16.89 / ESD.352

SYLLABUS AND PROGRAM PLAN

Space Systems Engineering

"Extensible Architectures for Space Transportation"

MWF 1-3 (4-6-2) (33-218)

http://stellar.mit.edu/S/course/16/sp04/16.89/index.html

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"Extensible Architectures for Space Transportation"

SUMMARY

Motivation

On January 14, 2004 President George W. Bush set a new course for NASA and the future of U.S. manned spaceflight[1]. He called on the agency to "gain a new foothold on the moon and to prepare for new journeys to the worlds beyond our own." The top priorities are (1) the completion of the International Space Station (ISS) by 2010, followed by the retirement of the remaining Space Shuttle fleet. (2) In its place, a manned "Crew Exploration Vehicle" (CEV) will be developed and tested by 2008 with full operational status achieved no later than 2014. Though its main purpose will be to leave Earth orbit, it may also be used to shuttle astronauts to and from the ISS. The third main goal (3) is a return of humans to the moon by 2020 with the goal of spending increasingly longer periods of time on the lunar surface and possibly developing the moon as the launching point for missions beyond. The return to the moon would occur gradually, first with robotic probes to the lunar surface starting in 2008, followed by human missions as early as 2015.

This new direction represents a significant paradigm shift in U.S. space policy. In order to achieve these new goals, NASA is embracing a "stepping stones and flexible building blocks" approach to space exploration. This is in contrast to the "giant leap" approach of programs like Apollo, the Space Shuttle or the International Space Station. This raises a number of challenging technological, architectural and policy questions.

Challenge

MIT has decided to take up this challenge in support of NASA's Space Architect. This year's 16.89/ESD.352 Space Systems Engineering class will engage deeply in the question of how to best architect and design a future, extensible space transportation system that is compatible with the new goals set forth by the president.

One of the fundamental questions is whether space missions that involve a mix of humans and cargo must be custom-tailored for each destination or whether there can be a fundamental set of components and processes that can be reused and recombined in efficient ways. This requires architectural thinking more than the invention of new technologies. A related question is whether the CEV should be a single vehicle, a family of vehicle variants, or a set of compatible spacecraft and rocket modules. Furthermore, it must be carefully considered how such spacecraft can be launched to Earth orbit without having to develop an entirely new heavy lift launch infrastructure. Can components of the existing launch infrastructure be used and combined in new ways to satisfy the required mass-to-orbit needs cost effectively?

[1] http://www.nasa.gov/missions/solarsystem/explore_main.html

Approach

In 16.89/ESD.352 the students will first be asked to establish the requirements for a new human space exploration system, together with requirements for launching crew and quantities of cargo appropriate for future space exploration to and beyond Low Earth Orbit. A set of lectures and notes will be given by the instructors to present fundamentals in rocket propulsion, orbital dynamics, system architecture and lifecycle costing, among others. NASA personnel will contribute ideas and experience to this course, in person or by video and teleconferencing. This course is meant to challenge MIT graduate students to take an unbiased, creative look at this problem and hopefully to produce results that will potentially impact future space transportation systems after the Space Shuttle's retirement.

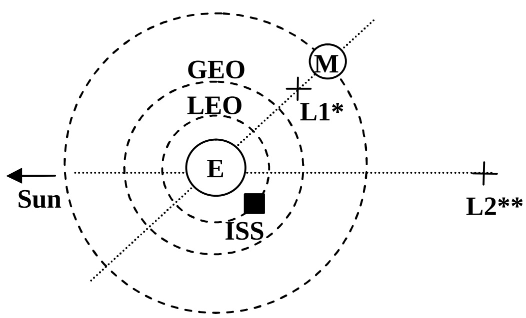
The class will initially be split into two teams.

The **"Earth-to-LEO"** team will be responsible for developing a set of launch options from Earth's surface to Low Earth Orbit. The initial launch requirements are driven by two missions in Low Earth Orbit: (O1) Resupply of the International Space Station at regular intervals, enabling rescue (after 2008) and transfer (after 2012) of a crew of four astronauts. The up and down cargo requirements for the ISS also need to be established. (O2) The second mission in LEO is maintenance, servicing, assembly and repair of complex orbital systems. Ultimately, this may relate to the assembly of large exploration vehicles launched in components. However, in order to deal with well-understood tasks, students in this course will consider using a CEV-based system for human servicing of the Hubble Space Telescope (HST). Emphasis will be placed on the reuse of legacy components wherever appropriate. The "Earth-to-LEO" team will be advised by Prof. Hoffman.

The **"In-Space"** transportation team will consider requirements and architectures for extended missions beyond Low Earth Orbit, but still within the Earth-Moon system (Fig.1). This team is tasked with developing three "extended" missions: (E1) Human servicing of HST-like spacecraft at the Earth-Moon L1 (Lagrange) point, (E2) Manned return to the lunar surface with an initial stay of 3 days – but with options for increasing length of stay and (E3) Trans-Earth Escape mission which reaches escape velocity from the Earth-Moon system with Mars orbit as the likely destination. The escape mission might consider launching crew and cargo modules separately for part of the mission. The "In-Space" team will be advised by Prof. de Weck.

Earth-to-LEO Missions:
O1) Resupply ISS (4 crew, cargo TBD)
O2) HST Servicing in LEO (h=569 km, i=28.5
In-Space Missions:
E1) (L2**)^2 HST Servicing at Earth-Moon L1*
E2) Return to the Lunar Surface (à la Apollo 1
E3) Trans-Earth-Escape Mission to Mars

E=Earth, M=Moon, *E-M system, ** E



system

Figure 1: *Representation of the mission environment for 16.89/ESD.352 (Spring 2004).*

Prof. Crawley will act as the main advisor and resource in the area of System Architecture.

A number of students in the class are also doing research in this area. They will be available as a resource to their peers for help with methods and tools such as architecting, costing, orbital dynamics and computer aided modeling.

Initially, both teams will operate independently from each other and will optimize their own missions without coordinating with each other. There are likely to be sub-teams, whose objective will be to establish the requirements for and to optimize the individual missions shown in Figure 1. This phase of the class culminates with a Presentation of Architectures review before Spring Break.

In the **second half of the semester**, the class will be reorganized in order to weave the optimized mission architectures together into an overall, integrated architectural plan. This will likely require the formation of new teams, the search for potential common modules and functions between missions as well as the resolution of complex interface, timing and cost sharing issues.

The process of arriving at a set of common, extensible architectures starting from special-purpose, disjointed mission architectures is what NASA and the faculty are most interested in. This process is not yet well defined and we expect that students will contribute insights and unorthodox ideas on how this can best be accomplished. This is the root of the extensibility problem.

Expected Outcomes

Students will be expected to approach this problem with modern methods and tools for Systems Architecting and Engineering, such as Object-Process-Methodology (OPM), Design Structure Matrix (DSM), and Multi-Attribute Tradespace Exploration (MATE). Lectures on these techniques and their applicability to space systems, together with a review of the current global space transportation situation, will constitute the major lecture content of this course.

Students will develop mathematical models of candidate space architectures, which will form the basis of Integrated Concurrent Engineering exercises in the Design Studio (33-218). Architectural elements will consist both of legacy components and of new elements suggested by the class. The class will attempt to identify a minimum set of common space systems that can be considered as "architectural elements" from which a rich set of space exploration missions can be constructed. The set of exploration missions is bounded by the set given in Fig.1 The class will develop and apply metrics to evaluate alternative space transportation systems architectures. The end result should be a "strawman" extensible space transportation system for the set of missions shown in Figure 1. Also, it is important to carefully document the process that was followed to arrive at the suggested solution.

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1.0 GENERAL DESCRIPTION – SPACE SYSTEMS ENGINEERING: 16.89

Note: The following paragraphs are a general description of the 16.89 Space Systems Engineering course as it is given most years. The Spring 2004 project is somewhat non-traditional for 16.89, and not all the descriptions are completely applicable. However, they are included here to allow students to appreciate the general context of 16.89 projects. The biggest difference compared to previous years is that the class will not work on a single mission, but rather on a set of missions that must be connected through an overarching architectural plan. A specific discussion of the Spring 2004 design project is given in the preceding summary as well as in Section 10.

Systems Engineering and Architecture (SE&A) tells a story. It is a careful marriage of fact and vision. The story must be self-consistent and factual. At the same time, the result must be visionary either in the way in which it meets the customer needs, advances scientific knowledge, exploits new technology and processes, or reaps return for investors. Good analysis guarantees success but vision sells the concept.

Systems Engineering and Architecting has different definitions for different people. However, each definition contains some common elements. One definition is "the ensemble of coordinated analyses, simulations, and processes which lead to the design of a technical product which best meets the needs of an identified customer." It is essential that any systems design tell the "whole" story. The whole story consists of why, which, what, how, when and where.

- *Why:* the requirements define the customers needs and why the mission is worth conducting.
- *Which:* The trades analysis compares different mission architectures and determines which architecture best meets the requirements and therefore the customer's needs.
- *What:* The design describes what will actually be built and operated to conduct the mission.
- *How:* The program plan describes the organizational structure, resource allocation, funding profile, and schedule. In essence, it describes how the mission will be deployed.

- *When:* As part of the program plan, the schedule describes when different mission development and deployment stages will occur and how they depend upon each other.
- *Where:* Also as part of the program plan, the hardware flow details where the following are located: component procurement sources, sub-system integration facilities, test and validation sequence as well as checkout and launch facilities.

2.0 ORGANIZATIONAL STRUCTURE

Space Systems Engineering (16.89) is a twelve (12) unit course consisting of four (4) hours of lecture, six (6) hours of laboratory, and two (2) hours of homework per week. (Note that for this course, there is not necessarily a hard distinction between laboratory and homework.) Lectures and some of the laboratory work will take place Mondays, Wednesdays and Fridays from 1 p.m. to 3 p.m. in room 33-218. Other laboratory work will be conducted are held during standard academic hours to be scheduled amongst the students in their respective teams. One or several periods can be regularly scheduled during the week based upon student conflicts, team topics, etc. Engineering trades analyses as well as most oral presentations will be held in 33-218, which is equipped for these tasks. Formal presentations will be held in 33-116 when available. The following Faculty and staff will support the class:

Jeffrey Hoffman	A/A Professor of the Practice: jhoffma1@mit.edu
Edward F. Crawley	A/A-ESD Professor: crawley@mit.edu
Olivier L. de Weck	A/A-ESD Assistant Professor: deweck@mit.edu

3.0 SCHEDULE AND WORK BREAKDOWN STRUCTURE

Good scheduling is key to getting the work done in the time allotted. Formal reviews provide not only an opportunity to present progress on the program but also provides intermediate milestones for making sure that the SE&A story makes sense and that the various parts of that story fit together. If problems are revealed, careful scheduling (planning) allows the team to understand how the remaining time can be most effectively used to finish the work, while correcting the problems. Figure 3.1 shows the schedule for 16.89 as it exists on the first day of classes. These may change as needed by the various demands that will be placed on the program. However, the final step in the program, the **Final Design Presentation**, can not be delayed.

3.1 Program Schedule

Traditional program planning consists of three formal presentations (milestones): the Trade Analysis and Requirements Review (**TARR**); the Preliminary Design Review (**PDR**); and the Critical Design Review (**CDR**). The work between these milestones is broken into three phases: the Conceptual Design Phase; the Preliminary Design Phase; and the Critical Design Phase. The work conducted will be captured in two systems-level documents: the **Trades and Requirements Document** and the **Design Document**. **This year (2004) the Design Document will have two main sections. The first section will show the set of optimized, non-coordinated space transportation architectures obtained before Spring Break. The second section will contain the overarching plan for a unified, extensible space transportation architecture as developed during the second half of the term.** These documents may exist in hardcopy but must also exist in electronic form accessible to the entire class and controlled when appropriate. These presentations and documents are described in more detail in Section 6.0.

For the Spring 2004 16.89/ESD.352 design project, the first document will concentrate on requirements rather than on trade studies. Rather than a traditional PDR and CDR, the class will give a series of progress reports, reflecting the work of the class teams. Details are given below.

The following description of the traditional design phases is included here for context, as described at the beginning of Section 1.0. Some but not all of these elements will be included in the Spring 2004 project.

The objective of the Conceptual Design Phase is to arrive at one or two mission architectures which meet the needs of the customer in a significantly more effective fashion than other candidate architectures. To this end, several tasks must be completed which are described below. The relevant document is shown in parentheses:

1. *Extract Customer Requirements:* The mission is being designed for a customer. It is essential that the team understand the needs of that customer. These needs must be translated into customer requirements which guide the development of the program. These requirements are stated in the language of the customer. The design should be periodically compared back to these requirements during the program. [Requirements Document]
2. *Functional Requirements:* The functional requirements are created from the customer requirements and mission timelining. The functional requirements explain what must be achieved by the mission design but not how it should be done. The functional requirements are stated in engineering terms. [Requirements Document]
3. *Architectural Options:* All plausible technical options for implementing the various elements of the mission will be listed. The open literature, space mission databases, textbooks, Internet, Engineering Advisors as well as other sources should be used to identify these options. Then, those element options which are compatible with other element options are combined into a systems architecture. If an architecture meets the customer and functional requirements, it is considered a candidate architecture for the mission. [Design Document]
4. *Metric Definition:* Only a formal and quantifiable method for measuring the ability of each candidate architecture to meet or exceed the requirements allows a fair downselection to the architecture to be further developed in subsequent design phases. These metrics should include performance and cost but can also include time, reliability, etc. [Design Document]
5. *Trade Analysis:* Given the metrics, each candidate architecture needs to be studied in some detail in order to quantify how each ranks with respect to the defined metrics. This study requires understanding of some of the functional dependencies between performance and cost and consumed resources such as mass, power, time, etc. [Design Document]
6. *Downselection:* A formal downselection must lead to one or two architectures which merit further study. If a second architecture is carried forward, it should only be retained if it provides an alternative to some very high-risk element in the first

architecture, if it represents a descoping, or if it is deemed comparable to the first architecture. [Design Document]

It is important to realize that decisions made during the Conceptual Design Phase, a phase which always consists of the least amount of funding, commits most of the funding that will be spent in subsequent phases. If a decision proves to be poor, it is difficult and expensive to change in the subsequent design phases. In other words, "Roughly 10% of the resources are used to determine how to commit the remaining 90%."

The objective of the Preliminary Design Phase is to take a "strawman" mission architectural concept and develop the design in more detail. Functional requirements are flowed down to technical system and sub-system requirements. The design explains how the system achieves its requirements and how the sub-system functions are allocated. The tasks to be completed are listed below:

1. *Respond to TARR Action Items:* A formal presentation such as the TARR allows outside experts to review the design and suggest alternatives, corrections, and solutions. These comments are collected at the end of the review, ranked by priority, and assigned to a representative of the team as "action items." Action items are completed as soon as possible and formally closed at a team meeting. [Design Document]
2. *Requirements Flowdown:* The customer and functional requirements are flowed down to the sub-system level. At this level, they are stated in technical terms and start to describe how the mission will work at the system and sub-system levels. {Requirements Document]
3. *Interface Refinement:* After the TARR, the organization of the team will change and groups of people will form more clearly defined groups around individual disciplines such as optics, power, propulsion, etc. A formal definition of the new organizational structure as well as definitions of each group's interfaces is needed. These interfaces define what each group needs to know in order to do their analysis as well as define the type and format of information that that group will provide to others.
4. *Module Development:* With the team broken down into sub-system disciplinary groups, software modules which relate sub-system performance and cost to sub-

system requirements will need to be developed. For example, the power group will need to relate cost, mass, volume, lifetime, and heat load of the power system to inputs such as peak power, average power, watt-hours, duty cycle, etc. [Appendices to Design Document]

5. *Module Analyses:* With sub-system modules in place, sub-system trades are conducted. For example, the impact of variations in power consumption, hardware mass, number of units, etc. on system cost, performance, reliability, etc. is calculated. This is a highly interactive process and works best if conducted concurrently among the team members. These software modules will enable integrated concurrent engineering sessions.
6. *Budget Development:* The systems group will develop budget tracking methods to monitor the inevitable growth in resource consumption during the semester. Resources such as mass, power, computation, reliability, volume and cost will be tracked. The systems group will hold margins (30% at PDR and 20% at CDR). The systems group will also re-allocate margins between groups in order to balance the difficulty of the design effort. [Design Document]
7. *Detailed Timelining:* The details of the chronology of events also impact the design and warrant further analysis. [Design Document]
8. *PDR Preparation:* Preparing for the review is not simply “viewgraph engineering.” It forces the SE&A story to be coherent and correct. Do not under-estimate the effort associated with this task.

The Preliminary Design Phase is where teamwork is defined. Most design failures can be traced back to poor teamwork. One of the hardest parts of systems engineering is the management of interfaces. There will be times when your work requires input from others in the class. Oftentimes, this input may not be forthcoming for a variety of reasons. Sometimes, it is in the best interest of the project to make assumptions, proceed with your analysis, and present your results to those with whom you need to interface. If you’ve performed the analysis correctly, changing the value of an input should not take too long. “Don’t demand or accuse, help!”

The objective of the Critical Design Phase is to develop the design such that once the CDR is successfully completed, the program is ready to "cut metal." This course will not go to this level. However, detailed designs of the sub-systems will be required. These must be sufficiently detailed such that they can be simulated to verify that they meet their requirements. Most of the tasks started during the Preliminary Design Phase are continued in more detail during the Critical Design Phase. The Program Plan details the organization, workforce, schedule, spending profile and other programmatic issues associated with the implementation of the mission beyond CDR. "The Design Document explains what you are going to do while the Program Plan explains how you are going to do it." The Critical Design Phase is where underestimates, design errors, and bad interfaces are revealed. Efficiency in the design as well as in how the team works together is critical.

3.2 Lecture and Laboratory Schedule

Table 3.1 lists the Lecture hours already scheduled and shows the topics to be covered. Periodically, an outside visitor (Engineering Advisor) will make a presentation to the class followed by an interactive hour of questions and answers. Formal presentations are also shown, with graded activities underlined. Concurrent Engineering sessions consist of the class working together in room 33-218. These sessions are not meant for individual work; instead, teamwork is required. They also provide scheduled times when the faculty and staff will be available to assist in the effort.

Table 3.1 – Course Schedule

16.89/ESD.352 - Space Systems Engineering

Spring 2004

"Extensible Architectures for Space Transportation"

MWF 1-3 (4-6-2) (33-218)

Professors Jeffrey A. Hoffman, Olivier L. de Weck and Edward F. Crawley

Monday	**Wednesday**	**Friday**
2 Feb Registration, No Class	4 Feb **Introduction** – Hoffman **Intro System Architecture -** Crawley	6 Feb **NASA's Challenges** Gary Martin, NASA Space Architect
9 Feb **Project Apollo** - Crawley **Launch/Reentry** – Hoffman	11 Feb **In-Space Transport** – de Weck	13 Feb **Legacy Hardware** – Hoffman **Lifecycle Cost Analysis** - de Weck
17 Feb (Tuesday) **GINA** – de Weck **Mission Analysis** – Hoffman	18 Feb **Trade Space Analysis Techniques** – de Weck	20 Feb **Modular Exploration Architectures** – Hoffman
23 Feb **Free Laboratory Time** **<u>Requirements Document</u> due**	25 Feb **Designing in a Climate of Uncertainty** – Prof. Annalise Weigel	27 Feb **TBD** Crawley
1 Mar **Free Laboratory Time**	3 Mar **Guest Lecture** John Mankins / John Grunsfeld	5 Mar **<u>Status Briefing</u>** Class
8 Mar **Free Laboratory Time**	10 Mar **Free Laboratory Time**	12 Mar **Free Laboratory Time**
15 Mar **<u>Presentation of Launch and In-Space Architectures</u>** Class	17 Mar **Flexibility, Modularity, Extensibility** – Crawley **Reusability** – de Weck	19 Mar **Free Laboratory Time** **<u>Peer Review</u> due**
22 Mar Spring Break - No Class	24 Mar Spring Break - No Class	26 Mar Spring Break - No Class
29 Mar **Space Policy Overview** Annalise Weigel	31 Mar **Real Options Analysis** de Weck	2 Apr **Free Laboratory Time**
5 Apr **Decision Analysis and Uncertainty Modeling** - TBD	7 Apr **Staged Deployment of Satellite Constellations** de Weck	9 Apr **Free Laboratory Time**
12 Apr **Astrodynamics** TBD	14 Apr **<u>Mid-Term Progress Report</u>** Class	16 Apr **Free Laboratory Time**
19 Apr Patriots Day - No Class	21 Apr **Free Laboratory Time**	23 Apr **Free Laboratory Time**
26 Apr **Free Laboratory Time**	28 Apr **Free Laboratory Time**	30 Apr **Free Laboratory Time**
3 May **First Draft of Final Report due -** Class	5 May **Free Laboratory Time**	7 May **Free Laboratory Time**
10 May **<u>Final Presentation</u>** Class	12 May Last Class - Luncheon **<u>Final Design Report</u> due**	

4.0 DELIVERABLES

The deliverables in 16.89 are underlined in Table 3.1:

1. Requirements Document
2. Informal Status Briefing (mid-term report #1)
3. Formal Presentation by Launch and In-Space Individual Architecture Teams
4. Mid-Term Progress Report (#2)
5. Final Presentation of Integrated Space Transportation Architecture
6. Final Design Report

5.0 MODULE DEVELOPMENT

Note: Traditional Space Systems Design projects are usually oriented towards hardware design, in which case the module development described below typically concentrates on modeling subsystems. The Spring 2004 design project will certainly utilize computer modeling, but in a unique way to be developed as the class progresses. The following is a description of the traditional, subsystems-oriented module development.

During the semester, each student will be responsible for developing and utilizing a software module. This module describes the particular discipline for which that student is responsible and mathematically captures the relationships between that discipline's inputs and outputs. There will be times during the semester when one person will ask another how much that second person's sub-system will change (outputs) in the event that the requirements on that sub-system change (inputs). For example, a power subsystem module might describe how the mass, volume, and reliability change if the required watt-hours, battery (dis)charge duty cycle, and mission lifetime change. As another example, a systems module might describe how the total cost of the spacecraft changes as required power, mass, mission lifetime, and reliability change. These relationships can be derived from SMAD as well as other reference material.

These modules serve several purposes and may be combined with other modules within that person's group. First, they force the student to understand and codify functional relationships within their discipline. Second, they help to define and clarify interfaces between the different groups and modules. These modules will be codified, grouped with other modules within that group, documented, utilized, and submitted to the Design Document as an appendix.

If codified in Matlab, they can be linked as function calls (subroutines) with their strict definitions of inputs and outputs. During an integrated concurrent engineering exercise, the computer display of key assumptions and system budgets will be projected onto a screen in front of the class. The class will then alter assumptions and view the impact of these changes in realtime on the screen. In this way, design spaces can be explored and compared in fractions of the time conventionally required. Students will be graded on their modules. Remember, the module must be complex enough to capture the important relationships yet simple enough to provide outputs that make sense and code which is available in time to be used in these integrated concurrent engineering exercises. The modules are only useful if their information is correct and they are available on time. The following deliverables are required for each student's module:

1. Definition of interfaces (inputs and outputs) and module content (i.e., module requirements). Be sure to specify units for different variables.
2. Module development: mathematical relationships, software code, and code validation.
3. Contribution to the Concurrent Engineering exercises.
4. Module refinement: list features to be refined, mathematical alterations, software code, and code validation.
5. Final submittal to Design Document appendix: module requirements, mathematical relations, code, validation, and use history.

6.0 COMMUNICATIONS

6.1 Daily Communications

An email list has been established (16.89-students@mit.edu). It should be used to augment communication between individuals and groups in the class. Faculty and advisors will not be on this list. Ms. Jacqueline Dilley (jdilley@mit.edu) will help administer the list. The staff can be contacted en masse at 16.89-faculty@mit.edu.

6.2 Weekly Communications

The instructor staff will meet every Tuesday at 3:00 p.m. in 33-410 to discuss progress in the class. Representatives from the class will on occasion be asked to come and talk with the staff at this meeting.

Each student will from time to time give informal progress reports for their team that will be graded. Report assignments will be made as the semester evolves. The purpose of the reports is to make the other students aware of the progress and needs of that team. These reports will summarize the progress of that student's team, plans for near term work, and solicit and information needed from other teams.

6.3 Oral Presentations

High quality presentations are important for communication of what you are doing. Every student is expected to make at least one oral presentation during the term. The five oral presentations are listed in the table below. Part of the grade for each student will be on the technical contribution to all formal presentations as well as on the delivery of their portion of presentations. A small group of students will be assigned to coordinate each of these presentations (a different coordinating group for each presentation). These reviews are discussed in more detail below:

1. *Requirements Document Presentation:* The primary objective is to present and formally accept and place under configuration control the written Requirements Document. This is the guiding document for the development of the space transportation system architecture that will comprise the bulk of the work for the course. It is critical that the class agree early on what requirements the system will

have to satisfy. A design effort without clearly stated requirements is doomed to failure.

2. *Status Briefing (mid-term report #1):* The **Earth-to-LEO team** and the **In-Space team** will each present an informal progress report on their work to date. This is an opportunity for each team to hear what the other is doing and for “mid-course corrections” to be made.
3. *Individual Team Presentations:* The **Earth-to-LEO** team and the **In-Space teams** will each present the final status of their individual design efforts, showing how their selected architectures meet the design requirements. After these presentations, the class will come together to try to merge the architectural elements of the two teams.
4. *Mid-term Progress Report #2:* At this point in the course, the class should be well along in the process of integrating the launch and in-space architectural elements presented in Item 3 and should present the progress made. An important part of this review will be to estimate how much can be accomplished in the remaining course time and to lay out a plan of action for completing the work and writing the final design document.
5. *Final Presentation:* This will be a unified presentation for the entire class, similar to a CDR presentation. The main content will be the unified, extensible space transportation architecture that the class recommends NASA to implement. The process that was followed for arriving at this unfied architecture as well as supporting rationale (calculations …) must also be included.

6.4 Documents

The lasting value of the work done for this course will consist primarily of the two documents which the class will produce. The documents will include sections written at two different levels. The documents must be technically correct and should represent an appropriate level of work for MIT graduate students; however, if the work is to have an impact outside MIT, the documents should include sections addressed to non-technical audiences, people with an interest in space but not a high level of technical expertise (such as the media or congressional staffers).

The following two (2) documents will be prepared, maintained and eventually integrated by the class. Always reference the sources of information and ideas in the documents. These documents must be electronic in nature and accessible to the entire team (as "read only" once under configuration control).

1. *Requirements Document:* defines the "goods and services" that are required of the design. This document constitutes the "contract" between the customer and the systems engineering and architecting team. Sometimes, part of this document is written by the customer. At other times, it results from a study by the systems team to determine the needs of a customer in order to assess the viability of a new product. **For the Spring 2004 design project, the class will determine the design requirements flowing from the new national space policy described earlier in this document.**
2. *Design Document:* captures the specifications for the system. It also captures the rationale that led to these specifications. To this end, the trades analysis, requirements pushback, budgets, system and sub-system designs, analysis tools and simulation results are included. Requirements pushback is the analysis that verifies that the design meets the requirements. This is in contrast to the requirements flowdown, which simply allocates requirements with minimal knowledge of the implications of these allocations. Requirements pushback is essential to determine whether the design meets the requirements and whether one or more part of the overall system is facing particularly stringent requirements while others face more lenient requirements. This allows proper balancing of the allocated requirements. **For the Spring 2004 the design document will contain multiple complementary views (operational, form-function, deployment strategy, lifecycle cost…) of a unified space transportation architecture as well as the process that was used to arrive at the answer.**

6.5 Web Page

A web page will be maintained as the electronic repository of the current 16.89/ESD.352 documents **[http://stellar.mit.edu/S/course/16/sp04/16.89/index.html].**

This page will provide all team members access to the current versions of the program documents. In addition, it will enable our engineering advisors to have access to this same information. This will allow them to track the progress of the class and provide comments and suggestions throughout the duration of the semester.

It is the students' responsibility to check frequently if updates or new materials and announcements have been posted.

7.0 GRADING

Grading for 16.89/ESD.352 will be based upon the criteria shown in the following table. The percentage weights of each item and a brief description are provided. These grades will be reported to the students in their end-of-term grades as well as at least once during the term.

Table 7.0: Grading Categories and Weights

Criteria	Grader	Total Weight	Number
Written documents	Faculty and Staff	20%	2
Oral presentations	Faculty and Staff	20%	5
Presentation View Graphs	Faculty and Staff	15%	5
Colleague reviews	16.89 students	15%	1
Analysis/SW development	Faculty and Staff	20%	1
Class Participation	Faculty and Staff	10%	-

1) *Written documents:* Each student will author portions of the two required documents. Their contribution will be clearly indicated using initials.
2) *Oral presentations:* Each student is required to participate in at least one of the oral presentations during the semester. The faculty and outside advisors will grade both the students' presentations as well as the quality of the presentation material.
3) *Formal presentation View Graphs:* Each formal design review presentation will be accompanied by annotated viewgraphs provided electronically and in written form by

the students to the faculty. Each student's contribution to the written presentation will be indicated by their initials.

4) *Colleague reviews:* Students will turn in, shortly before Spring break, their evaluations of their student colleagues. These will include discussions of the ways in which each student interacted with other students in the class, the usefulness of these interactions, areas in which the other students excel, and areas in which the other students can improve. If none of the students say that they worked with you, it will reflect poorly on your team working skills. The specific format of this evaluation will be discussed later.
5) *Software development:* Each student will be responsible for the development of some software or analysis that contributes to the class design effort. In some cases, contributions other than software may be used instead.
6) *Class Participation:* This design project is a team effort. Class attendance and full participation is critical and will be graded.

Academic Honesty: The fundamental principle of academic integrity is that you must fairly represent the source of the intellectual content of work that you submit for credit. 16.89 is a design course heavily dependent on teamwork. It is important that individual contributions to the team effort be properly identified.

8.0 RESOURCES

Books:

1) Required Textbook: Human Space Flight: Mission Analysis and Design (HSMAD), Wiley J. Larson and Linda K. Pranke, McGraw-Hill, 2000; *available at the Coop and on reserve in the Aero-Astro Library*.
2) Lunar Base Handbook, Peter Eckardt, ed.; *on reserve in the Aero-Astro Library.*
3) Rocket Propulsion Elements, George P. Sutton and Oscar Biblarz, John Wiley and Sons, 2001; *on reserve in the Aero-Astro Library.*
4) International Reference Guide to Space Launch Systems, Third Edition, Steven J. Isakowitz, Joshua B. Hopkins, Joseph P. Hopkins; AIAA Publications.

Web Sites:

1) New Space Policy: http://www.whitehouse.gov/infocus/space/vision.html
2) Apollo by the Numbers: http://history.nasa.gov/SP-4029/Apollo_00a_Cover.htm
3) General Exploration Documents: http://ares.jsc.nasa.gov/HumanExplore/Exploration/EXLibrary/EXdocuments.htm
4) NASA Budget: http://www.spaceref.com/news/viewnews.html?id=924 (with links)
5) Columbia Accident Investigation Board (CAIB) Report – See Volume 1, recommendations: http://www.caib.us/news/report/default.html

Additional reading materials and references will be made available during the semester as appropriate.

9.0 Contact Information

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10.0 Class

10.1 Class Mission Statement

Students will consider the requirements for a new human space transportation system both from Earth to LEO and beyond (Moon, Lagrangian Points, Mars, asteroids) together with requirements for launching quantities of cargo appropriate for future space exploration. Architectural elements will consist both of legacy components (recycling as much as possible from current systems) and of new elements suggested by the class. The class will attempt to identify a minimum set of common space systems that can be considered as "architectural elements" from which a rich set of space exploration missions can be constructed.

Specifically;

- Identify function-form architectural elements that can be combined to meet the mission requirements of the LEO missions (O1,O2) as well as the extended missions (E1,E2,E3).
- Create models that capture the essential attributes of these architectural elements including masses, volumes, interfaces among others
- Validate these models using appropriate data.
- Show how the architectures are interconnected and how they operate over the timeline of each mission
- Combine these models into an integrated analysis framework
- Assess the cost benefit of various mission architectures
- Conduct a detailed design of some aspect of the favored mission architecture.

10.2 Project Approach

This course will attempt to recreate the environment currently faced by the professional space community in thinking about space transportation in the twenty-first century. If human exploration is to expand, as well as robotic systems of sufficient value and complexity to require periodic maintenance, repair and upgrades (like the Hubble Space Telescope), then new ways of getting to and from and working in space are necessary. This must be done in a fiscal environment where space budgets are unlikely to expand significantly.

Students will be expected to approach this problem with modern Systems Architectural techniques. Lectures on these techniques and their applicability to space systems, together with a review of the current global space transportation situation, will constitute the major lecture content of this course. Students will develop mathematical models of candidate space architectures, which will form the basis of Integrated Concurrent Engineering exercises in the 33-218 laboratory. The goal is to take a new look at future space transportation systems architecture in a way that will be useful and stimulating to the professional space community.

The entire class will work together at the beginning of the semester to understand the basic architecture and technologies of the Apollo program. A problem set will be given to develop this initial understanding. The class will then divide into two sections: one oriented towards Earth-to-LEO transportation and one oriented towards In-space transportation. Each team will create a requirements document to set the scope for its work and will then develop a space transportation systems architecture which satisfies the requirements. These architectures will be presented about halfway through the course, after which the class will reunite and attempt to identify points of commonality between the architectural solutions. As stated above, by the end of the course, the class will have identified a minimum set of common space systems that can be considered as “architectural elements” from which a rich set of space exploration missions can be constructed. The results of the study will be presented both orally and as a written design document.