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The Next Generation of Space Manufacturing: Model Based and Digitally Assured

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ABSTRACT

Increasing interest in affordable space has created a parallel need for low cost, rapid manufacturing of small spacecraft. Raytheon along with several partners has engaged in an activity that is geared around the demonstration of semi-autonomous manufacturing of small satellites. By using modern tools, processes, and techniques, Raytheon is heavily investing in smart automation for manufacturing and test capability. Starting with Model Based Systems Engineering (MBSE), Raytheon has successfully developed a model of the design space starting with the Operationally Responsive Space (ORS) 6U sized CubeSat. Future product access to the manufacturing line will require minimal investment from outside customers; it is being designed to be as product independent as possible. Common tooling, robotic material handling, and agnostic test equipment are all hallmarks of the Raytheon manufacturing design. When integrated with the ORS Digital Assurance system a next generation space factory is here today at Raytheon.

Along with increasing the speed of manufacturing low-volume, high-value space assets, this manufacturing capability has the ability to augment traditional mission assurance practices. By capturing significant events that occur on the manufacturing line digitally, a robust mission assurance record with a minimal amount of manpower can be created.

Combining a robust semi-autonomous manufacturing capability with a new form of digital assurance is enabling Raytheon to manufacture low cost, highly reliable small satellites for the ORS office.

BACKGROUND

Raytheon Missile Systems (RMS) is the largest designer and manufacturer of missile products in the free world. Headquartered in Tucson Arizona, with over 14,000 employees and 2014 sales of 6.3 billion dollars, RMS has built over one million tactical missiles and maintains contracts with all United States armed services as well as those from 40 other foreign countries.

In recent years, the tactical missile business has evolved towards smaller and lower cost products as customer emphasis has tilted increasingly towards quicker time to market and increased affordability. Accordingly, RMS has invested significantly in automated assembly and test capabilities.

In 2013-2014, these resulting new manufacturing lines were adapted for usage on small space products; notably the ***SeeMe*** and ***Phoenix*** programs. In 2015, RMS continues to down the path of creating a small satellite manufacturing line open to all interested parties without requiring that customers “buy the line”.

A BRIEF HISTORY IN SMALL SPACE MANUFACTURING AT RAYTHEON

This paper extends the work reported by Raytheon in the 2014 Small Sat conference paper number SSC14-VII-10, which described the adaptation of missile manufacturing lines to the mass production of nanosatellites. It was discovered that much of the same testing is required for missiles as it was for small satellites. Thus, Raytheon began down the journey of adapting missile assembly, integration, and test lines to the completely new product of a small spacecraft for a relatively low cost.

Multi-Use Manufacturing

Over the past ten years, Raytheon has expended a significant amount of IRAD funding in order to create a factory setting able to produce multiple disparate models of missile. Raytheon factories around the United States have begun to adopt this methodology and inside it is common to see automated material handling technologies moving components around. Along with the advanced automation, ergonomically designed workstations are designed for optimal operator comfort and are adjustable, allowing the assembler to work on a variety of different products at a single common use workstation.

The Next Generation Space Factory

In Tucson, Arizona a next generation space factory has been created and is currently being used to build and test a mixture of space and traditional products. This factory has been designed to be an assembly, integration, and test line outfitted with robotic material handlers and contains an "agnostic" or product independent, set of test equipment. The next generation space factory possesses a variety of different test equipment from optical testing (collimated light sources, semi-active laser), to RF communications testing, and finally to a wide range of environmental stimuli (thermal, vibration, and thermal vacuum).

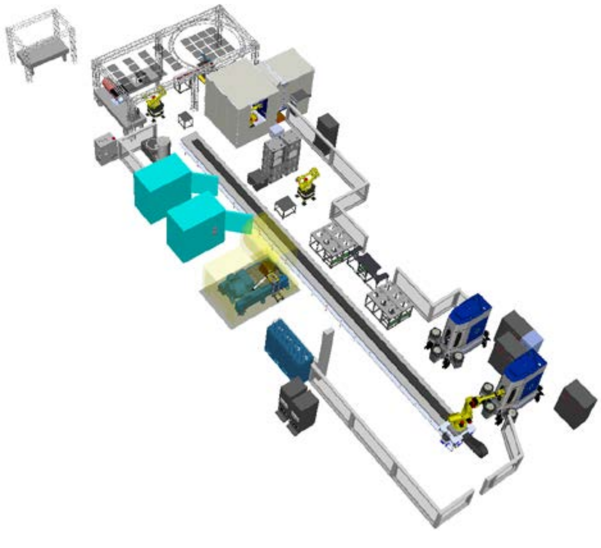

Figure 1: Raytheon's Next Generation Space Factory – Space Fusion

Small Sat Manufacturing Adaptations

A special set of test equipment has been added on the north side of the factory in order to specifically address the requirements of small satellite products. Raytheon has invested in a group of test equipment and has installed it as part of what is being called the Small Space Work Cell.

The test equipment found in the Small Space Work Cell is as follows:

- Solar simulator
- Starfield generator
- 3-axis magnetometer
- GPS roof relay

In addition to these specialized pieces of test equipment, Raytheon has installed an industrial Fanuc robot affectionately known as "Bumblebee" in the Small Space Work Cell. Bumblebee is being used to run a series of robotic assisted tests on spacecraft components. It is able to use a variety of different end effectors to run tests on various components of the spacecraft. There is a reaction wheel end effector, a weight and CG end effector, and an inertial measurement unit end effector.

This robot is able to perform multiple iterations of tests in a "lights out" environment while collecting data on the spacecraft as needed.

Transition to Production

Last year at the 2014 Small Sat conference, this advanced manufacturing capability was nothing more than a proposed system. In the second quarter of 2015, this capability is nearly fully functional with real product running down the line. The first full production spacecraft will be built in the fourth quarter of 2015. This production spacecraft is intended to be a 6U CubeSat design created by the Space Dynamics Laboratory in Logan, UT.

MODEL BASED SYSTEMS ENGINEERING

A critical component to the rapid acceleration of a conceptual prototype factory to a functioning system was made possible through the practice of Model Based Systems Engineering (MBSE). The evolution of a documents based approach, MBSE is the formalization of the systems engineering discipline through the usage of models. A multi-use factory is an extremely complex system and the traditional method of placing information in documents was not conducive to the proper management of complexity and risk.

A benefit identified in the usage of MBSE for the small space factory was the increased amount of communication between all stakeholders. Customers, business partners, and Raytheon engineers were able to look at the same information in one cohesive model and provide valuable feedback. This resulted in a quality and productivity improvement by enforcing rigor and precision in the systems engineering process.

Starting with a set of high level mission objectives provided by the customer, Raytheon used MBSE throughout the course of the project in order to properly validate and verify requirements.

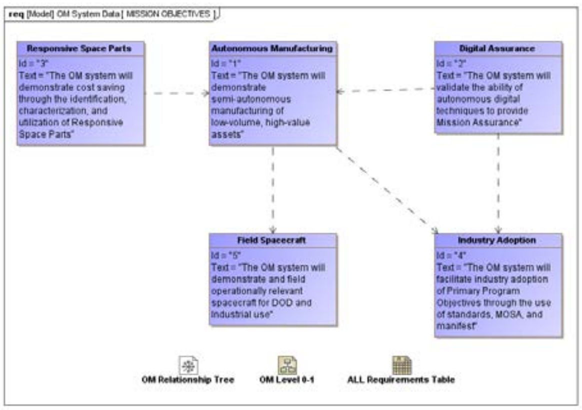

Figure 2: Top Level Mission Objectives

The development of the small space factory did not follow the traditional Aerospace and Defense development model. The "Systems V" or waterfall development model was not fast or agile enough to set up a multi-product factory with the given time constraints on the project. Therefore, a modified approach often known as the spiral development cycle was adopted. Using MBSE, the systems engineers were able to cope well with the rapid changes in scope, budget, and technical capability being developed.

Usage of SysML

A common method used to implement MBSE is through the usage of a language known as "SysML", or the Systems Modeling Language. SysML is a graphical language developed by the Object Management Group (OMG) and the International Council on Systems Engineering (INCOSE). SysML is a child of a commonly used language for software development, the Unified Modeling Language, or UML. There are ten types of diagrams that can be used in SysML and not all of them were used by Raytheon during the definition of the small space factory. Primary diagrams used for this project are as follows: Requirements, activity, package, use case, and block definition. A significant amount of time was spent on the requirements diagram with direct feedback from customers. The manufacturing capability was developed concurrently with the Space Dynamics Laboratories (SDL) 6U design and therefore many of the requirements had to be reviewed and altered during the initial factory conceptual design. Following the traditional approach of documents based requirements management would have been exceedingly cumbersome during this phase of rapid iteration. The system model, constructed in a commercial off the shelf (COTS) tool called MagicDraw, was flexible enough to allow change to occur with little to no time lost documenting. Raytheon considered the model the "Authoritative Source of Truth" for all systems engineering artifacts. A documents based requirements approach in Excel, or another tool such as DOORS, was never created as it was not needed. The system model itself was kept under configuration control and treated in the same manner as any critical piece of technical data.

A benefit of using the model based approach was the ability to export to a web-based format for review by all stakeholders. The MagicDraw tool exports the model to HTML; this instance of the model can then be opened in any web browser. The web based version has a simplified graphical user interface (GUI) that allows non-modelers to easily navigate through the system in the same manner as a browser through a webpage. It also has a robust search feature which allows the user to quickly find what they are looking for inside the model.

A secondary benefit of having a web-based model is that ability to share it outside of Raytheon's firewalled environment. Customers and business partners were able to view, navigate, and suggest changes to the model without needing the modeling software itself.

Finally, the model based specification lays the groundwork to create an executable system model. Engineers can rapidly reconfigure parts of the system and be able to judge how much of an impact these changes have. An analogy can be made to a physical fit check inside of mechanical modeling tool such as SolidWorks or Creo. The executable system model allows engineers to perform a "functional fit check" to see the impact of proposed changes in terms of the systems functional decomposition.

Application to a CubeSat Design

A CubeSat is a type of small, low-cost spacecraft that adheres to a published standard. They are comprised of one or more units commonly referred to as "Us". A 1U is a cube that is 10 cm on a side (10 cm x 10 cm x 10 cm) and weighs no more than 1.33 kg per U. These small spacecraft typically are developed by academia and are launched as secondary payloads. Due to the nature of desiring a low-cost, rapidly developed spacecraft, the ORS office established a partnership with Raytheon and Space Dynamics Laboratory to design and manufacture several 6U sized spacecraft using state of the art manufacturing technologies.

Inserting a brand new product into an existing manufacturing line is a complex, difficult task. The usage of MBSE has enabled the Raytheon/SDL team to quickly perform trades on whether it was more cost effective to modify the manufacturing line or the product design.

Using a methodology more often seen in the commercial manufacturing industry, Raytheon has chosen to impart requirements onto the product design instead of modifying the existing manufacturing infrastructure. By modeling the entire manufacturing line in the system definition, Raytheon was able to understand where the design constraints existed in terms of manufacturing and test.

The primary diagrams used in the impact of the product design were the requirements model and the block definition diagram(s) of the factory itself. The physical and functional attributes of all pieces of factory equipment were modeled and shared with the spacecraft design team. An example of a constraint is the weight limit of a Raytheon material handling robot. This becomes a design constraint as the mass and CG of a spacecraft intended to be manufactured at Raytheon must adhere to certain guidelines.

Other examples of constraints modeled and shared are size limitations for environmental test chambers such as a thermal vacuum chamber (TVAC). The spacecraft was designed to fit within the parameters of the existing missile test equipment including the digital data interface, the size and weight limits, and the environmental tests to be conducted.

Without the system definition model, this task would have been tedious and perhaps impossible to properly execute. The complexity of designing both a spacecraft and a manufacturing line combined makes a documents based systems engineering approach inefficient and unwieldy.

Digital Assurance

The concept of Digital Assurance revolves around using digital data to augment traditional mission assurance practices which was devised by the ORS OM project. Digital Assurance in the small space factory is primarily comprised of three elements:

- The continuous custody of all design, build, and transport of spacecraft
- The archiving and subsequent discovery of all data in an object-graph system
- A powerful application of machine vision to recognize, categorize, and exploit existing data to increase digital assurance

Applied Minds Incorporated Partnership

In a partnership sponsored by the ORS office Raytheon has teamed with Applied Minds Inc. (AMI) in order to instantiate their customer's vision of Digital Assurance. AMI was tasked with the design, build, and test of a complete system to place in Raytheon's small space factory that allowed for continuous custody, machine vision, and a powerful archival and discovery system known as the Agile Manufacturing Object Graph (AMOG).

Figure 3: Digital Assurance Physical Framework (Courtesy of Applied Minds Inc.)

The AMI design was concurrently placed into the MBSE model along with the rest of the factory equipment. Facility requirements, space constraints, and functional requirements were all inserted into the model to ensure that the Digital Assurance system would both physically fit and functionally perform as intended.

Vision System

Multiple high definition cameras and microphones are positioned around the Raytheon small space factory. Continuous, real time recordings capture all aspects of test and assembly operations performed by human operators and machines. In conjunction with Raytheon's information system, the AMI Vision System verifies the correctness of each part and each assembly step. This mitigates the need for human quality assurance observers. More importantly, the time stamp of every event allows them to be correlated with these recordings for forensic analysis.

At the time of the writing of this paper, the Digital Assurance system is installed but is currently undergoing integration and test inside the Raytheon small space factory.

The Open Manufacturing Information System

The Open Manufacturing Information System (OMIS) is a tightly coupled system of applications, data agents, and programatic interfaces. Event driven and utilizing a state-of-the-art data repository, extensive details about every aspect of space system components, test results and manufacturing operations are captured. Product quality insight is available from a variety of viewpoints and to any level of detail. The real time progress and status of each order is always visible. Continous real time notifications keep management alerted to significant events for immediate resolution or after-the-fact analysis. Big data analytics allows information exploration and correlation.

Figure 4: Open Manufacturing Information System (OMIS)

CONCLUSION

A first of its kind manufacturing facility for small spacecraft has been setup at Raytheon in Tucson, Arizona. A novel approach toward the design, building, and setup of this facility has opened the door for small spacecraft designers around the world.

This new capability will allow designers of all types to leverage world class manufacturing technology along with a complete set of agnostic test equipment.

The usage of the SysML language in an MBSE tool has allowed for rapid cycles of learning all the way from the conceptual product design down to the factory implementation. This model based environment allows for the easier integration of future upgrades and new product insertions into the factory.

A model based and digitally assured factory allows for lower cost small spacecraft to be assembled, integrated, and tested in controlled environment with the rigor normally only found on extremely high value space assets.

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