. Concurrently with that coarse performance testing, the initial set of requirements were being developed.

The software process model employed is a combination of extreme programming and the iterative waterfall model. The team and customer understood the need to anticipate and accommodate changes in the requirements. The customer, as much of the development team, had little experience with rule based systems so there was a learning curve in how best to represent knowledge and interface the data stream with Jess. After about six months, a baseline set of requirements existed but the requirement space is still fluid and undergoes change over time. These changes are seen as a

learning process through which we explore the possibilities of the system. As releases are delivered to the customer, new requirements are elicited and old ones may become defunct.

3.3. Development Tools

In addition to Java and Jess, other tools used include:

- Eclipse as an integrated development environment.
- Visio 2000 to develop Unified Modeling Language models.
- CVS for configuration management.
- Ant for automating builds.
- JUnit for automated Java unit testing.
- Emma for Java code coverage including measurements and reporting.
- Optimizeit by Borland for profiling performance and detecting and isolating problems.

3.4. Technical Difficulties

3.4.1. Data Validity

As indicated earlier in the chapter, the data stream is based on User Datagram Protocol (UDP). As such, the connection is not always reliable and packets may get dropped. This poses problems when rules are waiting for data to arrive. Data health and validity become questionable. If the data stream connection is lost entirely or data becomes stale (i.e. not updated), false positives or false negatives may result. That is, notifications of hardware events may never be sent or be sent in error.

To partially address this data validity issue, additional measurements are included in the rules to check for the validity of the stream. Measurements are now marked invalid for a dropped packet(s) or when the source of the measurement becomes bad. There is still a larger problem of false negatives and never receiving an email if the data stream drops packets while a monitored event occurred. Aside from notifying the Shuttle engineer of a data loss when it happens, we have not yet identified a mechanism that guarantees all notifications since the data stream is unreliable.

3.4.2. Measurement Databases Changes

Multiple data streams and control rooms exist. Often, the measurement database, which is used to decode the SDS, dynamically changes on the stream as a result of operations. When that happens, decoding measurements becomes impossible and facts can no longer be updated in Jess' working memory. A short term fix to this problem was to simply notify the NESTA system administrator when the stream changes. A measurement database Java bean was added and is used within a user rule as a fact. When the measurement database changes, the administrator automatically gets an email and may restart NESTA accordingly. Longer term, automatic restarts of the agent will be provided.

3.4.3. Flood of Emails

If an end user incorrectly writes a rule, a possibility existed of flooding the network and servers with hundreds or even thousands of notifications. To prevent that, multiple

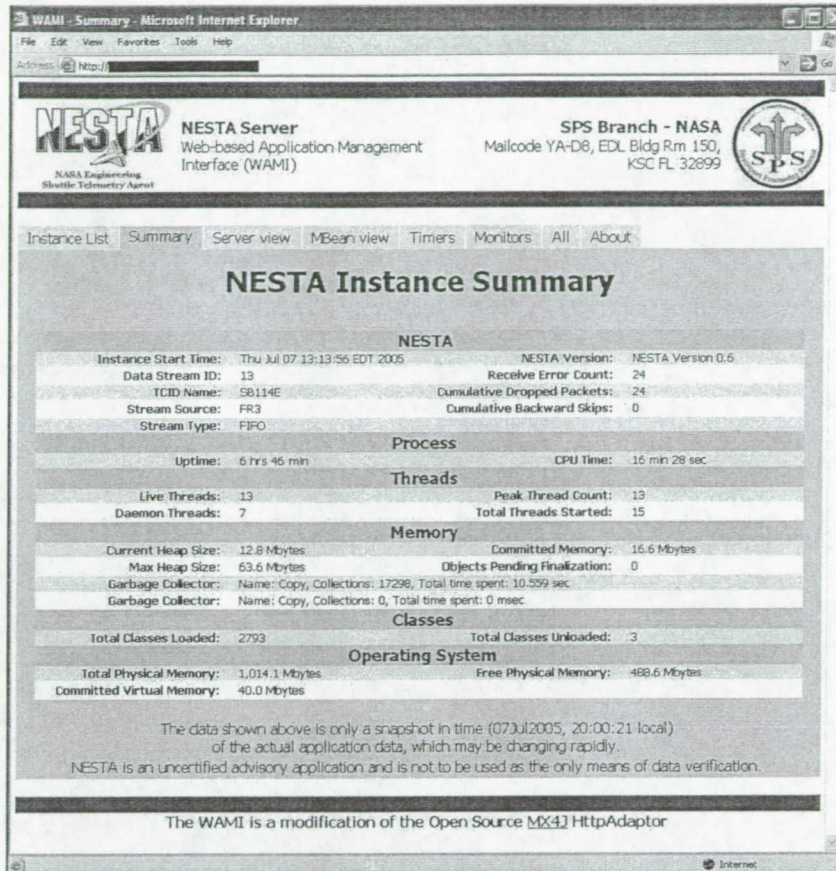


Figure 6. Web Application Maintenance Interface Summary Page

During launch countdown, NASA Shuttle engineers are required to monitor shuttle telemetry data for violations of launch commit criteria (LCC) and to verify that the contractors troubleshoot problems correctly. When a violation is recognized by the system engineers it is reported to the NASA Test Director. The problem report, or call, includes a description of the problem, the criticality, whether a hold is requested, and whether a preplanned troubleshooting procedure exists.

The Shuttle is composed of many subsystems (e.g. Main Propulsion, Hydraulics). Each of those subsystems has a team of engineers responsible for troubleshooting problems for that respective system during a launch countdown. Many systems have a large number of measurements with associated LCC limits and a large number of LCC requirements.

Shuttle Engineers must monitor for many types of limit violations ranging from simple high and low limit boundaries to much more complex first order logic expressions. Each team has its own tools for identifying LCC violations. Many of these tools use the LPS software and simply change the color of the displayed data

safeguards, such as user defined limits, were provided to filter emails after a given number have been generated for a particular email account.

Beyond that possibility of user error, there was a separate need to queue emails that may be related to some sequence. Queuing provides a mechanism where multiple messages expected to occur within a short time period are grouped together before being emailed in bulk. For example, four flight control avionics boxes are often powered up in a short time period. Rather than a user receiving four separate flight control emails that may be interrelated, it was necessary to provide a queuing mechanism that allows a user to tie related emails to the same queue and receive one bulk email that was a compilation of what would otherwise be multiple emails. Both the queue time and queue length are configurable by the end user.

3.5. Maintenance

New releases are delivered approximately every month by the development team. Those releases may include bug fixes for problems reported in the former release. However, new releases are generally driven by new functionality as opposed to being driven by software errors.

The design of the NESTA application facilities update by the end user. The application uses a data driven approach for the user files. All of the rules and facts are stored in Jess scripts. When rules have to be created or modified, the user has access to several text based files. A facts file allows a user to add measurements that should be monitored. A rules file allows the entry of new rules. Since these are text-based script files, no compilation is required by the end user. The files are parsed at application startup. This data driven approach is powerful in that it enables the end users to maintain their own files and not be at the mercy of the development team to add new support for new facts and rules.

3.5.1. Web Application Maintenance Interface

A Web Application Maintenance Interface (WAMI) was developed to aid the users in managing and monitoring the agent. WAMI is based upon JMX[16] and MX4J[17]. Figures 6 and 7 show the Summary and Management Bean Views, respectively. The Summary View shows the current state of the agent, presenting information such as agent starting time, the data stream being monitored, the number of dropped packets, memory usage, and more. The Management Bean page shows a snapshot of the values of a particular set of measurements from the data stream and also allows the customer to query the value of any arbitrary measurement on the data stream. Further information is provided in other pages and views.

4. Launch Commit Criteria Monitoring Agent

Another agent using Jess has also been developed at NASA KSC. The Launch Commit Criteria Monitoring Agent (LCCMA)[18] identifies limit warnings and violations of launch commit criteria. As opposed to being used for day to day operations for which NESTA was developed, LCCMA's scope is targeted for launch countdown activities.

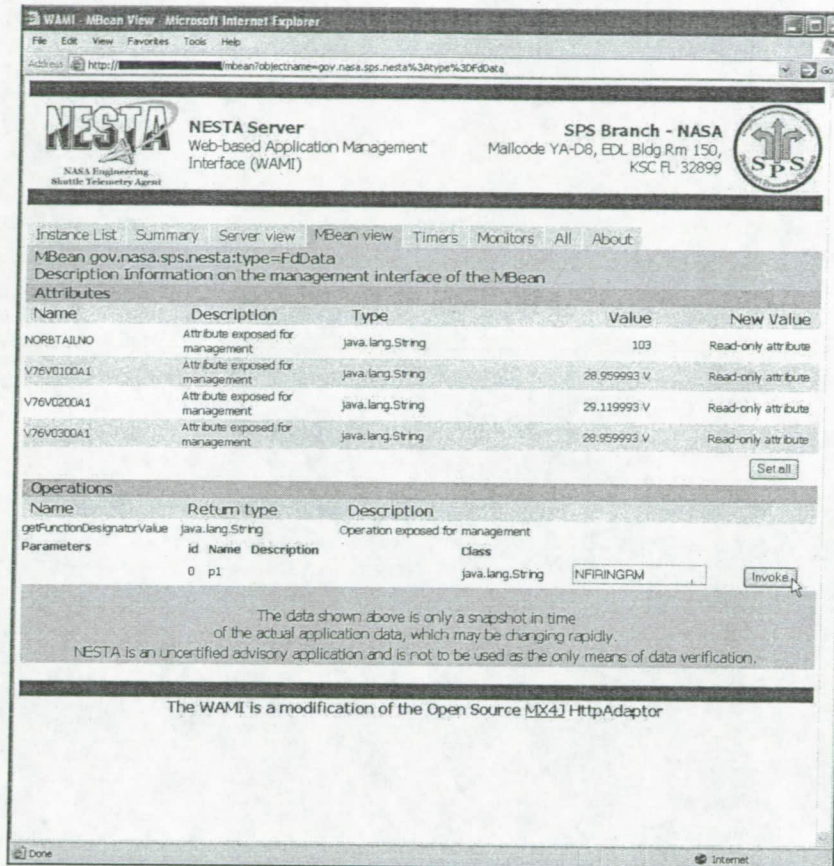


Figure 7. Web Application Maintenance Interface Management Bean View Page

and/or present a text message to the user or set off an audible alarm. Troubleshooting may require other displays such as plots and troubleshooting flowcharts. Valuable time is spent locating these procedures and locating the data that supports them.

With LCCMA, when a launch commit criteria violation is detected, the Shuttle engineer is notified via a Status Board Display on a workstation. Troubleshooting procedures are automatically made available on the Display. This precludes the Shuttle engineer from manually searching for the correct procedure mapped to the given violation.

4.1. Graphical User Interface

A graphical user interface currently exists for the Status Board Display. It is being upgraded and Figure 8 shows a storyboard representative of that future interface. The

5. Conclusion and Future Work

NESTA has increased situational awareness of ground processing at NASA KSC. More and more Shuttle engineers are relying on NESTA each month and are creating additional rules for monitoring the data stream. The infusion of AI technologies, particularly the Jess rule-based library, has proved very fruitful. Interfacing and integrating these modern AI tools within a legacy launch system demonstrates the scalability and applicability of the tools and paradigm.

The knowledge patterns that are evolving within NESTA will make it easier to train new users and also allow faster creation of rules. Many other enhancements are planned such as providing an advanced graphical user interface for creating the rules.

5.1. Future Exploration Agents

As indicated in the national Vision for Space Exploration[19], an increased human and robotic presence will be cultivated in space, on lunar and Martian surfaces, and other destinations. Spaceports will now span from the Earth to the Moon and beyond. A new set of challenges is presented by this Exploration Vision. In particular, the need for autonomy significantly increases as people and payloads are sent greater distances from Earth.

Agents for these future applications will demand much higher degrees of autonomy than today's Shuttle agents. Few or no human experts will reside at remote lunar or Martian sites to correct problems in a timely manner. More automation will be required along with advanced diagnostics and prognostics. This requires higher levels of reasoning.

Today on Earth, system and hardware engineers along with technicians leverage multiple skills when monitoring, diagnosing, and prognosticating problems in Shuttle ground support equipment. For the Exploration Vision, the need for extending these skills to support other vehicles and payloads at remote locations from the Earth to Mars becomes essential. These skills include being rational, collaborative, goal driven, and the ability to reason over time and uncertainty. The agents discussed earlier in the chapter, NESTA and LCCMA, are capable of shallowing reasoning of short inference chains within the Shuttle domain. However, these existing agents can be endowed with higher levels of rationality enabling a deeper reasoning. We are investigating how to mature these agents into Spaceport Exploration Agents (SEAs) in support of the Exploration Vision.

SEAs will need to communicate and collaborate along multiple and lengthy logistics chains. This does not simply include agents monitoring pre-flight checkout of vehicles at a terrestrial spaceport (e.g. NESTA monitoring Shuttle activities). Rather, SEAs will reside in multiple locations at great distances. Logistics, scheduling, and planning are just some of the activities that these agents will manage.

Within this virtual collaborative management chain, SEAs will be inundated with massive amounts of data that must be sorted and processed. It becomes necessary for them to revise their sets of beliefs as new data arrives. It is simply not enough to revise singular data points within an agent's working memory and to have an agent blindly react to those changes. Rather, an agent must possess the ability to revise previously concluded assertions based on what may be now stale data. This activity is called truth maintenance[20][21][22], also known as belief revision, and is particularly important when deep reasoning of long inferences is necessary. An assumption based truth

LCCMA Status Board Display

Stream ID: 7	Limit File: Fuel Cell Activation	User Inhibited: 1	Non-Certified
Stream Status:	GMT: 328:0055/54	Masked Values/Rules: 2 / 1	LCCMA Ver: 0.1c
TCID: SAA113B	CDT: +00:0010/23		

		Limit Details		
		328:0052/12.359 GMT (+00:0009/07 CDT) PRSD-02 O2 Manifold Isolation Valve Indicates Closed V45X2141E1 (PRSD O2 MANF 3 ISLN VLV-OPEN) is OFF. V45X2146E1 (PRSD O2 MANF 4 ISLN VLV-OPEN) is OFF.		
		328:0051/12.359 GMT (+00:0008/07 CDT) PRSD-04 O2 Manifold Isolation Valve Indicates Closed V45X4141E1 (PRSD O2 MANF 7 ISLN VLV-OPEN) is OFF. V45X4146E1 (PRSD O2 MANF 8 ISLN VLV-OPEN) is OFF.		
		328:0050/12.359 GMT (+00:0007/07 CDT) PRSD-03 O2 Manifold Isolation Valve Indicates Closed V45X3141E1 (PRSD O2 MANF 5 ISLN VLV-OPEN) is OFF. V45X3146E1 (PRSD O2 MANF 6 ISLN VLV-OPEN) is OFF.		
		328:0049/12.359 GMT (+00:0006/07 CDT) [OUTDATED MESSAGE] PRSD-02 O2 Manifold Isolation Valve Indicates Closed V45X2141E1 (PRSD O2 MANF 3 ISLN VLV-OPEN) is OFF. V45X2146E1 (PRSD O2 MANF 4 ISLN VLV-OPEN) is OFF.		
		328:0048/12.359 GMT (+00:0005/07 CDT) PRSD-01 O2 Manifold Isolation Valve Indicates Closed V45X1141E1 (PRSD O2 MANF 1 ISLN VLV-OPEN) is OFF. V45X1146E1 (PRSD O2 MANF 2 ISLN VLV-OPEN) is OFF.		

Act on selected:

<input type="button" value="Select All"/>	<input type="button" value="Acknowledge"/>	<input type="button" value="Pause"/>	<input type="button" value="Rules"/>	<input type="button" value="Print..."/>
<input type="button" value="Select None"/>	<input type="button" value="Remove"/>	<input type="button" value="Options"/>	<input type="button" value="Help"/>	<input type="button" value="Exit"/>

Figure 8. LCCMA Status Board Display

Status Board Display shows the health of the network connection, data stream status, countdown time, and other relevant information.

When LCC limits are violated, the LCC call is displayed in the text box. The user reads the text and, if there is an associated troubleshooting file, clicks the file button next to the text. This brings up a Troubleshooting Display for that particular LCC and limit. The LCC text remains bold until the Acknowledge button is pressed. Message text can be displayed with one of three icons representing a violation, warning, or informational cue. Measurements associated with the LCC may also be plotted.

The text messages can be read over the Operational Intercommunication System as LCC calls during the countdown. Calls will change based on what limit is violated (e.g. warning, LCC, high/low limit), the time criticality of the call, and LCC effectivity. The agent aids the NASA engineer in making a Go/No-Go decision for launch.

maintenance system (ATMS) can reason over many contexts simultaneously. By capturing, maintaining, and deploying spaceport expertise within ATMS-enabled SEAs, the costs and manpower required to meet the Exploration Vision are reduced while safety, reliability, and availability are increased.

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