Improving AIT through integration of supply chain data into early-phase concept design

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ABSTRACT

As the global small satellite (smallsat) industry begins to transition to mass development and deployment of constellations, emphasis on streamlined Assembly, Integration, and Testing (AIT) is increasingly necessary for mission assurance and risk reduction. Small businesses are leading the way in providing “NewSpace” solutions throughout a program life cycle that will have significant impact on AIT for smallsat missions and feed into the mega-constellations of the future. This underpins a growing trend across the space industry towards commercialization, enabled by greater transparency, reliability, and cost-effectiveness within the global supply chain.

This paper outlines an international collaboration of small businesses, focused on developing a toolchain that supports the commercialization of space. Satsearch and Oakman Aerospace, Inc. (OAI) have teamed together with the combined objective of streamlining the early phases of a program lifecycle and injecting higher fidelity modeling and simulation environments into a program for high confidence AIT.

INTRODUCTION

Traditionally, mission designers have traded mission reliability for quick on-orbit deployments, in order to test innovative flight experiments using small satellites (smallsats). Now that the “smallsat” class of spacecraft is being pursued for large constellations, mission designers cannot afford to sacrifice assurance. The new driving metrics for smallsats are mission reliability and assurance. Streamlining Assembly, Integration and Test (AIT) is an effective way to maintain reliability within smallsat production lines. The first operational constellations maintain this via vertical integration of their supply chain. Vertical integration brings the entire supply chain “in-house” and requires each component of the spacecraft to be designed to achieve compatibility with the entire system. Instantiating vertical integration requires heavy upfront/acquisition costs, high development costs for next-generation upgrades, and can limit the business agility for that production line. The majority of the commercial space industry, especially small-businesses, cannot afford vertical integration; small businesses rely on partnerships and 3rd party vendors to execute their space missions.

To enable organizations across the global space supply chain to dedicate resources towards excelling in specific technologies, products, and services and relying on 3rd party vendors, it is of paramount importance that information is openly accessible for space engineers to exploit, when conducting trade studies to determine design optimality and robustness [1]. The integration of supply chain information across the mission lifecycle opens up the opportunity for efficiencies to be won across multiple, international organizations. The solution described in this paper, focussed specifically on the gains that can be achieved for AIT within the context of the entire mission lifecycle, enables collaboration and compatibility between small businesses in the industry to achieve the mission reliability required to support mass development and deployment of constellations.

Our paper is structured as follows. Firstly, we present an overview of supply chain digitalization and the rationale for digital transformation in the space industry. We also briefly outline the work that we are conducting to integrate supply chain information into the early phases of space mission design. We reflect on the relevance of choices made during the early design phases on AIT, and the need for supply chain digitalization across the mission lifecycle to achieve greater mission assurance. Next, we delve into the nature of AIT and the opportunities to streamline processes, to enable greater mission assurance and reliability, particularly in the context of smallsat development. We detail our work to explore integration of digitalized supply chain information into engineering systems based on Modular Open System Architecture (MOSA). Our assessment of the opportunities to streamline AIT allows us to outline areas for future work in the subsequent section. Finally, we summarize our conclusions on the impact of integrating supply chain information directly into early-phase design and high-fidelity modeling & simulation environments on modern spacecraft AIT.

SUPPLY CHAIN DIGITALIZATION

Digital transformation of supply chains is underway in a number of high-tech sections, including automotive, aviation, and shipping. The purpose of digitalization in each of these sectors is to enable organizations to rapidly adapt and respond to dynamic changes in global, connected, and integrated commercial markets. In the aviation industry, for instance, digitalization is driving the reduction of risk, optimization of cost, and control of lead times, by enabling scalable and adaptable supplier relationships built on *data-driven trust* [2].

There has been increased focus on the role of digital transformation in the space industry, towards achieving the ambitious goals of government agencies, private industry, and academia over the coming decades. As the space sector transitions from primarily government-led enterprise to full-scale commercialization, democratization of the global space supply chain will become increasingly important. Supply chain digitalization can enable the degree of democratization required, by enabling participants within the marketplace to drive rapid decision-making using data.

The greatest drivers for success in the space industry are management and control of cost, schedule, and risk. This is of particular relevance during AIT, when the intricate complexities of the "system-of-systems" nature of space missions comes to the fore. Open, standardized, and interoperable design, test, and interface data can help drive robust decision-making, pinpoint bottlenecks, and troubleshoot problems during AIT. To unlock the ability of organizations to rapidly respond to off-spec events during AIT, building an open standard to capture data is essential.

Satsearch has been building an online platform since mid-2015, focussed on consolidating, curating, and structuring global supply chain information. Currently, with over 5000 products & services from over 700 suppliers, and over 1700 missions listed on the platform, satsearch is looking towards opportunities to deploy this data across the space mission lifecycle to streamline key processes. The data that satsearch has collected to date comes from public sources, and is based on a combination of highly unstructured documents (typically PDF) and webpages. The process of digitalization in this context is focussed on extracting data from these sources and converting the embedded knowledge into structured, machine-readable, human-readable format.

These "smart" documents are often termed "Electronic Data Sheets" (EDS), and are richer in their ability to contextualize supply chain information in terms of entities and their relationships. EDS has a number of benefits over traditional documents and presents an opportunity to "eliminate much of the publishing time lag and help to ensure that the latest information is used by the systems designer in contrast to the printed data sheet, which is often obsolete the minute it is printed" [3]. The use of EDS extends beyond enabling self-consistency checks, as it allows for information to be transacted across teams and organizations with greater traceability. Satsearch and OAI are investigating the generation, maintenance, and use of EDS to reduce errors and standardize processes through automatic injection of supply chain information into Modeling and Simulation (M&S) environments.

The work to develop a standard "language", i.e., ontology, to underpin the formulation of EDS for the global space supply chain is on-going. Fig 1. provides a snippet of an EDS generated by satsearch from a PDF datasheet for a reaction wheel. The document snippet shows data stored in JavaScript Object Notation (JSON) format, which is typically used for message passing between cloud-based applications.


```
{
    "attributeClassUuid": "1f8bf2f8-ff20-4f47-ab19-2732a83be1de",
    "description": "",
    "maximumValue": "",
    "measurementUnit": "N m s",
    "minimumValue": "",
    "name": "angular-momentum-storage",
    "productConfiguration": "base",
    "productUuid": "b79236dc-407a-59bb-9215-8bda084cc317",
    "uuid": "3e8755c0-c8f8-4293-912f-51026089bee3",
    "value": "0.015"
},
{
    "attributeClassUuid": "a992c4ca-7889-464f-a3b5-f5bba4d7a26e",
    "description": "Annotated in datasheet: 'Custom options are available'.",
    "maximumValue": "",
    "measurementUnit": "N m",
    "minimumValue": "",
    "name": "maximum-torque",
    "productConfiguration": "base",
    "productUuid": "b79236dc-407a-59bb-9215-8bda084cc317",
    "uuid": "dfba18ef-e9c0-43bd-abe4-c45ada956ede",
    "value": "0.004"
},
```


Fig 1. Snippet of an Electronic Data Sheet (EDS) generated by satsearch, representing attributes of a reaction wheel.

The introduction of structured supply chain data into M&S tools for space engineering has been termed as "Integrated Mission Design" (IMD) [4]. Work is already underway to integrate digitalized supply chain information into different parts of the space mission lifecycle through IMD. Satsearch has been working on enabling engineers to tap into the plethora of products and services available on the global market by building integrations into leading industry software. Recently, in [5] and [6] a study was presented based on an integration of supply chain information provided by satsearch into a custom-built Attitude Control System (ACS) simulator. Given the ability of IMD to help unlock the supply chain for space engineers during early-phase design, the question Satsearch and OAI have sought to address is whether this approach can help to streamline AIT too, generating the gains necessary to achieve the level of mission assurance and reliability that underpin commercialization of the space industry. In the next section, we take a closer look at the nature of AIT and an approach towards streamlining processes to achieve the envisioned improvements.

STREAMLINING AIT

The entire smallsat industry supply chain, inherently, consists of disparate systems and subsystems. Pulling components and subsystems from multiple vendors provides many advantages (cost-competitive choices, lead-time alternative options, various performance ranges, and more) as well as disadvantages (initial incompatibility, custom adapters, non-lean flight software, etc.). A streamlined AIT phase utilizing various vendors requires a direct link from the early-phase concept design through AIT (Fig. 2). The only efficient way to drive this link, other than a full vertical integration plan, is through a full-fledged M&S environment.

A robust M&S environment throughout the program lifecycle provides the consistency needed to reduce AIT burdens that commonly occur when implementing a system of disparate subsystems. However, common burdens in the AIT phase include inconsistent hardware/software interface control descriptions, data communication protocols, time sequencing protocols, and others. These burdens are more common when the system of disparate systems transcend international borders and are often the most relevant inhibitors, preventing collaboration of small businesses in smallsat constellation production. Incorporating component data into the early design phases enables a more robust and higher fidelity M&S system. This also enables built-in emulation and test throughout the program lifecycle. Higher fidelity M&S ensure that once a program reaches AIT, the component, subsystems and interfaces have been tested relatively thoroughly.

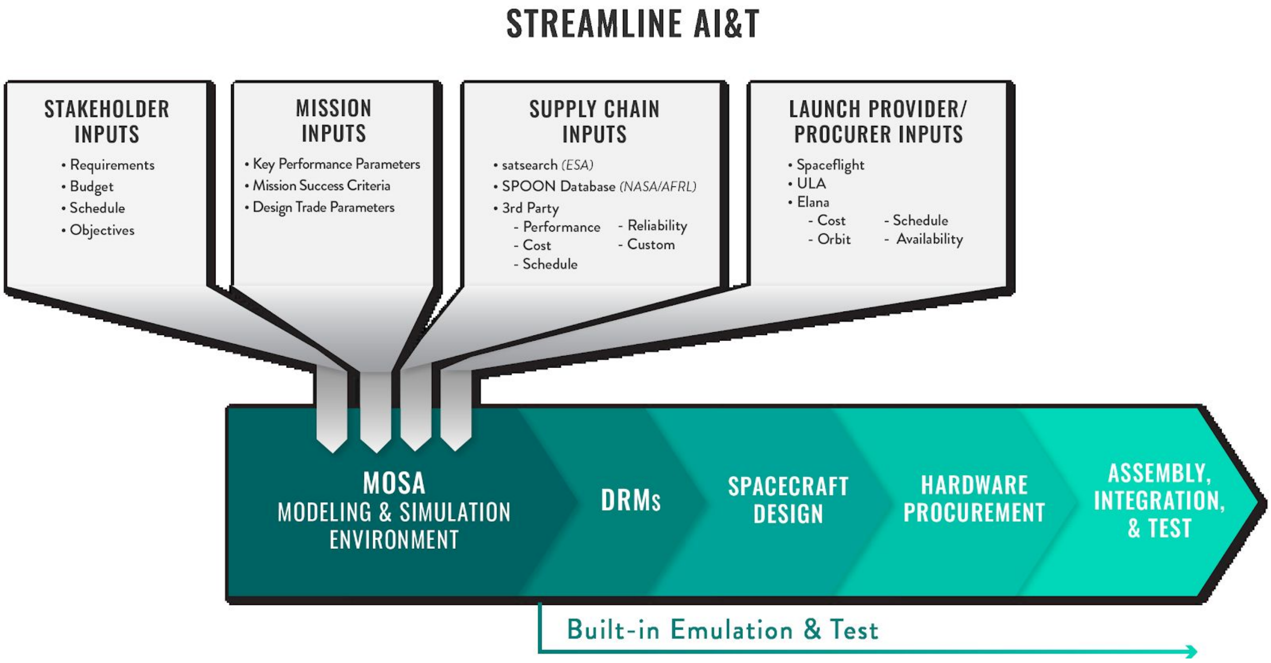

Fig. 2. A streamlined AIT process builds on early-phase component data integration, enabling built-in emulation and test throughout the program development cycle.

Common open standards have been widely identified as the solution for disparate systems to become compatible. Other technical industries have addressed this, for instance, in the cases of mobile phones, app markets, Linux, USB, demonstrating the success achievable through industry-wide, common, open standard adoption.

Unfortunately, the widespread adoption of a single, common open standard in the space industry has not been achieved. This is mostly due to the inability for a common, open standard to emerge as dominating. There are many capable open-standards available and used in current space systems. There are also many “open-standards” developed by traditional space system providers that are, in-fact, closed or hidden for select use. Establishing a single, open-system standard throughout the global space industry is a very difficult problem to solve for many reasons; performance characteristics of standards, security vulnerabilities, geopolitical considerations, to name a few. Examples of industry collaborative bodies seeking to establish common open standards include ISO, CCSDS, ECSS, AIAA and others. Harmonization between these public standards will be critical for the smallsat industry to operate efficiently on the basis of MOSA practices.

In the relative near-term, industry-wide adoption of a single, open standard for spacecraft components is unachievable. By reversing the responsibility of open standard adoption from the supply chain to the mission designers, an alternative solution was discovered. This solution implements a MOSA-defined M&S tool [7]. A MOSA M&S environment ingests non-MOSA-compliant Commercial Off-The-Shelf (COTS) components, or disparate open-system COTS components to create high-fidelity models. This process pulls the interface characteristics of the components from the supply chain and uses a MOSA-compatible messaging system to facilitate compatibility and integration between the disparate systems. The more this process is applied, the greater reduction in engineering development is required.

Additionally, a digitalized supply chain integrated into the program's M&S environment during the concept design provides even more opportunity for a streamlined AIT phase.

MOSA is the backbone to enabling the rapid development of high-performance, high-reliability smallsat constellations through this method and has the potential to lower costs and increase innovation in space systems. A MOSA-enabled M&S environment increases reliability through iterative development and testing, by ingesting a more diverse and dynamic set of inputs and integrating a larger number of spacecraft components. These inputs create higher fidelity models and add reliability to Design Reference Missions (DRMs). DRMs are typically used in mission conceptual designs. Within the MOSA M&S environment, DRMs can also be employed during the spacecraft design phase. The component models include interfacing data such as communication protocols, message managers, electrical and physical interfaces. The MOSA environment also enables rapid reconfigurability of the modeled components. Systems engineers use this feature to conduct multiple (scripted or Monte Carlo) simulations and detailed trades and analyses. These iterations in the spacecraft design translate into increased mission reliability without trading schedule consequences.

The mature spacecraft design that is derived from the use of MOSA-enabled M&S tools allows for a direct, punctual, and reliable AIT phase. As flight hardware is procured, incremental integration and test can take place. As each subsystem of the spacecraft is integrated, the components are tested and validated within the same DRM and interfacing with the high-fidelity software emulators of accompanying subsystems. This leverages into high confidence with each hardware integration into the system. Eventually, the full "flat-sat" is instantiated, still running within the mission DRM. All results of the testing are compared to the baselined DRM performance line. Any and all discrepancies from the baseline are addressed at the sub-component level, minimizing engineering effort to solve multiple issues typically occurring in AIT phases. This streamlined AIT phase enables small businesses to compete in the market.

For constellations and production line spacecraft, the AIT phase is continuous. A significant cost driver in constellation upkeep is subsystem upgrades. Typically, the spacecraft must go through another design process to flush out the impact of the upgraded system, as it flows through the spacecraft. MOSA promotes COTS interoperability, which can reduce integration and test costs, while enabling system/subsystem replacement and system sustainability. COTS integration of interchangeable components into constellations is the alternative solution to vertical integration of the supply chain for developers. This capability is particularly critical for cost-effective sustainment of large constellations, and further reduces development of software, drivers, and interface modules. MOSA environments are reused throughout constellation set-up, replacement nodes, and block upgrades. The iterative testing and lessons-learned accumulated during the early part of the process are directly leveraged to increase reliability later in the process.

Satsearch and OAI have embarked upon a project to demonstrate the benefits of MOSA-enabled M&S tooling with direct supply chain integration to AIT. Although the details of the implementation are specific to the toolchain being developed by both parties, the underlying principles of MOSA are agnostic to specific tools being built. The toolchain being developed by satsearch and OAI, which plugs into the whole mission lifecycle, serves as an example of how MOSA can be utilized as the bedrock upon which design teams across the world can deliver smallsat programs that satisfy the high levels of mission assurance and reliability required, against the backdrop of a dynamic commercial market.

FUTURE WORK

Targeting COTS hardware in M&S environments is not a trivial task and takes significant time to create high-fidelity models. Enabled by MOSA and a digitalized supply chain built on EDS, the M&S environment will drastically reduce the time to create these models. It will also ingest non-traditional data inputs for COTS components, which would significantly increase the fidelity of the models created. Examples of these non-traditional inputs include communication protocols, higher fidelity mechanical models to include Moments Of Inertia (MOI) and Products Of

Inertia (POI), fault detection protocols, and others. These criteria are not advertised on marketing product datasheets and therefore are not included in early mission concept design at present. This leaves early DRM analysis incomplete and exposed to risk.

Satsearch and OAI have defined a roadmap for greatly improving the digitalized supply chain, the MOSA-enabled M&S environment, and the automated integration of the two. Future work begins with the development of an advanced, state-of-the-art supply chain database that uniquely captures parts, subsystems, and components in standardized, human-readable, machine-readable format, i.e., EDS, much like the CCSDS standard. This builds on the work that satsearch has already commenced. The generated EDS is then imported into a next-generation, rapidly-configurable modeling and simulation environment. The combination of targeted, commercially-available flight hardware with the high-power modeling and simulation environment produces high-fidelity mission scenarios and spacecraft models. OAI's ACORN M&S tool will be modified to ingest these descriptive EDS and automate the simulation model development. This process will be conducted iteratively and verified against a relevant experiment with flight hardware.

CONCLUSIONS

Supply chain digitalization promises to bring significant advancement across the mission lifecycle. In this paper, we detailed the efforts being undertaken by satsearch and OAI to develop a standard to capture global supply chain data, and to subsequently integrate this information into systems that implement MOSA, like OAI's ACORN M&S suite.

There is strong rationale to pursue supply chain digitalization in the space industry, as it provides an avenue for streamlining AIT, by transparently connecting the choices made during the early phases of the design process through high-fidelity M&S. MOSA provides a robust principle to achieve this goal, enabling smallsat teams to rapidly evaluate design concepts and propagate decisions taken during early-phase design into AIT, where the complexities relating to systems engineering and procurement typically styme accelerated development.

We touch on the need for the development of a core space systems ontology and EDS that enables capture of heterogeneous supply chain information. Satsearch has embarked on a project to incrementally design, test, and evaluate such a standard. In concert with OAI's work to implement MOSA into the ACORN M&S tool, to support the whole mission lifecycle, the goal is to enable data-driven design across multiple, international, commercially-driven organizations.

Future work will be focussed on testing the integration of a supply chain database into a MOSA-enabled M&S toolchain again a relevant case study, to further detail the benefits to smallsat teams of adopting this to drive greater mission assurance and reliability during complex AIT processes.

REFERENCES [KK]

[1] A. Dunn, S. Kennedy Jr., "Reducing Small Satellite Development Timelines through Market Analytics and Systems Engineering", Spanish Small Satellites International Forum, Malaga, Spain, 2019.

[2] SupplyOn AG, "AirSupply: Efficient SCM processes in the aerospace industry", available online: https://www.supplyon.com/en/solutions/airsupply, unpublished, 2019.

[3] Dewey, F.R., "A Complete Guide to Data Sheets. Sensors Magazine", available online: http://www.allegromicro.com/~/media/Files/Technical-Documents/pub26000-Complete-Guide-To-Datasheets.ashx, 1998, unpublished.

[4] K. Kumar, A. Vaccarella, N.P. Nagendra, S. Gerené, and L. Lindblad, "Integrated mission design using satsearch", 8th International Systems & Concurrent Engineering for Space Applications Conference (SECESA 2018), Glasgow, United Kingdom, 2018.

[5] Cherukuri, S.D., "Integrating hardware data into simulation models for Attitude Control System design", MSc thesis, Delft University of Technology, 2019.
[6] Cherukuri, S.D., Kumar, K., Noomen, R, "Integrating hardware data into simulations for attitude control design", IAC–18–D1.IP.31, 69th International Astronautical Congress, Bremen, Germany, 2018.
[7] A. Dunn, S. Kennedy Jr., "New Techniques in Spacecraft Modeling and Simulation Environments to Support Next Generation Satellite Constellation", 12th IAA Symposium on Small Satellites for Earth Observation, Berlin, Germany, 2019.