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International Space Station Large Scale Integration Approach

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International Space Station
LARGE SCALE INTEGRATION APPROACH

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ABSTRACT

The International Space Station is the most complex large scale integration program in development today. The approach developed for specification, subsystem development, and verification lay a firm basis on which future programs of this nature can be based.

International Space Station is composed of many critical items, hardware and software, built by numerous International Partners, NASA Institutions, and U.S. Contractors and is launched over a period of five years. Each launch creates a unique configuration that must be safe, survivable, operable, and support ongoing assembly (assemblable) to arrive at the assembly complete configuration in 2003.

The approaches to integrating each of the modules into a viable spacecraft and continue the assembly is a challenge in itself. Added to this challenge are the severe schedule constraints and lack of an "Iron Bird", which prevents assembly and checkout of each on-orbit configuration prior to launch.

This paper will focus on the following areas:

1) Specification development process explaining how the requirements and specifications were derived using a modular concept driven by launch vehicle capability. Each module is composed of components of subsystems versus completed subsystems.

2) Approach to stage (each stage consists of the launched module added to the current on-orbit spacecraft) specifications. Specifically, how each launched module and stage ensures support of the current and future elements of the assembly.

3) Verification approach, due to the schedule constraints, is primarily analysis supported by testing. Specifically, how are the interfaces ensured to mate and function on-orbit when they cannot be mated before launch.

4) Lessons learned. Where can we improve this complex system design and integration task?

BACKGROUND

The International Space Station began with Space Station Freedom as the point-of-departure for definition and implementation of the functional baseline. Freedom left the following as initial conditions for the International Space Station baseline:

1) A vertical and horizontal requirement system in the middle of being converted to a vertical system.

2) A combination of "build to" (i.e., statement of work and design direction) and functional requirements.

3) A software requirement set not integrated with the hardware to define the functional baseline.

4) Hardware and software in different levels of maturity and to different requirement baselines that had to be used to create the lowest cost implementation.

5) An allocation of the hardware and software components to elements.

6) No clear definition of the mission and performance of each stage.

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7) An undefined integrated verification program.

8) Three major U.S. contractors and four International Partners/participants who were to deliver hardware and software that functioned together.

These initial conditions and a preliminary assembly sequence were then used to develop the technical baseline that today is reaching the stage of integrating real hardware and software. The process of integration used to date and planned, as the hardware and software are tested, is described in this paper.

INTEGRATION PROCESS MACRO-PROCESS

The macro-process used in the International Space Station program is based on standard System Engineering principles.

1) Define a detailed requirement set (functional, performance, and design constraints) that translates the desired functions into a design that can be manufactured.

2) Define and document the functional performance baseline that allows each of the U.S. contractors and International Partners/participants to work independently to produce an integrated system.

3) Check preliminary and critical designs against functional performance requirements.

4) Check preliminary and critical designs to ensure physical integration (interfaces, hardware, and software)

5) Show compliance to the functional performance baseline, including the interfaces.

As these principles are applied to the International Space Station model the following occurs.

1) Establishment of the functional performance baseline for each stage that allows assembly of the vehicle on-orbit (top level assembly/final manufacturing) and ultimately the assembly complete configuration. This creates:

   a) The Assembly Implementation Requirements Documents, which acts as the system specification for each stage.

   b) A unique set of external interfaces for each stage, which is defined and documented in Interface Control Documents.

   c) The assembly complete system specifications.

2) Performance of the Design Analysis Cycles to check preliminary and critical designs against performance requirements.

3) Performance of interface analyses and tests, both functional and physical, for each stage proving the ability to provide safe and survivable assembly and operation to the next stage.

4) Conduct of the Flight by Flight and Stage Assessment Review to define the assembly operations and any unique functional performance capabilities required to ensure safe assembly.

5) Performance of an integrated test program, based on the documented definition (Assembly Implementation Requirements Documents and Operational Sequence Diagrams) of each stage and future stages, uses the highest fidelity hardware and software available prior to any launch to gather data used to validate integrated stage models. These models are used to show compliance with the Assembly Implementation Requirements Documents. This is done in:

   a) Software stage verification tests performed in a laboratory environment with: software that is flying; software to fly; and future flight software. The purpose is to prove that the integrated software correctly operates.

   b) Shuttle Avionics Integration Laboratory testing, which tests

Station integrated software with the Shuttle software and the Mission Control Center for those flights where the Shuttle system is performing functions allocated from International Space Station. This is used to prove that the Mission Control Center, Shuttle, and International Space Station software, when integrated in a high fidelity Shuttle environment, correctly work together.

c) Cargo Element testing, which tests elements that are integrated on the ground before launch, with simulations of the on-orbit vehicle and future vehicles, to prove operability of the next stages and the ability to support operability of future stages.

d) Integrated Verification Testing, which tests high fidelity and real Shuttle flight hardware with the International Space Station flight hardware to prove integrated operability of the real hardware and software of both systems. This is done for those flights where the Shuttle system is performing functions allocated from International Space Station.

e) Multi-Element Integration Testing, which tests multiple International Space Station flight elements at one time with Mission Control Center and Shuttle to prove integrated operability of multiple stages with real flight hardware and software.

6) Performance of the Verification Analysis Cycle. This analysis uses the as-built configuration and validated models to prove compliance with the Assembly Implementation Requirements Document for Certification of Flight Readiness.

Functional Baseline Development Process

Figure 1 is the specification tree that resulted from ensuring the integration of the three U.S. contractors, five International Partners/participants, ground system, the Government Furnished Equipment, and the assembly sequence constraints.

The functional baseline definition started with expanding the definition of the mission using Operational Sequence Diagrams and then functionally decomposing the mission. These functions along with their associated performance requirements were then documented in the specifications and Interface Control Documents/Interface Requirement Documents.

The specification and interface development process started by defining the on-orbit assembly complete requirements and documenting them into the System Specification. These requirements were then allocated to the International Partners, the ground system, and the U.S. on-orbit segment. The U.S. segment was then allocated to deliverable elements. These deliverable elements represent the functionality of an element at the time of delivery, with interfaces to other elements and the interfaces for any future functionality to be added on-orbit (as defined in the assembly sequence).

After the assembly complete requirement set and interfaces reached a point where the implementation was well known, the unique stage-by-stage performance requirements and interfaces were and continue to be developed. These unique requirements are then flowed down to the segment or element that will provide the unique functionality and interfaces.

Assembly Complete Specification Development Process The specification development process started with defining the assembly complete states and modes of the integrated space station system (A state is defined as a set of modes that the station would operate in. A mode is defined as a group of capabilities, functions.).

The first definition of these states and modes was based on a set defined in the Space Station Freedom Data Management System. These

states and modes were then better defined by taking the mission statement that can be found in the System Specification for the International Space Station, SSP 41000, "The mission of the Space Station is to perform engineering research, conduct scientific experiments in an international, Earth orbiting, research facility in a microgravity environment at a nominal orbit of 220 nautical miles at a 51.6 degree inclination", and performing a functional decomposition.

This functional decomposition was then mapped into the specifications as shown in Figure 2.

These functions, or groups of functions, represent subsystems that run horizontally across elements and segments. Using the subsystem point of departure architecture, the functions were allocated to the specific segment and/or deliverable element.

The process for allocation of subsystem functions used the following techniques:

1) Assessment of the Freedom allocation of components to elements.

2) First order assessment of the safe, survivable, assemblable, and operable requirements defined by the assembly sequence.

3) First order assessment of the operation of the subsystem.

4) First order assessment of packaging limitations.

5) First order assessment of the testability of the architecture.

Then verifiable performance requirements were added to each of these functions based on mission need and previous experience.

In parallel the mission statement and operational concepts were being expanded with the operators and users, resulting in the Concept of Operation and Utilization. The Concept of Operation and Utilization was continually bounced against the functional decomposition and performance requirements to ensure that the operators and users' needs were fully addressed.

Also during this process the hardware and software development status of the Freedom components were considered with the goal of using all of the Freedom hardware and software with minimal changes to implement the requirement set. To reach that goal the U.S. contractors were allowed to take exception to requirements that did not jeopardize crew safety or the mission success, but would result in rework of Freedom hardware and software. This resulted in the collision of the classical top down requirement allocation approach and the bottom up, known functional performance of the existing Freedom components. Ultimately what resulted was:

1) A set of requirements that had been scrubbed for necessity and "design-to" efficiency.

2) A set of issues that would manifest into requirement changes that ultimately resulted in a moving baseline hampering the ability to solidify the verification planning.

Stage by Stage Requirements Development Approach As the implementation and the assembly complete requirements matured, a Flight by Flight review of Operational Sequence Diagrams was and is being performed. In this review a determination is made of how the hardware and software design will be used to assemble and operate the stage safely. The result is a set of stage unique requirements and Operational Sequence Diagrams that define the safe, survivable, operable, and assembly requirements of the hardware and software that make up the stage.

Start of the Flight by Flight review requires prior development of a preliminary set of Operational Sequence Diagrams and the preliminary stage functional performance requirements documented in the Assembly Implementation Requirements Document. The Assembly Implementation Requirements Document also includes:

1) Preliminary stage Requirement Allocation Matrix showing the minimum functions necessary to ensure a safe, survivable, operable, and assemblable stage. (Minimum is define by the level of analysis performed.)

2) Preliminary Stage Interface Matrix which depicts the interfaces of the elements for all the stages, including unique stage interfaces. This matrix is also used to define the configuration of the interfaces during element and integrated testing.

During the Flight by Flight review the Assembly Implementation Requirements Document is matured and any unique requirements (functional and performance) are allocated to the element that provides this uniqueness. Also in this review the Operational Sequence Diagram is matured to be in concert with the design and the Stage requirements as documented in the Assembly Implementation Requirements Document.

At the point when the critical design is available for an element or group of elements, the Stage Assessment Reviews was and is being performed. During the Stage Assessment Reviews the Assembly Implementation Requirements Document and Operational Sequence Diagrams that resulted from the Flight by Flight process are validated against the design and any changes in the assembly sequence. This results in a final Assembly Implementation Requirements Document and Operational Sequence Diagrams under configuration control.

This process of Flight by Flights and Stage Assessment Reviews is not yet complete for all flights at one time due to the unavailability of design details for the late flights. To ensure that an early element has all the functionality required to support later stages, a second order assessment is performed using the subsystem architecture and whatever Operational Sequence Diagrams are available. This is documented in the stage Requirement Allocation Matrices and Stage Interface Matrices.

At a later time when the design matures enough to perform the Flight by Flight review and Stage Assessment Reviews for all the flights, the stage requirements will be completed.

Verification Development Process

The International Space Station verification process is based on the concept that each level of assembly will be verified before being integrated into the next level, (i.e., the majority of the environmental testing is done at the component level).

The International Space Station verification program has two types of verification testing:

1) Qualification and acceptance testing. Qualification testing is used to qualify the design, and acceptance testing is used to prove workmanship on subsequent units (serial numbers).

2) Proto-flight testing. Proto-flight testing is not as severe as qualification testing and not always as benign as acceptance testing. The purpose of proto-flight testing is to test the design and workmanship in concert and still be able to fly the unit without degradation of reliability. This is done without exposing the unit under test to the normal qualification margins. This is usually reserved for a one of a kind unit.

The verification philosophy requires the International Partners/participants, U.S. contractors and Government Furnished Equipment providers to deliver hardware and software qualified to the specification containing the allocated International Space Station requirements. This verification is a combination of test, demonstration, analysis, and inspections. The results of these verifications are used in the integrated verification program.

Verification of the integrated International Space Station system is mainly concentrated on two areas:

1) Functional and performance verification

2) Physical integration verification to ensure the elements will mate on-orbit.

Integrated Functional and Performance Verification The functional and performance verification of the International Space Station integrated system is mostly performed by analysis for each stage. These analyses are based on test data from either lower level testing or the integrated testing described earlier. This test data is either used as a condition for the analyses or to validate models used in the analyses.

The integrated verification development process employed on International Space Station is a five step process:

1) Establish that a verifiable requirement exists.

2) Establish the verification logic and success criteria necessary to show compliance to a requirement. The process employed at the integrated system level is to use Verification

Logic Networks and Detailed Verification Objectives.

3) Perform the verification.

4) Document the results and compare to the success criteria.

5) Generate the Verification Completion Notice.

After establishing that a verifiable requirement exists, the verification planning process begins with the establishment of the strategy to be employed to close the requirements. This includes establishing the type of analysis to be performed, the model to be used if required, and the approach to validating the model, including the test data and conditions required. The logic network developed from the strategy identifies the data required from each end item provider in support of the integrated verification. The logic network also links to the integrated testing as needed. For each activity on the logic network a Detailed Verification Objective is developed to ensure that the objectives, success criteria, configuration, conditions, and prerequisites are planned for and met.

Next is the performance of the steps outlined in the logic network. This is the execution of the integrated tests discussed earlier and/or unique subsystem tests. Also, this is the execution of the model validation and model configuration management, and the execution of the analysis as part of the Verification Analysis Cycle. The Verification Analysis Cycle is the orchestration of all the integrated analysis so that each user of other analysis data uses consistent data that is the resultant of a validated model.

The results of the integrated testing and Verification Analysis Cycle are then compared to the success criteria on the Detailed Verification Objectives. Any discrepancies are corrected, maintaining the philosophy that each stage must be safe, survivable, operable, and able to be assembled and support future assemblies (assemblable). At the completion of correcting the discrepancies, the verification report is released and a Verification Completion Notice is completed.

Completion of all the Verification Completion Notices for the logic network proves the integrated stage functional performance is ready for flight.

Physical Integration Verification To ensure success of the International Space Station program, assembly on-orbit must be successful. The alternatives of returning elements to earth or leaving elements half mated where they may freeze or break in other ways must be avoided. Due to schedule constraints (i.e., elements which mate are developed, manufactured, and launched over a 5 year period) and elements design constraints (inability to mate in a 1g environment), an alternative to mating flight elements had to be developed. Concentration on the mechanical mating of berthing mechanisms and fluid and electrical connections yielded two schemes which are being executed today to ensure mating on-orbit:

1) Digital Pre-Assembly which is a technique of developing as-built models on Computer Aided Three Dimensional Interactive Applications and analyzing the designs of two elements that berth to ensure there are no interferences that will keep the elements from mating. This technique combines the tools of Computer Aided Three Dimensional Interactive Applications with the technology of photogrammetry to produce a high fidelity evaluation of the mating capability of the elements.

2) Cable and Fluid line mating and fit check are processes where the actual cables and fluid lines that are mated on-orbit are mated in a 1g environment on the ground by a crew person in a configuration that closely represents the on-orbit constraints. The mating and fit checks are combined with "design-to" Interface Control Document audits and a second check of the "as-built" hardware to the Interface Control Document and design to further reduce the risk of interface incompatibilities.

LESSONS LEARNED

Many of the lessons learned have been incorporated in the process outlined here. Some lessons learned have not been incorporated, since that part of the process has been completed, but may be applicable in other future applications, possibly on a "Mission to Mars" or some other large scale, complex integration tasks. These lessons learned are as follows:

1) Hardware and software must naturally integrate by working the integration task from day one. This is solved by education, working together, and removing barriers.

2) The verification logic should be thought out and documented during the requirement development and allocation process. This would assure a complete understanding of all test configurations, test points, analysis models, and data requirement usages.

3) The macro-process, which gets a program from a mission statement to launch, needs to be worked out, documented, and communicated to all program participants. As more detail is added to the macro-process, process reviews with objectives in line with reviews like Preliminary Design Reviews and Critical Design Reviews should be conducted. As this detail is created, additional communication and documentation to all program participants must be maintained.

4) Processes that do not work or are not efficient should not be thrown out but slowly changed over time to a more efficient, better process. This always needs to be done within the scope of the macro-process.

5) Not only is there a need to integrate analysis using a Design Analysis Cycle or Verification Analysis Cycle, but also a need to cyclically check interface implementation (physical integration), verification logic implementation (verification integration), and functional implementation (checking the software design, human interface design, Operational Sequence Diagrams, and requirements to assure they are in concert with each other). Some of this is being executed in the Stage Integration Reviews today.

6) More attention needs to be paid to verification of functions allocated to the astronauts, such as cable mating.

7) More attention needs to be paid to functions allocated to Government Furnished Equipment and external interfaces, such as portable computers on the Shuttle.

8) Reviews, Preliminary Design Reviews, Critical Design Reviews, Stage Integration Reviews, Test Readiness Reviews, etc. are a necessary evil that should be primarily embraced as risk mitigation by program management and supported by the integration team, customer, and user. This is the only way to assure a program will deliver an integrated verified design that meets the user and customer needs documented in the requirements and schedule.

9) The process of cost convergence (achieve program fit to funding mandate) created issues and customer needs that were not fulfilled. This created a moving baseline that has impeded verification planning along with Functional Configuration Audit planning. Implementation of a strong change board that builds agreed-to integrated schedules is mandatory to get to a successful flight.

Other lessons learned become more evident as companies merge and contracting relationships change. Some of these lessons are:

1) Deletion of the functional deliverable of end items in trade for the formal delivery of stages. For stages this is just a paperwork change, but for the program this is a deletion of analysis done at the end item level, which can result in a large savings. This concept is sound in system integration theory, but would require more explanation and research.

2) Common process deployment (one company process) versus process assessment (understanding other company processes) allows for learning curves and lessons learned to be used to gain efficiencies later in the program.

The lessons learned here are just some of the lessons that have been learned on this multi-stage (multi-spacecraft), multi-dimensional, large scale, complex system integration task.

Figure 1
ISS Specification Tree

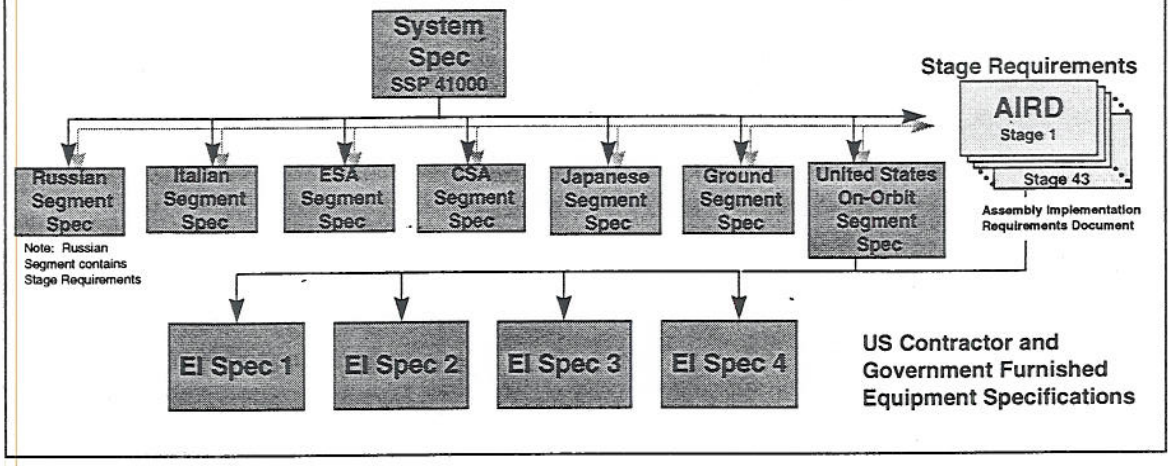
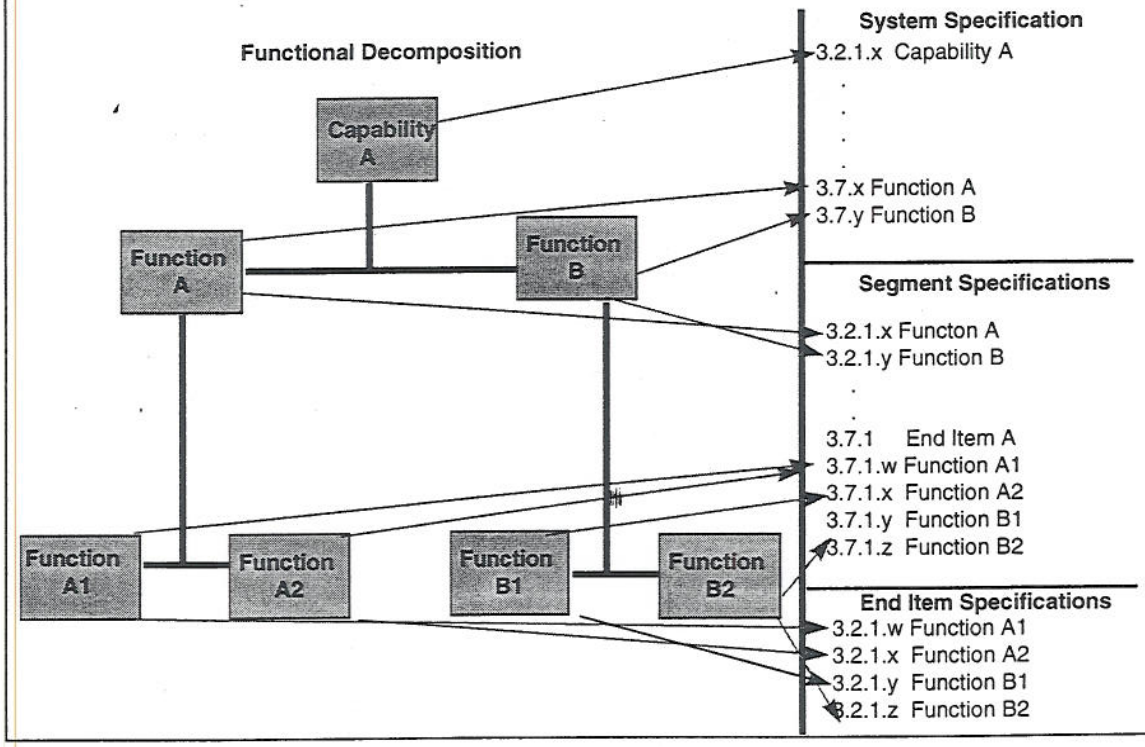
Figure 2 Functional Decomposition Incorporation into Specifications