

NASA UNSOLICITED PROPOSAL
Technical Proposal

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COVER SHEET

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**Comprehensive Analysis and Synthesis of
System Architectures for Space Exploration**

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1. Introductory Material

Comprehensive Analysis and Synthesis of System Architectures for Space Exploration

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2. Abstract

MIT proposes a three year research project in analysis and synthesis of system architectures for space exploration. The study results will support ongoing efforts at NASA to generate an integrated architectural plan that is consistent with the new flexible stepping stone approach to space exploration. MIT's efforts will focus on space transportation and extravehicular activities as a first task by leveraging the latest scholarship in system architecture, multidisciplinary design optimization and a number of frameworks developed under previous space systems projects. The research approach consists of an analysis of existing space architectures (baseline), followed by goal and functional decompositions of future missions. Architecture synthesis involves concept generation and concept selection via quantitative trade space analyses. Particular emphasis will be placed on contributing architectural aspects to current orbital space plane (OSP) definition efforts. A second, optional task of the project would be carried out during the second and third year and would broaden the scope to include planetary surface mobility and human habitats. The impact of the project to NASA will be an enhanced capability to describe, analyze, synthesize and implement new space system architectures using principles, methods and tools developed in academia and relevant industries. The concepts of modularity-enabled staged deployment, reconfigurability and extensibility are important ingredients of the research. The central question is whether such ideas can break the current mission-specific-architecture paradigm by reusing modules and common platforms between multiple missions. An opportunity for educational involvement exists in the form of both undergraduate (16.83) and graduate (16.89) design capstone courses in Space Systems Engineering at MIT. The proposal concludes by discussing the competency and experience of the investigators and the adequacy of MIT's facilities to ensure project success. The frequency and quality of communications between the sponsor (NASA Space Architect) and the MIT team will be crucial in order to benefit NASA.

This proposal has been prepared in accordance with NASA's guidelines for unsolicited proposals [1]. Exploratory technical discussions were held with Gary L. Martin, NASA Space Architect, at MIT on March 21, 2003 and at NASA Headquarters on June 10, 2003.

3. Project Description

3.1 Background

Traditionally, space exploration has been viewed and practiced in essentially separate domains such as manned spaceflight, robotic planetary exploration, astronomical space science or Earth observation. This includes the set of required mission-driven aerospace technology development programs. These efforts have been led by NASA's Enterprises with varying degrees of coordination and success. Recently, NASA has articulated the need for an integrated space strategy that cuts across organizational boundaries.

The development of such an integrated strategy has led to the creation of a new position at NASA: The Space Architect. The primary responsibilities of the Space Architect are as follows:

- Develop and recommend an integrated space strategy
- Identify long-term investment plan to implement the strategy
- Collect and integrate the supporting rationale for the evolving strategy including formulation of science and research goals, seeding of commercial space development opportunities and ensuring broader impact on education
- Develop technology and strategic roadmaps
- Continuous assessment and reporting of progress towards achieving the goals of the integrated space strategy
- Communication with various stakeholders inside and outside the agency

A flowdown of these activities is shown in Figure 1.

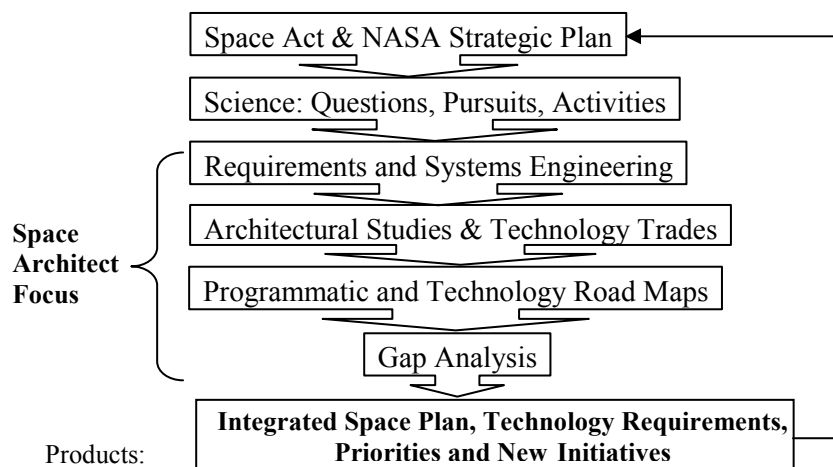


Figure 1: Flow Diagram of NASA Space Architect Activities, Ref. [2]

The desire for an integrated space strategy is motivated by a fundamental shift in the nation's space exploration strategy. The traditional focus of space exploration has centered on a relatively small number of very large, complex missions such as Project Apollo or the International Space Station (ISS). This traditional approach has been dubbed the "Giant Leap" approach. This approach did not absolutely require an overarching architectural plan as it was natural to compartmentalize and focus major space projects. While this approach has led to a number of

spectacular successes such as the first human landings on the Moon (1969-1972) and the establishment of a permanent laboratory in Low Earth Orbit, it must be said that many of these undertakings have been designed with emphasis on short or mid-term mission goals. The argument goes that the resources consumed by and systems designed for these missions were successful as measured by their specific goals, but that they did not deliberately benefit a greater long-term architecture for sustainable space exploration. Incorporation of “long-term goals” or extensibility options are usually viewed (mainly by program managers) as “requirements creep”, which jeopardizes mission success by diverting resources and focus away from the primary mission. An example of a persistent and controversial argument in this context is the choice of Lunar-Orbit-Rendezvous (LOR) for Apollo. One side argues that LOR enabled the mission from a mass and schedule standpoint; with the other side asserting that an Earth-Orbit-Rendezvous architecture might have been more complex in the short term, but more beneficial for space activities in the long term. Regardless of these historic arguments, a new strategy for space exploration is emerging at NASA: “Stepping Stones and Flexible Building Blocks”. The traditional approach and the new approach for space exploration are contrasted in Table 1.

Table 1: Comparison of “Giant Leap” and “Stepping Stone” approaches to space exploration

<i>Traditional Approach: Giant Leap (e.g. Apollo) → 1960-2000</i>	<i>New Approach: Stepping Stones and Flexible Building Blocks → 2000+</i>
- Cold War competition set goals - National security justified investment - Focus on the moon - Human space presence an end unto itself - Robotic missions are secondary - Single mission focus with little reuse of components or systems between missions - Rigid timeframe for completion, goals that are frozen as early as possible - Technologies are destination and mission-specific - Quest for maximum performance subject to (almost) unlimited budgets - Fixed mission scenarios, with few in-situ decision options, avoid improvisation - Limited educational outreach	- NASA vision and mission drive goals and justify investment - Robust and flexible capability to visit several potential destinations - Human presence is a means to enable scientific discovery - Integrate/optimize human-robotic mix to maximize scientific output - Timeframe paced by capability (“as needed”) and budgets (“as afforded”) - Key technologies enable multiple, flexible capabilities - Quest for maximum affordability and flexibility subject to performance and risk constraints - Inspiration and educational outreach is an integral part of space exploration

Source is Reference [2].

This new strategy is partially forced upon NASA by the fiscal realities of stagnant budgets and is partially due to a proactive realization that new architectural concepts (e.g. satellite clusters, staged deployment, reconfigurability) and new technologies (e.g. hybrid propulsion systems, active materials, reconfigurable electronics, software agents) enable such a paradigm shift.

Developing a new integrated space strategy that is consistent with the new approach, cf. Table 1 right hand side, will be a very challenging undertaking. Some of the key challenges and needs for the Space Architect are likely to include the following:

1. Documenting the existing space exploration architectures in a coherent fashion that captures both the form and function of these systems in sufficient detail. (Baselining)
2. Determining the needs and utilities of the key stakeholders involved in space exploration, including Congress, NASA internal enterprises, functional offices and centers, the space science community, the aerospace industry, other space-related federal agencies, universities and educational institutions as well as international partners.
3. A rigorous process for flowing down needs to goals to functional requirements and constraints that can serve as inputs to the systems architecting process.
4. Methods and tools of System Architecture that allow to document and assess the complexity, modularity and goodness of competing architectures. Formal means of synthesizing new architectures.
5. Architecture trade methodologies that can enable trade studies of large design spaces involving multiple, competing objectives such as performance, robustness to failure, system capacity and lifecycle cost.
6. Formal methods to quantify the impact and value of modularity and flexibility on extensibility (=evolvability) of space exploration architectures.
7. Methods and tools to carry out quantitative technology assessment and selection in the context of the previous system architecture trade studies. Such an assessment has to take into account financial and performance uncertainties associated with particular technology readiness levels (TRL's).
8. Quantification of “non-technical” influences on the systems architecting process such as budgetary policy, international cooperation, launch vehicle strategies and technology export restrictions.
9. Formulation of flexible implementation plans that are consistent with the “stepping stone” approach. Development of appropriate staged deployment strategies.
10. Ensuring general acceptance of the integrated space strategy inside and outside NASA
11. A process and decision framework for adapting the integrated space strategy over time.

The NASA System Architect and his team will require a number of specific principles, methods and tools to meet these challenges. This proposal specifies a research project that will support the Space Architect in meeting some of these critical challenges. The project focuses on those aspects, where (1) MIT can add value as an independent, academic institution and (2) where methods and tools developed under previous projects can be leveraged to NASA's benefit. The following sections spell out the specific objectives and plan of work of the project as well as previous work in space systems architecting that will be extended by this project.

3.2 Project Objectives, Domains and Expected Significance

The overall objective of the project is as follows:

To develop a coherent set of principles, methods and tools that will directly support NASA's Space Architect in developing an integrated space exploration strategy, and to apply these to a selected set of architectural studies.

The research is broken down into four domains, corresponding to the areas of expertise of the MIT team as defined in Section 5. The first task (Task A) will be carried out during years one, two and three and will focus on Space Transportation and Extravehicular Activities (EVA). The second task (Task B) is optional and would extend the research to Planetary Surface Mobility and Human Habitats during years two and three.

Task A (Years 1 to 3)

Domain 1: Space Transportation

- Current launch vehicles and infrastructure from Earth to Low Earth Orbit (LEO)
- Architecture of planned systems (STS life extension, OSP, EELV, NGLT)
- Manned and unmanned rescue, transfer and resupply vehicles in LEO
- Vehicles and technologies to reach higher orbits and other bodies and planetary surfaces
- Modules for grappling and sensing, crew and cargo modules, propulsion and power units as well as reentry and landing systems

Domain 2: Extravehicular Activities

- Next generation space suit architectures as well as accessories and tools
- Astronaut mobility and dexterity requirements for various environments and missions
- Ingress/egress procedures and implications of suit pressure levels and atmosphere composition on astronaut effectiveness and safety
- EVA imposed vehicle requirements on domain 1 (e.g. air lock architectures, pressures)

Task B (Year 2 and 3) – optional

Addition of domains 3 and 4.

Domain 3: Planetary Surface Mobility

- Planetary surface rovers and general mobility enhancement systems
- Power, propulsion, life support and over-the-horizon communications technologies
- Modularity strategies and self-assembling, reconfigurable mobile robots for flexible planetary exploration

Domain 4: Human Habitats in Space

- Architectures for potential planetary habitats: Moon, Mars, Asteroids, Jovian Moons
- Next generation space station architectures, ISS evolvability

- Application of modern ground-based architectural principles (e.g. “context”, “circuitry”²) to space habitats
- Enabling technologies: in-situ power and resource generation, inflatable materials, tensegrity structures ...

For each of these domains the overall research objective from above can be decomposed as follows:

Detailed Research Objectives

1. Obtain a comprehensive and detailed representation of the current space exploration architecture using multiple views, to at least two levels of decomposition. (Baseline)
2. Quantify present and future utilities of stakeholders for a set of potential mission scenarios and destinations³. (Utilities)
3. Flow down of needs → goals → functional requirements for the architectures considered in each of the domains. (Requirements)
4. Develop key architectural concepts and find critical issues during concept generation. Carefully consider implications of modularity by functional aggregation. Establish the design vector for subsequent quantitative analyses. (Concepts)
5. Identify families of interesting architectures using principles of multi-attribute utility analysis and multiobjective optimization. Understand the mapping between interesting concepts and potential destinations/missions (“Exploration Metro Map”). (Trades)
6. Develop lifecycle cost models to evaluate architectures. Distinguish recurring and non-recurring costs to facilitate reusability decisions. (Costs)
7. Identify the technical, financial and policy factors that are key drivers (sensitivity analysis) in the architectural trade spaces. (Drivers)
8. Recommend key enabling technologies and concepts that allow for robustness and extensibility, without jeopardizing short-term mission success. (Extensibility)
9. Communicate study results as well as methods and tools used to generate the results to NASA using the most effective processes. (Communication)

The following paragraphs discuss the expected significance of the research in each of the four study domains. As an independent academic institution MIT does not have a vested interest in or bias towards any particular architecture in these domains.

Significance of Space Transportation Architecture to Space Exploration:

The current U.S. space transportation infrastructure is based on two pillars: the Space Shuttle (STS) for crewed missions and expendable launch vehicles for unmanned missions. In the latter case energy (ΔV) beyond LEO is obtained from a combination of orbital transfer stages and planetary gravity assist maneuvers. Limitations are primarily due to legacy architecture, rather than the lack of capable propulsion technology. We propose a comprehensive architecture study of current and future space transportation architectures. The short term needs center around a

² These are concepts used in Civil Architecture, see Reference [3]. “Context” explores the mutual relationship between a building and its environment. A building needs to “fit” into its environment, but also changes the environment itself due to its presence. “Circuitry” defines the flow of people and objects inside a building.

³ The selection of mission scenarios and destinations to consider will be decided jointly between NASA’s Space Architect and the MIT Principal Investigator.

replacement for the Space Shuttle for moving crews and equipment to and from the International Space Station (ISS)⁴. The long term needs include a mix of human crew and cargo to higher Earth orbits and beyond, cf. Figure 6. The study will consider a large trade space and emphasize modular concepts that allow to mix-and-match crew, cargo, propulsion and sensor modules to best suit a set of (uncertain) future missions. A key result will be a better understanding of whether the short term ISS transportation architecture and long-term exploration needs are at odds with each other, or if a common, extensible architecture can be found.

Significance of EVA Architecture to Space Exploration:

Current space suits are designed for weightlessness. They are too heavy and provide too little leg mobility for use on planetary surfaces, especially for the sort of geological fieldwork which is one of the prime justifications for sending humans to explore other worlds. Most EVA activities that will eventually be performed on Mars can be performed on the Moon. We also believe that some EVA technology necessary for lunar and Martian exploration can be tested in Earth orbit. Part of the proposed study will be a systematic analysis of what new developments in EVA technology are necessary to support future exploration and where each aspect of new EVA technology can be tested.

Significance of Surface Mobility Architecture to Space Exploration:

The precedent for human planetary surface mobility enhancement is the Apollo Lunar Roving Vehicle (LRV) which was used on Apollo 15, 16 and 17. Examples of purely robotic surface rovers are the Mars Pathfinder Microrover (Sojourner) which operated on the Martian surface in the summer of 1997 as well as its larger cousins MER-A (Spirit) and MER-B (Opportunity), which were launched on June 10 and July 7, 2003, respectively. A study of surface mobility must consider the possibility that rovers might have to support both human and robotic payloads in the future. Thus, scalability is an important issue. Architectural choices are impacted by range, autonomy and endurance requirements. Enhanced human surface mobility implies portable life support, sustainable energy sources and self-repair capability. A critical analysis will be done with respect to emerging propulsion and power technologies such as hydrogen fuel cells and small nuclear electric propulsion systems. This portion of the study will also consider the implications of surface mobility architectures on space transportation requirements⁵.

Significance of Habitat Architectures to Space Exploration

Human planetary habitats have long been restricted to the realm of science fiction. Recent developments such as light weight, large, self-supporting structures (e.g. Cargolifter hangar in Brand, Germany, <http://www.cargolifter.de>) and the confluence of virtual and physical architectures open new possibilities for planetary habitat design. Ambitious planetary habitats are challenging due to the need for in-situ component fabrication and assembly, radiation and micro-meteorite shielding and the multi-functional nature of such volume-limited spaces. MIT's School of Architecture has indicated an interest in participating in such a study. The results of the study could enhance NASA's planetary habitat architecture plan and could guide prototype and

⁴ The Orbital Space Plane (OSP) Level 1 requirements call for a rescue capability (ISS → Earth) for a human crew of at least four by 2010 and for a round-trip transportation capability (Earth → ISS → Earth) by 2012.

⁵ Complex, large surface mobility systems will have to be transported from Earth and must be accounted for in space transportation mass budgets and manifests, unless some components can be fabricated in-situ, including final assembly.

technology development for on-Earth (e.g. Devon Island Mars Station) or lunar testing. Most researchers in this area agree that real progress can only be made by committing to actually building a set of prototype structures.

The proposed research plan (Section 3.4) will present more detailed research activities and the way in which coherence between the four domains will be ensured. The next subsection (3.3) discusses the literature in space systems architecting and previous, relevant work at MIT.

3.3 Previous Work in (Space) Systems Architecture

The Space Architect has to be familiar with the key engineering disciplines required in conceiving, designing, implementing and operating space exploration systems: electrical, chemical and nuclear propulsion and power systems, structures and materials, avionics, software and communications, flight and attitude controls, sensor technologies, life support and so forth. A detailed review of the state-of-the-art and recent developments in these technical fields is beyond the scope of this proposal. We believe, however, that two disciplines in particular hold the key to successful space systems architecting: System Architecture (SA) and Multidisciplinary Design Optimization (MDO).

System Architecture (SA) is a young, emerging field whose underpinning is the realization that many complex, engineering systems such as computers and software, buildings, naval vessels, automobiles, airplanes and, of course, spacecraft can be described, analyzed and synthesized using common methods and tools. The search is ongoing for a universal language of system architecture, similar to what Latin used to be in science, what HTML is for the world wide web (www) and what “U,G,C,A” represent in genetics⁶. The literature in the field of System Architecture is embryonic, but “The Art of Systems Architecting” by Maier and Rechtin [4] is widely regarded as a primer into the field. The primary contribution of this book lies in the collection of a number of heuristics (= rules of thumb) that can guide system architects. Crawley [5] goes a step further in suggesting the existence of “principles of system architecture” that are universally true. Such principles have been collected as part of MIT’s System Design and Management (SDM) program and will be applied to this research project. In this context System Architecture is defined as follows:

Definition of System Architecture

System Architecture is the embodiment of concept, the allocation of functionality and definition of interfaces among system elements.

This definition is quite general, but requires some further explanation. Examples of what is meant by “System Architecture” are shown in Figure 2. In this case we show three typical architectures of computer networks: *hub-spoke*, *token ring* and *bus*. These three architectures use similar elements and technologies and perform essentially the same function. However, they differ fundamentally in terms of topology, detailed operations, scalability and robustness. Architectures are not the physical artifacts (systems) themselves, but rather their abstraction. Architectures describe both what the system *is* made off (i.e. the form) as well as what the system *does* (function).

⁶ “U,G,C,A” represent the four bases of the nucleotide building blocks of messenger RNA: Uracil, Guanin, Cytosin, Adenin; ultimately all biological DNA sequences are decoded using only these four symbols.

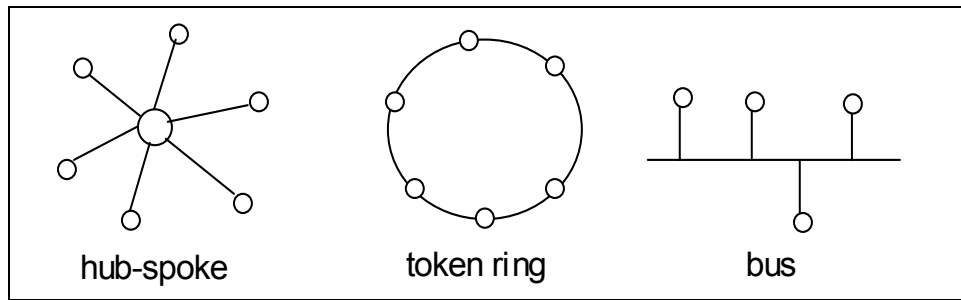


Figure 2: Typical architectures of computer networks, shown as undirected graphs. The circles represent the nodes (=computers), the lines are the physical connections (arcs) between the nodes.

The architectures of existing systems are not immediately visible to the novice observer; rather, they have to be gradually discovered. An alternate view of the architectures shown in Figure 2 is offered in Figure 3.

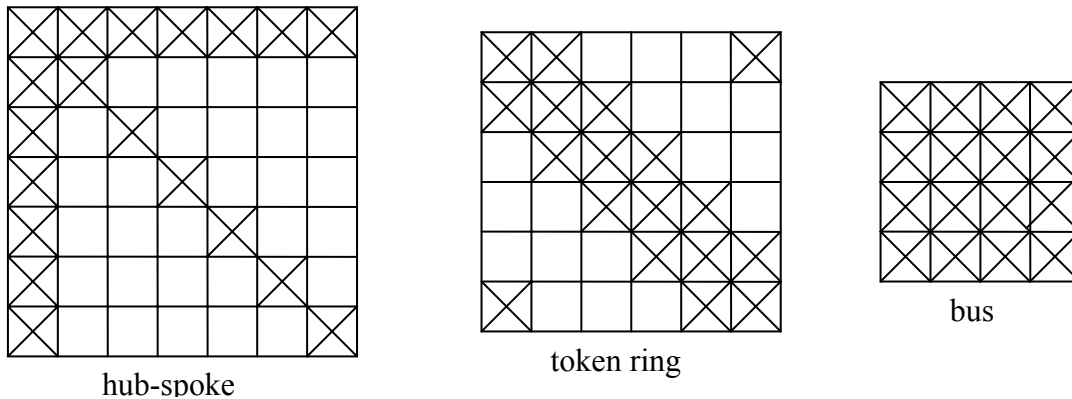


Figure 3: Alternate representation of architectures from Figure 2 using a Design Structure Matrix (DSM). The hub-spoke architecture (left) is centralized and peripheral elements are only connected via the hub. The ring architecture (middle) is a closed, linear topology. Each element has exactly two neighbors. The bus architecture (right) yields a fully populated DSM.

A traditional paradigm has been that new technologies (e.g. electric propulsion) are primarily responsible for enabling new capabilities. There is increasing awareness that both technologies *and* architectures must be considered jointly. A fundamental contribution in this respect was made by Henderson and Clark [6]. They classified the types of innovation in products, and by extension in systems, according to their technological (“concepts”) and architectural dimensions (“linkage between elements”), see Figure 4.

NASA’s Space Architect will have to effectively deal with all four types of innovation in the integrated space strategy.

Types of innovation

Incremental – Relatively minor changes to the existing product/system

Modular – Linkage between core concepts and components remain unchanged, yet a core concept changes.

Architectural – Reconfiguration of the established system to link existing components in a new way.

Radical – Different set of engineering and scientific principles, often opens up whole new markets and potential applications.

		Core Concepts	
		Reinforced	Overtaken
Linkage between core Concepts and components	Unchanged	Incremental Innovation	Modular Innovation
	Changed	Architectural Innovation	Radical Innovation

Figure 4: Classification of innovation according to Henderson and Clark [6]

Advanced topics in system architecture include the use of *legacy elements*, the incorporation of *flexibility* and the design of *families of systems*, possibly using common elements and platforms. The mission-scenario based development of a family of space tugs has been recently researched by de Weck et al. [7]. A major issue for system architects is how to decompose a system (top down) or how to define self-contained modules by aggregating lower level functions together into the same physical unit (bottom up). Research in modularity is ubiquitous, see a recent example by Eppinger [8], but not yet converged. Crawley [5] identifies sixteen different drivers for modularity and decomposition (e.g. delivered function, suppliers, extensibility).

Since the system architect (in consultation with other stakeholders) defines the concept and designs the high level “form” of a system, the elements of the design vector are determined at this stage. *Capsules* versus *winged orbiters* are different concepts for a crew transport vehicle; therefore, both are described by different design vectors. In the former case the critical design variables might consist of the capsule diameter, cone angle and thickness of the ablative heat shield. In the latter case the design vector embodies the wing geometry, fuselage diameter and thruster locations among others. This is the principal connection between System Architecture and design optimization. The field of Multidisciplinary Design Optimization (MDO) exists since the mid 1980’s and specializes in finding optimal values for design vectors, by taking into account couplings between multiple disciplines. Significant contributions in this area were made by NASA’s Langley Research Center in general and Sobieski and co-workers [9], specifically. The underlying issue here is that a collection of individually optimized, connected subsystems will not usually yield an optimal overall system if the degree of coupling between subsystems is high. The number of disciplines included in designing and optimizing aircraft and spacecraft has recently increased and now also includes financial models for revenue and lifecycle cost. This last point is of particular importance to NASA’s Space Architect.

It is expected that a major decision will be whether to make particular vehicles or modules reusable or expendable. Aside from technical considerations the relationship between manufacturing costs (for single use) and refurbishment and maintenance (for multiple uses) will be critical. Larson and Wertz [10] have developed some system design guidelines and cost estimation relationships (CER’s) in this context. One of the major difficulties for NASA’s Space

Architect, however, will be to realistically estimate lifecycle costs for future systems where no historical technical or financial database exists. This will require a major research effort.

MIT's Department of Aeronautics and Astronautics has been active in the field of Space System Architecture over the past decade. Table 2 summarizes a set of frameworks that were developed for facilitating Space Systems Architecting along with their principal investigators and research sponsors. Table 3 presents a list of space systems that have been analyzed with these frameworks. This work contains elements from both SA and MDO to varying degrees.

Table 2: Frameworks for Space Systems Architecting developed at MIT

Framework	Description	Faculty , Students	Sponsor	Ref.
GINA	Generalized Information Network Analysis, modeling and analysis of distributed satellite systems (constellations) with emphasis on information and communications systems	Hastings, Miller, Shaw	DARPA, AFRL	[11]
DOCS	Dynamics-Optics-Controls-Structures, integrated , multi-disciplinary modeling and simulation framework for conceptual design of opto-mechanical space science missions	Miller, de Weck, Blaurock	NASA GSFC, JPL	[12]
MMDOSA	Multiobjective, Multidisciplinary Design Optimization of Space Architectures, application of MDO to space systems architecting	Miller, Jilla	DARPA, AFRL	[13]
MATE⁷	Multi-Attribute Tradespace Exploration , utility theory based framework for conceptual design and tradespace exploration	Hastings, Ross	SSPARC consortium	[14]
SA	System Architecture – generic framework for early systems architecting developed as part of the System Design and Management Program (SDM)	Crawley, Koo, Speller	MIT SDM, Draper Labs	[5]

These frameworks have been applied to systems architecting and conceptual design of a number of scientific, commercial and military missions. Detailed references are available upon request.

Table 3: Space System Architectures previously analyzed

System	Mission	Faculty	Sponsor	Year
Iridium, Globalstar	Communications Satellite Constellations	Hastings, de Weck	AFRL, Sloan Foundation	1995-2003
Terrestrial Planet Finder (TPF)	Space Science – single spacecraft/cluster – IR nulling interferometer	Miller, de Weck	JPL	1998-2000
Space Interferometry	Space Science – single spacecraft	Miller, de Weck	JPL	1997-2001

⁷ MATE includes MIST – a web-based environment to conduct stakeholder interviews in order to generate utility curves and preferences that are used for utility-based design exploration.

Mission (SIM) Next Generation Space Telescope (NGST) –JWST	Space Science – single spacecraft	de Weck, Miller	NASA GSFC	1998-2002
B-TOS, C-TOS, X-TOS	Ionospheric mapping mission, satellite swarm	Hastings, Ross	DARPA, AFRL	2000-2002
Mars Exploration Rovers (MER)	Conceptual design software for Mars rovers	Hoffman, Miller	JPL	2002-2003
TechSat-21	Space Based Radar surveillance – satellite constellation	Miller, Sedwick, Hastings	AFRL	1998-2001
Space Tug	Active orbital transfer vehicle	de Weck, Hastings	DARPA	2002-2004

The work in these projects was typically focused on a single mission and followed a similar process: (a) definition of utilities and/or requirements, (b) architecture synthesis, (c) tradespace exploration, (d) identification of an “optimal design” or a family of multiobjective Pareto-optimal designs within the architecture trade space defined in step (b), and (e) sensitivity analysis and “what-if” scenarios.

This proposed project in space exploration architectures will extend the state-of-the-art in space systems architecture in the following ways:

- multiple missions must be considered at once
- some of the future mission requirements (destinations, science payload, crew) have not yet been fully defined, yet, meaningful technology development has to be initiated
- the space exploration architecture must include legacy elements such as launch vehicles, ground and space communications networks (e.g. TDRS, DSN)
- many enabling technologies have low TRL levels and are therefore uncertain from both a technical performance and cost standpoint. Hence, the fidelity of simulation models and conclusions drawn from them might be questionable.

3.4 Proposed Research Plan – Statement of Work

The proposed research plan includes two dimensions. One dimension corresponds to the domains: space transportation, EVA architecture, planetary surface mobility and habitats. The other dimension comprises the activities that will achieve the research goals discussed in Section 3.2: *Baseline, Utilities, Requirements, Concepts, Trades, Costs, Drivers, Extensibility and Communication*. The “big picture” project roadmap is shown in Figure 5.

The following subsections discuss some initial ideas for research on space transportation and EVA architecture followed by an itemized Work Breakdown Structure (WBS). It was deemed premature to discuss a plan of work for the other two domains (Task B) for this initial proposal. A detailed plan of work for Planetary Surface Mobility and Human Habitats would be developed in the future if NASA decided to exercise the option for Task B (cf. Section 3.2) after the first year.

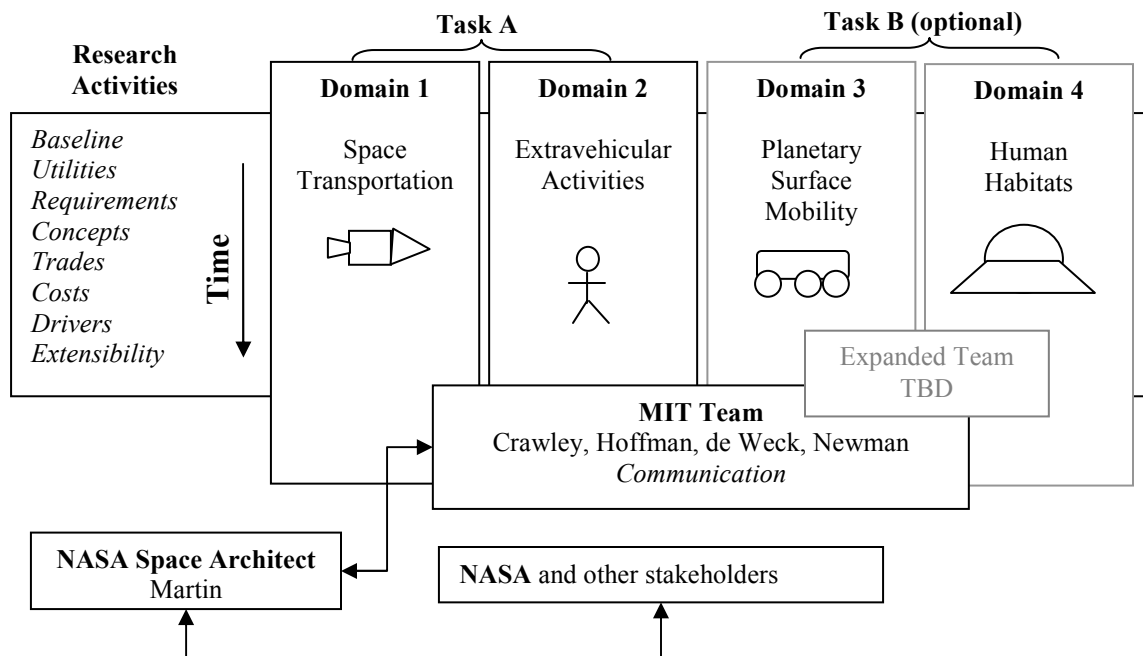


Figure 5: Space Exploration Architecture: Research Project Roadmap

3.4.1 Research Plan for Space Transportation Architecture (Domain 1)

The first task consists of a detailed architectural analysis of the present space transportation infrastructure. Detailed statistics will be gathered and analyzed in terms of available versus actually utilized payload fractions and refurbishment costs (e.g. from Orbiter processing facility). This last point is of particular interest, since it might expose those systems of the Space Shuttle (heat protection system, main engines) that cause most of the refurbishment costs in between flights. In a new architecture one would choose to make those subsystems expendable, where refurbishment costs are likely to exceed the per unit manufacturing costs.⁸ The aspects of modularity will be key in this part of the study. Both, the Space Shuttle and expendable launch vehicles feature some level of modularity. The modularity of STS consists of staging (solid rocket boosters, external fuel tank, orbiter), where no flexibility is currently allowed, and of the arrangement inside the payload bay, where some (internal) flexibility is allowed. The overall dimensions of the payload bay, however, remain fixed for each flight. Most expendable launchers are modular in terms of various payload fairings and strap-on booster configurations (e.g. Delta II).

Next, we envision a task where future utilities and needs of space transportation stakeholders would be gathered on behalf of NASA's Space Architect. A candidate tool for this study is MIST, the web-based utility interview software developed at MIT. The Space Architect's current framework to go from Science Questions → Pursuits → Activities → Destinations is compatible with this approach. The destinations drive the energy (ΔV) requirement. The manifest and

⁸ Taking into account learning curve effects when several units are manufactured. It is expected that the anticipated rate of flights per year will be a major uncertain parameter that drives the learning curve.

endurance drive the payload mass, and therefore, coupled with the type of propulsion system, the mission lifetimes. Figure 6 shows a portion of the “Space Exploration Metro Map”, Ref. [2], superimposed with potential, modular systems that could reach these destinations, while partially reusing modules between missions.

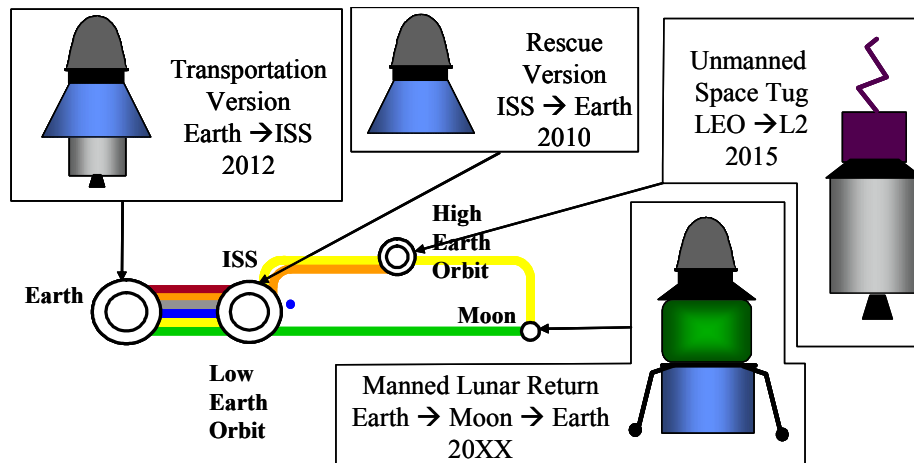


Figure 6: (Partial) Space Exploration Metro Map and modular architectures superimposed. Modules shown include: crew modules, propulsion and power, landing and reentry, grappling and sensing, adaptor rings, pressurized cargo modules

Understanding the functional requirements of future missions will lead to the definition of a number of functions that could potentially be encapsulated into separate modules. Candidate functional module types are: Crew modules, manipulator and sensor-pack attachments, propulsion and power modules for LEO, GEO, L2, the Moon, Mars and other interplanetary destinations prescribed by the Exploration Map, cargo modules, reentry and landing modules and adaptor modules. The idea here is to create an architecture that has “external modularity” in contrast to the Shuttle, which has “internal” modularity. Each mission would be custom-assembled from a set of basic modules. The basic modules themselves would, however, be standardized and reusable between missions. Interface definition between modules is expected to be a major challenge for such an approach.

It is not expected that such modular craft will perform as “best in class” and it is likely that mass and performance penalties will have to be paid, relative to integral architectures that are optimized for specific missions. It has been said that *Hermes*, the 1990’s version European crew transfer vehicle encountered such difficulties, when attempting to mate the vehicle with the Ariane V booster in a modular fashion. Nevertheless, new materials, technologies and ideas can overcome such hurdles.

The research would then proceed to conduct an architecture trade study for OSP, considering both the 2010 rescue and 2012 transport missions. Existing frameworks for architecture trade studies, see Table 2, could be applied relatively quickly and efficiently to this problem⁹. The “design vector” for an OSP architecture trade study could potentially comprise the following:

⁹ Also, there is an opportunity for an educational component in these trade studies as discussed in Section 8.

- Staging: 1 (SSTO) – 2 – 3 (the current level 1 OSP requirements mandate EELV compatibility)
- Chemical Propulsion Type: Solid – Liquid – Hybrid
- Stack: Vertical Only – Horizontal Only - Hybrid
- Payload Shape: Blunt Body (capsule) → Winged Body (A/C-like)
- Architecture: Integral → Modular
- # of Astronauts accommodated: 4 – 8
- Cargo Volume: 100-5,000 ft³
- Reusability: Reusable → Partially Reusable → Disposable
- Maximum ΔV : 7.5 → 30 km/s
- Extensibility: None → # and Type of compatible modules
- On-Orbit Autonomy: 5 days → 6 months

Details would be extensively coordinated with NASA’s Space Architect (see Section 4.1). The key question to be answered is whether making OSP truly extensible (so that other destinations beyond ISS could be ultimately reached) by adding functionality via new modules is feasible or not. There is concern among a number of stakeholders (e.g. astronauts, aerospace contractors) that imposing such extensibility requirements on OSP would jeopardize the 2010 and 2012 goals. A well known failure mode in aerospace projects is “requirements creep”, where more and more requirements are added over time such that the feasible design domain shrinks and ultimately disappears. Such programs often implode under their own weight. The difference in our proposed approach is that additional requirements don’t have to be met immediately in the first incarnation of the system. Rather, only the provisions for such future capability have to be included and, “if needed” and “if afforded” the capability is achieved by adding chunks to the system at a later time. We suspect that this is primarily an architectural, rather than a purely technological challenge.

This leads to the last part of the Space Transportation study, which considers the “provisions for future capabilities” as real options. The ideas of staged deployment and valuation of flexibility via real options theory (a recent subfield of financial engineering) will be explored in this context. The modular approach allows adjusting the pace of development, test and implementation of new modules to the ebb-and-flow of policy decisions such as varying funding profiles. The benefits of flexibility can be demonstrated quantitatively. Real options, however, only have value in the presence of uncertainty. The main uncertainties in future space exploration lie in the choice of destinations, the required human and robotic payloads, the mission durations, the evolving technology base and future funding.

3.4.2 Research Plan for Study of EVA Architecture

MIT proposes to apply principles of modularity and extensibility to EVA systems similar to what it will apply to space transportation, as discussed earlier. Space suits have undergone considerable development from Project Mercury up to the present, but they have all been “point designs”. Once a space suit is built, making any changes is extremely time-consuming and costly. This is normally attributed to safety reasons, however at a deeper level it is a design issue.

The capacity for evolution has never been a factor in space suit design tradeoffs, so any changes normally involve redesign and recertification from the ground up.

Developing a new space suit requires a large expenditure of resources. The next time NASA makes a major investment in new space suit technology, it should ensure that the design allows for continuous tests and improvements. We propose to investigate modularity and extensibility as a factor in future space suit designs. Specifically, we propose to develop principles for the design of future space suits that will allow new EVA developments to be tested and incorporated as they come online without requiring complete suit recertification. This effort will develop the concept of space suits as engineering testbeds. Figure 7 shows examples of pertinent future EVA scenarios.

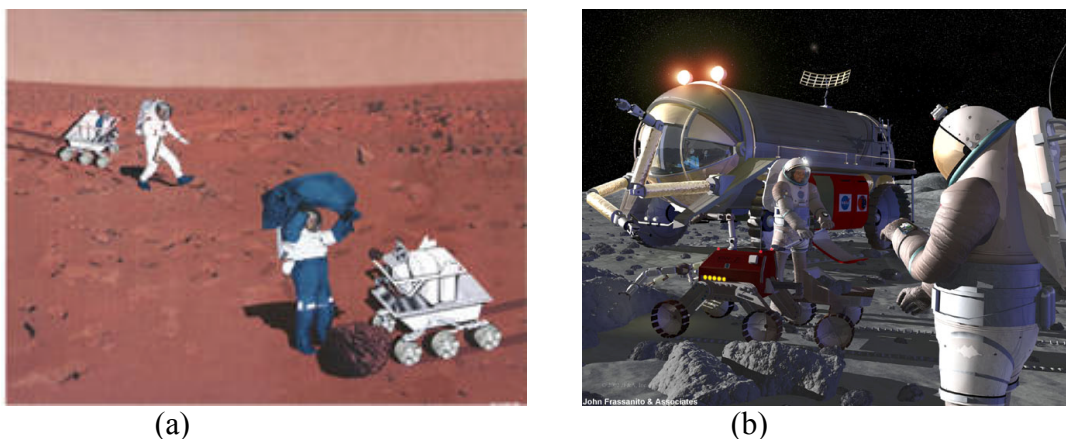


Figure 7: (a) EVA activities on Mars, (b) EVA on lunar surface with robotic assistance

We will also attempt to develop plans for a modular approach that will allow some space suit technology specifically developed for use on planetary surfaces to be tested in weightlessness, opening the possibility of using the ISS as an EVA engineering testbed to support future exploration. Modularity should apply not only to the physical parts of the suit (arms and legs, helmet, life support system, etc.) but also to the information systems interfaces between the suit and the outside world. Adding electrical wiring inside a space suit, even if it carries only data, is at present extremely difficult because of safety hazards associated with the pure O₂ suit environment. Any new suits that NASA or its contractors develop must include adequate electrical feedthroughs and internal wiring, even if not required at the beginning, to allow future evolution of EVA information systems. Increased robustness and repairability can also be considered as “modular elements” that need to be incorporated into the space suit design process.

3.4.3 Work Breakdown Structure (WBS) - Statement of Work

This subsection shows the Work Breakdown Structure (WBS) of the proposed project. This is an itemized summary of all the activities discussed in this proposal. Tasks in the domains of Surface Mobility and Planetary Habitats can be added if the Task B option is exercised. It is likely that the WBS will be modified (following mutual agreement) as the needs of the project evolve over time.

WBS – Space Exploration Architecture

1. Domain 1: Space Transportation

- a. Baselineing
 - i. Inventory of past NASA Space Exploration missions
 - ii. ΔV requirements, payloads, mass fractions, lifetimes
 - iii. Architectural representations (OPM¹⁰) of past and present ST infrastructure
 - iv. Manufacturing and refurbishment cost analysis of Space Shuttle
- b. Utilities
 - i. Personal utility interviews with a small set of key stakeholders (TBD) to obtain attributes, utility curves and preference weightings
 - ii. Web-based utility interviews using MIST with a larger group of stakeholders
 - iii. Scenario development and population of Exploration Metro Map with specific missions – joint work with NASA Space Architect
- c. Requirements
 - i. Needs identification
 - ii. Goal decompositions for Space Transportation that are consistent with the teachings of 16.882/ESD.34
 - iii. Functional requirements definition for subsequent trade studies
 - iv. Independent analysis of current OSP level 1 requirements
- d. Concepts
 - i. Create functional decompositions for Space Transportation Architecture down to two levels of decomposition
 - ii. Generate concepts using various creativity techniques
 - iii. Develop high level form to two levels of decomposition
 - iv. Probe various modularity options by function/form aggregation
 - v. Define design vector(s) for subsequent trade studies
- e. Trades
 - i. Map design vector to functional requirements and identify important models/simulation modules
 - ii. Create simulations (likely in MATLAB), benchmark against existing systems and integrate overall simulation flow
 - iii. Conduct full-factorial analysis for a small, initial combinatorial trade space
 - iv. Expand design space, use design optimization and identify Pareto optimal set of architectures
- f. Costs
 - i. Develop RDT&E models for space transportation architectures

¹⁰ OPM – Object Process Methodology: A new framework for rigorously describing system architectures with objects (form) and processes (functions) in a unified representation. Developed by Prof. Dov Dori. OPM has both a graphical and a natural language component.

- ii. Expand cost modeling to include lifecycle cost, including manufacturing and operations
 - iii. Identify cost drivers for both non-recurring and recurring costs with particular emphasis on operations and refurbishment costs
 - iv. Repeat trades from e) with cost models included
- g. Drivers and Sensitivity Analysis
 - i. Conduct sensitivity analysis with respect to parameters that were held fixed during previous trades
 - ii. Identify key system variables (drivers)
 - iii. Technology impact analysis, including uncertainty due to TRL level
 - iv. Attempt to quantify cost and performance penalties as a function of the degree of modularity
- h. Extensibility
 - i. Evaluate performance of Pareto-optimal designs identified in (2.e.iv) against new mission scenarios
 - ii. Identify a ranked list of interesting modules to be added at a future time
 - iii. Module interface definition
 - iv. Platform, module reuse analysis over a family of systems, investigate similar approaches in related industries (e.g. aircraft, automobiles)
 - v. Real Options Analysis (ROA)

2. Domain 2: Extravehicular Activities Architecture

- a. Baselineing
 - i. Inventory of current U.S. and foreign space suits and accessories
 - ii. Performance envelopes of current space suits in terms of operating environments, endurance, mobility and dexterity
 - iii. Overview of current ingress/egress procedures and impact on space exploration efficiency
 - iv. Architecture representation of current and past space suits (e.g. using OPM)
- b. Utilities
 - i. Stakeholder interviews regarding attributes, utility curves and preference weightings of current and future space suits
 - ii. Prioritized list of suggested improvements
- c. Requirements
 - i. Develop specific suit functional requirements for “nodes” on the Space Exploration Metro Map
 - ii. Goal decompositions for Space Suits that are consistent with the teachings of 16.882/ESD.34
 - iii. Show imposed requirements on enabling systems such as air locks, hand rails and grappling equipment among others
- d. Concepts
 - i. Develop new space suit concepts
 - ii. Generate space suit modularity and extensibility options based on functional aggregation

- iii. Concepts for incorporation of information and navigation technology in space suits, possibly borrowing from other fields (e.g. soldier battlefield awareness technologies, nanotechnology, advanced uniforms etc...)
- e. Trades
 - i. Perform qualitative and quantitative trades for the concepts developed under (2.d.i).
 - ii. Assess penalties imposed by making suits modular and extensible
- f. Costs
 - i. Develop parametric suit cost models as a function of: suit pressure, atmosphere composition (e.g. pure O₂ versus more air-like), # layers and components, autonomy (hrs)...
 - ii. Rerun previous trades by incorporating cost models
- g. Drivers and Sensitivity Analysis
 - i. Repeat trades with fixed parameters that were previously held constant
 - ii. Identify key system variables (drivers)
 - iii. Attempt to quantify suit cost and performance penalties as a function of the degree of modularity
- h. Extensibility
 - i. Identify a ranked list of interesting modules/capabilities to be added to future space suits
 - ii. Module interface definition
 - iii. Platform, module reuse analysis over a family of systems for different operating environments, e.g. could a life-support unit for the Moon be reused on Mars?

3. Project Management and Communications

- a. Identify cross-architectural issues between space transportation and EVA/Space suit domains
- b. Internal MIT Team Management
 - i. Weekly team meetings
 - ii. Project website (password protected)
 - iii. Coordinate educational opportunities (16.83, 16.89)
 - iv. Software and Data Configuration Management
 - v. Track budgets and expenditures
- c. External Communications
 - i. Bi-weekly teleconference with NASA Space Architect
 - ii. Quarterly review meetings, annotated viewgraphs
 - iii. Joint 2-day System Architecture work shop between MIT, NASA and related parties
 - iv. Written Annual Report
 - v. Conference and Journal Articles
 - vi. MIT theses

4. Management Approach and Deliverables

4.1 Coordination with NASA Space Architect (HQ)

In contrast to some narrowly defined, purely technical project, this research will require regular two-way communications between NASA Space Architect's team and the MIT team. Architectural, multi-mission research is unprecedented and we expect to learn and make adjustments as the project matures. As a starting point we propose the following:

- A two-day kickoff meeting, implemented as a mini-symposium where the NASA Space Architect's team has an opportunity to present the current integrated space strategy along with their needs in terms of methodology and tools. The MIT team would present their past and present research in Space System Architecture (see Section 3.3) in a coherent, summarized fashion. Fine tuning of the SOW would occur at that time.
- Bi-weekly teleconference: this would be a brief 30-60 minute opportunity to present data needs, discuss project progress at a detailed level and take corrective action. The MIT investigators, students and advisors (see Section 5) would attend.
- Quarterly Review Meetings: To alternate between NASA Headquarters, Washington, D.C. and MIT, Cambridge MA. These would mainly comprise briefings of project progress from MIT (annotated viewgraphs) and updates on NASA's integrated space strategy by the Space Architect and his team.

Note: A short version of the System Architecture course (16.882/ESD.34J) could be held at NASA HQ. This would ensure a common vocabulary between the NASA and MIT teams, but this would have to be set up under a separate arrangement.

4.2 MIT Internal Coordination

MIT's culture fosters collaborative projects among faculty. A number of tools will be used to coordinate the project internal to MIT:

- Weekly team meetings: These meetings include the Principal Investigator, co-Investigators, the students working on the project (RA's) and project advisors on an as-needed basis.
- Project Website: An internal website will be used to manage the project, maintain all data, software and reports generated under this project. The site will be password protected, but NASA's Space Architect will be given a guest account upon request.

4.3 Deliverables

The previous sections of the proposal discussed what we intend to study, why it is important, what previous work and literature exists, and what our approach will be. This section summarizes what we will produce as a result of the study. The following items will be delivered to NASA under this research contract:

- 4.3.1 Annual Report for years 1, 2 and 3 (summarizing results, ongoing activities and future work, reference list of work published during the year). The scope of the annual report will be on the order of 100-200 pages.
- 4.3.2 Tools (these will be self-contained, functional software programs) that can facilitate the job of the Space System Architect. Tools will be provided as either Matlab source code (.m functions), Excel macros with Visual Basic source code, or compiled functions compatible with MS Windows and MAC formats. Each tool will be accompanied by a short user manual and some worked examples. We intend to develop and deliver the following three tools:
 - o Stakeholder interview software (MIST derivative for space exploration, EVA)
 - o Tool for goal analysis, decomposition and formulation from requirements
 - o MSDO concept generation and selection tool - software/simulation codes generated for the trade space studies conducted under WBS items 1.e) and 2.e).
- 4.3.3 Deliverables of the Architect for Space Transportation and EVA. The main deliverables of a system architect, according to Crawley [5], are as follows:
 - o A clear, complete, consistent and attainable (with 80%-90% confidence) set of goals (with emphasis on functional goals)
 - o A functional description of the system, with at least two layers of decomposition
 - o A concept for the system
 - o A design for the form of the system, with at least two layers of decomposition
 - o A notion of the timing, operator attributes, and the implementation and operation plans
 - o A document or process which ensures functional decomposition is followed, and the form at interfaces is controlled

Efforts will be made to format these deliverables in such a way that they are compatible with NASA's integrated space strategy.
- 4.3.4 Minutes of Meeting, from bi-weekly telecons via email, within 72 hours after telecon
- 4.3.5 Annotated Viewgraphs from quarterly review meetings
- 4.3.6 Databases generated under this program, particularly for WBS items 1.a), 2.a). This includes any Object-Process-Diagrams (OPDs) or DSMs generated under this project. Most databases are expected to be in Microsoft Excel format.
- 4.3.7 Conference Papers and Journal Articles generated under this project. Review and co-authorship procedures are governed by separate MIT-NASA agreements
- 4.3.8 MIT Theses: Any masters or doctoral thesis written by a student funded under this project as a Research Assistant (RA) will be delivered to NASA in hardcopy and in electronic format.

5. Personnel

The MIT project team consists of the principal investigator (PI), three co-investigators (co-I), a number of dedicated research assistants (RAs) and a set of informal project advisors (Adv). Detailed C.V.'s are available upon request.

5.1 Principal Investigator (PI)

The PI is NASA's main point of contact for this project. He is responsible for meeting the overall research objectives and deliverables and manages the MIT team internally.

Prof. Edward Crawley, Professor of Aeronautics & Astronautics and Engineering Systems, recently served as Department Head of Aeronautics and Astronautics at MIT (1996-2003) and has an extensive research and consulting record in space systems engineering. He founded and led the Space Engineering Research Center (SERC) at MIT and pioneered the use of active materials and high performance controllers on large, flexible space structures. He was principal investigator on a number of Space Shuttle in-orbit experiments such as MACE (STS-67) and MODE (STS-48 and STS-62). He was a finalist in the 1980 astronaut selection program. He has served on a number of NASA external review panels. He was co-founder of MIT's System Design and Management (SDM) program and has taught a new course in System Architecture (16.882/ESD.34J) for the past six years. Prof. Crawley is a member of the NAE, the NASA Advisory Council and the Board of Directors of the Lockheed Martin Space Operations Company and Orbital Sciences Inc.

5.2 Co-Investigators (co-I)

The co-I's report to the PI and are responsible for the research objectives associated with the items of the statement-of-work (SOW) that are assigned to them. They contribute to the deliverables and overall team success and will typically advise 1-2 graduate students each.

Dr. Jeffrey A. Hoffman, Professor of the Practice of Aerospace Engineering in the Department of Aeronautics and Astronautics, is a former NASA astronaut who has made five space flights, becoming the first astronaut to log 1000 hours aboard the Space Shuttle. Dr. Hoffman has performed four spacewalks, including the first unplanned, contingency spacewalk in NASA's history (STS 51-D; April, 1985) and the initial repair/rescue mission for the Hubble Space Telescope (STS-61; December, 1993). He worked for several years as the technical representative of the astronaut office for EVA and participated in developing a series of flight tests of new tools and procedures needed for the assembly of the International Space Station. He also conducted extensive testing of advanced space suit designs.

Dr. Olivier de Weck, Assistant Professor of Aeronautics & Astronautics and Engineering Systems, is a junior faculty member with experience in Multidisciplinary Design Optimization (MDO) and System Architecture. He has developed and analyzed integrated models of space missions such as JWST, SIM and TPF for NASA GSFC and JPL. He is the head of the Platform Architecture initiative of MIT's Center for Innovation in Product Development. His research is

sponsored by JPL, DARPA, General Motors, and the Alfred P. Sloan Foundation. He was recently named the Robert N. Noyce Career Development Professor at MIT. He is co-creator of a new course on Multidisciplinary System Design Optimization (MSDO) (16.888/ESD.77J). Before joining MIT he served as engineering program manager for the Swiss F/A-18 program at McDonnell Douglas (now Boeing) in St. Louis, MO (1993-1997).

Dr. Dava Newman, Associate Professor in the Department of Aeronautics and Astronautics, has led EVA research at MIT for over a decade. She is an expert in the areas of human movement in low gravity and has also made novel contributions in physics-based modeling of astronaut EVA activities. She has been a funded NASA PI throughout the past decade to investigate and establish an EVA database for microgravity and partial gravity environments as well as to utilize technology and robotics for advanced EVA.

5.3 Research Assistants (RA)

There will be three students involved in this project. The number and level of students directly funded under this project as Research Assistants (RAs) is called out explicitly in the attached budget (1 PhD candidate, 2 SM candidates). It is possible, but not guaranteed, that some other students will contribute to this study, even if they are not funded directly under this contract. Examples are NASA employees who are participating in the System Design and Management (SDM) program. The MIT investigators will select students whose interests, intellectual abilities and previous experiences will provide the best chance of project success.

5.4 Informal Project Advisors (Adv.)

A number of other current faculty are active in Space Systems Architecture related research at MIT. Even though they are not explicitly called out as co-Investigators, they will be consulted during the course of the project on an as-needed basis.

Prof. Daniel Hastings: co-Director of the Engineering Systems Division (ESD)

Prof. David Miller: Director of the Space Systems Laboratory (SSL)

Prof. Sheila Widnall: Institute Professor, Member of the Space Shuttle Columbia Accident Investigation Board (CAIB), Chairman AIAA Foundation

6. Facilities and Equipment

A brief description of the facilities involved in this project is provided. These are all part of the MIT Department of Aeronautics. It is not expected that actual hardware¹¹ will be developed or that experimental equipment will be needed.

6.1 Complex System Development and Operations Laboratory

The Department of Aeronautics & Astronautics at MIT possesses a state of the art computer laboratory, which has been designated as the "Design Studio" (33-218). This concurrent engineering facility is comprised of 14 networked CAD/CAE workstations that are used for

¹¹ With the possible exception of small (rapid prototyping) geometric models of proposed architectures for visualization and conceptual purposes.

complex systems design and optimization. It is our intent to carry out part of the research in this facility, particularly those project activities that require coordination among the whole team. The Design Studio is part of the *Complex Systems Development and Operations Laboratory*. Previous systems designed in this facility include a mini-satellite formation flying testbed that will be launched to the International Space Station in 2004 (SPHERES), a multi-aperture telescope (ARGOS) and new concepts for regional business jets. See Figure 8 (a) below for an artist's rendition of the "Design Studio". This setting will allow active participation of graduate and undergraduate students in the project.



Figure 8: (a) Artist's rendition of the Design Studio at MIT's Department of Aeronautics & Astronautics (33-218), (b) Complex Systems Development and Operations Laboratory

6.2 Space Systems Laboratory (SSL)

The Space Systems Laboratory (SSL) is part of the Space Engineering Research Center (SERC) in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology. Founded in 1995, the SSL engages in cutting edge research projects with the goal of directly contributing to the present and future exploration and development of space. Specific missions include developing the technology and systems analysis associated with small spacecraft, precision optical systems, and International Space Station technology research and development. The laboratory encompasses expertise in structural dynamics, control, thermal, space power, propulsion, MEMS, software development and systems. A major activity in this laboratory is the development of small spacecraft thruster systems as well as looking at issues associated with the distribution of function among satellites. In addition, technology is being developed for spaceflight validation in support of a new class of space-based telescopes that exploit the physics of interferometry to achieve dramatic breakthroughs in angular resolution. The objective of the Laboratory is to explore innovative concepts for the integration of future space systems and to train a generation of researchers and engineers conversant in this field.

6.3 Man Vehicle Laboratory (MVL)

MIT's Man Vehicle Laboratory has established a worldwide reputation for studies of the performance of humans in space suits. Areas of current research are physics-based modeling of astronaut EVA activities, analysis of dynamic loads induced on spacecraft by EVA astronauts, incorporation of advanced information technology into space suits to enhance astronaut

performance, geological traverse planning techniques for planetary exploration, human-robotic interaction, and development of mechanical counter-pressure space suit technology. The MIT EVA group maintains close ties with numerous companies that produce EVA equipment.

7. Proposed Costs and Schedule

7.1 Budget: A detailed project budget (*Proposed Cost Estimate*) is provided as a separate attachment. The budget includes the cost of graduate students, travel, computer and software expenses, some faculty summer salary as well as MIT's overhead. Some commercially available software (e.g. MATLAB, OPCAT for making Object Process Diagrams, Excel....) is not included, since it is already available in the current infrastructure at MIT. The current budget covers only Task A (Space Transportation and EVA, i.e. domains 1 and 2). Task B would be negotiated separately after year one.

Dr. Hoffman is a NASA employee working at MIT under an IPA. As such, he will draw no salary support from any NASA funds committed under this proposal.

7.2 Schedule: The project will last for three years, with a current overall schedule of October 1, 2003 – September 30, 2006. Figure 9 shows a tentative Gantt chart of the project, along with major milestones of related NASA efforts in Space Transportation [16,17].

8. Educational Project Component

This project provides an opportunity for educational involvement, which is consistent with NASA's new thrust in educational outreach, see Table 1, right side. Portions of this project could be given as a challenge to one or both of the undergraduate (16.83) and graduate (16.89) Space Systems Engineering Classes at MIT. Mission analyses and conceptual vehicle development were undertaken by these classes in the past, with some noteworthy results and publications, e.g. reference [15]. In our experience, concept generation and trade studies (items 1.d/e and 2.d/e of the WBS) are particularly well suited for this type of activity. An example would be to task the class to come up with an alternate OSP architecture with supporting rationale and models. Catalogue descriptions of these two classes are provided below.

Note: The Investigators will strive to connect 16.83 and 16.89 with this project, but it must be said that there can be no absolute guarantee that this will happen, since the course content and particular missions to be analyzed are negotiated with the course instructors on a year-to-year basis.

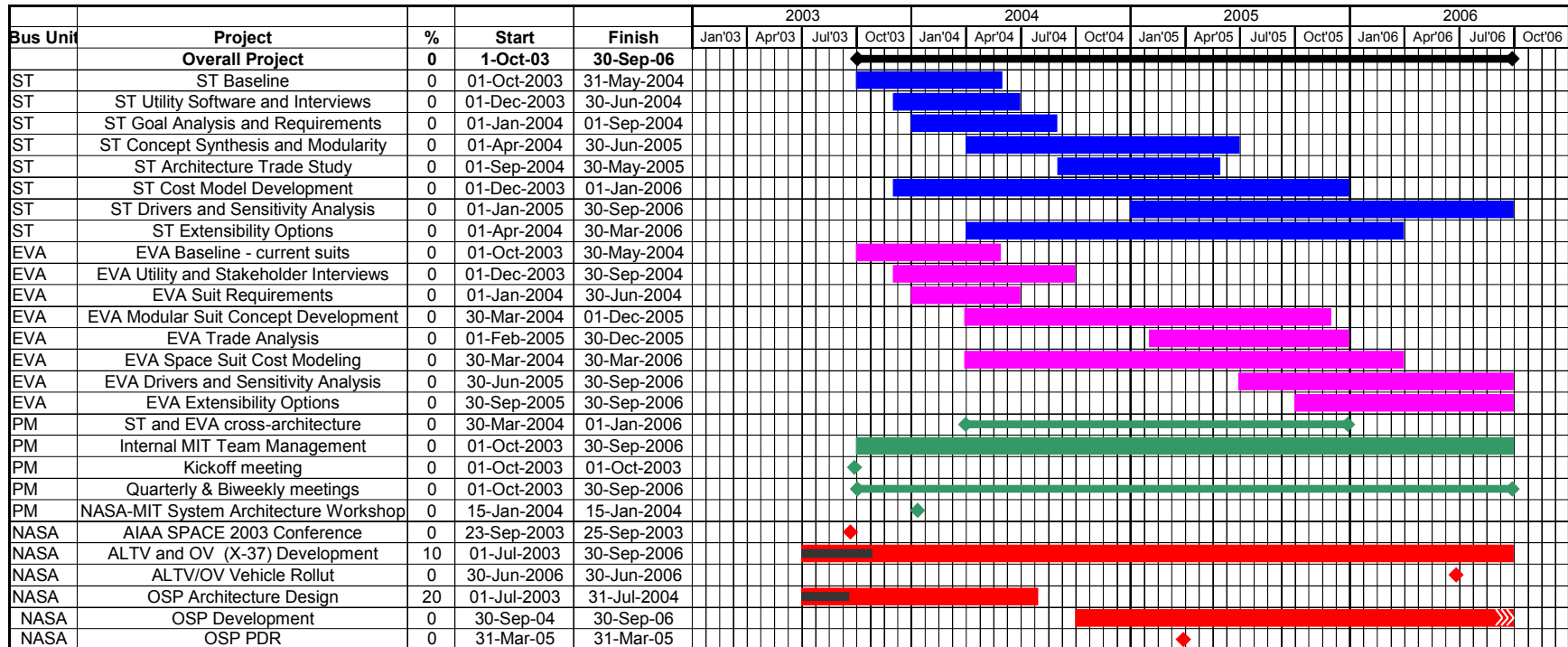


Figure 9: Space Architecture Project – Master Schedule: Space Transportation Activities (ST) shown in blue, EVA shown in purple, MIT Project Management (PM) tasks in green, parallel NASA activities in red

16.83 Space Systems Engineering



Prereq: Permission of department

Units: 3-3-6



Lecture: *W3-5, F1-3* ([33-218](#)) **Lab:** *F3-5* ([33-218](#))

Design of a complete space system, including systems analysis, trajectory analysis, entry dynamics, propulsion and power systems, structural design, avionics, thermal and environmental control, human factors, support systems, and weight and cost estimates. Students participate in teams, each responsible for an integrated vehicle design, providing experience in project organization and interaction between disciplines. Subject includes several aspects of team communication including three formal presentations, informal progress reports, colleague assessments, and written reports. Subject not offered Fall 2004.

D. W. Miller, J. Hoffman, P. W. Young, J. Keese

16.89 Space Systems Engineering



Prereq: [16.851](#) or permission of instructor

Units: 4-6-2

Subject focuses on developing space system architectures. Applies subsystem knowledge gained in 16.851 to examine interactions between subsystems in the context of a space system design. Principles and processes of systems engineering including developing space architectures, developing and writing requirements, and concepts of risk are explored and applied to the project. Subject develops, documents, and presents a conceptual design of a space system including a preliminary spacecraft design.

D. E. Hastings

Another opportunity exists to involve NASA Personnel participating in the MIT System Design and Management (SDM) Program. NASA has sponsored a number of mid-career engineers and executives over the past 6 years. All of them have to write theses that could benefit this research project. An example is a recent thesis on Architecture of Nuclear Electric Power and Propulsion (NEPP) systems by Bryan Smith (NASA Glenn) which was supervised by Prof. de Weck.

Details of the educational component will be discussed during the kickoff meeting.

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