TAMU: A New Space Mission Operations Paradigm

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Abstract: The Transferable, Adaptable, Modular and Upgradeable (TAMU) Flight Production Process (FPP) is a model-centric System of System (SoS) framework which cuts across multiple organizations and their associated facilities, that are, in the most general case, in geographically diverse locations, to develop the architecture and associated workflow processes for a broad range of mission operations. Further, TAMU FPP envisions the simulation, automatic execution and re-planning of orchestrated workflow processes as they become operational. This paper provides the vision for the TAMU FPP paradigm. This includes a complete, coherent technique, process and tool set that result in an infrastructure that can be used for full lifecycle design and decision making during any flight production process. A flight production process is the process of developing all products that are necessary for flight.

Background

The new vision for human space exploration calls for the development of a broad range of space missions and the participation of the commercial industry in the development and operation of flight projects. This requires NASA to collaborate with both NASA and non-NASA (e.g. commercial) space vehicle providers to prepare Operations products. An optimized architecture for future endeavors in human space flight leverages the strength of national assets such as the Mission Operations Directorate (MOD) at the Johnson Space Center (JSC). MOD pioneered human space flight operations and has been conducting it over the last fifty years. Other NASA centers, such as the Jet Propulsion Laboratory (JPL) and the Goddard Space Flight Center (GSFC), are the primary centers for building and operating non-human based space projects. The end-to-end architecture of the ground system associated with a NASA mission often includes multiple control centers and facilities (e.g., Kennedy Space Center (KSC) which is a primary center for launching spacecraft, Payload Operations and Control Centers, International Partner Centers) , other agencies, and academic and research institutes that are often the home institute associated with the scientists and principal investigators. The underlying methodology required for enabling the optimal utilization of all these resources for the

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development of Operations flight products and the approach for building an end to end architecture will be revolutionary as compared to previous NASA Programs.

MOD supports the crew and flight controller training, pre-mission planning and flight operations through a methodology known as the Flight Production Process (FPP). This process is a compilation of work tasks, which are conducted by a number of technical disciplines within MOD and its operations contractors. The FPP provides the products required to reconfigure the control centers and training facilities, and flight software/data products required for pre-mission planning and reconfiguring the flight vehicles. The training and certification of flight personnel, including crew, flight controllers and analysts, are also included within the scope of the FPP.

The MOD Space Shuttle Program (SSP) and International Space Station Program (ISSP) flight production processes were not built as one integrated system; instead, as separate and distinct production processes, based on very different architectures, built a piece at a time by each of the large functional areas within MOD. There are six distinct organizations within MOD. Each of these organizations has their own process for providing products to the FPP. At the advent of the SSP and ISSP, Systems Engineering and Integration was not yet an established discipline and the range of tools and technologies that exist today to support this discipline did not exist. As a result, there was no structured Systems Engineering & Integration (SE&I) effort across these organizations during the production process design. As a result, there is overlap in the activities conducted by these separate organizations; and integration of their associated processes is inefficient.

Based on the many years of experience with the Space Shuttle Program (SSP) and the International Space Station (ISS), the Constellation Program which preceded the current program and aimed on returning humans to the moon, has been building a modern model-based Systems Engineering infrastructure to Re-engineer the FPP. This infrastructure uses a structured modeling and architecture development approach to optimize the MOD mission operational design thereby reducing the sustaining costs and increasing system efficiency, reliability, robustness and maintainability metrics [18].

The new era of space exploration brings with it the diversification in the type of space missions and the partners with whom to collaborate. Therefore, it becomes necessary to further generalize the FPP framework to take into consideration a broad range of Design Reference Missions (DRMs) and the participation of multiple organizations outside of the MOD; hence the Transferable, Adaptable, Modular and Upgradeable (TAMU) concept. TAMU is a technological infrastructure that enables the flexibility for the production of flight products per defined need, and the ability to rapidly make changes to the orchestration and/or design of the FPP in service for any DRM, as well as the collaborators and partners involved in this process.

The concept addressed in this paper is intended to put in place a framework that can be used by all space vehicle providers with as few changes as possible from one vehicle to the other, thus allowing each Space vehicle provider to put in place the most cost effective process for Operations product development.

The TAMU Concept

The goal of the TAMU concept is the rapid exploration of the trade space associated with the development of flight products for a broad range of missions, and then the design, development and execution of an optimal concept, along with an architecture and the corresponding workflow processes associated with an FPP. In order to meet this goal, a team structure and a technological infrastructure is created and established.

An end result of the implementation of the TAMU concept is an integrated FPP framework across all relevant space companies. The operations concept and the needs, goals and objectives of each of the space missions will determine the optimal architecture and division of FPP across the agencies on a case by case basis. Moreover, the technologies used for the development of TAMU are extensible across NASA and other space agencies and may result in an optimal integrated infrastructure.

A standard approach that NASA uses for the rapid exploration of trade space is concurrent engineering teams [1], [6], [7]. This approach is based on bringing together a team of domain experts who each develop the respective design for their subsystem in a concurrent and iterative manner. Each of these experts use modeling tools and approaches commensurate for their discipline and the interfaces between the subsystems are well defined. The team facilitator and system engineer use appropriate tools and techniques to lead the design sessions and integrate the individual designs into a coherent product. This product may include cost estimates which are developed based on cost models associated with each of the associated subsystems. While this concurrent engineering approach is currently used at NASA at the spacecraft design level, it has not been applied for the development of the design of the Mission Operations System (MOS), or its associated flight products per se. The MOS developed by the MOD using a concurrent engineering approach does include low level details in terms of associated flight products and that is a leap in the state of the practice for concurrent engineering design teams at NASA.

TAMU enables the rapid trade space exploration of MOS systems and architectures by creating the infrastructure, in terms of the underlying models, the approach for integrating them, and the process for the development of the architecture and associated workflow processes for a broad range of missions. It is based on a reference architecture [19], and the repository of design information associated with it, which has been created as part of the Cx Program and extended to take into consideration a broader range of functions in the post-Cx program era. Most importantly, it includes a team of experts with representation from each of the major disciplines involved in the development of flight products. This team of domain experts, along with experienced systems engineers, flight directors, modeling, analysis, optimization and architecture development experts forms what we call the Special Analysis Team (SAT). For each of the major disciplines represented in this team, there is a sub-team of experts that can provide related support as necessary and upon demand. The software developers, modeling and architecture development experts are mainly involved in the development of the TAMU infrastructure. The premise is that once this infrastructure is developed and established, it will be readily useable by the domain experts. The technological infrastructure created by TAMU enables the development of FPP concepts and designs such that (1) the design knowledge is readily “transferable” from one project to another, (2) the design and architecture is “adaptable” to different sets of project requirements, (3) the design is “modular”, which provides the flexibility for adopting to new requirements and making changes in a structured and contained manner, and (4) the design is “upgradeable”, which indicates that it is readily updated and refined as new information is obtained through analysis.

The purpose of an MOS is to create trained personnel to conduct the flight project (crew, flight controllers, flight directors), the products that are used to support the development, planning and flight of the vehicle. The design of an MOS would therefore start with the identification of the products associated with a proposed operations concept for a space mission. The underlying approach for the TAMU concept is shown in figure 1. A broad range of spacecraft providers or study leads then use the infrastructure provided by TAMU to determine the optimal configuration for the MOS associated with their spacecraft.

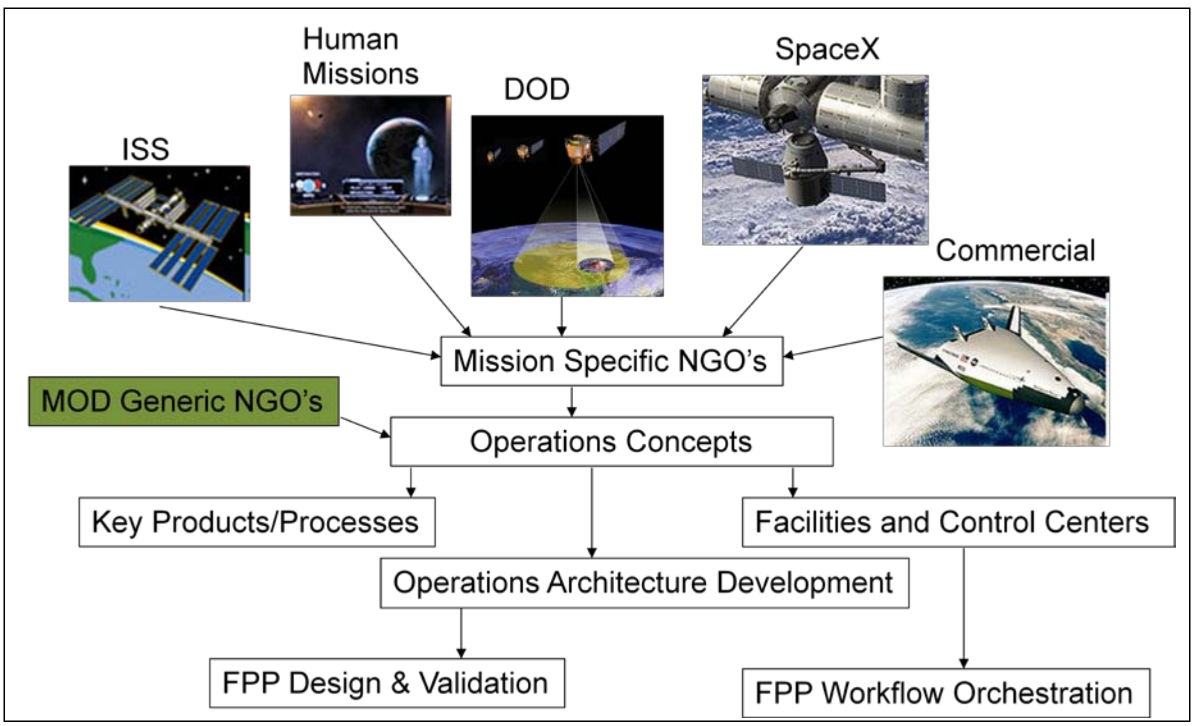

Figure 1: TAMU Design Approach

These study leads are potential customers for the MOD once TAMU has been established. The starting point for a study is the Needs, Goals and Objectives (NGO) of the mission in question, which combined with the more generic NGO’s that the MOD already has in existence create the idea for an operations concept, in terms of the spacecraft and the type and duration of a proposed mission. SAT team representatives will work with these customers to fully specify the requirements for their study and determine the type of services that are necessary for satisfying those requirements. The range of systems engineering services available to the customers includes:

- Trade studies for MOS design options.
- Sensitivity analysis
- Cost estimates for each option.
- Detailed architecture development for preferred option.
- Detailed workflow process design for preferred option.
- Design Simulation
- Probabilistic Risk Assessment of design.
- Design Validation
- Workflow execution
- Workflow re-planning
- Workflow execution.

The underlying TAMU infrastructure required for providing these services are:

- User-friendly, distributed software tool for capturing design and architecture data.
- Reference architecture and workflow process.
- Reference models for discipline workflow processes.
- Reference architecture artifacts.
- Reference probabilistic risk assessment models.
- Reference Cost models
- Reference Simulation models
- Workflow executive
- Workflow re-planner.
  Note that the technological infrastructure as well as a generic reference architecture and corresponding modeling, risk analysis, cost and simulation model is created and in existence to support the provision of these services in a timely manner for the upcoming customers.

TAMU & Responsive Space

The current cost-constrained environment for the space industry, coupled with the technological advancements of this era, lead to the vision for an agile space operations paradigm [8]. The underlying concept of the responsive space operations architecture is the achievement of the agility that space capabilities will need to respond to dynamic world environments, national priorities and operational requirements. The manifestation of such changes on the MOS associated with a space mission includes the change in the mission requirements and the order and type of products needed to operate it. TAMU provides the key features that contribute to an agile and responsive space mission.

- Transferability: The TAMU paradigm is based on producing a design that can be implemented in geographically disperse locations using distributed facilities and control centers. The design is therefore not restricted to a specific location and is therefore transferable.

- Adaptability: The TAMU paradigm is adaptable to a wide range of operations concepts. Each operations concept that is used for developing a design becomes a point design in the repository and is used as a reference. As more points of reference, or point designs are created, their adaptation to arbitrary operations concepts each of which lead to a different set of design requirements becomes more straightforward. This adaptability is possible because of the underlying models that are used to develop and represent the designs.

- Modularity: Modularity has been identified as the single most important feature that contributes to a flexible design [9], [10]. TAMU provides modularity by using a functional decomposition of the MOS in question. The reference architecture and reference models are all based on creating design modules for each of the key functions and processes with the MOS and integrating them.

- Upgradeability: This feature applies in two different dimensions. On one hand, the TAMU infrastructure is built with consideration of the maintenance and upgradeability issues associated with it and on the other hand the products of this infrastructure are upgradeable. As far as the infrastructure is concerned, we have a requirement for using tool-neutral approaches and for the seamless transfer of information between tools. In terms of the actual design product, because this product is represented by models, it can readily be upgraded and the changes that result from it will ripple through the model and upgrade the design accordingly.

The changeability of a system is defined in terms of the various states that the system can change to and the complexity of the transition to those states [12]. In a sense, all the metrics that we described above (Transferability, Adaptability, Modularity, and Upgradeability) contribute to changeability. Modularity makes the transition of the design to other design options possible. Transferability implies the change from one location to another. Adaptability implies the change from one operations concept to another. Upgrade-ability is the change from one technological basis to another or from one design to another. Therefore, in a nutshell, the TAMU paradigm is changeable and therefore responsive to dynamic world environments, national priorities and operations concepts.

TAMU & Autonomy

Autonomy has been suggested as a means for increasing reliability and decreasing cost for human space missions. While the concept seems straightforward its implementation for various activities such as mission planning, selective flight control operations, or vehicle health management systems require special considerations. MOD has examined this concept [14], [17], and there are currently certain human activities within the MOD that are augmented with autonomous systems. [22]. The examination of this concept has

led to the recommendation for an adaptable and evolvable autonomy architecture which is well defined from the early phases of design [14].
TAMU design is based on the development of the workflow processes associated with flight products. The implementation of these processes may have the option of being autonomous. That is one of the trades that are conducted during a design session performed by the SAT team. In order to correctly perform these trade studies, the team needs an assessment of the risks and costs associated with the autonomous performance of tasks. This is part of the infrastructure and is represented by the models and probabilistic risk analyses studies. These studies, in turn, take into consideration the data associated with human reliability and the cost of human operations as opposed to autonomous operations.

An important part of TAMU is the workflow executive. There are currently commercial off the shelf tools available for the autonomous execution of workflows. Adopting one such tool and/or building the underlying infrastructure for it is a consideration. Since the execution of the optimal workflow process is conducted after its design, the detailed requirements associated with an executive and trades associated with them are studied in detail in the later phases of the project.

TAMU & Cost Reduction

The system characteristics that lead to lower mission operations cost have been described as: multi-mission design infrastructure, use of standards, advanced technology tools, ground system automation, concurrent design, and de-coupling of instrument operations from spacecraft design [15], [16].

TAMU is a multi-mission capability. One of the key features of the reference architecture and models developed for the FPP project is that it establishes a standard ontology or language for the representation of the MOS [18], [19]. Further, the transfer of information between the tools that are part of the TAMU infrastructure is also conducted based on standard associated protocols such as XML and XPDL.

Another feature associated with low-cost MOS is a small and highly skilled staff [15]. This is represented in TAMU by the select and low number of individuals that are represented in the SAT team.

The staffing plan for the SAT team has been developed based on the lessons learned at various NASA centers, including JPL [29] and GSFC [21] and the best practices in the space industry.

TAMU Implementation

TAMU builds on the FPP project, which is explained in [18]. The key elements of the current architecture associated with this project include the apparatus and process for the development of Discrete Event Simulation Models, an activity orchestrator, a re-planner, and a data repository associated with the architecture.

The TAMU concept generalizes each of these key elements to be applicable to a broad range of missions.

The TAMU concept is based on defining a broad set of “abstract” or class-level functions that are performed for the development of flight products. The specification of these functions permeates an abstract “architecture” for the FPP development process. A multitude of concrete scenarios can then be developed for this architecture by specifying the details associated with each of the abstract architectures. Each scenario is a complete operational design. This design specifies the processes for the development of the flight products, their associated activities, process and data flows, and associated tools, repositories, and the operational nodes that perform each activity. Each of the abstract functions are a “module” of the design. Modules are not inherently independent. They require inputs from other modules and provide outputs to other modules. Nonetheless, the modular approach that FPP uses contains and structures the complexity of the problem by decomposing the system appropriately and formally defining these dependencies.

TAMU & Uncertainty Management

There is much uncertainty associated with space mission operations and some of this uncertainty ripples through to the FPP. For one thing, many of the atomic level activities involved in an FPP are performed by humans; as such there is variance in the amount of time required for performing them and there are inevitably human errors that can result in faulty products On the other hand, there may be changes in the products required based on last minute changes to the space mission profile and these changes need to be taken into consideration in a dynamic and efficient manner. The TAMU approach for managing uncertainty is two-fold. On one hand, the uncertainty associated with the time to perform each task and the resources required for it are taken into consideration within the context of the models using probability distribution functions. On the other hand, the error rates and failure paths associated with various human tasks are considered in a systems level probabilistic risk assessment model which aids in trade studies for choosing better designs. Moreover, the simulation analysis element allows for the sensitivity analysis of various modeling options in the context of different resources being allocated to each of the tasks.

Conclusions and Future Directions

This paper presents a new paradigm for space mission operations which is based on using state of the art modeling, simulation, and analysis technologies as well as Industry best practices for the rapid design and development of the flight products associated with space missions. This paradigm leverages the 50 year wealth of knowledge and experience of the NASA’s Mission Operations Directorate which pioneered human space flight operations. Furthermore, the approach proposed in this paper is already being used for re-designing the FPP at the MOD and has yielded significant benefits, in terms of identifying redundant processes and products and providing structure and solidity for re-designing the facilities and mission control center. Based on our experience, we forsee extending this approach to other NASA centers which also contribute to the NASA-wide FPP process.

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