BEYOND INTEGRATION Readiness Level (IRL):

A Multidimensional Framework to Facilitate the INTEGRATION OF SYSTEM OF SYSTEMS

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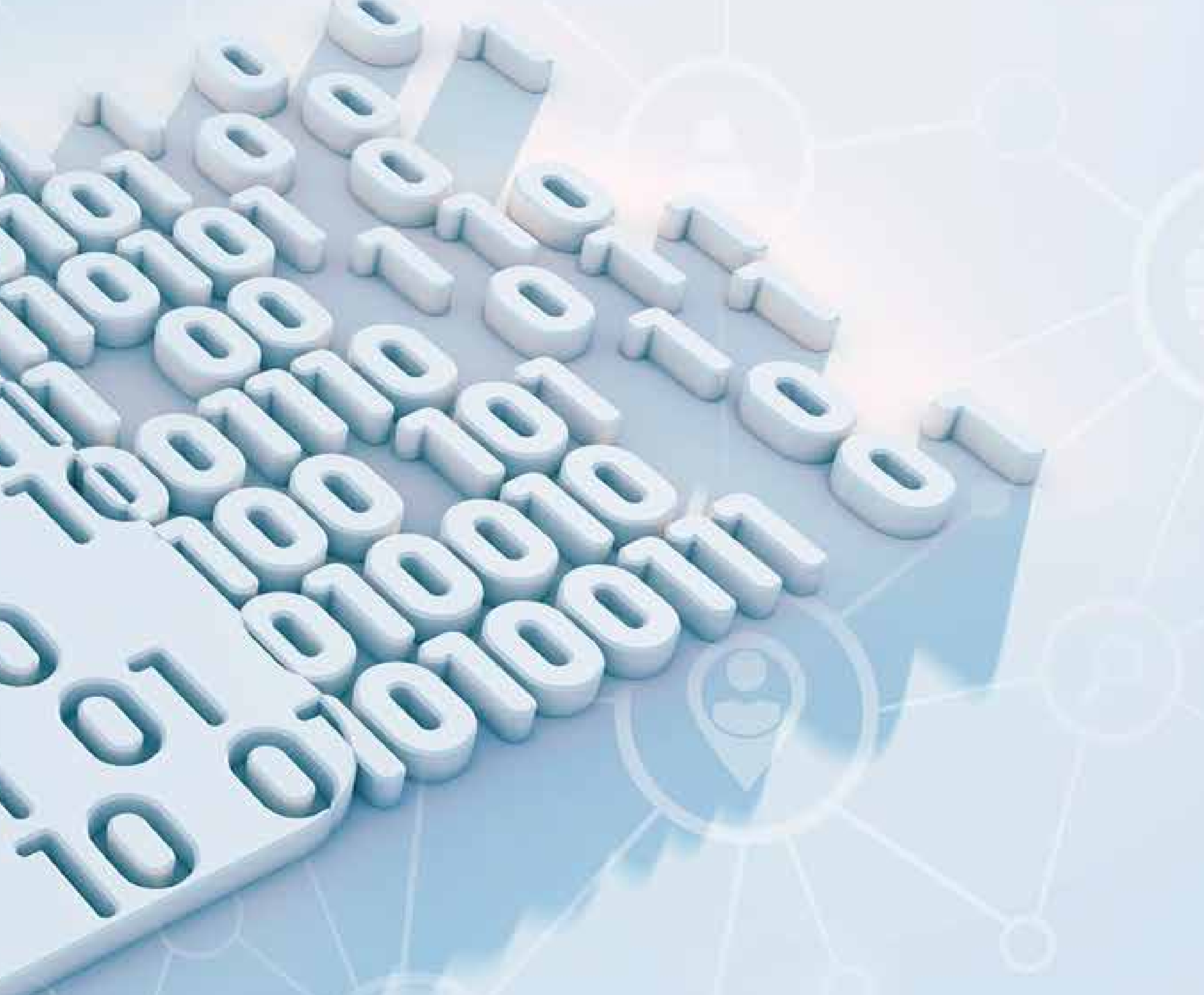

Integration Readiness Level (IRL) can be an effective systems engineering tool to facilitate integration of systems. Further research in systems integration, analysis of integration data, and the development of systems architecture framework can help enhance IRL principles for systems integration use in Department of Defense (DoD). IRL was developed to support Technology Readiness Level, but DoD never implemented IRL. Expanding the use of IRL can address growing integration challenges of DoD acquisition programs. DoD Space Systems are prime examples of System of Systems that can help identify attributes for an integration framework that can enhance IRL assessment.

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Integration Readiness Level (IRL) was introduced to help understand the maturity of integrating one system into another (Sauser, Gove, Forbes, & Ramirez-Marquez, 2010). The need to expand the use of IRL is becoming increasingly more relevant in U.S. Department of Defense (DoD) acquisition as program managers aim to develop and acquire weapon systems with ever increasing multiple capabilities and interfaces. Likewise, understanding integration feasibility early in the program is beneficial in managing and planning for the success of overall System of Systems (SoS) integration.

Throughout the years, the DoD acquisition community has implemented several systems engineering processes and tools to help meet budgetary requirements while still trying to produce the best weapon systems available. Also, DoD Space Systems acquisition has increased in actual systems costs from the initial estimates while the capability of the systems decreased from original intent. According to a Government Accountability Office (GAO, 2011) report, "the total estimated costs for major space programs increased by about $13.9 billion from initial estimates for fiscal years 2010 through 2015, which is an increase of about 286 percent" (p. 4). This needs to be managed better within DoD, and additional tools are needed to understand future impacts to system delivery.

DoD also implemented initiatives in place to expedite the deployment of capabilities into operations as part of the Urgent Warfighter Needs efforts.

Based on a GAO (2012) report, various practices have been implemented by program offices in order to meet challenges to deliver capabilities within short timelines. Having additional integration tools available to help program/product teams understand the feasibility of weapon systems deployment on aggressive timelines could prevent schedule delays.

> ***Understanding the feasibility of integration early in the process can help temper the expectations needed throughout the development and deployment of new systems.***

The DoD acquisition issues of uncontrollable cost growth and the need to expedite the deployment of capabilities into operations trigger the drive to improve systems engineering processes and tools that program managers can depend on when making program decisions. In order to make decisions about systems and technology availability, the DoD acquisition community adopted the use of Technology Readiness Level (TRL) in 2002 (DoDI 5000.02, 2017). TRL provides measurement for explaining the maturity of a system based on the technology used for that system.

To further the use of TRL, IRL was introduced as an integration tool to complement TRL as illustrated in Table 1 (Sauser et al., 2010). IRL was developed to align with the TRL definitions, but it was never officially implemented by DoD to help with integration assessment. Other readiness levels such as System Readiness Level (SRL) and Test Readiness Level were also introduced, but not officially recognized by the DoD acquisition community. Although not implemented, the use of IRL could become a necessary tool to help reduce integration risks of complex systems. Integrating SoS is becoming more complex, and the current definitions of IRL do not allow it to be independent of the TRL process, which could be one reason why IRL is heavily scrutinized in current systems engineering literature. IRL was developed to support the limitations of TRL in evaluating complex interfaces. According to London, Holzer, Eveleigh, & Sarkani (2014), while TRL is used for "considering discrete technology elements, IRL is only limited to connecting these technology links between components" (p. 380).

TABLE 1. INTEGRATION READINESS LEVEL (IRL) AND TECHNOLOGY READINESS LEVEL (TRL) LEVELS

Level	TRL	IRL
1	Basic principles observed and reported	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship
2	Technology concept and/or application formulated	There is some level of specificity to characterize the interaction between technologies through their interface
3	Analytical and experimental critical function and/or characteristic proof of concept	There is compatibility between technologies to orderly and efficiently integrate and interact
4	Component and/or breadboard validation in laboratory environment	There is sufficient detail in the quality and assurance of the integration between technologies
5	Component and/or breadboard validation in relevant environment	There is sufficient control between technologies necessary to establish, manage, and terminate the integration
6	System/subsystem model demonstration in relevant environment	The integrating technologies can accept, translate, and structure information for its intended application
7	System prototype demonstration in relevant environment	The integration of technologies has been verified and validated with sufficient detail to be actionable
8	Actual system completed and qualified through test and demonstration	Actual integration completed and mission-qualified through test and demonstration in the system environment
9	Integration is mission-proven through successful mission operations	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle

Note. As defined by Sauser et al. (2010)

Based on Sauser et al. (2010), IRL was introduced as, "a metric for systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points" (p. 18). The concept itself could be more useful, but it is currently limited to support TRL concepts (Table 1). The main concept of IRL is to be used to evaluate integration of two technologies that were evaluated by the TRL process.

The principles of IRL can be used and enhanced to facilitate the integration of SoS. As indicated by Ge, Hipel, Kewei, & Chen (2013), "SoS is defined as large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal" (p. 363).

Many commonly used SoS terms such as *interoperable* and *synergistic* are important factors that need to be considered when integrating SoS (Madni & Sievers, 2014). The challenges of SoS integration are constant in DoD acquisition as technology continues to improve and new capabilities emerge as better options for the warfighter. Understanding the feasibility of integration early in the process can help temper the expectations needed throughout the development and deployment of new systems.

Problem Focus

The focus of the research is to understand the integration issues and challenges of major DoD Space Systems so that they can be used to further analyze facilitation of SoS integration. As challenges continue when integrating new capability into a family of systems, the need for understanding the overall effort is necessary for upfront planning. The components that make up SoS usually have different purposes, and the different organizations associated with those purposes typically use different terminologies and concepts. Thus, SoS integration must be able to address the differences in semantic and syntactic between their organizations. Identifying these issues ahead of time helps highlight areas that need additional focus on IRL assessment. DoD Space Systems have to satisfy integration requirements that may include affordability, reliability, security, resilience, and adaptability (Madni & Sievers, 2014).

Understanding systems integration itself is a very challenging task due to several factors that impact the integration processes. Systems integration can be interpreted differently, and although integration is a commonly used word, it is not clearly defined by both industry and academia on its application (Djavanshir & Khorramshahgol, 2007). As explained by Tien (2008), "integration can occur through functional, physical, organizational, and temporal dimensions, which can also include management and processes of the actual system" (p. 393). Elements involved in integration tend to be multidimensional, which can be more complicated than evaluating technologies. Also, most current systems integration efforts focus on products instead of the process, which can lead to inadequate analyses when trying to understand the impacts of integrating components (Magnaye, Sauser, & Ramirez-Marquez, 2010). Integration of SoS is complicated, which goes beyond merely assembling components.

The focus of the research is to develop a framework to help address SoS integration issues using IRL principles. The subjectivity of TRL and IRL processes has been widely criticized through several journals.

Arguably, the literature has oversimplified facets of system readiness and maturity. The risk and effort required for higher readiness levels does not factor into the current assessment of TRL and IRL (Kujawski, 2013). However, the process of conducting an initial assessment of the system prior to the development and integration is beneficial in understanding overall feasibility. Defining feasibility of integration early enough in the process can impact decisions that could avoid integration pitfalls later in the process.

This research provides a tool to facilitate the integration of SoS; however, it does not focus on the development of systems integration requirements. Integration requirements are critical, but this research assumes that the stakeholders have agreed to the requirements before planning the scope that allows integration activities to be executed. Requirements need to be clearly defined to the lowest level and the assumption is to have clear requirements before conducting integration assessment(s). The proposed IRL assessment process will be iterative based on the changes in scope (if any) by the stakeholders. Understanding enterprise-wide integration requirements is necessary before developing a specific architectural framework to help with the integration process (Bolloju, 2009). Understanding integration requirements processes can help with traceability of derived requirements during the integration planning and implementation stages.

Theory

IRL can be an effective systems integration assessment tool, and given the right multidimensional framework, it can facilitate the integration of SoS. Utilizing other integration variables and expanding the current notional definitions of IRL can significantly impact the assessment of SoS integration. IRL was also proposed as an intermediate step by making it part of a matrix function with TRL in order to determine the SRL (McConkie, Mazzuchi, Sarkani, & Marchette, 2013). When IRL is used as a function of SRL, IRL could be overlooked from being a significant independent assessment value, and the IRL level may be influenced by what is needed as the SRL value. Current IRL definitions can be useful as an input to the framework as opposed to an intermediate assessment conducted merely to understand technology or system maturity.

Other acquisition practitioners may determine that integration readiness can be assessed as part of the DoD acquisition community's Technology Readiness Assessment (TRA) process (the official process to determine TRL score), but this process does not capture the purpose of integration. TRL was never intended to measure integration maturity (Magnaye et al., 2010).

A system with mature technology does not automatically equate to having a high IRL when interfacing with another system with mature technology.

DoD Space Systems continue to provide examples of complex SoS. With very limited opportunities to do operational tests and analyses for satellite systems and rocket launches, space systems provide a platform to incorporate the latest technologies and processes to attain successful operational systems. As part of space system complexity, space systems also factor in the need for expediting the insertion of cutting-edge technology while adapting to evolution of new technology and reducing qualification timelines (Pittera & Derrico, 2011). IRL can be used to assess the integration of these types of complex SoS given a rigorous process that accounts for other variables.

Literature Review

Use of the IRL process has been documented through abundant literature with different strategies of application. The most common use is an interim tool to support TRL and/or SRL processes. TRL metrics were initially developed from seven levels promulgated by the National Aeronautics and Space Administration in the late 1990s, and then to the nine levels that were adopted by DoD in 2002 (Mankins, 2009). Assessment of TRL became more necessary as technology assessment moved into complex SoS, and DoD acquisition programs needed tools to help make decisions in complex environments (McConkie et al., 2013). The original intent of IRL was to provide a systematic analysis of integrating different technologies and understanding the maturity between the points of integration (Pittera & Derrico, 2011). IRL was focused on being a tool to understand the maturity of technologies used to integrate the systems as opposed to merely a tool to integrate two or more systems.

When the goal is to incorporate the use of IRL into systems integration processes, systems integration strategies and challenges must be identified. Systems integration is a strategy advocated in order to achieve sustainable development—it is very diverse and can be interpreted in many different ways (Vernay & Boons, 2015). System integration strategies have been explained in several journals, which provided different perspectives and helped narrow the focus of this research from supporting technical/system maturity to readiness of integration.

According to Gagliardi, Wood, Klein, and Morley (2009), "severe integration problems can arise due to inconsistencies, ambiguities, and gaps in how quality attributes are addressed in the underlying systems" (p. 12). One of the main reasons for this is not identifying the right quality attribute that supports the integration activities early in the process. This is where a set of quality attributes derived from the DoD Space Systems integration issues can be identified and leveraged to help with systems integration.

Application of systems integration processes can be enhanced when additional systems, processes, and organizations are involved in order to integrate SoS. Generally, SoS can be defined as a collection of interoperating components and systems producing results that are not achievable by each of the individual systems. Adding capabilities to an already complex system epitomizes the definition of SoS (Zhang, Liu, Wang, & Chen, 2012). To fully realize the analysis of SoS, engineering and systems architecture must be used to address allocation of functionality to component interaction as opposed to merely dealing with individual components (Ender et al., 2010).

To understand the properties of SoS, DoD Space Systems will be used as examples of complex SoS. DoD satellites are complex SoS that cannot be accessed for upgrade or changes after they have been placed into orbit. Conducting technical demonstration also requires significant funding and resources for these types of complex SoS (Dubos & Saleh, 2010). Thus, it is imperative that integrating them successfully the first time becomes a high priority.

To understand the comprehensive processes involved in the integration of complex SoS, one must understand how complex SoS are managed. Literature is replete with architectural framework proposals to design, develop, and manage these types of systems (Suh, Chiriac, & Hölttä-Otto, 2015). Many of these larger systems involved multiple organizations as stakeholders, and according to Rabelo, Fishwick, Ezzell, Lacy, and Yousef (2012), "large scale organizations, which have significant operations management needs, seek out and execute complex projects that involve a very large number of resource and schedule requirements" (p. 112). In addition to the wide range of factors involved in complex SoS, recent SoS development requires intensive information technology software, which also triggers the use of an architectural framework (Piaszcyk, 2011).

Architectural frameworks are developed to illustrate operations and functions to help clearly define roles of entities within complex SoS. Understanding and implementing the right architecture and component design will improve performance, resulting in faster integration processes and reduced complexity (Jain, Chandrasekaran, Elias, & Cloutier, 2008). The resulting data from this research will provide the components needed to develop an architectural framework. This framework will help explain how major attributes will contribute to the assessment of enhanced IRL and will help illustrate the different factors needed for consideration during evaluation of IRL at certain, specific timelines.

Major attributes to support the integration assessment framework will be finalized based on the results of the data collection. As explained by Jain et al. (2008), "attribute is a property or characteristics of an entity that can be distinguished quantitatively or qualitatively by human or automated means; the attributes of a system or architecture are used to describe the properties of the system or system architecture in a unique distinguishing manner." Attributes are usually basic elements related to requirements, which can be interpreted that a requirement consists of multiple attributes (Lung, Xu, & Zaman, 2007).

For attributes to be an effective tool for integration, they need to be integrated into the framework and optimized to balance complexity and simplicity. Organizations can adopt these attributes when integrating capabilities into the family of systems. Complex systems can have unpredictable behaviors, and using multiple attributes can help measure the performance of these behaviors by quantitatively and qualitatively weighing the individual attributes (Gifun & Karydas, 2010).

The initial list of attributes that will be considered for this research is derived from discussions with space systems integration experts, journal articles on integration variables (Jain, Chandrasekaran, and Erol, 2010), and key integration process areas (Djavanshir & Khorramshahgol, 2007). Table 2 shows the list of attributes considered for purposes of this research.

TABLE 2. LIST OF ATTRIBUTES

System Availability	Architecture and Design	Commercial-off-the-Shelf (COTS)
Complexity	Configuration Management	Concept of Operations
Documentation	Functionality	Hardware/Software Verification and Validation
Interface Control	Information Assurance	Internal/External Organizations and Coordination
Processes and Procedures	Planning and Scheduling	Programmatic and Risks
Quality Assurance	Requirements Management	Resources (Funding)
Risk Analysis and Management	Semantic Consistency	Standards
Schedule Control	Strategic Planning	Technology Insertion
Testing	Training	

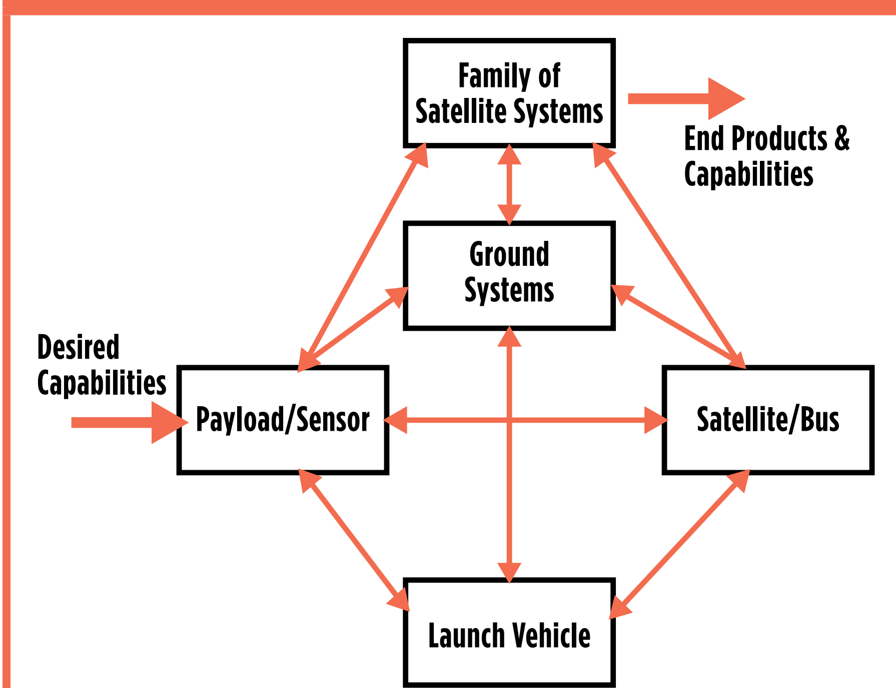
These potential attributes will be used to help define each integration issue data set that is aligned to a specific integration variable. Some of these attributes may overlap or become part of another attribute. Collecting DoD Space Systems data will help identify and provide the criteria for the major attributes associated with each data set.

Goals

The goal of this research was to collect data on six major DoD Space Systems integration issues over the past 16 years, align the data into items that impact integration, group the items into major attributes, and use the attributes to develop a systems integration architectural framework to assess integration feasibility. After the integration items were grouped into major attributes, a survey was solicited from experienced systems engineers, systems integrators, space integrators, and DoD space acquisition personnel. The goal of the survey was to verify the derived integration attributes and help determine how the attributes are weighted when used in the systems integration assessment framework. Understanding the feasibility of integration ahead of time would help identify risks and mitigation strategies.

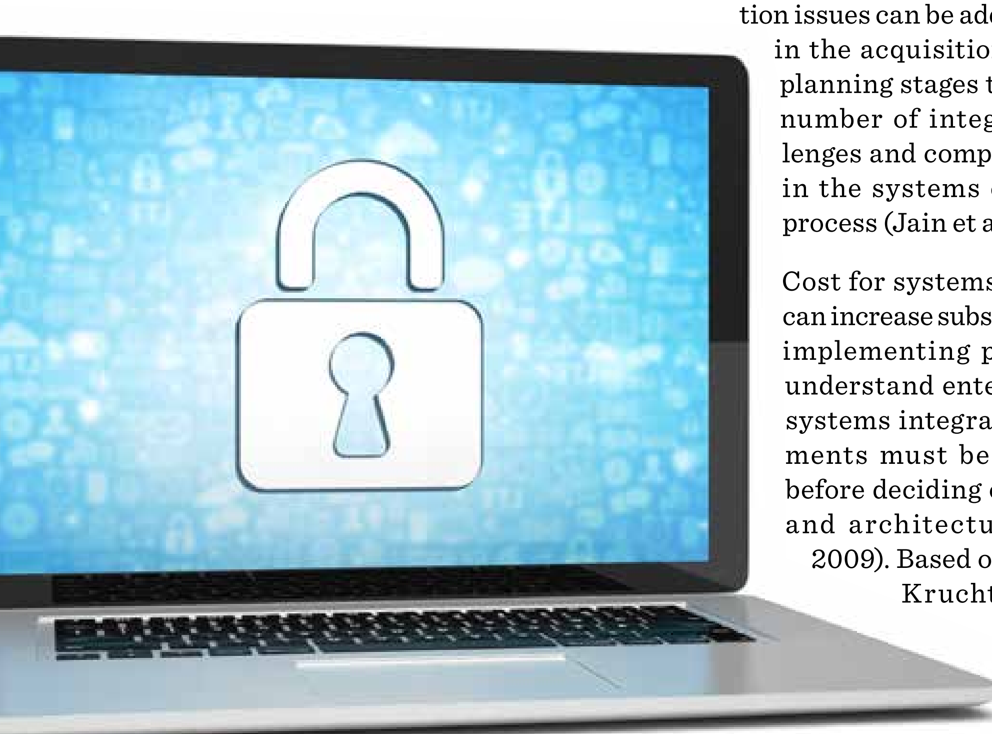
The goal of integrating desired capabilities into a family of DoD space/satellite systems is defined notionally in Figure 1. The desired capability of DoD Space Systems is usually integrated into a sensor, which becomes the payload of a satellite. The payload is integrated into a satellite bus and both systems become the satellite system. The satellite system is integrated into ground systems for communications and data exchange. The ground systems are the satellite operations centers, ground antennas, tracking stations, and the locations that process the mission data transmitting from the satellite system.

FIGURE 1. NOTIONAL DOD SPACE SYSTEMS ARCHITECTURE AND MAJOR INTEGRATION POINTS



Due to its uniqueness, the integration of desired capabilities into the payload is usually the most challenging effort in development and integration of space systems. After the payload has been developed and integrated into the satellite bus, it is rigorously tested on the ground. From there, the satellite system is integrated onto a launch vehicle (its ride to get into orbit). The satellite system is also integrated into the family of systems to ensure interoperability with existing systems and produce the final product/data to its users. The launch vehicle is integrated into the ground systems and the satellite system. The ground systems enable communication with all systems throughout launch, deployment, and operations of the satellite system. The desired end state or successful SoS integration includes successful launch and deployment of a satellite system in orbit that meets (or exceeds) performance of all systems involved.

The goal is to develop a systems integration assessment framework tool based on the attributes identified through data analysis. It is imperative that assessment of complex systems must address common interfaces, interoperability, reliability, and operations (Bhasin & Hayden, 2008). Methods and processes in systems engineering are used for defining requirements and provide the framework to identify a generalized architecture (Bhasin & Hayden, 2008). One of the major goals is to understand how integration issues can be addressed early in the acquisition process or planning stages to reduce the number of integration challenges and complexities later in the systems engineering process (Jain et al., 2010).



Cost for systems integration can increase substantially, and implementing processes to understand enterprise-wide systems integration requirements must be considered before deciding on a solution and architecture (Bolloju, 2009). Based on findings by Kruchten, Capilla, and Duenas (2009), architectural elements are the primary constituents of describing "components and connectors, while nonfunctional properties shape the final architecture" (p. 36).

To improve integration of SoS, the understanding of integration issues must first be identified. Table 3 defines the process.

TABLE 3. PROCESS FROM DATA COLLECTION TO INTEGRATION ASSESSMENT FRAMEWORK DEVELOPMENT	
1.	Collect high level integration issues from six major DoD major Space Systems from 1999–2014
2.	Identify the integration variable that is impacted by each integration issue
3.	Group the integration variables based on common focus areas
4.	The integration variables will define the parameters for the final set of attributes
5.	Analyze how each attribute is distributed throughout all six major space systems in the 16 years of data sets
6.	Complete regression analysis of the attributes and determine weights of each attribute
7.	Validate attributes and the type of integration variable associated with each attribute by completing a survey of systems integration experts in DoD
8.	Analyze survey results using regression and correlations
9.	Compare both data analysis and survey analysis; identify final weight of each attribute
10.	Based on the analysis, develop a systems integration framework tool with weighted attributes to help facilitate SoS integration process

Once the integration assessment framework is developed, it can be used to help facilitate SoS integration. The output of the framework is the IRL score for the entire SoS, and as each major attribute matures, the IRL score improves. The framework can be used throughout the design, development, and deployment of the SoS. The stakeholders or designated Subject Matter Experts (SMEs) provide upfront analysis and agree on what constitutes the initial IRL level for each of the major attributes. The initial IRL levels for each attribute will be the inputs to the framework. The initial IRL definition for each attribute will be identified from 1 to 9 (using Table 1 as a reference) once the criteria are defined for each major attribute.

Data Collection and Exploration

Major Space Systems

The integration data will be collected from six major DoD Space Systems. As defined in DoD Instruction 5000.02 (2017), the six space systems are considered "Major Defense Acquisition Programs (MDAP) Acquisition

Category I (ACAT I), which are defined as overall program procurement cost of over $2.79 billion (using Fiscal Year 2014 constant dollars)" (p. 49). The major space systems are: (a) Advanced Extremely High Frequency (AEHF) Satellite Communications (SATCOM); (b) Evolved Expendable Launch Vehicle (EELV); (c) Global Positioning Satellite (GPS); (d) National Polar-Orbiting Operational Environment Satellite System (NPOESS); (e) Space Based Infrared Systems (SBIRS); and (f) Wideband Global SATCOM (WGS).

For 16 years from 1999–2014, major integration reporting data from the Director, Operational Test and Evaluation (DOT&E), with additional GAO supporting documents, were collected (DOT&E, n.d.), which explained major integration issues encountered by the six major space programs for each year. The issues identified in the reports are explained, but additional background information was gathered from the U.S. Air Force Space & Missile Systems Center (SMC) program offices. Additional interviews of SMC personnel to gather background information were also conducted for better understanding of some of the issues. These space acquisition programs have encountered challenges in planning, designing, developing, integrating, testing, and deploying different systems throughout the 16-year reporting period. Each major issue identified per year was counted as one issue (i.e., if one issue persisted through 4 years, it will be counted as four issues). Table 4 presents the description and data collection summary of each of the six DoD space systems.

TABLE 4. SIX MAJOR SPACE PROGRAMS: 1999–2014

Description	Data Collection Summary
1. **AEHF (Advanced Extremely High Frequency) Satellite Communications (SATCOM)** is a communications satellite SoS that provides secure and survivable communications capability to U.S. military during any level of conflict. The AEHF capability ensures continuous secure communication during all levels of conflict for warfighters.	There were 79 major integration issues identified for AEHF SATCOM during the 16-year span. Some of AEHF major integration issues included: testing processes for digital processors, integrating nuclear hardening and shielding, electric propulsion, phased array antenna, and nuller spot beam.
2. **EELV (Evolved Expendable Launch Vehicle)** is an SoS launch vehicle and service provided to DoD and commercial customers. It was developed to provide launch capability that reduces the cost of alternative launch options while meeting mission assurance requirements.	There were 24 major integration issues identified for EELV during the 16-year span. Some of the major issues were data availability to the stakeholders for test verification processes, documentation of flight analysis plan, and integration of several design processes.

TABLE 4. SIX MAJOR SPACE PROGRAMS: 1999-2014 (continued)		
3.	**GPS (Global Positioning System)** is a major SoS, providing data that both DoD and civilian users are dependent upon to precisely determine their velocity, time, and position. The GPS constellation calls for 24 satellites that provide real-time and highly accurate positioning and location data. It can function through all weather and provides passive data to worldwide users.	There were 71 major integration issues identified for GPS during the 16-year span. Some of the major issues were communications between cross-link systems, development and integration of GPS Military-Code and civil signal capabilities, integration of receivers into major platforms (i.e., ships and aircraft), and refinement of end-to-end test strategy.
4.	**NPOESS (National Polar-orbiting Operational Environmental Satellite System)** was an enhanced weather SoS program that was administered by three different government organizations: DoD's Air Force; Department of Commerce (DoC)'s National Aeronautics and Space Administration (NASA); and DoC's National Oceanic and Atmospheric Administration (NOAA). NPOESS provided the platform to acquire satellite SoS to collect and disseminate environmental data for the three organizations. Although development planning and integration started in 1999, the program was eventually cancelled in 2011. There are many valuable integration lessons learned and information to be derived from the program throughout the years.	There were 18 major integration issues identified for NPOESS during its existence. Some of the major issues included field terminal integration and interoperability, integration of quality environmental data record, and integration challenges of program sensor design and algorithm development.
5.	**SBIRS (Space Based Infrared System)** is a remote sensing satellite SoS that supports DoD by providing unprecedented timely and improved infrared data quality. SBIRS's top missions of improving missile warning and missile defense have been realized through complex development and integration processes. It has also greatly enhanced the other mission areas of technical intelligence and battlespace characterization.	There were 46 major integration issues identified for SBIRS during the 16-year span. Some of the major integration issues included defining multiple test strategies, development of Modeling & Simulation systems to support operations of integration and testing, ground software development and integration, and flight software integration into satellite.
6.	**WGS (Wideband Global SATCOM)** SoS enables communication to U.S. military and Coalition partners and allies during war and all levels of conflicts. Its wideband capability provides greater bandwidth to transfer data during conflicts.	There were 33 major integration issues identified for WGS during the 16-year span. Some of the major issues included integration complexity of X-band and Ka-band cross-banding for the on-board satellite, integration technical issues on orbital placement, frequency reuse, and launch services integration, interoperability complexity of control software development.

Attributes Derived from Data Collection

To understand the impact of each major integration issue, each issue was aligned with an integration variable to best describe the major area impacted by the issue. The integration variables were then grouped together based on similar focus areas and aligned with their contributing attribute. Interviews with integration experts and additional research were conducted to scope the right number of attributes from the initial list. The definition of each potential attribute continued to be refined based on the different groups of integration variables supporting them. After identifying the integration issues and integration variables, the list of contributing attributes was finalized. Each integration variable was assigned to a major attribute, which also helped define the criteria for that attribute. A discussion of the resultant list of seven final attributes follows.

Availability. To enable integration activities, Availability is critical to understanding the benefits to be derived from accessibility of supporting hardware, software, documentation, and expertise. Integration of new systems into legacy systems may be made more difficult by improper or insufficient support documentation or the unavailability of expert personnel/training expertise. This attribute is critical in identifying these supporting entities. The items derived from the integration issues that support this attribute are access to high TRL supporting systems, subsystems and components, and access to supporting documentation and expertise.

The availability of the right supporting systems is critical to the success of the overall system delivery. To help address Availability, the reuse of existing infrastructure and the use of COTS items are identified before integration activities. To meet time commitments, the reuse of systems, subsystems, and components from the current infrastructure are highly encouraged with the possibility of replacing them with COTS items on future updates (Tyree & Akerman, 2005).

Complexity. Complexity is the attribute that manages the technical risks of integration. The items derived from the integration issues that support this attribute are managing low technical maturity of system design, development, and integration, and determining complex interfaces. According to Jain et al. (2008), "complexity can be defined as the degree to which a system or component has a design or implementation that is difficult to understand and verify" (p. 211). The complexity of systems integration has significant influence on driving schedule delays (Dubos, Saleh, & Braun, 2008). Complexity affects the degree of complication of several factors such as the number of interfaces and intricacies of different components (Jain et al., 2008). Although it has been widely studied, there is no defined mathematical model for systems related to Complexity (Haghnevis & Askin, 2012).

Interoperability. Interoperability is the attribute that will address compatibility, connectivity, and communication between systems, subsystems, and components. The items derived from the integration issues that support this attribute are understanding compatibility and interface issues, addressing semantic/syntactic issues, and managing communications issues between systems. Interoperability assessments can be very challenging in SoS because of the different testing involved to verify their functionality (Lin et al., 2009). According to Madni and Sievers (2014), "interoperability is the ability of distinct systems to share semantically compatible information and then process and manage the information in semantically compatible ways, enabling users to perform desired tasks" (p. 342). Interoperability can be improved, which means that the metrics to measure it can be defined. However, Interoperability is still a complex and broad topic, and its condition may not be easily quantified (Rezaei, Chiew, & Lee, 2013).

Management. Management is the attribute most critical to planning and developing integration strategies. The items derived from the integration issues that support this attribute include leading coordination between stakeholders, providing guidance and directives, determining scope, managing requirements, and developing and implementing policies and agreements. Management ensures that the stakeholders' derived integration requirements are met throughout the integration process. Managing stakeholders' decisions is critical in shaping the final design of the system (Booch, 2006). Management must be able to navigate through the challenges of diminishing budgets, changing politics, and evolving technologies to support integration activities.

The Management methods for integration address issues of philosophy, operation, and collaboration (Tien, 2008). Management addresses requirements traceability. As indicated by Piaszcyk (2011), "traceability is used to evaluate the impact of top-level requirements changes" that can help eliminate requirements creep (p. 325).

Processes. Processes is the attribute that enables the development, documentation, and execution of all integration activities. The items derived from the integration issues that support this attribute are processes that develop, document, and execute the following: testing, verification and validation, configuration management, training, modeling and simulation

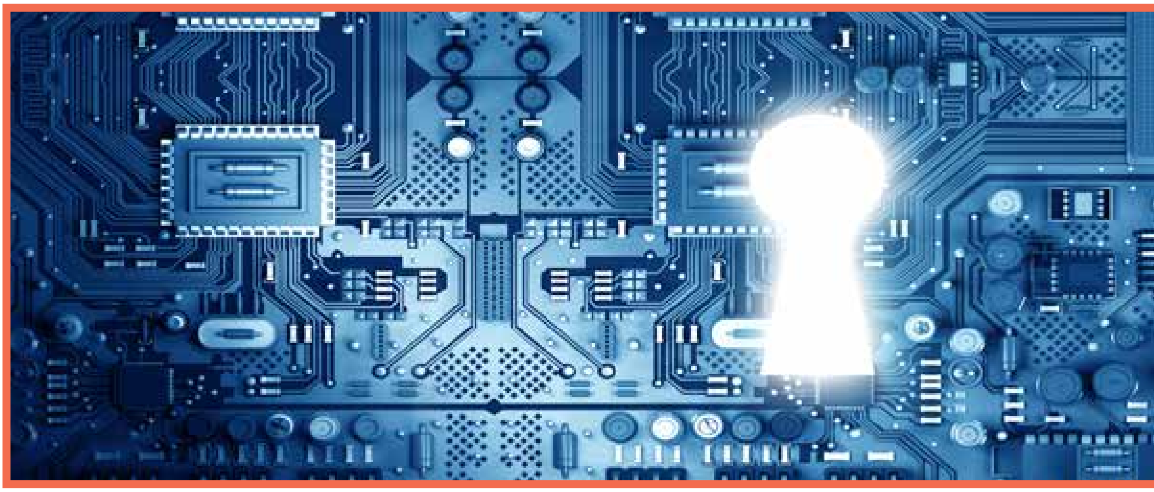
(M&S), M&S activities, information assurance, mission assurance, communications and decision making, security, safety, quality assurance, and manufacturing and assembly. Processes implemented during integration must be clearly defined and documented. Many organizations' efforts in key process areas for integration did not have much success due to ill-defined Processes (Djavanshir & Khorramshahgol, 2007). Processes for integration include standards, procedures, and algorithms associated with integration activities (Tien, 2008).

The goal is to identify necessary Processes needed for successful integration and the impacts to the integration requirements. Great examples from the space integration data also explain how the integration issues are impacted due to the different test and verification Processes that have been implemented. Using M&S as part of the integration process will help minimize risks. Computer-based M&S early in the process can help thrust systems engineering methods throughout the integration process (Ender et al., 2010).

Resources. Resources is the attribute that enables integration of SoS through funding and providing the right integration tools. The items derived from the integration issues that support this attribute are sufficient funding to support all integration activities, providing the right amount of trained personnel, and providing the right tools and facilities throughout the integration activities. Resources planning throughout SoS integration is critical to overall success. During the early phase of integration, information is scarce, but SMEs are potential sources of information with valuable inputs to address life-cycle cost of development and overall integration of a system (Tien, 2008).

Schedule. Schedule is the attribute that manages Schedule impacts throughout the integration activities. The items derived from the integration issues that support this attribute are understanding timeline goals (i.e., need dates, expected deliveries, and milestones), understanding scheduling parameters, and understanding critical path and impacts to Schedule delays. Schedule can be impacted by several of the attributes mentioned; however, an independent assessment is needed to understand how different changes impact scheduled milestones and activities. Need date and allowed time of integration must be established early on with analysis for fluctuations and critical path. Usually, the more time given for integration, the better the IRL score, which can be attributed to system maturity through time and processes.

Schedule delay usually increases the overall cost of the system and may impact the current requirements (i.e. launching a satellite at a certain month/year as required). Based on Dubos et al. (2008), "schedule slippage plagues the space industry and is autonomic with the recent emphasis on space responsiveness; the GAO has repeatedly noted the difficulties encountered by the DoD in keeping its acquisition of space systems on schedule, and they identified the low TRL of the system/payload under development as the primary culprit driving schedule risk and slippage" (p. 386).



Space Integration Data Using Derived Attributes

Some of the attributes derived from the data may slightly impact the other attributes based on how they are interpreted. Therefore, the stakeholders need to establish clear definitions (as summarized previously), understand the distinctions between attributes, and document assumptions being made for each major attribute. Each integration issue is aligned with an integration variable and then grouped with one of the seven major attributes based on their focus areas. Tables 5a to 5f capture the top issues for each attribute from each space system. They show how a specific integration issue is aligned to an integration variable and how it becomes a subset to one of the seven attributes. Tables 5a to 5f also provide the number of years that the issue impacted each of the space systems.

TABLE 5A. TOP ISSUES FOR EACH ATTRIBUTE IN AEHF SATCOM			
AEHF Satellite Communications (SATCOM)			
Integration Issue	**Integration Variable**	**Contributing Attribute**	**# of Yrs Impacted**
Nuclear hardening and shielding integration into system	System Design Maturity	Complexity	6
Lack of terminal synchronization within system	Communications between Systems	Interoperability	4
Planning of space, mission control, and user segment integration & synchronization strategy	Strategy Development	Management	3
Testing anti-jam capabilities; test processes to evaluate AEHF capabilities	Test Process	Processes	3
Fidelity of available system test simulator	Supporting System Availability	Availability	2
Schedule issues by development contractor to resolve first-time test article and test fixture problems	Schedule Impacts	Schedule	1
Insufficient budget to fund additional filters to meet High-Altitude Electro Magnetic Pulse (HEMP) testing and certification	Insufficient Funding	Resources	1

TABLE 5B. TOP ISSUES FOR EACH ATTRIBUTE IN EELV			
Evolved Expendable Launch Vehicle (EELV)			
Integration Issue	**Integration Variable**	**Contributing Attribute**	**# of Yrs Impacted**
Design issues on reliability, logistics, supportability, multiple payload interfaces, and information assurance	System Design Maturity	Complexity	2
Lack of contractual requirement for test reporting	Contracted Agreement and Policies	Management	2
Insufficient processes to obtain data of system qualification tests for verification	Verification Processes	Processes	2
Lack of additional development and integration funding to satisfy government and industry launches	Insufficient Funding	Resources	1
Availability of modified ground system	Supporting System Availability	Availability	1
Integration of legacy upper stage to the new launch vehicle design	System Interfaces and Compatibility	Interoperability	1
No major integration issue identified that the Schedule attribute impacted			

TABLE 5C. TOP ISSUES FOR EACH ATTRIBUTE IN GPS			
Global Positioning System (GPS)			
Integration Issue	**Integration Variable**	**Contributing Attribute**	**# of Yrs Impacted**
Ongoing issues with the integration of GPS receivers into different platforms (ships, aircraft, etc.)	Communication between Systems	Interoperability	8
Availability of M-code and civil signal capabilities through development and integration	Supporting System Availability	Availability	7
Planning and refinement of integration and test strategy; insufficient rigorous end-to-end planning	Planning Test Strategy	Management	7
Configuration management process issues on operations control system development and integration	Configuration Management Process	Processes	3
Schedule delays impacting integration, tests, and supporting resources	Schedule Impacts	Schedule	3
Design issues on Control Software Integration	System Design Maturity	Complexity	1
Funding availability to system development and integration causing event delays	Insufficient Funding	Resources	1

TABLE 5D. TOP ISSUES FOR EACH ATTRIBUTE IN NPOESS			
National Polar-Orbiting Operational Environment Satellite System (NPOESS)			
Integration Issue	**Integration Variable**	**Contributing Attribute**	**# of Yrs Impacted**
Design issues with the quality of environmental data record on algorithm, sensor performance, quality control of interface data processing segment	System Design Complexity	Complexity	2
Insufficient interoperability of field terminals and ground systems	System Interoperability	Interoperability	2
Funding issues to support interoperability of high rate data in X Band and low rate data in L Band	Insufficient Funding	Resources	1
Inconsistent agreement and definitions of different decision makers' roles and responsibilities	Stakeholder Agreements	Management	1
Lack of documentation process of adequate threshold definitions in data terminals	Documentation Processes	Processes	1
Lack of available space environment sensors that can be used for integration, test, and upgrades	Supporting Subsystem Availability	Availability	1
No major integration issue identified that the Schedule attribute impacted			

TABLE 5E. TOP ISSUES FOR EACH ATTRIBUTE IN SBIRS			
Space Based Infrared System (SBIRS)			
Integration Issue	**Integration Variable**	**Contributing Attribute**	**# of Yrs Impacted**
Insufficient definition of integrated test strategy to meet current schedule, ground architecture, and overall systems operational requirement	Strategy Development	Management	6
Lack of tools and resources to support M&S development of operational integration and testing	Insufficient Tools and Resources	Resources	3
Availability of ground software delivery for integration (delayed in development)	Supporting Software Availability	Availability	3
Degraded test data from Sensor Test Integration Lab due to Infrared Starer sensor and telescopic assembly process	Assembly Process	Processes	3
Communication issues of space control and telemetry, and flight software integration in satellite	Communications between Systems	Interoperability	3
Compressed schedules to accreditation of operational test scenarios increased software integration issues	Schedule Impacts	Schedule	2
Software instability in tracking, telemetry, and control functions	Software Design Maturity	Complexity	1

TABLE 5F. TOP ISSUES FOR EACH ATTRIBUTE IN WGS			
Wideband Global SATCOM (WGS)			
Integration Issue	**Integration Variable**	**Contributing Attribute**	**# of Yrs Impacted**
Complexity of designing and integrating effective cross-banding between X-band and Ka-band onboard the satellite	System Design Maturity	Complexity	4
Lack of software tools to support development of system configuration control element	Insufficient Tools	Resources	2
System interoperability issues of WGS and transmission system	System Interoperability	Interoperability	2
Insufficient documentation processes to support development and integration	Document Process	Processes	1
Ill-defined requirement definitions to separate legacy and new systems on orbit	Strategy Development and Requirements Management	Management	1
Insufficient schedule assessment to account for development and integration	Schedule Impacts	Schedule	1
Lack of upgraded automation software operations center networks	Supporting System Availability	Availability	1

The result of the data collection based on the attributes gathered from the six major DoD Space Systems is summarized in Table 6. The total number of major integration issues collected from the six DoD space systems for the 16 years is 271 with a total of 35 for Availability, 51 for Complexity, 64 for Interoperability, 37 for Management, 52 for Processes, 16 for Resources, and 16 for Schedule.

TABLE 6. SUMMARY OF INTEGRATION DATA: SIX DOD MAJOR SPACE SYSTEMS (1999–2014)

TOTAL (Major Integration Issues/Year)	Availability	Complexity	Interoperability	Management	Processes	Resources	Schedule
1999	3	2	2	2	2	0	2
2000	4	2	8	4	4	2	0
2001	3	7	4	3	5	1	0
2002	2	10	8	3	8	3	1
2003	3	7	9	1	8	3	0
2004	4	7	6	1	5	1	0
2005	5	9	6	5	8	0	2
2006	2	5	4	4	3	0	1
2007	0	1	4	3	1	1	3
2008	1	0	6	3	2	3	3
2009	4	0	3	3	3	1	1
2010	2	0	2	2	2	1	1
2011	1	1	1	2	1	0	1
2012	0	0	0	1	0	0	0
2013	0	0	0	0	0	0	0
2014	1	0	1	0	0	0	1
TOTALS	35	51	64	37	52	16	16
Total Major Integration Issues	271						

Data Analysis

Regression analysis was completed to assess the current data and how the attributes impacted the different years. The summary of analysis is highlighted in the Normal Probability Graph shown in Figure 2.

The resulting numbers are provided in Tables 7a-d, with Table 7d providing the regression equation of the relationship between the attributes and the 16 years defined.

FIGURE 2. NORMAL PROBABILITY GRAPH OF 7 ATTRIBUTES DERIVED FROM COLLECTED DATA

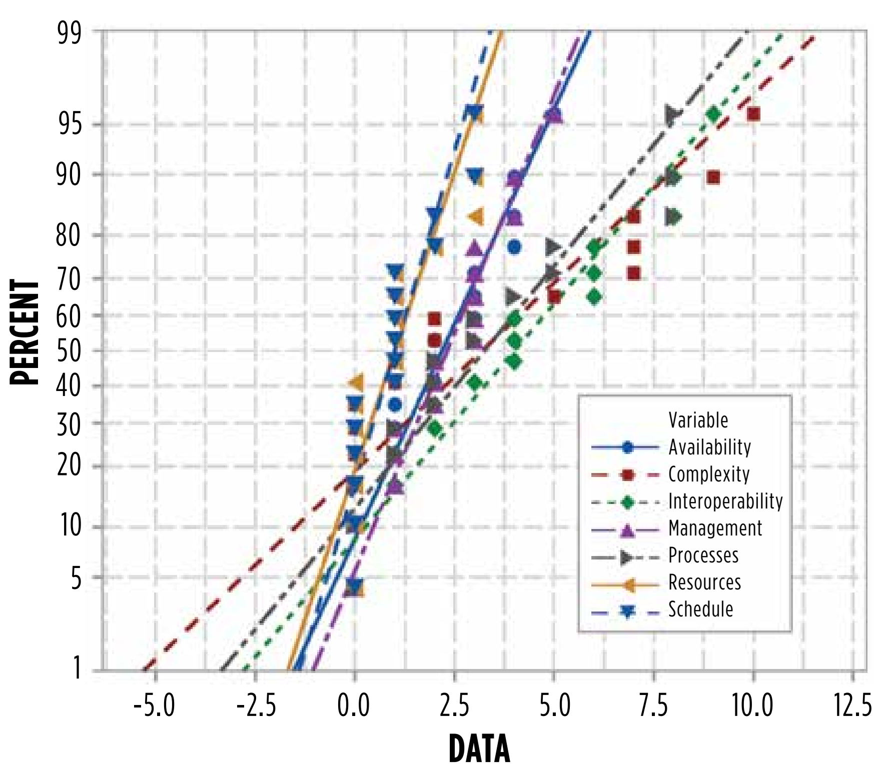


TABLE 7A. SUMMARY STATISTICS					
Variable	**N**	**Mean**	**Standard Deviation**	**Minimum**	**Minimum**
Availability	16	2.1875	1.6008	0	5
Complexity	16	3.1875	3.6555	0	10
Interoperability	16	4	2.9212	0	9
Management	16	2.3125	1.4477	0	0
Processes	16	3.25	2.8402	0	8
Resources	16	1	1.1547	0	3
Schedule	16	1	1.0328	0	3

TABLE 7B. ANALYSIS OF VARIANCE		
Source	**DF**	**P-Value**
Regression	***7***	***0.1177***
Schedule	1	0.9536
Resources	1	0.3814
Processes	1	0.2031
Management	1	0.5817
Interoperability	1	0.7945
Complexity	1	0.1569
Availability	1	0.1393

TABLE 7C. MODEL SUMMARY		
S	**R-sq**	**R-sq(adj)**
3.6838	68.07%	40.13%

TABLE 7D. REGRESSION EQUATION
Year = 15.140 − 0.070 Schedule − 2.183 Resources + 2.341 Processes − 0.5640 Management − 0.290 Interoperability − 1.5063 Complexity − 2.162 Availability

The highest mean is Complexity, which also had the highest standard deviation. The lowest average is 1.0 for both Resources and Schedule, but with a lower standard deviation on Schedule. The null hypothesis in this case is that all the attributes have a relationship with Year. Based on the analysis, the P-Value for each attribute is greater than 0.05; therefore, all attributes have an impact on the Year. For statistical measure, R-squared helps explain how close the data are to the fitted regression line. The goodness of fit (R-squared) shows that it is 68.0 percent, which is just below the acceptable 75 percent value. This shows that there is correlation between the variables and the Year. A modified version of the R-squared value is the Adjusted-R-squared, which accounts for the number of predictors in the model. In this case, the Adjusted-R-squared significantly drops the R-squared value. The Regression Equation helps with predicting attributes for the upcoming years.

Validation through Survey

The integration data were very useful in identifying critical attributes to support a framework for facilitating SoS integration. SoS integration is complex, and the ability to develop a systems integration assessment framework tool to determine integration feasibility is necessary for system integration planning. Although the previously described seven attributes can help improve the integration feasibility assessment, they need to be validated by integration experts.

> ***Integration of new systems into legacy systems may be made more difficult by improper or insufficient support documentation or the unavailability of expert personnel/training expertise.***

Therefore, a survey was conducted to help validate the usefulness of the seven major integration attributes. The survey lasted 4 weeks and targeted 159 systems integration experts with varying experiences in systems engineering, DoD acquisition, space systems, and/or complex SoS. From the 159 integration experts surveyed, 88 responded, which helped validate the attributes derived from the data of the six major space systems (Table 4). The 88 participants were systems engineers, DoD acquisition professionals, and SMEs who primarily have backgrounds in space systems.

The survey asked the participants to list specific systems on which they worked (current and prior experience), their specific field (systems engineering, DoD acquisition, systems integration etc.), and years of experience in their chosen field of work. Once their credentials had been provided, they were asked to rank the attributes from one to seven—one being the most important; the respondents were then asked if they agreed with the seven attributes. They were also given the opportunity to provide additional attributes, and to explain if they agreed or did not agree with the list of attributes and the integration items supporting each attribute. They were asked to provide examples on how useful an SoS integration framework using IRL principles would be in helping with integration activities. Finally, a set of questions was asked to provide examples based on their experience on major integration risk areas, integration timelines, and potential usefulness of IRL.

Summary of Survey Results

There were a total of 18 questions in the survey; some questions, however, were for clarification of responses to prior questions. The survey participants were a very experienced group, with an average of 19.4 years of experience in their respective field. Of the 88 participants, only seven said they were not in complete agreement with the attributes; however, their concerns were all addressed throughout the research process and through the updated definition for each attribute. The concerns were: exclusion of management guidance (addressed under Management); exclusion of concept of operations, which is developed as part of the scope of integration (also a Management task); exclusion of M&S tools (addressed under Processes); exclusion of overall planning (addressed under Management); exclusion of requirements (which is outside the scope of this research, but addressed in Problem Focus); and exclusion of risk areas (technical risks were addressed in Complexity and overall program risks are the output of the systems integration assessment framework). Most of the survey participants agreed that given the right supporting tools, an enhanced IRL assessment would be useful. Based on the results of the initial research (literature reviews and interviews with system integration experts), data collection, and expert survey, the final criteria for each attribute are summarized in Table 8.

TABLE 8. CRITERIA FOR EACH ATTRIBUTE USING DERIVED INTEGRATION VARIABLES

Integration Variables (Criteria to Major Attributes)	Major Attributes
Access high TRL supporting systems, subsystems, and components (i.e., COTS, operational ground systems, operational simulators)	Availability
Access overall expertise and supporting documentation to execute integration activities	
Access supporting hardware and software to execute integration activities (i.e., COTS, Hardware/Software reuse)	
Manage technical risks and low maturity of system design, development, and integration	Complexity
Determine complex interfaces between systems, subsystems, and components	
Manage low TRL supporting systems, subsystems, and components	
Understand compatibility and connectivity of systems, subsystems, and components; inputs into integrated systems produce desired outputs	Interoperability
Manage communications between systems, subsystems, and components; address semantic/syntactic issues	
Develop and document interface control documents	
Plan and develop integration strategies and priorities	Management
Lead coordination, execution, and communication between stakeholder organizations	
Provide guidance and directives to integration activities	
Determine scope of integration activities and concepts of operation	
Manage requirements changes (i.e., eliminate/minimize requirements creep)	
Manage support to integration activities and changes (i.e., supply chain)	
Develop and document policies and agreements with all stakeholders	
Document overall integration activity processes (i.e., overall communication and decision-making processes)	Processes
Develop, document, and execute risks/mitigation processes	
Develop, document, and execute configuration management processes	
Develop, document, and execute information assurance and mission assurance processes	
Develop, document, and execute standards, procedures, and algorithms	
Develop, document, and execute M&S activities	
Develop, document, and execute test, verification, and validation processes	
Develop, document, and execute security and safety considerations	
Develop, document, and execute Training processes	
Develop, document, and execute manufacturing and assembly processes	
Allocate sufficient funding to support all integration activities	Resources
Provide trained personnel to support integration activities	
Provide the right tools and facilities to support integration activities	
Meet timeline goals (i.e., need dates, expected deliveries, milestones etc.)	Schedule
Understand schedule impacts, parameters, and critical path	
Plan for schedule changes and impacts of delays	

All 88 participants ranked the seven attributes in order. Table 9 captures the first and last five survey entries. The ranking of the attributes is distributed by having the No. 1 ranked attribute equal to 7/7 (1.0). Values for the subsequent ranking: No. 2 is 6/7 (or 0.857), No. 3 is 5/7 or (0.714), No. 4 is 4/7 (or 0.571), No. 5 is 3/7 (or 0.429), No. 6 is 2/7 (or 0.286), and No. 7 is 1/7 (or 0.143)

TABLE 9. SURVEY RESULTS: YEARS OF EXPERIENCE AND RANKING OF ATTRIBUTES (PART I)

#	Years of Exp.	Availability	Complexity	Interoperability	Management	Processes	Resources	Schedule
1	39	1.000	0.857	0.714	0.571	0.429	0.286	0.143
2	35	0.143	0.714	0.571	0.286	1.000	0.857	0.429
3	40	0.571	0.714	0.857	1.000	0.429	0.286	0.143
4	34	0.714	0.857	1.000	0.429	0.571	0.286	0.143
5	16	0.857	0.143	0.286	0.714	0.571	1.000	0.429
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
84	26	1.000	0.286	0.857	0.143	0.571	0.714	0.429
85	27	0.286	0.429	0.571	1.000	0.857	0.714	0.143
86	14	0.571	0.857	0.714	1.000	0.143	0.286	0.429
87	35	0.286	0.429	0.143	1.000	0.571	0.857	0.714
88	8	1.000	0.571	0.143	0.857	0.429	0.286	0.714

Survey Analysis

Weights of the attributes will be determined using the years of experience and the ranking of each attribute. The Years of Experience is set up where the values are a lot higher than the value of ranking the attributes. To reduce the skewness of the dependent variable (Years of Experience), the log function will be used for the regression analysis. The log function will help normalize the Years of Experience relative to the scores given to attribute rankings. The results of the survey showed that almost all participants were in agreement with the derived attributes.

The summary of analysis is highlighted in the Normal Probability Graph in Figure 3. The resulting numbers are provided in Tables 10a to 10d, with 10d providing the Regression Equation for the Log Years and the attributes. The ranking of each attribute differed with each person, but there was a clear emphasis on the two highest attributes (Management and Resources) as indicated in Table 10a as well as two of the lowest ranked attributes in Schedule and Interoperability. Based on the analysis, the P-Values for all attributes are slightly greater than 0.05; therefore, the null hypothesis for each attribute impacting the Log Years of Experience is true. The goodness of fit (R-squared) is a very low 18.84 percent, which is expected due to the ranking of each variable where no variable has the same value per sample.

FIGURE 3. NORMAL PROBABILITY PLOT FOR ALL ATTRIBUTES BASED ON SURVEY

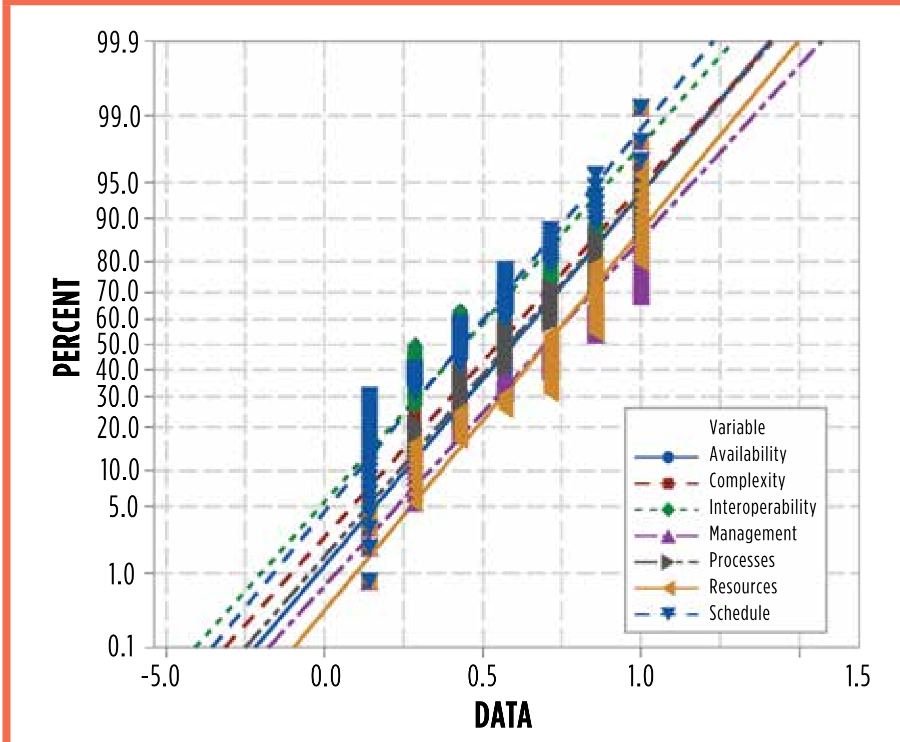


TABLE 10A. SUMMARY STATISTICS					
Variable	**N**	**Mean**	**Standard Deviation**	**Minimum**	**Minimum**
Availability	88	0.59569	0.2618	0.143	1
Complexity	88	0.55038	0.27935	0.143	1
Interoperability	88	0.44165	0.27522	0.143	1
Management	88	0.69642	0.28298	0.143	1
Processes	88	0.58276	0.26971	0.143	1
Resources	88	0.69963	0.25802	0.143	1
Schedule	88	0.43672	0.25645	0.143	1

TABLE 10B. ANALYSIS OF VARIANCE		
Source	**DF**	**P-Value**
Regression	***7***	***0.0161***
Availability	1	0.0883
Complexity	1	0.0716
Interoperability	1	0.0503
Management	1	0.1185
Processes	1	0.0697
Resources	1	0.109
Schedule	1	0.0876

TABLE 10C. MODEL SUMMARY		
S	**R-sq**	**R-sq(adj)**
0.283784	18.84%	11.74%

TABLE 10D. REGRESSION EQUATION
Log Years = −5.925 + 1.776 Availability + 1.857 Complexity + 2.051 Interoperability + 1.601 Management + 1.888 Processes + 1.654 Resources + 1.758 Schedule

Comparing Results

Evaluating the mean and standard deviation for each attribute for both the integration data analysis and the survey analysis will determine the weight for each variable to be used in the integration feasibility framework. Tables 11a to 11c illustrate the derived weight of each attribute.

Based on the percentage for each attribute, there are a lot of disconnects between the integration data analysis and the expert survey analysis on how the attributes should be weighted. The closest numbers for the Data and Survey are Availability at about 12–14 percent and Management at about 13–17 percent. Using the standard deviation, the High and Low for the Means have also been calculated. The percentages for the High and Low values show significant variances. In this case, using the average of two Means will provide a better estimate to use as the final weight of each attribute (Table 11c).

Systems Integration Assessment Framework

The integration requirements are addressed through an architectural framework, which according to Jain et al. (2010), "includes both the physical and functional architectures of the system" (p. 279). Based on the data analysis, subsequent attributes, and the survey analysis to validate the weights of the attributes, a systems integration assessment framework to determine an enhanced IRL value has been developed. When the models of a system are related through transformation, the collective frames can be referred to as a framework (Lin et al., 2009). In this case, the items that were derived from the integration data (and identified by the stakeholders) were used to support the major attribute.

TABLE 11A. MEAN AND STANDARD DEVIATION FOR INTEGRATION DATA AND SURVEY RESULTS

Comparing Analyses	Integration Data, Mean	Integration Data, Standard Deviation	Survey, Mean	Survey, Standard Deviation
Availability	2.188	1.601	0.596	0.262
Complexity	3.188	3.656	0.550	0.279
Interoperability	4.000	2.921	0.442	0.275
Management	2.313	1.448	0.696	0.283
Processes	3.250	2.840	0.583	0.270
Resources	1.000	1.155	0.700	0.258
Schedule	1.000	1.033	0.437	0.256

TABLE 11B. PERCENTAGE OF EACH MEAN AND STANDARD DEVIATION FOR INTEGRATION DATA AND SURVEY RESULTS

Weight	Integration Data, Mean	Integration Data, High	Integration Data, Low	Survey, Mean	Survey, High	Survey, Low
Availability	12.9%	12.0%	25.7%	14.9%	14.6%	15.7%
Complexity	18.8%	21.7%	-20.5%	13.7%	14.1%	12.8%
Interoperability	23.6%	21.9%	47.2%	11.0%	12.2%	7.9%
Management	13.7%	11.9%	37.8%	17.4%	16.6%	19.5%
Processes	19.2%	19.3%	17.9%	14.6%	14.5%	14.8%
Resources	5.9%	6.8%	-6.8%	17.5%	16.3%	20.8%
Schedule	5.9%	6.4%	-1.4%	10.9%	11.8%	8.5%

TABLE 11C. DERIVED WEIGHT OF EACH ATTRIBUTE		
Average Weight	**Mean Total**	**Final Weight**
Availability	27.8%	13.9%
Complexity	32.6%	16.3%
Interoperability	34.6%	17.3%
Management	31.1%	15.5%
Processes	33.7%	16.9%
Resources	23.4%	11.7%
Schedule	16.8%	8.4%

In architectural framework, understanding how the problem is framed is the most important step because it helps define the subsequent steps. Frameworks and standards define what should be modeled as opposed to which models should be used and how these models are related to one another (Zalewski & Kijas, 2013). According to Martin (2008), "problem framing techniques have been found to be useful in avoiding rework and maximizing results" (p. 306). Architectural approaches include conveying options, change, and implications, as well as identifying easier traceability by providing agile documentation (Tyree & Akerman, 2005). The change, based on initial IRL scores to enhanced IRL scores, supports this approach. Architecture analysis includes a key foundation that provides consistency, data completeness and transformation, lack of ambiguity, and flexibility to support iterative processes (Ge, Hipel, & Chen, 2014). Static Analysis is used in which, according to Ge et al. (2013), helps leverage "static architectural models for analyzing and comparing the associations captured from the data elements" (p. 370).

The resulting systems integration assessment framework to facilitate SoS integration is illustrated in Figure 4.

In the framework, one of the initial steps is to determine the IRL value of the integration items supporting each attribute by using the current IRL definitions as guidelines. Tables 12a and 12b provide guidance on how initial IRL for each attribute is defined.

FIGURE 4. SYSTEMS INTEGRATION ASSESSMENT FRAMEWORK

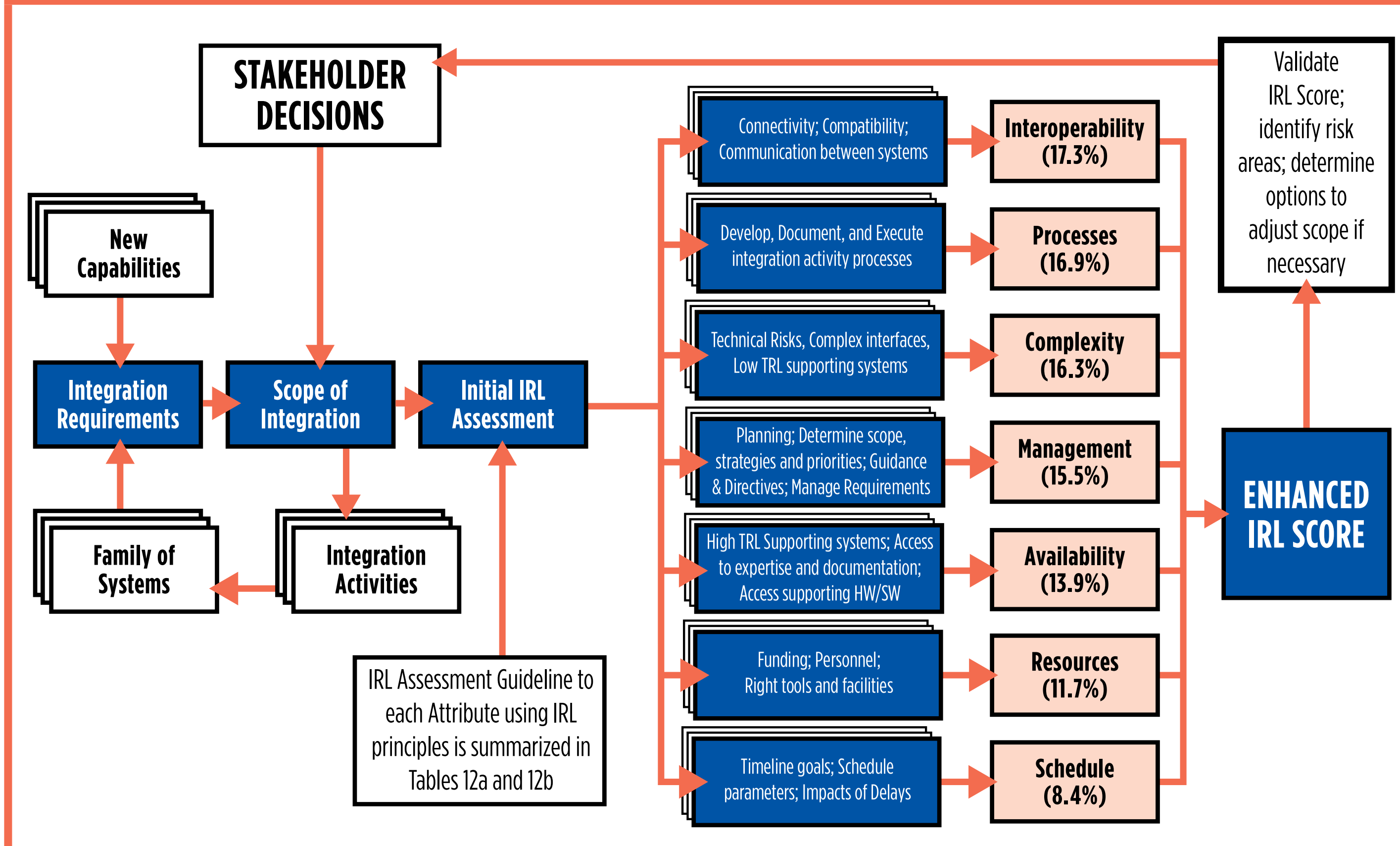


TABLE 12A. GUIDLINES TO INITIAL IRL FOR EACH ATTRIBUTE USING IRL PRINCIPLES (PART I)

IRL Level	IRL Principles	IRL Availability	IRL Complexity	IRL Interoperability
1	Interface has been identified	All currently available and unavailable supporting integration items (systems, subsystems, components, expertise, and documentation) are identified	Complexity and technical risk areas of design, development, and integration are identified	Interfaces and connectivity areas of systems, subsystems, and component items are identified
2	Interaction has been specifically characterized	Available and unavailable items are characterized	Technical risk areas are characterized	Interaction between items is characterized
3	There is compatibility	Initial plans to obtain unavailable items are compatible with overall strategy	Initial mitigation strategies are compatible to technical risk areas	Interoperability strategies are compatible with integration activities
4	Sufficient detail in quality and assurance	Plans to obtain unavailable items provide sufficient details	Sufficient detail for mitigation strategies is defined	Interoperability strategies have sufficient details
5	Sufficient control	Plans are delivered and have sufficient control	Proposed mitigation strategies are delivered and have sufficient control	Proposed strategies are delivered and have sufficient control
6	Accept, translate, and structure information	Proposed plans are accepted and executed	Mitigation strategies are accepted	Proposed strategies are accepted and executed
7	Verified and Validated	Plans are verified and validated	Mitigation strategies are verified and validated	Proposed strategies are verified and validated
8	Mission-Qualified	All items are delivered and mission-qualified	Mitigation strategies are mission-qualified	Proposed strategies are mission-qualified
9	Mission-Proven	All items are mission-proven	Mitigation strategies are mission-proven	Proposed strategies are mission-proven

TABLE 12B. GUIDLINES TO INITIAL IRL FOR EACH ATTRIBUTE USING IRL PRINCIPLES (PART II)					
IRL Level	**IRL Definition**	**IRL Management**	**IRL Processes**	**IRL Resources**	**IRL Schedule**
1	Interface has been identified	Management strategies, scope, requirements, and priorities are identified	All integration activity processes are identified	All resources and funding risks to support integration are identified	Detailed integration schedule and schedule risks are identified
2	Interaction has been specifically characterized	Key management decisions are characterized	Processes are characterized	All resources and funding risks are characterized	All schedule items and risks are characterized
3	There is compatibility	Current strategies are compatible with management decisions	Processes are documented and are compatible with management strategies	Initial mitigation strategies to funding risks are compatible with integration strategy	Initial mitigation strategies to schedule risks are compatible with integration strategy
4	Sufficient detail in quality and assurance	Management strategies have sufficient detail in quality and assurance	Processes are sufficient detail in quality and assurance	Mitigation strategies have sufficient detail in quality and assurance	Mitigation strategies have sufficient detail in quality and assurance
5	Sufficient control	Management strategies are implemented with sufficient control	Processes are documented with sufficient control	Mitigation strategies are delivered with sufficient control	Mitigation strategies are delivered with sufficient control
6	Accept, translate, and structure information	Management strategies, goals, and scope are accepted and executed	Processes are accepted and executed	Mitigation strategies for funding risks are accepted and executed	Mitigation strategies for schedule risks are accepted and executed
7	Verified and Validated	Management strategies are verified and validated	Processes are verified and validated	Mitigation strategies are verified and validated	Mitigation strategies are verified and validated
8	Mission-Qualified	Management strategies are mission-qualified	Processes are mission-qualified	Proposed strategies are mission-qualified	Mitigation strategies are mission qualified
9	Mission-Proven	Management strategies are mission-proven	Processes are mission-proven	Mitigation strategies are mission-proven	Proposed strategies are mission-proven

Approaches to determine IRLs include: (a) individual estimation by an SME; (b) group discussion estimation through meeting or conference; and (c) individual-group estimation where SMEs complete independent estimations and then discuss them with a group for a consensus decision (Tan, Ramirez-Marquez, & Sauser, 2011). Some of the current techniques that can be used to formulate the estimate of IRL assessment also include educated guess (not enough knowledge and not enough time), analogy (comparing prior work), and standards (developed within different organizations) (Tan et al., 2011). Using the framework for systems integration will be an iterative process.

The process of using the Systems Integration Assessment Framework, consisting of 11 steps, is as follows:

1. SoS integration begins with the concept of integrating new capabilities to either an existing Family of Systems or a new SoS.

2. Integration requirements are written clearly and approved by the stakeholders.

3. The Scope of Integration (i.e., cost, schedule, performance, integration planning, Concept of Operations etc.) are determined by the stakeholders.

4. Based on the Scope, the integration activities can either proceed (if integration has been done before) or assess the overall feasibility of the Scope of Integration.

5. To begin understanding the overall feasibility of integration, the stakeholders and designated SMEs determine IRL score for all possible integration items supporting each major attribute.

6. Using IRL principles (as described in Tables 12a and 12b), determine the initial IRL value for each attribute.

7. Use the derived weighted percentage to determine the enhanced IRL score for the SoS (IRL_{SoS}). The resulting equation becomes:

$$IRL_{SoS} = (IRL_{Availability} \times 0.139) + (IRL_{Complexity} \times 0.163) + (IRL_{Interoperability} \times 0.173) + (IRL_{Management} \times 0.155) + (IRL_{Processes} \times 0.169) + (IRL_{Resources} \times 0.117) + (IRL_{Schedule} \times 0.084)$$

8. The Enhanced IRL score will determine integration feasibility.

9. Stakeholders evaluate and validate the enhanced IRL score, identify risk areas, and determine options to adjust the scope of integration, if necessary.

10. Determining integration feasibility is an iterative process, and this framework allows the stakeholders to look at options to improve the scope when new information is obtained.

11. Assessment of IRL can also be tied to major events and reviews throughout the development and deployment processes. It allows program managers to make adjustments to their programs based on the results of the IRL assessment.

Conclusions

Based on the research, integration data collected from the six major DoD Space Systems, and expert survey, seven attributes were derived in order to develop a framework that can facilitate SoS integration. A systems integration assessment framework tool provides an enhanced IRL score that will help determine integration feasibility in planning and facilitating integration activities. Based on a survey of experienced systems engineers, systems integrators, and DoD space acquisition personnel, the attributes were necessary to help plan and implement integration processes. The attributes were validated through the expert survey, and the results proved that other attributes were more important than those initially defined.

The attributes with their derived weights are the primary entities for the integration assessment framework tool. The tool can be used as many times as new information is provided, and adjusting the expectations and scope can help with understanding the feasibility of the IRL score. Calculating the enhanced IRL score is an iterative process with the thought that the IRL score could improve through time due to additional information and adjustments to each attribute. Although the current DoD process of deploying space system capabilities for operational use does not require assessment of integration maturity, the result of this research should help quantify the feasibility of integrating SoS using IRL principles.

Limitations and Future Work

Although several processes have been provided to assess TRL and IRL, there is still some subjectivity to these analyses. Every program has some uniqueness on how to integrate its systems, but the past data and past experience can help put some rigor in the analysis. IRL has effective principles if it complements other analyses and helps with program manager decisions. Results can offer areas of emphasis as opposed to detailed solutions. For IRL to be used effectively, high-level assumptions need to be clear, upfront, and agreed to by stakeholders.

When grouped with other readiness metrics, IRL may have some applications in DoD research and development (Ross, 2016), but IRL itself does not have the capacity to critically assess research and development efforts. It also does not evaluate cost and schedule (Sauser et al., 2010). A more quantitative algorithm may be required for the assessment of IRL for complex systems. Without rigorous criteria, assessment for the determining IRL could lead to inaccurate analysis. Assessment of TRL and IRL sometimes can lead to oversimplification (Ramirez-Marquez & Sauser, 2009).

Although some of IRL may be subjective, there are several analyses using IRL principles that can be done to develop processes and help with program managers' decisions on SoS integration. Throughout DoD acquisition and large complex programs, integration challenges will continue to persist, and the need for additional analysis and tools to overcome those challenges is real and necessary.

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