Evolving Space Architecture – Opening the Door for the Space Industry

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It is an understatement to say that the evolution of the space industry has been rapid and almost unconstrained in the past decade, characterized by growing complexity of systems,

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enterprises, organizations, and engineering tools and methods. New approaches to fielding space-based capabilities and new entrants in the space community are reported on almost a daily basis, from countries across the globe. New starts are often not constrained by convention. Simultaneously, conventional space organizations are challenged by new technologies and new capabilities such as faster, cheaper, and more flexible access to space. These are true for robotic landed and on-orbit systems as well as space transportation systems, human spaceflight missions, and their support. They are true for all space infrastructure, including space traffic coordination, launch, and, ultimately, the deployment and management of distributed, networked, interoperable systems from multiple organizations. The thesis underlying this paper is that a common conceptual foundation, including appropriate ontologies and shared architectural frameworks, is essential to success in this era of "new space." This includes a rigorous and appropriately standardized strategy for evolving architectures at multiple levels, from large scale space enterprises to individual systems and their components. Our specific focus is on three independent but complementary efforts that build on the common meta-framework of ISO/IEC/IEEE 42010:2011, which "addresses the creation, analysis and sustainment of architectures of systems through the use of architecture descriptions". These are (1) the CCSDS/ISO 311.0-M-1, *Reference Architecture for Space Data Systems (RASDS)*; (2) the newly published NASA Handbook 1005, *Space Mission Architecture Framework (SMAF) Handbook for Uncrewed Space Missions*, and (3) ANSI/AIAA S-153-2021, *Human Spaceflight: Spacecraft Architecture and Systems Engineering Ontology*.

I. Nomenclature

AF = Architecture Framework, a common practice for creating, interpreting, analyzing, and using architecture descriptions within a particular domain of application or stakeholder community {ISO 42010]

ANSI = American National Standardization Institute

CCSDS = Consultative Committee for Space Data Systems

HDBK = Handbook

IEC = International Electrotechnical Commission

IEEE =Institute of Electrical and Electronics Engineers

ISO = International Organization for Standardization

MBSE = Model Based Systems Engineering

Ontology =A set of concepts and categories with definition of their properties and the relations among them to establish a knowledge base in a subject area or domain

PPP = Public/Private Partnership

RA = Reference Architecture, a set of models or documents that abstract characteristics of physical systems to provide a common vocabulary, reusable design, best practices, and other content appropriate to the domain for which it is created

RASDS = Reference Architecture for Space Data Systems

ROI = Return on Investment

R&D = Research and Development

SACoS = Space Architecture Committee on Standards

SE = Systems Engineering

SMAF = Space Mission Architecture Framework

Space Architecture = An informal term describing astronautical architectures

Spacecraft = A technological system designed to operate in the outer space environment which may be a device, vessel, vehicle, or habitat, including, but not limited to, orbiters, capsules, modules, landers, transfer vehicles, rovers, EVA suits, and habitats [Adapted from ANSI/AIAA S-153-2021]

Space Infrastructure = The (un)crewed/manned/occupied space systems, or multi-mission elements and processes supporting one or more space operations or space missions [ANSI/AIAA S-153-2021]

Taxonomy = A system of classification according to presumed natural relationships among types and their subtypes [Adapted from ISO/IEC International Standard 11179, Part 1]

Terminology = Definitions of the meaning of language elements used in a selected area of concern

II. New Space

At latest count, almost one third of the countries in the world have some type of space agency [1]. New space companies are rejecting many conventional space business and development tried-and-true practices to achieve mission performance faster and at lower cost. Over time, these thrusts will continuously challenge our understanding of mission success, technical success and interoperability, and flexibility in achieving and evolving system and enterprise capabilities. Generally, many aspects of Systems Engineering (SE) are evolving to enable success and long-term growth. These include, among many others, interoperable standards for data exchange and communication, Model-Based Engineering (MBE) in general and Model-Based SE (MBSE) in particular; artificial intelligence (AI) and machine learning (ML), and large-scale data engineering [6].

The establishment of accepted, shared ontologies (careful definitions of terms along with their relationships and common attributes) is an essential foundation for systems and infrastructure. Ontologies provide formal models that capture the knowledge foundation of a given domain and establish a consensus-based and precise meaning for the information communicated among different sources and consumers [7]. One challenge is accommodating the stylistic and organizational differences among sources while preserving content. Others are translating from expressive to restrictive languages (as required for SE approaches) and structuring system-independent approaches while preserving the necessary dependent computational efficiencies for the implemented systems [8]. In the space economy, the ontological challenges may not be fully resolved for some time due to the inherent complexities within and across disciplines. Nevertheless, the effort to achieve shared understanding is extremely important in the near term.

This paper addresses these challenges in terms of several independent but complementary advances in Space Architecture that build upon concepts and structures from existing open standards, notably **ISO/IEEE 42010:** *Systems and Software Engineering – Architecture Descriptions*. We explore three independent efforts: **CCSDS 311.0-M-1:** *Reference Architecture for Space Data Systems* [3]**; NASA HDBK 1005:** *NASA Space Mission Architecture Framework (SMAF) Handbook for Uncrewed Space Missions* [4]; and **ANSI/AIAA S-153-2021:** *Human Spaceflight: Spacecraft Architecture and Systems Engineering Ontology* [5]. We refer to these as reference architectures (RA) because they serve as templates for system-specific architectural descriptions.

III. The Architectural Foundation

A. Enterprise and Systems Architectures

We start this discussion with architecture fundamentals, following Maier and Rechtin's view [9], that "The architecture process begins with an understanding of the enterprise and the data that constitute its information infrastructure. To be most useful, information systems must be derived from this base of knowledge about the enterprise." Enterprise and information infrastructure are fundamental architecture elements. Acquisition of complex systems and collaborative vs non-collaborative architecture are further supported by Systems Architecture in spiral developments[10]. Maier and Rechtin also describe modeling, integrated modeling and architecture frameworks. The fundamental concepts of enterprise architecting and systems architecting are made more useable by standardization of core structure and language.

B. An Overarching Architecture Standard – ISO-42010

ISO 42010 defines foundational systems architecture terminology and abstract relationships among terms; it defines and establishes concepts like perspectives (viewpoints, in ISO 42010 language) and creates a generalized baseline architectural description framework that the industry at large can use to create and evolve specific RAs for specific domains, including space. The use of ISO 42010 as a common reference point enables some degree of harmonization going forward among the listed RAs, each of which addresses different concerns and are focused on a different set of topics and viewpoints, as well as other elements of a complete Space Architecture framework. ISO 42010 and its direct predecessors define a set of terms for describing complex architectures from one or more viewpoints, each of which guides creation of a related set of specific views or models. The viewpoints are to be selected to meet stakeholder concerns and they also define means to represent aspects of a systems architecture from each viewpoint. These concepts are, in and of themselves, straightforward, but they leave open the question of what constitutes a useful set of viewpoints. With the exception of some hints provided in examples at the end, ISO 42010 is silent on this topic. The RAs described in this paper seek to bridge this gap. They deal with architecture at a conceptual level, which is appropriate for RAs as the foundation for system realization, and they define essential structure and content of complete architectures that enable the realization of systems.

It is useful to understand the evolution of MBE over the past forty years or so. In the mid-to-late-1980s, efforts to deal with software and software models by the International Organization for Standardization (ISO) and International Telecommunications Union Standardization Sector (ITU-T) produced **ISO 10746**, *Reference Model – Open Distributed Process* (RM-ODP) [11]. Some of the examples in ISO 42010 were drawn from RM-ODP. **ANSI/IEEE 1471-2000**, *Recommended Practice for Architecture Description of Software-Intensive Systems* [12] was first published in 2000. Application to non-software systems resulted in **ISO/IEC/IEEE 42010:2011**, which subsequently replaced IEEE 1471. There is a clear evolution in modeling and a desire to apply total system modeling to SE. RASDS directly grew out of RM-ODP, with viewpoints aligned to the needs of space data systems, as opposed to systems in general. In parallel with these efforts to improve the description and analysis of space systems architectures, effort continues to be directed at improving the development processes for the software on which these systems increasingly depend. In 1995, the IEEE, in collaboration with ISO, produced **IEEE Std 12207**: *Systems and Software Engineering – Software Life-Cycle Processes* [13]. In short, architecture concepts that originated in Software Engineering are now generalized to the definition, optimization, and development of entire systems.

Models come in a variety of forms, including visual (e.g., diagrams and other graphics), logical (e.g., functional description of structures and behaviors), physical (e.g., mockups, computer-aided design (CAD) files, and early prototypes), and computational (e.g., numerical solutions of fluid dynamics and electromagnetics problems). It has become apparent as total system modeling has evolved that a variety of techniques is essential for effective SE. These include modern MBSE tools, mathematical/ computational models, CAD and physical representations, performance models, and reliability and risk models. A well-structured and properly supported modeling environment supports every aspect of space system definition, design, development, optimization, and operations, including current space situational awareness analytics. Most recently, a practical implementation of the holistic modeling approach called Digital Twin [14, 15] enables an enhancement of modeling efficacy through unification of the modeling framework and harmonization of interdisciplinary language and environments. Well-crafted frameworks for describing the complexities inherent in these space systems, and systems-of-systems, makes the integration of these modeling and analysis tasks more tractable.

C. The Utility of Correspondences

One of the valuable contributions of RM-ODP and ISO 42010 is to define the concept of Correspondence. A correspondence defines the relationship between architecture elements that may appear in different views. Correspondences and correspondence rules are used to express and enforce architecture relations of interest within an architecture description or between architecture descriptions. They express and enforce architecture relations such as composition, refinement, consistency, traceability, dependency, constraint, and obligation. In the Systems Modeling Language (SysML), much the same modeling content is defined using Dependencies. As an example of correspondence, it is common for Functional views to name data objects that get exchanged between functions. The format of those data objects, their syntax and semantics, will usually be carefully formulated in an Information view. Similarly, there is usually a correspondence relationship between abstract functions in an early design and the fully realized implementations of those functions, either in hardware or software, described in a Connectivity view or equivalent.

These correspondences are the "glue" that allows independent views to be considered together to form a holistic representation of a complex architecture and its evolution from initial abstract design to completed operational system. Hierarchies of requirements are a well understood approach to describing *what* a system must do. Use of this sort of RA methodology provides the means to describe *how* it must be designed and operated and promote rigorous traceability between a requirements baseline, a design baseline, and an implementation baseline. Such traceability is well supported by modern system architecture tools using SysML.

IV. Emerging Open Architecture Standards for Space

A. The Need for Open and Interoperable Standards

We now turn to application of general system architecture concepts and standards to the space domain. Space organizations have done little in the past to establish technical metrics for a space system architecture as a holistic entity. Instead, agency, national, and regional bodies have used requirements hierarchies and identified internal technical metrics for generally known mission-level parameters. Enterprise architecture for the space domain requires collaboration on space information views, but this has not historically been addressed by conventional space silos (non-collaborative architectures). One reason for this is the need for significant effort and funding to develop a framework before it can be used in developing a product. Since commercial space organizations develop products they can sell, interoperable standards need to be defined and specified through collaboration with independent parties to mitigate risks and assure a holistic approach, without the biases introduced by proprietary information, specific mission context, product marketability, and other influences. In that sense, a total-system (e.g., collaborative) approach provides universal guidance for the benefit of all with explicit foresight to not stifle needed innovation.

Adoption of interoperable standards, unless mandated by a customer, is a form of voluntary governance, but it is motivated by knowledge of the challenges involved in a complex environment and relevant phenomena. Architectural standards are different from product, component, or certification process standards in the sense that they are cross-disciplinary, and their creation has an implied fundamental collaborative clause of: "progressive evolution and applicability to all." As a result, agencies, regional bodies, and voluntary organizations are essential in creating universal solutions rather than leaving the task solely to an industry driven by economic considerations.

An example is the definition and validation of Mission Assurance (MA). To date, there has been a struggle in the space community in creating and applying universal standards for terminology, metrics, processes, organizational responsibilities, and other essential MA aspects. NASA-HDBK 1005 identifies an Enterprise Viewpoint, broadly capturing the agency, center, or mission level, as responsible for determining what is acceptable in MA. Also included in the RASDS++ Enterprise viewpoint, MA is one of many shared metrics. In the past this definition has been allowed to differ from program to program, but future collaborations in public/private partnerships (PPPs) demand definition and evaluation above any single program or even group of programs, as well as among international partners, in order to maximize shared understanding and ensure consistent practices across programs and among stakeholders.

As another example, international stakeholders have proposed a new work product for space traffic coordination (STC) using a systems approach as the fundamental basis for an informal PPP between the government and commercial space sectors to promote safe, efficient, and responsible behavior in space. This proposed new standard aims to provide requirements related to the subsystems of an STC framework, including STC servers and a network for an STC enterprise that has required orbit determination and prediction accuracy, space data interfaces, data aggregation and curation capabilities, operations, quality control, space situational awareness systems, and common algorithms and metrics. These are designed to ensure that STC analyses and services are interoperable, standards-based, timely, accurate, comprehensive, transparent, and highly available to support the operators' risk mitigation decision-making processes and among stakeholders. These new approaches to STC will support coordinated PPP space traffic management and space situational awareness needs and address operational risks. The creation of modern data architectures with global ontologies, supported on a modern data infrastructure equipped with proper cybersecurity attributes, will be essential.

Taken together, the standards described in the following sections build on RASDS, which itself extends ISO 42010 and other prior standards, to provide important elements of a framework for describing the architectures of complex systems, and systems-of-systems (enterprises) for space. They specifically describe the use of viewpoints and views to capture different stakeholder concerns, and their use to create models of complex systems. They are related by their heritage in ISO 42010, and complementary in their support for an evolving global space architecture.

B. A Reference Architecture Framework for Space – ISO/CCSDS RASDS++

Within the international standards community, space standards development organizations (SDOs) such as the Consultative Committee for Space Data Systems (CCSDS) and ISO have been working to address a common set of concerns and perspectives so future standards work can leverage a suitable RA to meet global industry needs. Originally based on RM-ODP and IEEE 1471, and now on ISO 42010, the CCSDS Reference Architecture for Space Data Systems (RASDS) defines a set of viewpoints that may be used to describe complex space systems architectures, from the abstract early phases of a mission, through development, deployment, and operations. It provides both a methodology for describing space systems architectures and a straightforward representation in “document” form. That said, the methodology can be, and has been, used with formalized MBSE tools to build SysML models by creating suitable profiles to define the different model elements. The scope at which it may be applied ranges from systems-level concepts to more granular subsystems, assemblies, and components. This RA is being evolved to also cover operations, process, and physical/structural concerns, and this is identified as RASDS++.

Intended for use in describing space data systems architectures, the original RASDS specification, published in 2008, included five viewpoints, each with a set of architecture objects:

1. Enterprise Viewpoint: objects are organizational elements, requirements, and use cases.
2. Functional Viewpoint: objects are abstract functions and data, and logical data exchanges.
3. Connectivity Viewpoint: objects are physical components and links and realized deployments of implemented functions.
4. Protocol Viewpoint: objects are protocols and protocol stacks, interface binding signatures, and end-to-end communications mechanisms.
5. Information Viewpoint: objects are information, data structures, syntax, and semantics.

Other viewpoints that adopted and extended these five have been introduced over time. The RASDS++ effort is now extending the Enterprise Viewpoint to include a more thorough treatment of requirements. It is also adding three new viewpoints to cover additional topics from **ISO TC20/SC14:** Space Systems and Operations and to extend the RASDS++ technical framework to cover viewpoints addressed in the abstract within other mainstream architecture modeling methodologies:

1. Services Viewpoint: objects are services (exposed via service interfaces) and the modeling of interface binding signatures.
2. Operational Viewpoint: objects are processes, procedures, activities, and tasks, plus modes and states.
3. Physical Viewpoint(s): objects are physical components and connectors, as in the Connectivity Viewpoint, but the described aspects include physical ones such as power, propulsion, thermal, structural, and orbital.

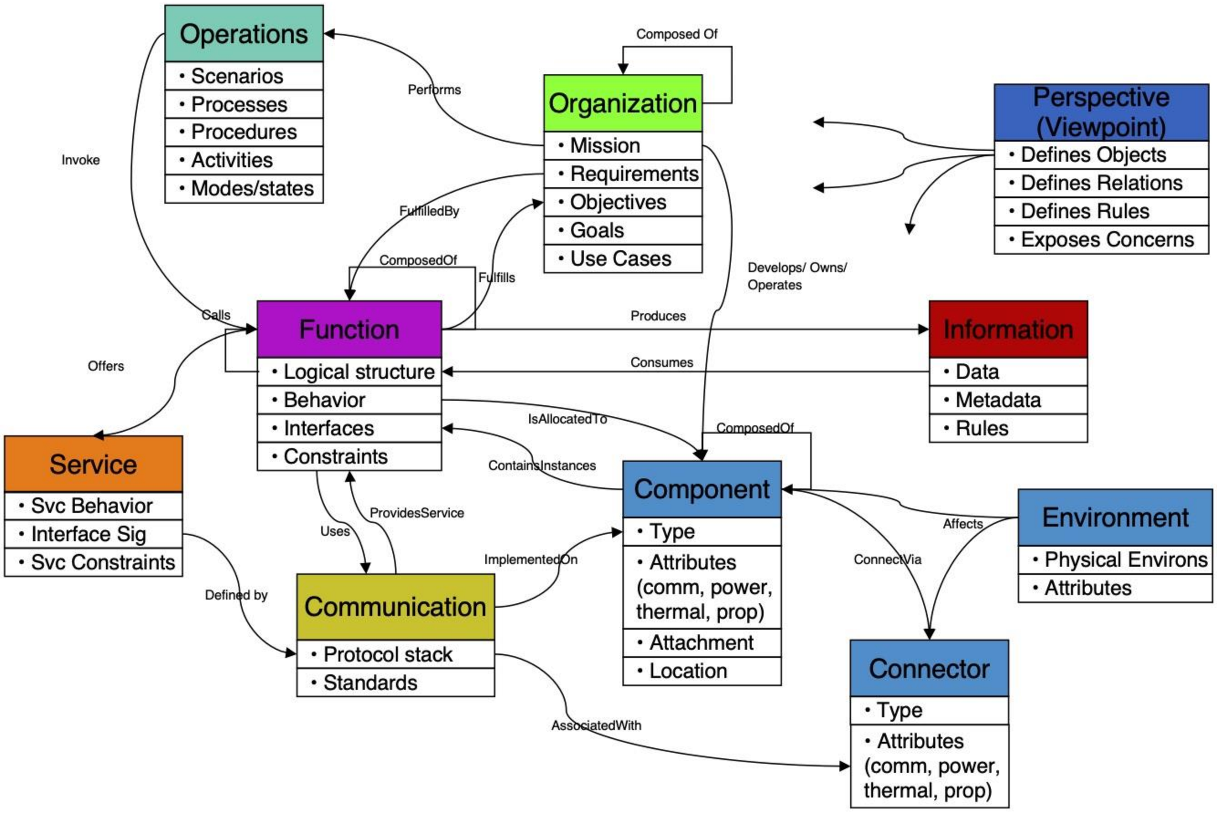

Fig 1 RASDS++ optional and standard top-level objects and relationships.

Figure 1 shows the top-level (or core) objects and attributes in RASDS++, illustrating how core objects from different Viewpoints are related. The Organization box captures the Enterprise Viewpoint in this representation. Details are in the RASDS++ documentation now in development.

C. An Acquisition Architecture Framework for Space – NASA HDBK 1005

Needs, Goals, and Objectives. While RASDS++ primarily provides the means to describe space system architectures and their technical and operational infrastructures, NASA HDBK 1005 provides guidance in application of MBE principles, and especially architecture, to the acquisition of a space system[9]. The handbook places specific emphasis on alignment with NASA policies, such as those expressed in NASA Process Requirements (NPRs) 7120.5, and 7123.1B, dealing with project management and SE, respectively. This alignment is a key element in promoting adoption of SMAF within NASA, but it also may show consistency with other approaches to system architecture, including those described in this paper.

Architecture is an essential element of managing complexity and achieving operationally effective solutions for the needs of system stakeholders. An architecture framework (AF) seeks to normalize the documents and models that describe and communicate a complex entity such as a system and thereby to maximize both their quality and the productivity of the architecture process. Widely used enterprise AFs include the Unified Architecture Framework (UAF) [16], The Open Group Architecture Framework (TOGAF) [17], and the Zachman Framework [18]. An effective AF addresses the often diverse and sometimes competing needs and concerns of system stakeholders, especially by facilitating exchange of information. While each of these existing frameworks has elements relevant to the NASA environment (domain), they do not align with the NASA acquisition process sufficiently well to readily support adoption. Thus, as a preliminary exercise in determining an effective AF for NASA, the SMAF was created. The specific objectives of the SMAF include:

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[9] A more general description of is available on [4] p 20-25

- Increasing the value of scientific investigations through tighter coupling of science objectives and mission architectures, as well as better integration of project teams,
- Improved effectiveness of end-to-end mission developments, including leveraging model-based engineering techniques for more efficient utilization of engineering resources and better,
- Enhanced management of institutional capabilities, facilities, and staff, and
- Improved collaborative application of digital models and products across a portfolio of missions to enhance sharing and reuse of products and designs.

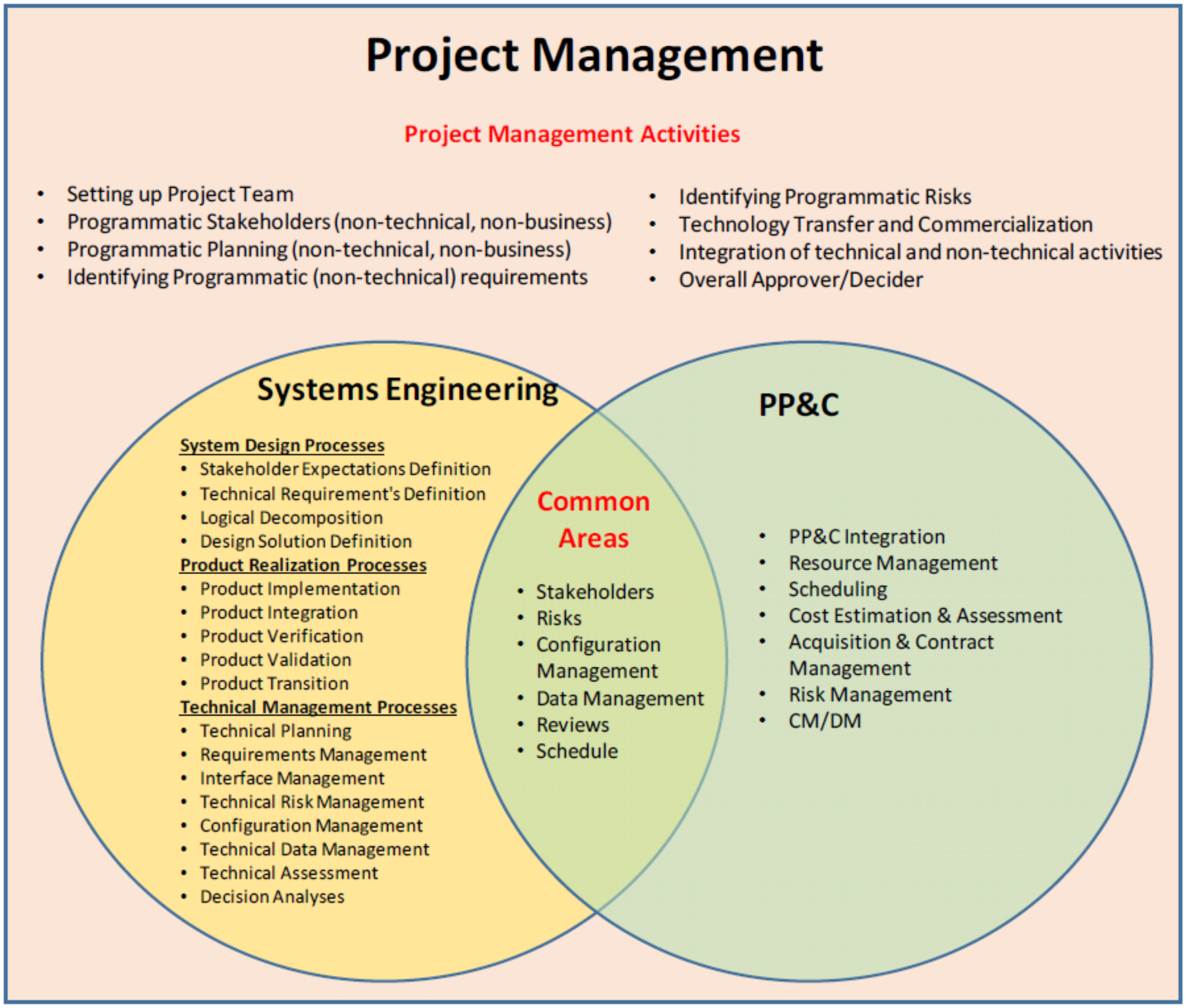


Fig 2 Relationship between Systems Engineering and Project Planning and Control (PP&C).

General Principles. The SMAF is intended to be realized in a specific project architecture in accordance with the following general principles:

- The project's foundation should be a high-quality Mission Architecture following the structure and methods of the SMAF;
- Both program management and SE should be model-based, using a suite of models appropriate to the specific project needs in the areas shown in Figure 2;
- Models and model-produced artifacts should be used to create Mission Architecture content, and where feasible should replace document-centric products and materials that require time-consuming manual processing;

- A modelling environment should be established with all required tools and methods and with the flexibility to tailor a modelling strategy to the project; and
- SMAF viewpoints and work products should be used to improve program reviews across the project life cycle to reduce the time and effort required, to establish common expectations across project and review teams, and to enhance communication in preparation for, participation in, and closeout of reviews. A SMAF work product is equivalent to a model of some sort and typically represents a very specific View in 42010 terminology.

Viewpoints and Work Products. Following the common practice established by ISO 42010 and other previous AFs, the SMAF is structured in terms of a set of viewpoints that capture diverse stakeholder perspectives, needs, and concerns. Figure 3 shows the overall organization of architecture content, and Figures 4, 5, and 6 show SMAF viewpoints and the names of the various work products, grouped by the major categories in Figure 3, that are used to satisfy a given viewpoint. In some cases, the SMAF offers a viewpoint that captures a category from Figure 3 and in other cases, it refines the category into more tightly focused viewpoints.

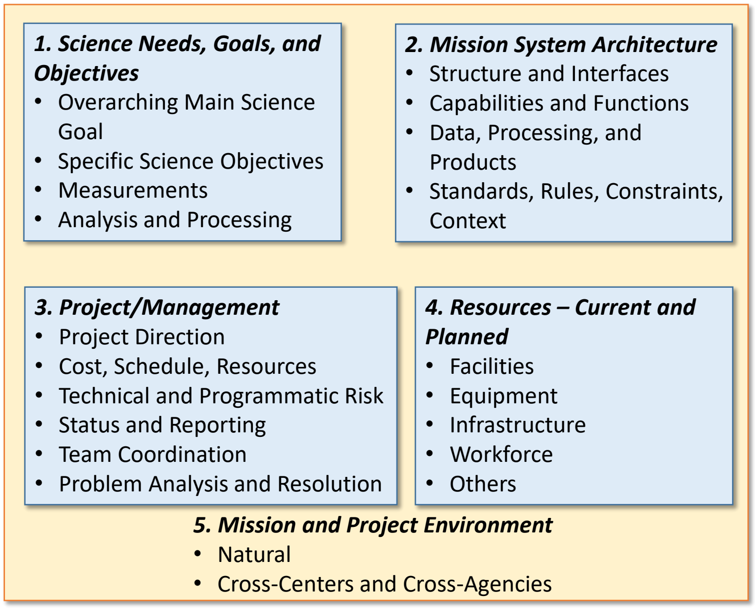


Fig 3 Organization of SMAF content.

The Science Viewpoint addresses mission architecture from the perspective of the mission science being conducted, starting with high-level goals and objectives and proceeding to define phenomena to be investigated, measurements and analysis steps, and science data work products at multiple levels.

The Engineering Viewpoint consists of three more specific viewpoints, which focus primarily on the definition and realization of the system, namely the Requirements Viewpoint, the Technical Solution Viewpoint, and the Product Realization Viewpoint.

The Requirements Viewpoint documents the project requirements, including both functional and non-functional requirements. The Solution Definition viewpoint addresses mission architecture from the perspective of the processes for documenting the functional and physical system architecture. The Product Realization viewpoint addresses mission architecture from the perspective of managing the implementation of the functional architecture in a physical system.

The Project Management Viewpoint consists of two more specific viewpoints, which focus on the implementation of the project that defines and delivers the system, as well as operation of the system. Many of the work products associated with the Mission Operations Viewpoint might not necessarily be associated with Project Management, however, at the Goddard Space Flight Center, mission operations lives within the Flight

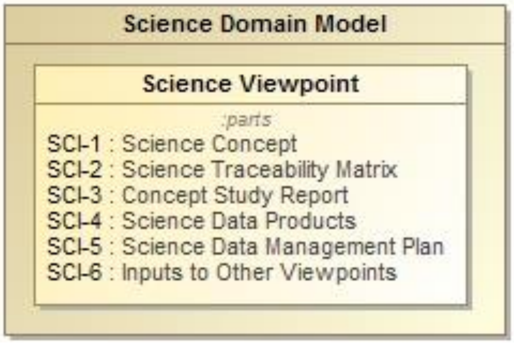


Fig 4 The Science Viewpoint and associated work products.

Projects Directorate, and thus it was determined that the AF viewpoint associated with this role would be put into the Project Management Viewpoint.

The Project Implementation Viewpoint addresses mission architecture from the perspective of overall project planning, management, and control. The mission operations viewpoint addresses the operations of the flight, ground, and launch segments in performing a mission.

In an understated manner, the final viewpoint in the SMAF is the Enterprise Viewpoint, representing an Enterprise role, which provides resources to a system development and operation activity, and performs monitoring and control of the endeavor. The enterprise viewpoint addresses mission architecture from the perspective of the Center and Agency stakeholders. The included work products link the project to higher level goals and objectives of strategic and program plans, as well as to overarching drivers of NASA science efforts such as decadal surveys. They also supply guidance and direction that applies across the Center portfolio and provide linkage between project concerns in areas such as safety and mission assurance (S&MA), resources, and higher-level plans and priorities for facilities, equipment, workforce development, and other Center and Agency responsibilities. This viewpoint reflects concerns of NASA Headquarters, the Science Mission Directorate (SMD), the division and sponsoring program, and the Center Director and staff.

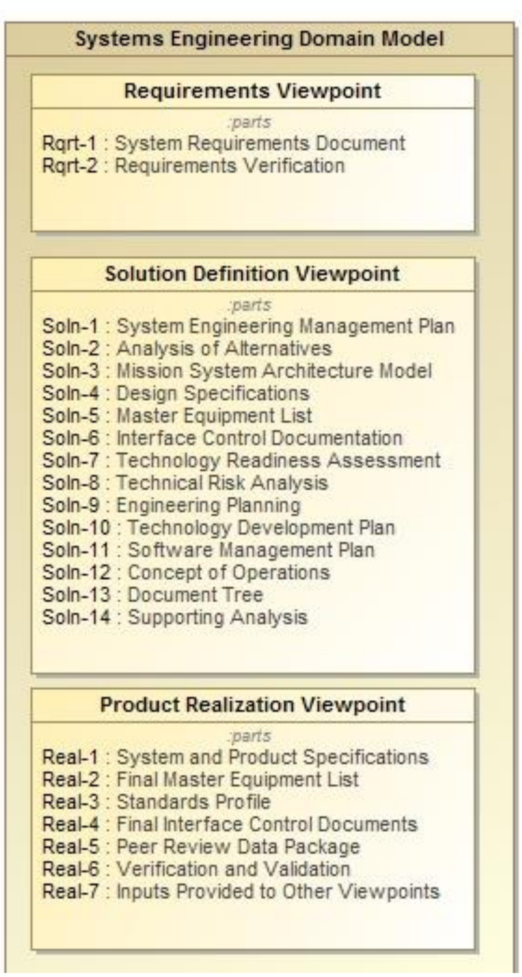
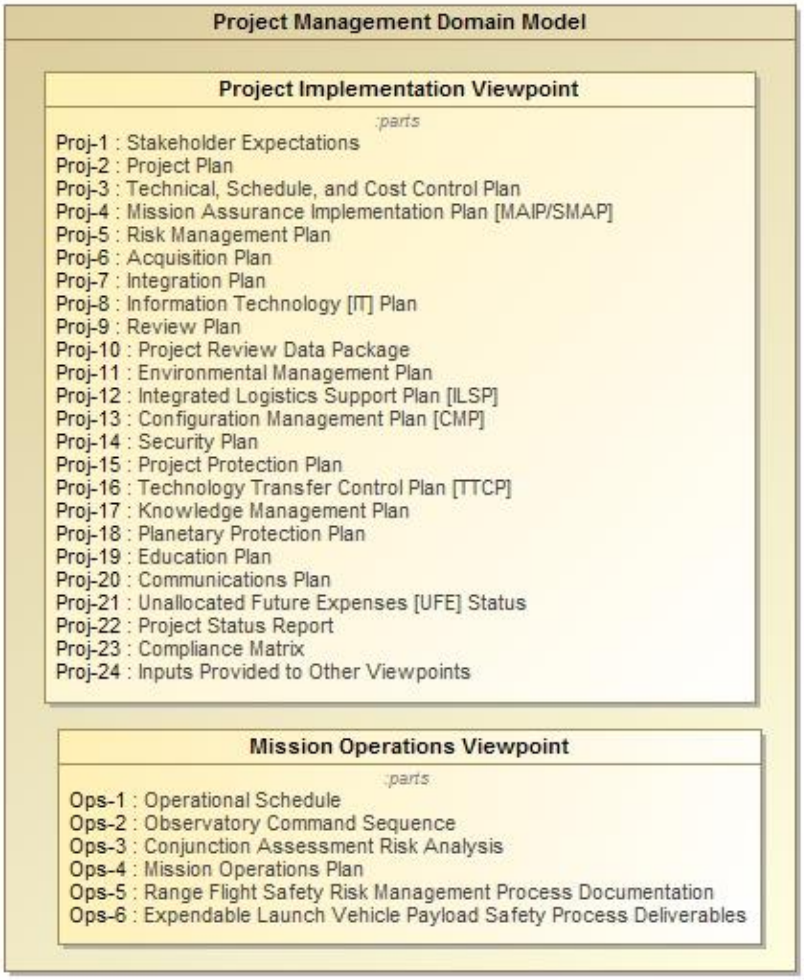


Fig 5 The Engineering Viewpoint and associated work products.

The SMAF is primarily focused on the Science, Engineering, and Project Management, processes, and gate products that are produced in the course of a development project. In RASDS++ terms this can be thought of as an elaboration of the Enterprise Viewpoint, and to an Engineering / Process Viewpoint that RASDS++ explicitly does not address since there are already many agency and international process standards, like SMAF. What RASDS++ does offer, in this context, is the technical architecture description framework that may be applied in the Solution Definition Viewpoint (Soln-2, Soln-3, Soln-4, Soln-6, and Soln-10). It also offers tools that may be applied to the Product Realization Viewpoint (Real-1, Real-3, and Real-4).

D. An Ontology for Human Spaceflight - ANSI / AIAA S-153-2021

S-153 Overview. In parallel with the CCSDS and NASA efforts just described, the AIAA Space Architecture Committee on Standards (SACoS) identified the need to clarify the nature of different types of human spaceflight spacecraft. While the space domain includes three core elements of spaceflight elements, launch elements and control elements, SACoS was focused on the language and structure of different human spaceflight systems. The first step therefore was to develop a hierarchy of terms (see Figure 7) and their definitions. Figure 7 leaves structure and definitions of unmanned spaceflight systems open for future collaboration. “Spacecraft” has been identified as the overarching term for technological systems designated to operate in the outer space environment with or without functions to support human activities on board. However, various organizations and disciplines use the term exclusively for either manned or unmanned vehicles; as a result, a detailed, hierarchical and topological description was developed in addition to ontological classification to guide the design teams to more effective interdisciplinary collaboration. In the RASDS++ context this can be thought of as an effort to define specific sets of objects types that might appear within the Connectivity or Physical viewpoint. Additionally, S-153 identified the need to unify architecture terminology, most importantly the Architecture Framework Classification that determines the scope, breadth and depth of areas of concern or project focus in five types:



Project Management Domain Model

Project Implementation Viewpoint

:parts

Proj-1 : Stakeholder Expectations
Proj-2 : Project Plan
Proj-3 : Technical, Schedule, and Cost Control Plan
Proj-4 : Mission Assurance Implementation Plan [MAIP/SMAP]
Proj-5 : Risk Management Plan
Proj-6 : Acquisition Plan
Proj-7 : Integration Plan
Proj-8 : Information Technology [IT] Plan
Proj-9 : Review Plan
Proj-10 : Project Review Data Package
Proj-11 : Environmental Management Plan
Proj-12 : Integrated Logistics Support Plan [ILSP]
Proj-13 : Configuration Management Plan [CMP]
Proj-14 : Security Plan
Proj-15 : Project Protection Plan
Proj-16 : Technology Transfer Control Plan [TTCP]
Proj-17 : Knowledge Management Plan
Proj-18 : Planetary Protection Plan
Proj-19 : Education Plan
Proj-20 : Communications Plan
Proj-21 : Unallocated Future Expenses [UFE] Status
Proj-22 : Project Status Report
Proj-23 : Compliance Matrix
Proj-24 : Inputs Provided to Other Viewpoints

Mission Operations Viewpoint

:parts

Ops-1 : Operational Schedule
Ops-2 : Observatory Command Sequence
Ops-3 : Conjunction Assessment Risk Analysis
Ops-4 : Mission Operations Plan
Ops-5 : Range Flight Safety Risk Management Process Documentation
Ops-6 : Expendable Launch Vehicle Payload Safety Process Deliverables

Fig 6 The Project Management Viewpoint and associated work products.

1. Fundamental Architecture – A description of the natural or artificial system purpose and relationships including ideological values, rules and principles regarding its environments (natural, artificial, physical, mental, social) to enable formation of the Enterprise Architecture
2. Enterprise Architecture – A description of all components (human, hardware, software) of an economically productive human-organizational environment designated to definition of goals, strategy, products, services and required infrastructure in current and future states based on the input from the Fundamental Architecture to enable Operational, System and Technical Architectures.
3. Operational Architecture – Description of the operational elements, assigned tasks and information flows required to accomplish or support the Enterprise function. It defines the type of information, the frequency of exchange and what tasks are supported by these information exchanges.
4. System Architecture – A description of the system and interconnections providing for or supporting functions. This architecture defines the hardware (physical) and/or software (virtual) connections, location and identification of the key nodes, circuits, siteworks, platforms, etc., and specifies its performance parameters. It is constructed to satisfy the Operational architecture requirements per standards defined in the technical architecture. It shows how multiple systems within a subject are linked and interoperate.
5. Technical Architecture – "Set of rules and relations governing the arrangement, interaction, and interdependence of the parts or elements whose purpose is to ensure that a conformant system satisfies a specified set of requirements. The technical architecture identifies the services, interfaces, standards, and their relationships."

The intent of the AIAA SACoS is to be clear on the types and terminology that may be used to describe the physical architecture of space facilities and processes, be they on-orbit (such as the International Space Station), planetary habitats, related operations, or subsystems. The SACoS, in the ANSI/AIAA S-153-2021 standard (referred to as S-153), establishes an ontological structure for manufactured space objects (commonly called "spacecraft") and provides structured distinctions between such items as a "Space Station" and a "CubeSat". In this section, we address actions needed to derive maximum payoff from S-153 and related standardization initiatives.

Many of the ontological definitions in S-153 can apply to NASA HDBK 1005 for uncrewed spacecraft or to spacecraft types identified in RASDS++ Physical Viewpoints and views. It is also helpful in developing space

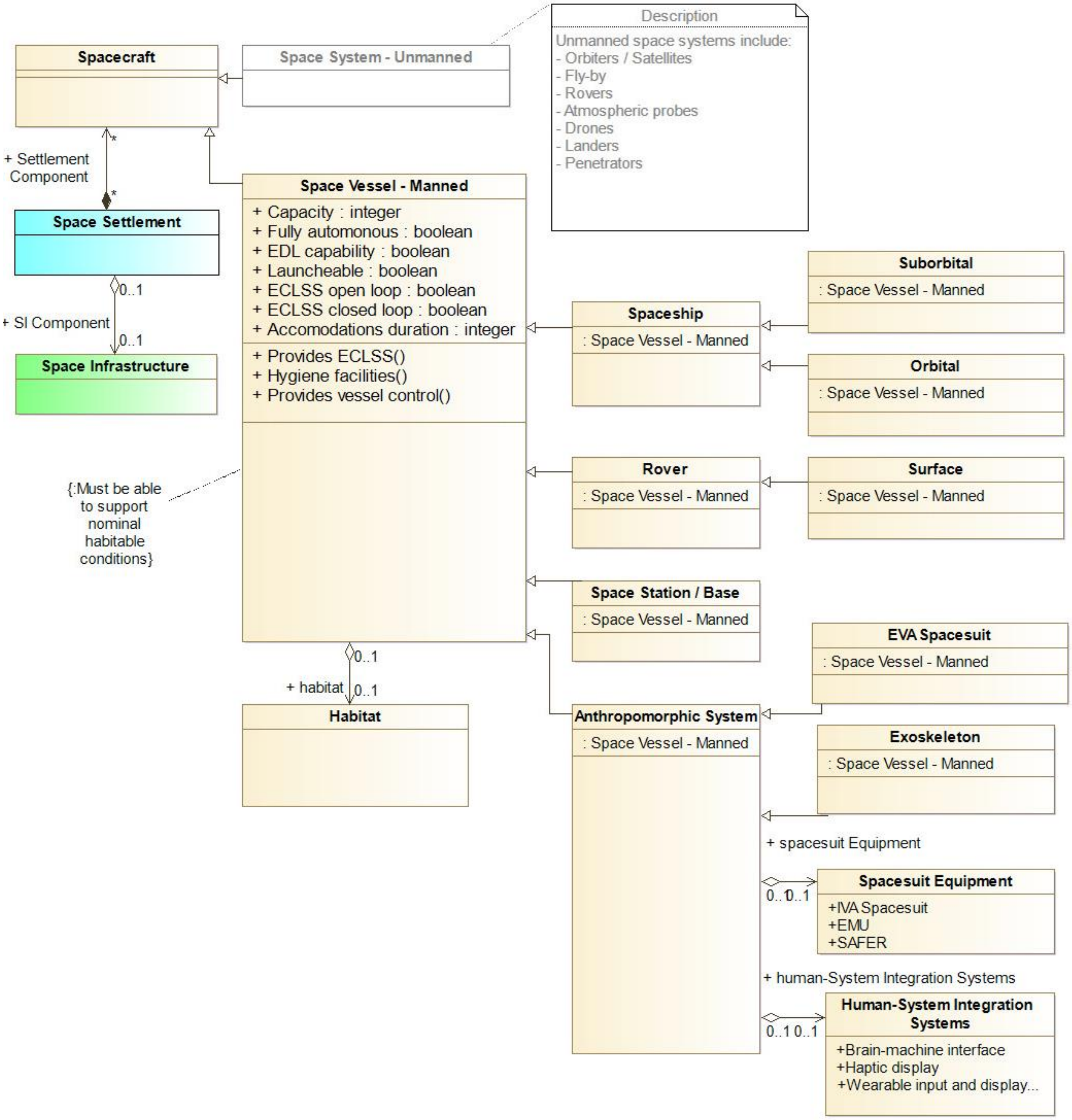


Fig 7 Spacecraft classification diagram using the Unified Modeling Language (UML).

standards in the ISO community, by adopting existing terms, their attributes, and their relationships, and explaining, unifying, and simplifying them for application in interdisciplinary industry environments.

The true marriage of MBSE and Standardization will not be complete until SDOs develop their standards with MBSE techniques and tools, just like their customers in space programs and projects, because only this approach can ensure the compatibility of standards with MBSE practices, as well as fostering rapid incorporation of the standards into the projects. Currently, usage of MBSE tools in standards working groups is sporadic, and not a coordinated methodology across any given SDO to be applied to all of that SDO's standards. Just as RASDS++ provides a technical systems architecture description framework and methodology, and NASA HDBK 1005 seeks to encourage unity of practice of MBE and MBSE across NASA programs and projects, each SDO should likewise flow systems architecture and MBSE practices down from their enterprise-level management to individual working groups' standardization projects. Even better would be a consortium of SDOs aligning MBSE practices across the space standardization community. The seed of this cooperation has been started by ISO TC20/SC14 coordinating with CCSDS (a.k.a. ISO TC20/SC13) on a harmonized RA framework and a harmonized set of terms and definitions across the two organizations, potentially the beginning of a cross-SDO ontology. The ultimate benefit will be realized when that collaboration expands to an industry-wide practice where (when applicable) standards are developed with MBSE terms and tools, and the SDO's resulting MBSE models are accessible to programs and projects for download from the SDO websites. The mission programs and projects can then rapidly and seamlessly incorporate the standards (for interfaces, architecture, etc.) into the program, spacecraft or system model.

The authors hope that this perspective can start a dialog which, at a minimum, will encourage individual SDOs to begin integrating technical systems architecture and MBSE techniques and tools into their standards, and at a maximum, may foster a consortium of SDOs (ISO, CCSDS, AIAA, OMG, etc?) to harmonize the incorporation of MBSE into standards development, leading to broad benefits for the SDO customer base, the industry's space programs and projects.

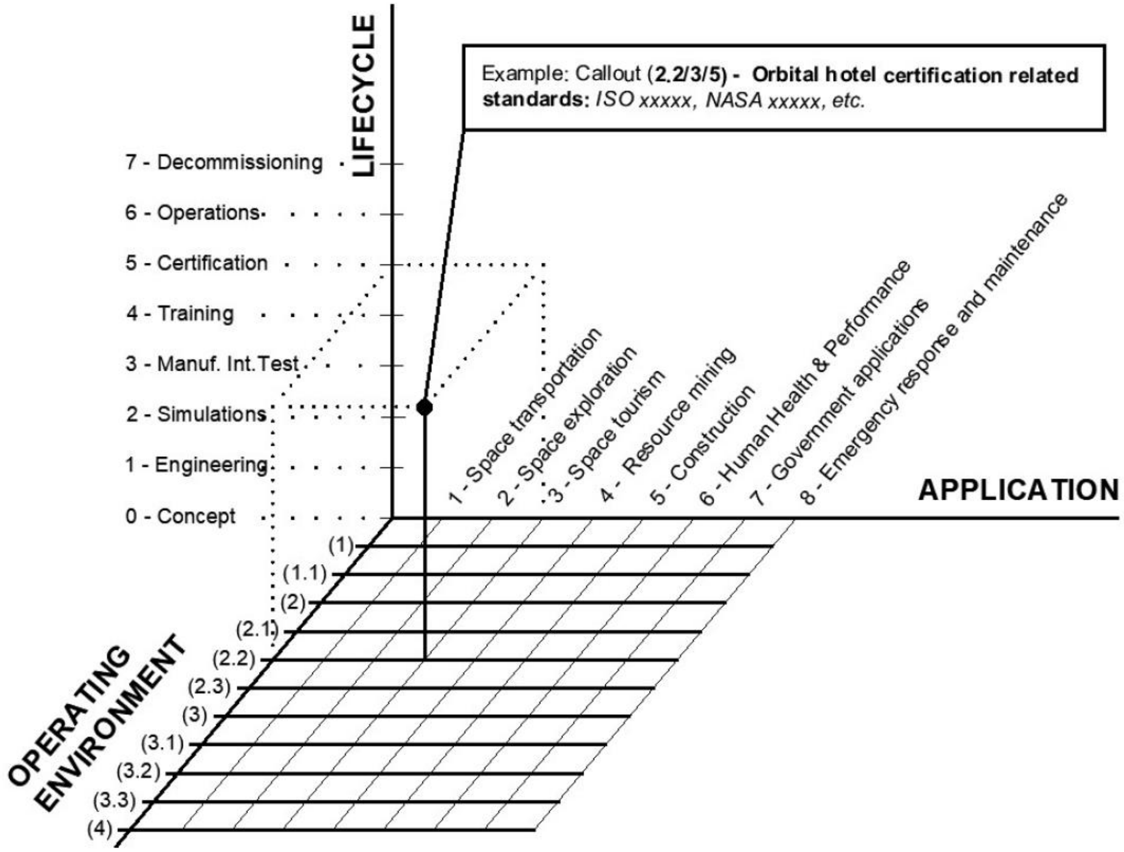


Fig 8 Spacecraft classification system as presented in S-153.

S-153 Applicability. The AIAA summarizes S-153 as ". . . the first level of a three-level standard defining a human spaceflight (HSF) spacecraft ontology from architectural and system engineering viewpoints." Figure 8 shows the dimensions of the "ontology space" that underlies the effort. It was developed within the HSF community and focuses on manned space flight, but the approach and much of the content should apply equally to other mission categories.

There are many perspectives that can justify an urgent need for architectural standardization in the HSF domain. The primary motivation to formulate a new ontological standard for HSF vehicles results from the absence of such a standard and the resulting uncertainty in even simple information exchanges among subject matter experts. A critical concern is interoperability among systems and infrastructure elements. Today, individual standards commonly employ their own terminologies and create, formally or otherwise, a set of ontologies that may align, overlap, or collide. Different terms may be used for the same thing, perhaps from a different perspective. The same term may mean different things, or may be used differently in different mission phases. As the development of open architecture standards for space continues, there will be equally urgent interoperability needs for ontological definition of data objects such as navigation data, collision assessment data, spacecraft communications configuration data, pointing information (for communication contacts), commands (or goals) to be executed, goal status, operational data sets, audio and video (especially for HSF), network routing rules and data (DTN), distributed network management, and the means to secure data exchanges.

The need for common ground in HSF is based on:

- Motivation to enable and speed up strategic planning and communication in the HSF domain, where currently three distinct sub-communities take very different approaches to strategic planning. With a common ontology, these groups can achieve better alignment of shared goals, skills, and agendas:
  - Academia: education and training.
  - Government: leadership, societal interests and conduct.
  - Industry: ROI in R&D, and socio-economic and socio-technological sustainable system development.
- The need for an outline of major information categories in a simple, taxonomic form, which can then enable coordinated focus on specific topics. For example, an ontology for facilities and related sets of standards has potential to reduce costs and time associated with prototype development. Just as the building industry applies different sets of standards to family homes, hospitals, and factories due to differing structures, uses, capacities, operational scenarios, and so forth, the S-153-2021 standard distinguishes spacecraft categories for tourism or industrial resource utilization that will face different hazards, trajectories, scope, and overall usage, again requiring different sets of standards.
- The need for a framework for existing standards and standards under development to rapidly identify their applicability to a variety of different types of systems.
- The need to unify terminology, explain existing terminology, and explain the correct use of terminology that was not developed with consideration of cross-disciplinary applications and may therefore cause confusion. This involves clarification of existing terminology and provisions to create new definitions that are common and understood across disciplines as well as clarification or elimination of domain-biased jargon.
- The need to establish and explain relationships among various system and subsystem categories using a common organizational framework.

The proposed S-153 framework addresses all five of these points and more, starting from and integrating existing standards that are frequently used in industrial or government settings as well as new standards arising from industrial and safety practices It will be enhanced over time following the structure in Figure EE but most importantly, it functions as a starting point for other expert communities and other standards development efforts that will dive deeper in defining individual vehicles, operational environments and subsystem parameters. Acceleration of technology development and safety of human spaceflight are thus the two primary goals of the SACoS as well as their first product, S-153.

Success will depend on developing a set of common, shared terms used by the organizations that establish and maintain standards, each of which addresses different aspects of space systems architecture. Effective standards are created through an open, voluntary process to arrive at consensus, and the entire community will benefit from consistent application of common terms and definitions. The resulting ontology could then provide cross-calibration for all space organizations which choose to leverage past, present, and future space infrastructure elements. Such an approach would ultimately promote greater efficiency in domestic and international markets. By adhering to standards that have been developed through consensus-based approaches, companies can use widely accepted requirements and specifications to negotiate products or services and avoid potential contract ambiguities that might otherwise undermine such matters.

V. Summary and Conclusions

In this paper, we have briefly considered three ongoing efforts whose common objective is to improve the quality and effectiveness of space enterprise architecture, space systems architecture and SE practices. The authors have been deeply involved in these efforts and share a belief, based on decades of experience, that better information sharing across organizations and disciplines, better application of lessons learned and best practices, better reuse of proven successful design elements, and better exploitation of standards and modeling are crucial elements to coping with the complexity and rapid pace of change in space systems. RASDS++, NASA HDBK 1005, and S-153 are only part of the needed foundation for evolving space architectures, but they illustrate an integrated approach and offer hope that conventional space discipline-centered stovepipes can be broken, and fact-based consensus can be established across policy, acquisition, and operational organizations and across the global space standards community.

Three key points deserve emphasis:

1. The three standards we have discussed came out of separate efforts but have important correspondences among them, showing that focused efforts addressing specific system and stakeholder needs can be knitted together into a larger and more powerful framework consistent with the fundamentals of enterprise architecture, systems architecture and systems engineering.
2. These standards are establishing a conceptual architecture basis that will continue to evolve a Space Architecture Framework that draws on successful prior system developments in the form of reuse and best practices. Incremental realization gives context for the development of new standards, and these new standards "calibrate" the framework. The authors maintain that the cycle of realizations and new standards development for space is a gateway to future commercial capability.
3. A conceptual architecture creates the front end of a complete architecture methodology, ultimately enabling specific physical system designs to meet specific mission needs reliably and affordably.

The vision we offer is of a future evolved architecture, encompassing business and systems models, assembled from many individual efforts and supporting, among many other things, an interoperable, forward-looking space infrastructure and the space ecosystem supply chain. A future evolved architecture, called for in enterprise and systems architecture disciplines, embodies the basic concepts of ISO 42010 while adding important ideas of ontology, formal modeling, system implementation through rigorous transformation of conceptual to physical architecture. Many of these are explicitly embodied in RASDS, RM-ODP, and other AFs such as The Open Group Architecture Framework (TOGAF). For example, RASDS++ is enhancing the Information Viewpoint following these principles. Outside the scope of this paper are standards developments in other areas, with other concerns, like Space Traffic coordination and On-Orbit Servicing. System architecture methodologies based upon these principles, will allow the spacefaring community to address a forward-looking space infrastructure and the space ecosystem supply chain.

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