Digital Assurance: Empowering Decision Makers in the Digital Age

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ABSTRACT

With support from DARPA and the Operationally Responsive Space (ORS) Office a new approach to conventional spacecraft mission assurance has been developed that has the potential to revolutionize current practices. The goal of this new approach, coined Digital Assurance (DA), is to provide decision makers with real-time, quantified information at any level of the program, including continuous, live custody of its comprising components. Digital Assurance will enable reduction in program costs and time associated with conventional mission assurance approaches. DA represents the intelligent integration of the digital design environment with the digital manufacturing environment to achieve unprecedented levels of knowledge about the physical configuration of a satellite.

The foundation for the successful implementation of DA is the concept of Continuous Custody and a Graph Database. Continuous Custody takes advantage of the physical reality that the majority of spacecraft Assembly, Integration, and Test (AI&T) takes place in a very well-defined and well-controlled physical environment, allowing capture of a broad scope of environmental factors.

THE DIGITAL ASSURANCE VISION

The impetus for Digital Assurance was to make mission realization and assurance more effective and less expensive through the use of digitally stored data and automated analyses while quantifying reliability, life, cost, and lead-time of parts, subsystems, and the system as a whole. In addition to reducing the cost and development schedule of systems composed of traditional space-rated components, it will accelerate technology transfer and the adaptation of Commercial Off-The-Shelf (COTS) parts and units for use in previously unintended applications or environments. DA will utilize Continuous Custody of the system and transparent decision-making by providing real-time information to key decision makers. In these ways, Digital Assurance will reduce the cost and time of build while facilitating more informed and thorough design and AI&T.

DA will accomplish these goals by dramatically extending and automating analyses traditionally performed using methodologies such as that of MIL-HDBK-217 and in many cases make these tasks predictive. Though the principles of MIL-HDBK-217 are as applicable today as ever, by moving the basis for application to a digital environment, the *intent* of governing documents like that are preserved while the *execution* is considerably advance by being positioned to take advantage of the modern conveniences a digital domain affords. A direct analogy can be drawn between traditional libraries and the internet; both contain similar data, but the internet affords much more interactive and rapid capability, primarily because it is founded in a *digital* domain. DA will collect and integrate data, using advanced automated search methodologies, from diverse internal and external sources, including internal and external databases, and past experience. DA tools will analyze available information and inform trade studies and decision-making processes, providing prediction capability that, in the ideal scenario, will be capable of predicting and preventing an error from occurring without any a priori knowledge of the specific task being performed. DA will also provide visibility into new and relevant information as it appears. Overall, these tools will provide more effective and efficient alternatives to over-testing and resource-draining full-scale design reviews. Digital Assurance will be scalable and flexible enough to follow the mission from inception through retirement.

The concept of DA becomes possible when both recorded data and the accompanying meta-data capturing expected components and processes are stored in a Graph Database. A Graph Database allows heterogeneous information with varying properties to be stored, and more importantly, allows any kind of relationship between data elements to be created and efficiently queried. This architecture allows for a very flexible yet rich and informed way of storing and retrieving information.

To turn these data into useful input for decision makers, DA dramatically extends and automates predictive analyses traditionally performed using methodologies such as that of MIL-HDBK-217 instead of following rote practices outlined by TOR-2011(8591)-9[1]. DA collects and integrates data, using advanced automated search methodologies, from diverse internal and external sources, including internal and external databases, autonomous vision systems, operator inputs, and work instructions.

Having fully demonstrated the ability to achieve DA, the first production-level DA system has been developed as part of the ORS Office's Open Manufacturing program and is currently operational in Raytheon Missile Systems Small Space production facility in Tucson, AZ. The specific details of this DA system will be provided in detail as well as a demonstration of the full capability of DA on a 6U cubesat production. The ability of customers to have real-time, original source data for decision making will be apparent as multiple scenarios will be demonstrated that illustrate the power and flexibility of a DA environment for spacecraft manufacturing. Demonstration of this DA capability represents one of three key pieces of the Open Manufacturing architecture, the others being Open/Autonomous Manufacturing and a Responsive Space Parts/Open Architecture spacecraft design.

The Digital Assurance system includes the following elements, as illustrated in Figure 1:

- Continuous Custody
- Data Collection
- Data Generation
- Data Integration
- Human Machine Interface

These elements will operate in the configuration shown and will be discussed in further detail in the next sections.

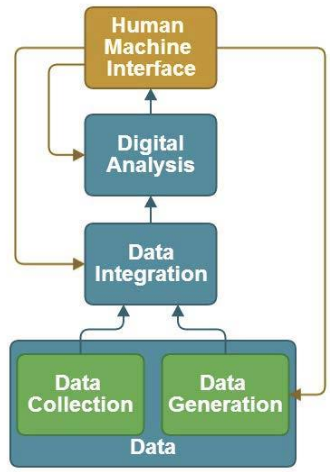

Figure 1: Elements of the Digital Assurance Architecture

CONTINUOUS CUSTODY

The most critical aspect of DA is the concept of Continuous Custody. Realized early on in the quest for an advanced mission assurance approach, the concept of Continuous Custody is the foundation that all DA principles are founded. DA begins by knowing every aspect of what is being done during the satellite design, AI&T, and operation of the satellite. While the amount of data generated during each phase of the development in the life cycle of a satellite varies considerably as it evolves and moves towards fabrication and testing, for most aspects of satellite manufacturing, a significant number of critical data are generated in the AI&T phase of the satellite development. For illustrative purposes, the concept of Continuous Custody represents the ability to know all aspects of the satellite AI&T activities that were performed within a known and defined volume (typically a clean room). As shown in Figure 2, the volume defined by the truss structure would represent the Continuous Custody volume being controlled and monitored in this example. Knowing all aspects of the operator's actions, the satellite design aspects, the AI&T protocol in that space during this phase of the satellite's evolution is a significant source of data generation for the elements detailed in Figure 1, but a long way from being the only source of useful data as described in the following sections.

Figure 2: Digital Assurance Achieved Through Continuous Custody

EXTERNAL DATA COLLECTION

Large amounts of data already exist for every aspect of satellite design, manufacturing, testing, and operation. Often those data in the form of reports, lessons learned, design reviews, red-line procedures, etc. and are unavailable for subsequent missions simply due to the inability of the related mission to access those data. Through the evolution of digital media manipulation for documents like this, the ingestion data sources like this are much more readily available than have been historically. Large amounts of such data are collected from various existing sources to provide Digital Assurance tools with the greatest amount of perspective and statistical significance. A broad knowledge base will be achieved connecting to the various expansive databases maintained by the government and industry. Because data are mined from diverse, potentially disparate sources, the quantity and quality of data will vary greatly. Data may be fragmented or peripheral rather than specific to the part or system. Potential sources may be traditional or non-traditional:

- Traditional Sources: Government, contractor, and commercial databases. This includes manufacturer specifications, historical test failure data, corrective action reports, part history, and material source data.
- Non-Traditional Sources: Blogs, product reviews, news reports, company announcements, financial reports, etc.

Data collected from these sources are either simply fed to decision makers or preliminary aggregation and analysis is done automatically. Collection of data (amount and technical relevance) is related to the system/sub-system risk sensitivity based on TRL and MRL.

INTERNAL DATA COLLECTION

Much of the most immediately relevant information are generated specifically for the mission of interest. This includes data from mission definitions, specifications, CAD designs, drawings, tests, simulations (thermal, structural, dynamics, acoustic, etc.), analysis (materials, failure, etc.), incoming component inspection, non-destructive analysis (NDA) such as radiological or sonic, destructive physical analysis (DPA), forecasting (time and money), qualification, etc. Deconstructing phases of the typical satellite life cycle with the concept of Continuous Custody paramount to successful DA led to a focused evaluation of the possible data sources to be harvested for DA use. Shown in Figures 3 and 4 as the DA Process and Sensor sources for the entire life cycle of a satellite life cycle, these two illustrations quickly became the guiding principles for the DA architecture. If all of these data could be harvested during the different phases, true DA could be achieved.

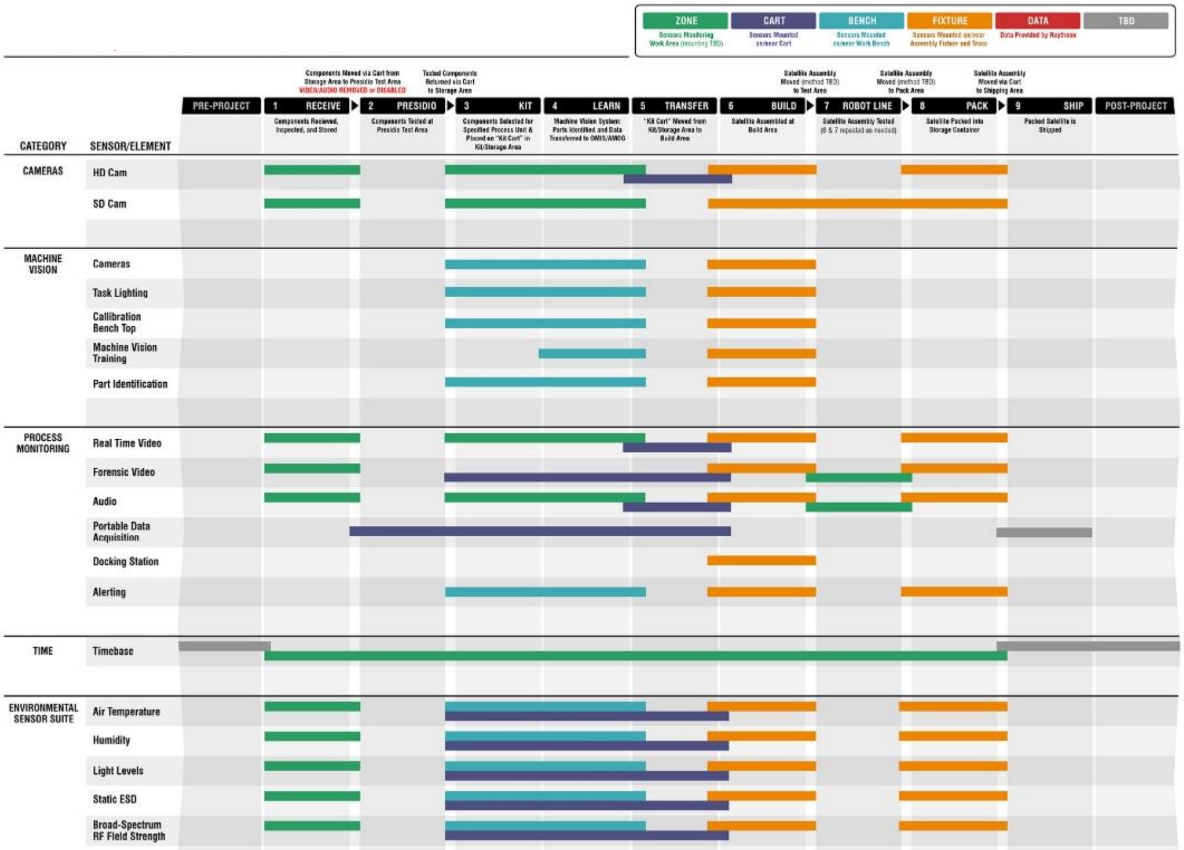

Figure 3: DA Process and Sensors (part 1 of 2)

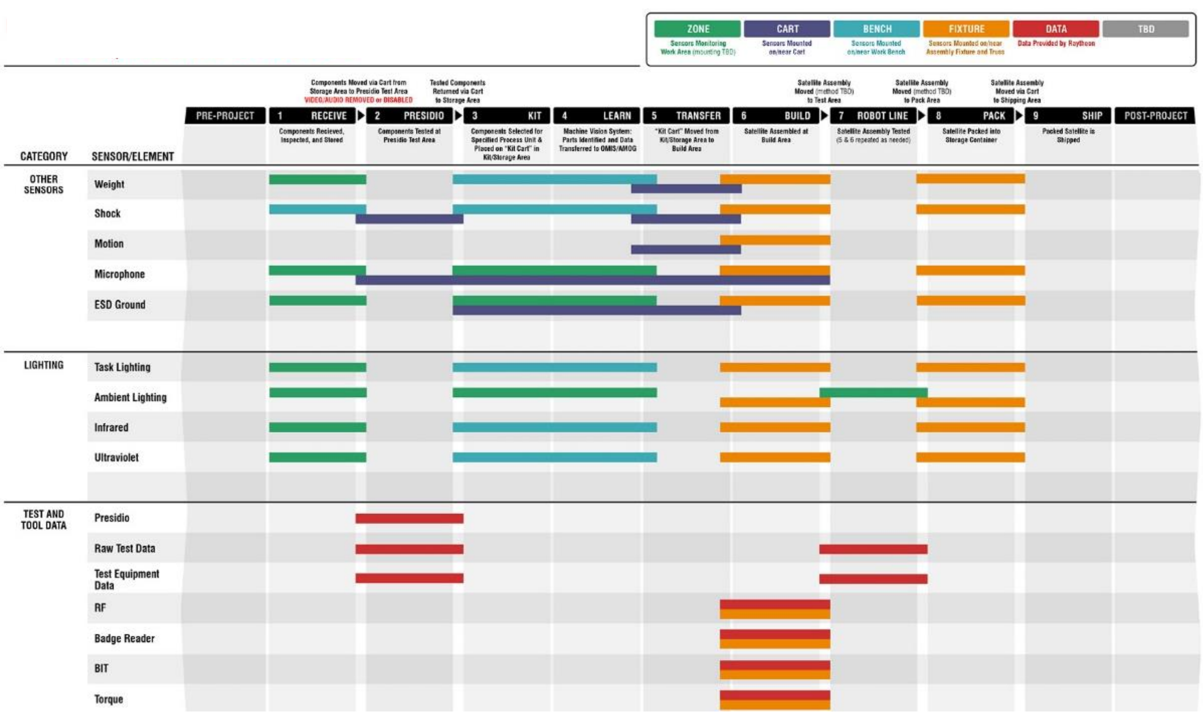

Figure 4: DA Process and Sensors (part 2 of 2)

One key data source that perhaps facilitates the concept of DA more than any other is shown on the second category shown in Figure 3 as Machine Vision. Machine Vision in the simplest form refers to the methods used to enable digital machines to perform image-based processing. When applied to the concept of DA, this powerful emerging technology begins to take on the form of a digital inspector if the proper technology can be brought to bear. As a result, one considerable task for the current instantiation of DA was to harness the power of machine vision to learn relevant satellite parts, learn relevant satellite AI&T processes and procedures, and be able to autonomously identify specific spacecraft parts during satellite processing. At which point, the machine vison can be used to compare what the computer 'sees' to specified work instructions to form the basis of a digital inspector that is capable of not only monitoring existing activities, but also has the ability to do predictive DA. For the current program the vision system is an integrated sensor suite within the Continuous Custody envelope that can observe detailed machine operations being performed by the operator in real time. Figure 5 illustrates the capture perspective of the current vision system in the Continuous Custody space that highlights the multiple perspectives available by the system.

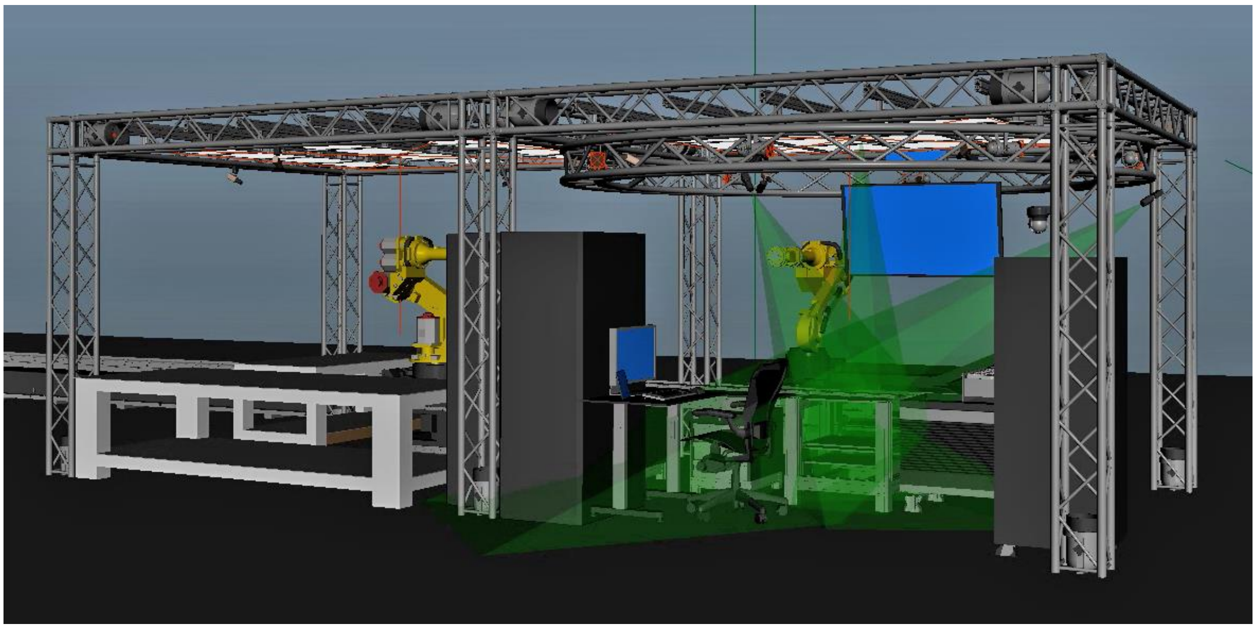

Figure 5: Machine Vision System Footprint in Continuous Custody Area

DATA INTEGRATION

Data integration is the process by which data from various sources link together. The large amounts of data must be organized, if not linked and analyzed, in order to be useful. The relationships among pieces of data are intelligent and have meaning. For example, components are 'part of' an assembly. This association allows some analysis to be built into the integrated data set. As an example, finding the mass of an assembly then becomes trivial - the tool simply sums the mass of the subcomponents in real-time. Although straightforward for mass calculations, having meaningful, multilateral relationships enables limitless types of interactions (assembly processes, thermal, emissions, power consumption, software, etc.). Current tools are limited to a very small subset of interaction types and data are not integrated in a flexible and scalable enough way to model the variety of possible system interactions that exist. However, data links from data generated in a Continuous Custody are live and information is automatically updated as changes are made.

A Graph Database and wrapper, reference data, hooks, a logic layer, data models, and a Human Machine Interface are integral components of the Digital Assurance system and are required before a basic functioning system was achieved. As a result, the most powerful component in the DA system is the Graph Database. Graph Databases allow any type of information with any kind of property to be stored. Stored pieces of information are called node, but more importantly, a graph allows any kind of relationship between any two nodes to be created. These relationships are called edges. The Graph Database allows for a very flexible yet rich and informed way of storing information. This relationship is illustrated in Figure 6 for a high-level satellite design perspective.

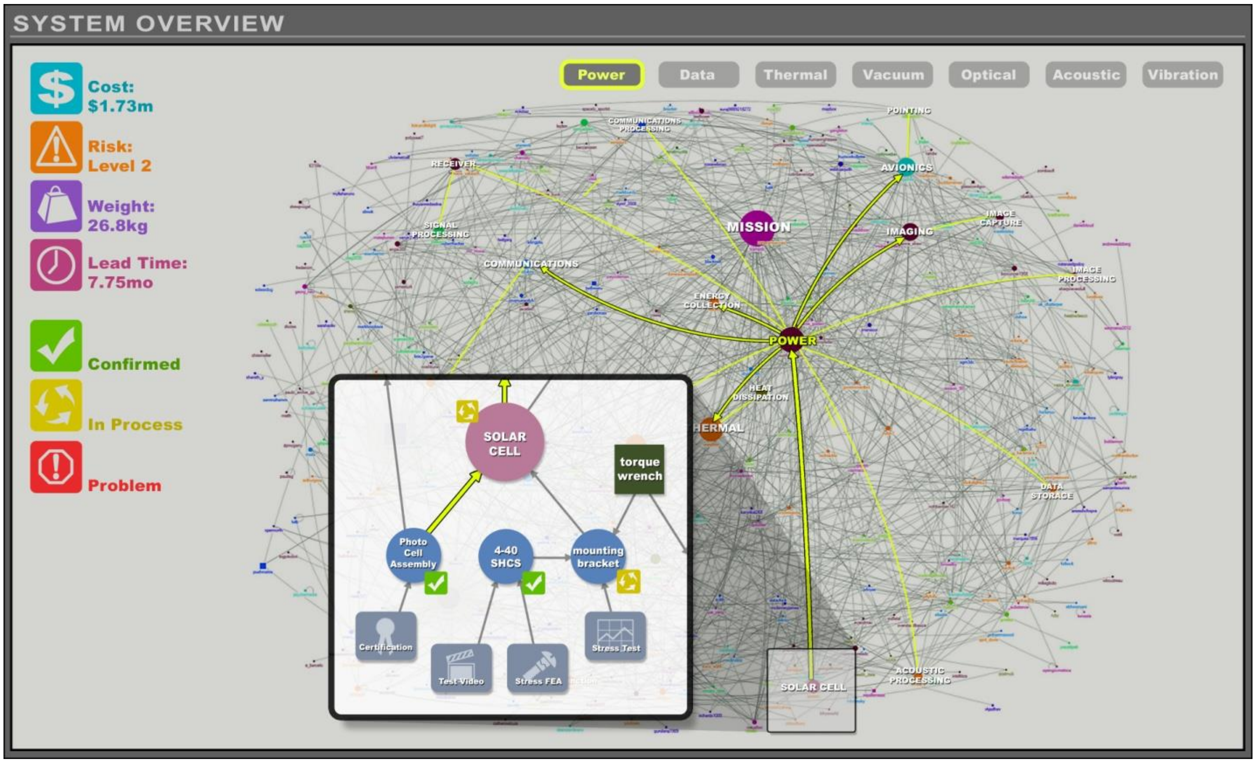

Figure 6: Graph Database with Selectable Subsystems

In the context of the DA system, a satellite component might be a node. Using a Graph Database, any piece of information about that component could be linked to it. For example, if the reaction wheel were the component, the Computer Aided Design (CAD) model would be linked to the reaction wheel as its model. The specification sheet would also be linked as such, the manufacturer would be linked as well, as would any historical data about the reaction wheel, simulations, test results, assembly information, and all other pertinent information. The database wrapper handles adding and editing data, nodes, and edges. Additionally, it was necessary to write a hook for the graph to automatically access each reference database, but leveraging these various existing databases brings substantial context to the mission and allows the information to reside in distributed locations.

Not only will the information be linked, but when using a Graph Database, all relationships are also understood. Continuing the previous example, if the CAD document generates a mass estimate for the reaction wheel, the Graph Database knows to associate that mass estimate with the proper component. Hooks for each type of data are what allow the Graph to understand and link data effectively.

As probably the most useful aspect from a mission assurance utility perspective, the Graph Database is real-time and dynamic as it evolves. When the CAD model is updated and the calculated mass changes, the graph will update the anticipated mass of the component autonomously. Thus, any information pulled from the graph will be current, independent of whether the reference is internal or external. The logic layer of the Graph Database handles these continuous calculations and is what provides the querying foundation for a digital search.

Finally, a Human Machine Interface is the mechanism by which a user views, adds, edits, and understands the vast amount of information generated by Continuous Custody and the Graph Database. Described in detail in the following sections, this interface offers Continuous Custody of the mission by displaying the current status of the spacecraft to include documentation, AI&T, test results, design criteria, technical requirements verification, and almost any other aspect of the asset. By presenting the salient *content* of all the digital data generated and presenting the entire dataset, if desired, efficient and informed decision-making can be achieved based on *unedited* data. Many of the features of the HMI will be described in the following section, thought much of the power of DA is not immediately obvious in a static format such as this paper. Digital Assurance is designed to be an interactive entity.

HUMAN MACHINE INTERFACE

The Human Machine Interface (HMI) is what the user will interact with to view, manipulate, and input data, while continuously displaying updated data generated from the system in near real-time. For example, when a test is run on an assembly, the precursor test procedure as well as the successor test report will be updated autonomously. When a supplier delivers a part, the timeline of the satellite build will be automatically updated. The HMI is the primary interface for the decision maker to interface with the DA system. It represents the current status of the program in near real-time, and is capable of generating multiple user-defined views that can be configured to best evaluate the data of interest to the particular user. For example, the main user interface screen is shown in Figure 7 as the situational awareness view that illustrates a thumbnail view of each satellite view in four main life cycle states: Receiving, Learning, Assembly, and Testing.

Emphasizing the power of the vision system detailed previously, the DA system is capable of generating error messages through autonomous sources like the vision system when a component is deemed to be in error some way. Whether the error is auto generated through the vision system or a user input from an experienced satellite designer or assembler, the user interface captures, manages, and presents each error instance in an identical format for the user to decide what course of action to take. As illustrated in Figure 7, on satellite #2, there was an error generated (yellow highlighted bar) during the receiving stage of the satellite. In this example, the GPS antenna arrived damaged. Figure 8 then illustrates what the user would see when querying the DA System regarding that specific error message by hovering over the yellow highlighted section with a mouse or other user input device.

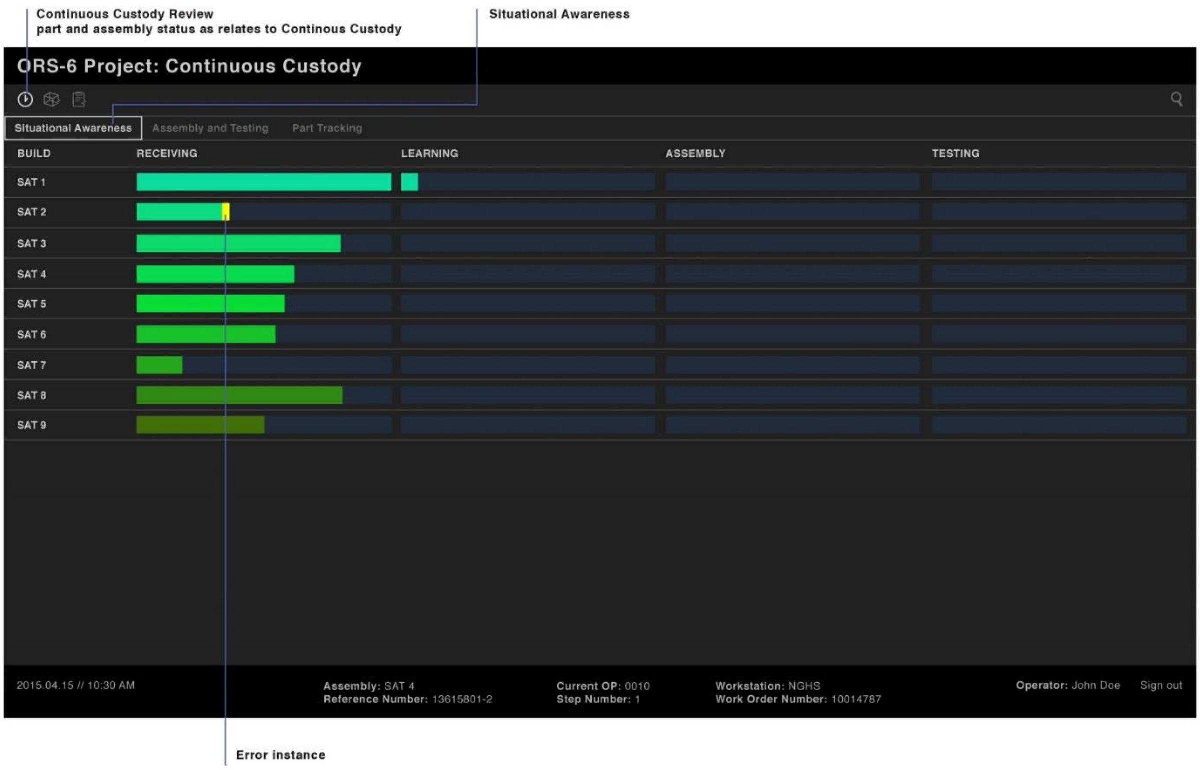

Figure 7: DA User Interface Situational Awareness View

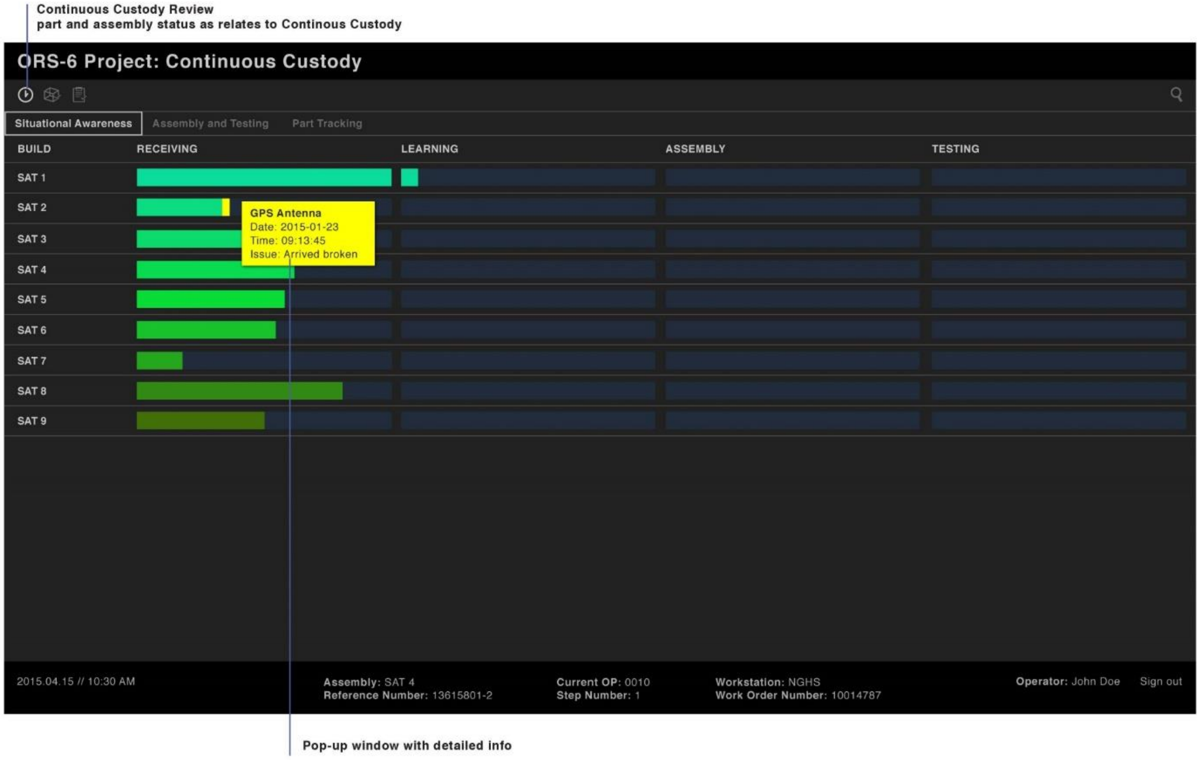

Figure 8: DA User Interface Illustrating a Pop Up Detailed Message

Continued evaluation by the user would reveal detailed supporting documentation by presenting the entire suite of data generated by the Continuous Custody system – unedited – in the time surrounding the event log. Illustrated in Figure 9, multiple visible camera perspectives are available to support the DA assertion that an error had occurred, much in the same fashion that football officials can review multiple recorded camera video feeds to review a play of interest (aka, an error). Further investigation by the operator using the DA system will allow the review all relevant data managed by the Graph Database such as that shown in Figure 9, but also all data surrounding the event, again in this case the GPS antenna. For example, the operator could review the technical documentation for the antenna as well as the environmental conditions during the receiving stage, the technician qualifications, impact to schedule, or a query to see what other satellite systems contain the same component, just to name a few examples. The specific use cases or error logs generated in a typical satellite build simply cannot be presented here due to space constraints, but this illustrative use case is offered here to demonstrate the ability of Continuous Custody and Digital Assurance.

To briefly demonstrate the ability of the system to manipulate relevant data into a variety of perspectives, Figure 10 illustrates the exact same dataset as shown in the previous HMI screens, but with an emphasis of time. Process steps are shown on the vertical axis against a horizontal abscissas of time, viewed normalized to the same time. In this example, it is very easy for an individual to evaluate the relative waterfall progress of each satellite build which makes out-of-family activities trivial to spot. The corresponding error messages, now highlighted by yellow markers (dots), when queried, takes the viewer to the similar screen as shown in Figure 9 with the drill down supporting views and metadata available for further investigation. Individual satellites call all be queried while being evaluated in different timescales simply by interfacing with the DA device as one would any website or digital tablet interface.

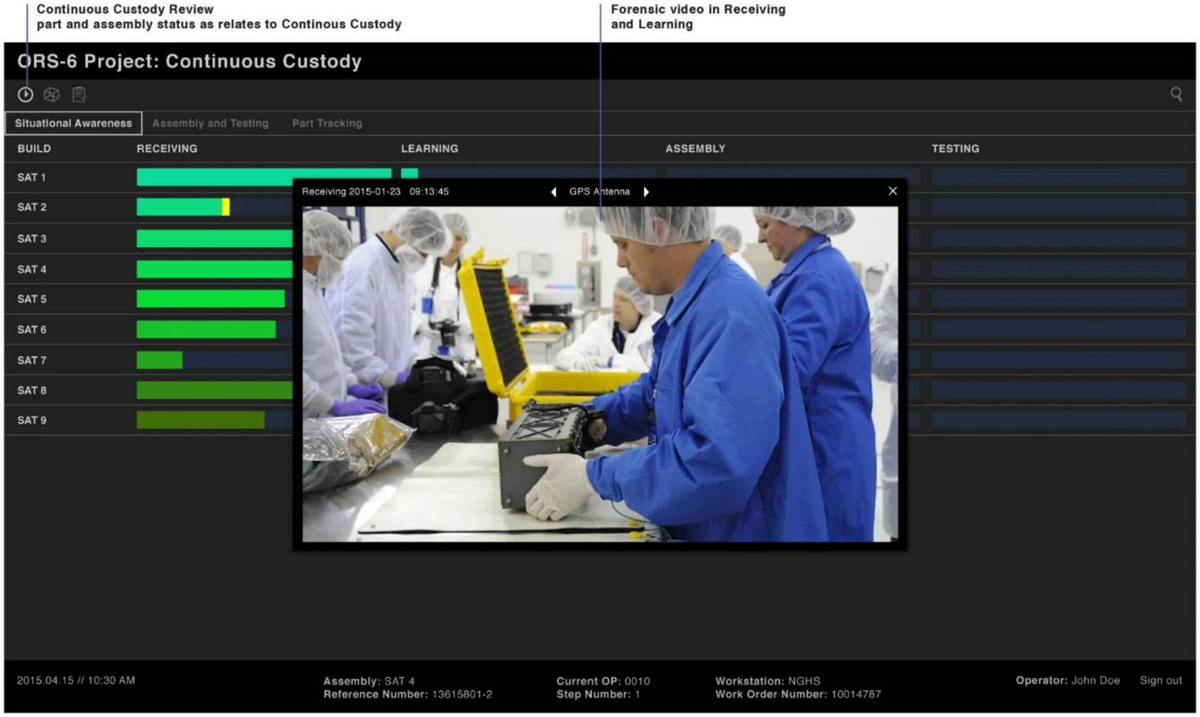

Figure 9: Drill Down Supporting Documentation for DA

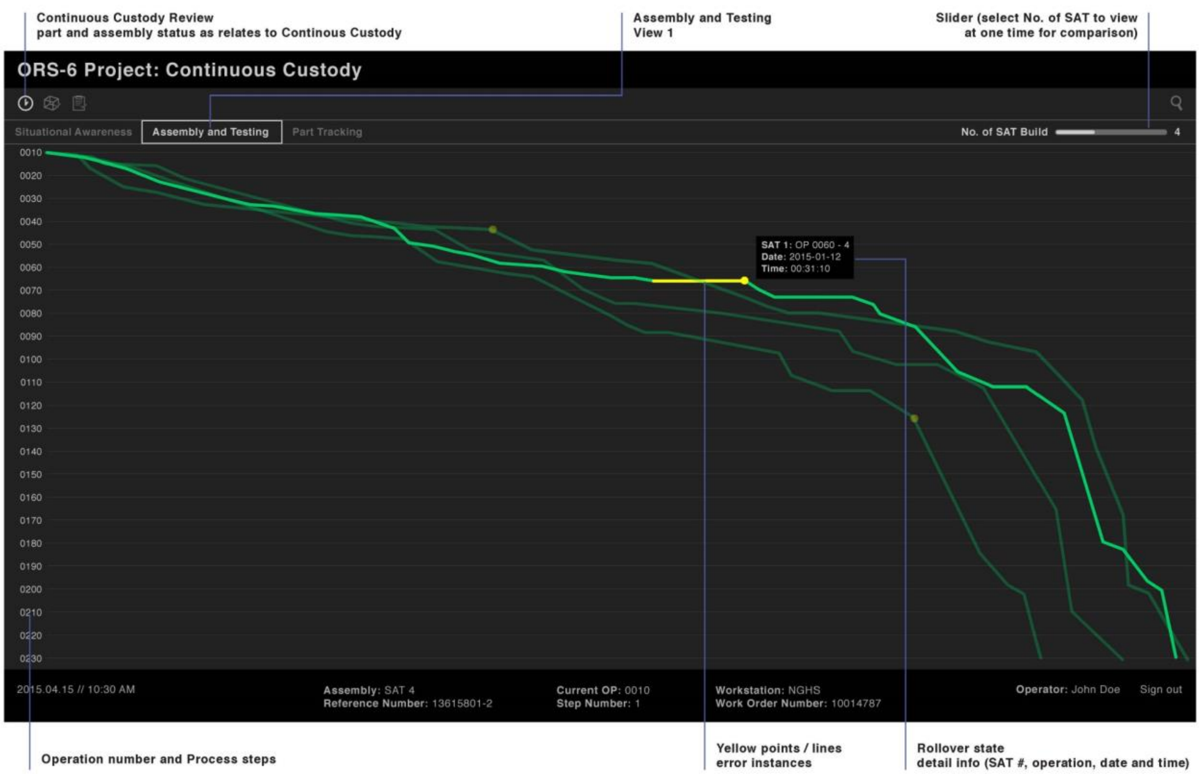

Figure 10: Operations View – AI&T Overview

CONCLUSIONS

The authors have developed and demonstrated the structure for a new era of mission assurance for high-value, low-volume assets that has the potential to provide near real-time access to all relevant data needed by decision makers to evaluate the state of reality unedited and accurately. Coined Digital Assurance, this new method is based on the concept of Continuous Custody that captures all aspects of a spacecraft's life cycle in a digital media that can easily be manipulated by a Graph Database which allows heterogeneous information to be efficiently stored and queried. True Digital Assurance becomes possible when the multiple data generation sources are autonomously working together to identify, document, and record the true (as built) condition of a satellite evolution from design to on-orbit operation. Once fully implemented, decision makers at all levels of a satellite will have all data available for that satellite instantaneously to make key, informed, and intelligent decisions to better enable Mission Assurance.

References

1. Aerospace Report No. TOR-2011(8591)-21, Mission Assurance Guidelines for A-D Mission Risk Classes.