Capstone Design Course
for NASA ESMD

developed by
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Course Scope

What is Capstone Design?

- How to develop products to exceed customer requirements and expectations
- This is the real thing
- Students synthesize their foundational knowledge and add new skills to deliver

Course Overview

- The Capstone Design course requires that students work in teams on "open-ended" engineering design projects. Students are given the opportunity to realize original and creative solutions to real engineering problems, not merely design changes of scale or duplication of existing systems. Important topics are presented in the lectures, including the design process, design tools, systems engineering, project management, engineering communication, engineering ethics, and intellectual property. Students are encouraged to take on new team roles and to test the limits of their capabilities.

Learning Objectives

- Students will understand the importance of a structured design process
- Students will understand and be able to implement the five phases of a structured systems engineering process
- Students will be able to implement the key tools of a structured design process
- Students will gain practice in working on self-managed teams
- Students will gain confidence in their abilities to deliver an engineering solution from need to parts

ABET Criteria for Engineering Education

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multi-disciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Engineering Design

- … a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.
  Dym *et al.*, "Engineering Design Thinking, Teaching, and Learning," *Journal of Engineering Education*, 2005.
- … the process of devising a system, component, or process to meet desired needs. It is a decision- making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.

Criteria for Accrediting Engineering Programs, ABET, 2008.

Engineering Design

- … the communication of a set of rational decisions obtained with creative problem solving for accomplishing certain stated objectives within prescribed constraints. Lumsdaine *et al.*, p. 316
- Design establishes and defines solutions and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way. … The ability to design is both a science and an art. … Good design requires both analysis and synthesis. Dieter, pp.1-3
- Design incorporates creativity, complexity, making choices between many possible solutions, and compromise in balancing many (sometimes conflicting) requirements. Dieter, pp.1-3

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What Makes this Coure Different?

Design Process Comparison - Stages

NASA	Capstone Design	Lumsdaine
	Pre-Phase A	
Concept Studies	Design Problem Analysis	Design Problem Analysis
	Phase A	
Concept and Technology Development	System Level Conceptual Design	Conceptual(System) Level Design
	Phase B	
Preliminary Design and Technology Completion	Parameter Level Design	Parameter Level Design
	Phase C	
Final Design and Fabrication	Optimized Parameter Design	Optimized Parameter Design
	Phase D	
Assembly, Integration, and Test Launch	Fabrication, Assembly, and Testing	-

Design Process Comparison – Reviews and *Documents*

NASA	Capstone Design	Lumsdaine
Pre-Phase A		
MCR- Mission Concept Review IPR- Informal Proposal Review *Program/Project Proposals* *Preliminary Mission Concept Report*	PCR- Project Concept Review *Project Approval Document*	Review by Instructor, Advisor, and Sponsor *Design Project Proposal*
Phase A		
SRR- System Requirement Review SDR- System Definition Review	SRR- System Requirement Review SDR- System Design Review	*Design Concept Keys* *Design Decisions*
Phase B		
PDR- Program Definition Review *Preliminary Design Report* *Interface Control Documents*	DOR- Design Objectives Review PDR- Product Design Review *Refined System Concept*	Review by Instructor, Advisor, Team, and Sponsor *Design Project progress Report*
Phase C		
CDR- Critical Design Review PRR- Production Readiness Review *Preliminary Operations Handbook*	DOR- Design Objectives Review CDR- Critical Design Review PRR- Production Readiness Review *Refined Parameter Design*	Design review panel and Instructor – Oral Presentation Review *Final progress Report*
Phase D		
TRR- Test Readiness Review SAR- System Acceptance Review ORR- Operational Readiness Review *Verification and Validation Report* *Operator and Maintenance Manuals*	TRR- Test Readiness Review SAR- System Acceptance Review ORR- Operational Readiness Review *Final Design*	-

Systems Engineering Proces

Systems Engineering

- Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system
- A "system" is a construct or collection of different elements that together produce results not obtainable by the elements alone

Objective

- "The objective of systems engineering is to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule and risk."
  - NASA Systems Engineering Handbook SP-6105

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System Engineering Functions

- Major functions that lay the ground work for a robust approach to the design, creation, and operation of system.

Key SE Functions

- Design Objectives and Constraints
- Weighted User Requirements
- Functional Descriptions
- Validation and Verification
- Interfaces and ICDs
- Milestone Reviews
- Risk Management

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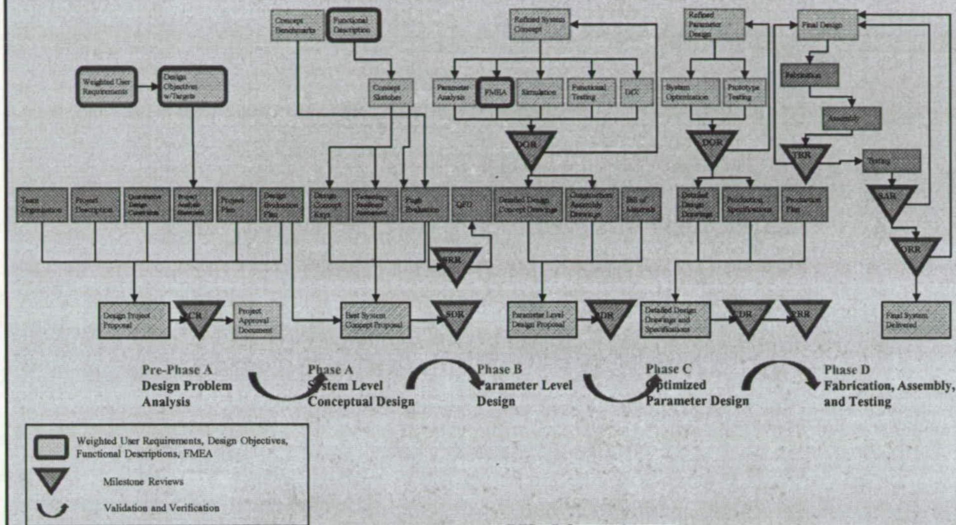
Key SE Functions in the Design Process



Design Objectives and Constraints

- *When?*
  - Pre-Phase A: Design Problem Analysis
- *What?*
  - Clearly define and document the design goals to make sure that the team is working towards a common goal
  - Capture quantitative constraints which can be used to validate product design

Weighted User Requirements

- *When?*
  - Pre-Phase A: Design Problem Analysis
- *What?*
  - Establish the various requirements like functional, performance, interface, environmental etc
  - Document these requirements in a formal manner
  - Refine these requirements by conducting trade studies

Functional Descriptions

- *When?*
  - Phase A: System Level Conceptual Design
- *What?*
  - Goal is to develop an architecture and design that meets the requirements
  - Block diagrams are key mechanism for documenting and communicating the functional analysis and architecture to the team.

Validation and Verification

- *When?*
  - Takes place over the systems engineering lifecycle to show that systems of interest meets the objective

Validation

- Assure design meets the *objectives*
  - For example, validate the ICDs to Weighted user requirements and Functional descriptions & Architecture

Verification

- Verify the design against the *requirements*
  - Use as an important risk reduction measure
  - Carry out functional tests and simulations as in Phase B
  - Using a Critical Design Review(CDR) in Phase C, assign the requirements a verification method

Verification

- Verify the design against the *requirements*
  - Verify the requirements in Phase C and D using the Production Readiness Review(PRR) and Operational Readiness Review(ORR) respectively
  - Review of the verification results is particularly effective in identifying and correcting problems

Interfaces and ICDs

- *When?*
  - Before Phase C
  - Establish before Product Design Review(PDR) to allow detailed design to proceed with minimal risk of changes
- *What?*
  - Describe and document where and how various system elements need to connect or communicate with each other

Milestone Reviews

- *When?*
  - Between and during all phases
- *What?*
  - Validate the quality and completeness of a system engineering phase or portion thereof
  - Facilitate knowledge sharing and identification and resolution of challenges and issues

Risk Management

- When?
  - Apply various tools at appropriate phases
- What?
  - Perform FMEA at Parameter level design during Phase B
  - Report results of FMEA at critical milestone reviews
  - Use other tools like FTA, Reliability Analyses etc.

Course Structure

Student Audience

- Capstone Design is intended for engineering students that have completed all of the core requirements of their education
- The purpose of the course is to teach students how to implement a structured design process on a real project in a team (perhaps multi-functional) environment
- Teams can contain a mix of students in various years as long as they are all exposed to the design process material

Faculty Audience

- The lecturer for this course may be different from the advisor(s)
- The lecturer should have familiarity and experience with structured design
- Faculty should use these modules as a text from which they will design their own course, possibly adding material

Projects

- Teams of 4 or more students work on one sponsored project lasting two semesters
- Projects encompass the entire design process — ideation through functional prototype build and evaluation
- The first semester ends with a formal project review, reflective of a typical stage-gate process, in which each team demonstrates their design progress to date and gain approval for their plan to complete the project during the second semester
- The second semester concludes with a project-ending full presentation before industry representatives, faculty members, and their peers
- Typical projects are design-intensive, where the team may be asked to develop a new product, design and build a portion of a new manufacturing process cell, or fabricate a special machine designed for a specific task

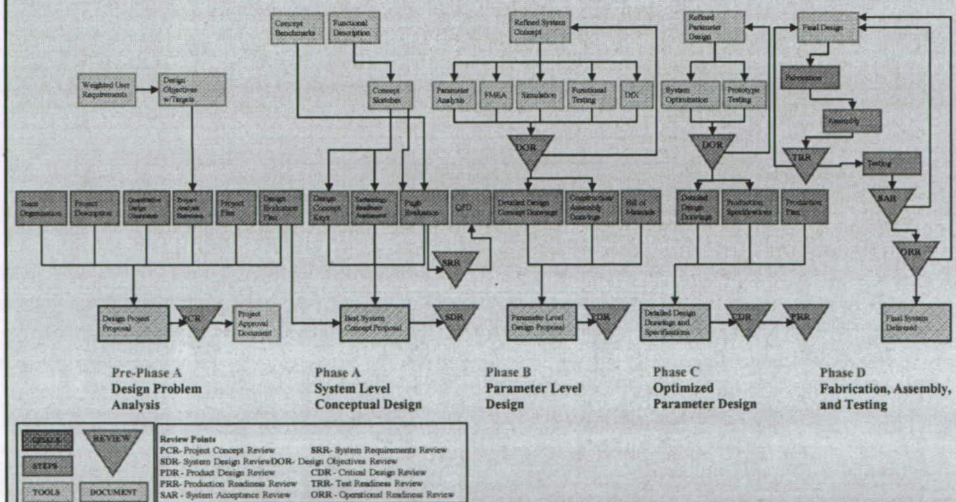
Module Structure

- Designed as training modules
  - Not necessarily one day
  - Not necessarily in a traditional class setting
  - Treat them as engineers, not students
- Module structures are parallel
  - Teach structured design tools with "traditional" and "space" examples
  - Relate it to the overall process and project deliverables
    - Integrate reviews and reports
  - Offer additional example that relates to their projects and motivate the importance of systematic design
  - Offer additional reading

Module Structure

- Designed as training modules
  - Not necessarily one day
  - Not necessarily in a traditional class setting
  - Will add in "space examples" from two new texts and pilot program
- Module structures are parallel
  - Trying to teach a "tool"
  - Relate it to the overall process and what they have to do (deliverables)
  - Teach it with examples
  - Offer additional example that relates to their projects
  - Offer additional reading
  - Treat them as engineers, not students

Capstone Design Process



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Abbreviations and Acronyms

CDR	Critical Design Review
DfX	Design-for-X
DOR	Design Objectives Review
FMEA	Failure Modes and Effects Analysis
ORR	Operational Readiness Review
PCR	Project Concept Review
PDR	Product Design Review
PRR	Production Readiness Review
QFD	Quality Function Deployment
SAR	System Acceptance Review
SDR	System Design Review
SRR	System Requirements Review
TRR	Test Readiness Review

Learning Modules

Module	Description
00	Course Introduction
01	The Design Process
02	Team Organization
03	Project Description
04	Project Requirements
05	Project Planning
06	Conceptual Design
07	Pugh Evaluation
08	Quality Function Deployment
09	System Design Review
10	Failure Modes and Effects Analysis
11	Design-for-X
12	Parameter Analysis
13	Parameter Level Design Proposal
14	System Optimization
15	Prototyping and Testing
16	Detailed Design Drawings
17	Fabrication, Assembly, and Testing

Lecture/Project Integration

- It is important to keep the project as the topic of the lecture
- All lecture topics should be framed in terms of what students need to do on their projects
- Students MUST use a structured design process, even when less formal procedures would suffice
- It is my feeling that additional, non-project assignments and exams do not add to the quality of the learning but can cause "mutinies"

Assignments

- If it is necessary for the course (as opposed to the advisor and the project) to dictate assignments, make sure that the assignments are part of the critical path of ALL projects
- One significant issue with sponsored projects (or even different projects) is that they will have differing milestone timelines and make blanket due dates impractical

Notes

- The notes in this course are designed for you to give to your students BEFORE the lecture
- You can then use your knowledge of the design process and your design experiences to help them "fill in the gaps"

Texts

- *Main text*
  - *Creative Problem Solving and Engineering Design,* Edward Lumsdaine, Monika Lumsdaine, and J. William, Shelnutt, McGraw-Hill College Custom Series, New York, 1999
- Additional suggested texts
  - *Engineering Design,* 3rd Edition, George E. Dieter, McGraw-Hill, Boston, MA, 2000
  - *A Guide to Writing as an Engineer,* David Beer and David McMurrey, John Wiley & Sons Inc., New York, 1997
  - *Patent Fundamentals for Scientists and Engineers,* 2nd Edition, Thomas T. Gordon and Arthur S. Cookfair, Lewis Publishers, CRC Press LLC, Boca Raton, FL, 2000

Additional References

- Bahill, T.A. and Gissing, B., Re-evaluating System Engineering Concepts Using Systems Thinking, IEEE Trans. on Systems, Man and Cybernetics, v.28(4), p.516-527, 1998.
- Ullman, D.G., The Mechanical Design Process,3rd edition, McGraw-Hill, 2003.
- System Engineering Paper Submission Template, http://education.ksc.nasa.gov/ESMDspacegrant/SE_Paper_Submission_Template.doc
- Blanchard, B.S. and Fabrycky,W.J., System Engineering and Analysis, 2nd edition, Prentice Hall, 1990.
- ANSI/EIA 632-1998, Processes for Engineering a System, Electronic Industries Alliance, 1999.
- Raju, P.K. and Sankar, C.S. Introduction to Engineering with the Use of Case Studies, Institute for STEM Education and Research, 2007.
- Larson, W.J. (Editor) and Wertz, J.R. (Editor), Space Mission Analysis and Design, 3rd edition, Space Technology Library.
- Fortescue, P. (Editor), Stark, J. (Editor), and Swinerd, G. (Editor), Spacecraft Systems Engineering, 3rd edition, Space Technology Library.
- Sarafin, T.P. and Larson, W.J. (Editor), Spacecraft Structures and Mechanisms from Concept to Launch, The Space Technology Library
- Space Vehicle Mechanisms: Elements of Successful Design (Hardcover) by Peter L. Conley
- The Space Environment: Implications for Spacecraft Design (Paperback) by Alan C. Tribble (Author)
- Space Vehicle Design (Aiaa Education Series) (Hardcover) by Michael D. Griffin (Author), James R. French
- Fundamentals of Space Systems (The Johns Hopkins University/Applied Physics Laboratory Series in Science and Engineering) (Hardcover) by Vincent L. Pisacane
- Principles of Space Instrument Design (Cambridge Aerospace Series) (Paperback) by A. M. Cruise (Author), J. A. Bowles (Author), T. J. Patrick (Author)
- Elements of Spacecraft Design (Aiaa Education Series) (Hardcover) by Charles D. Brown
- Spacecraft Power Systems (Hardcover) by MukundR. Patel (Author)
- Spacecraft Thermal Control Handbook: Fundamental Technologies (Hardcover) by David G. Gilmore
- Spacecraft Power Technologies (Space Technology) (Hardcover) by Anthony K. Hyder (Author), Ronald L. Wiley (Author), G. Halpert (Author), Donna Jones Flood (Author), S. Sabripour

Additional References

- Aircraft Structures for Engineering Students, Fourth Edition (Elsevier Aerospace Engineering) (Paperback) by T. H. G. Megson (Author)
- Printed circuits in space technology: Design and application (Prentice-Hall space technology series) by Albert E Linden
- Human Spaceflight: Mission Analysis and Design (Space Technology Series) (Space Technology Series) by Wiley J. Larson and Linda K. Pranke
- Solar Power Satellites: The Emerging Energy Option (Ellis Horwood Library of Space Science and Space Technology. Series in Space Technology) by Peter E. Glaser, Frank Paul Davidson, and Katlinka I. Csigi
- Spacecraft structures (Prentice-Hall international series in space technology) by Carl C Osgood (Unknown Binding - 1966)
- Cryogenic engineering (Prentice-Hall international series in space technology) by Joseph H Bell (Unknown Binding - 1963)
- Space mechanics (Prentice-Hall international series in space technology) by Walter C Nelson (Unknown Binding - 1962)
- Navigation and guidance in space (Prentice-Hall international series in space technology) by Edward V. B Stearns
- THE SECOND FIFTEEN YEARS IN SPACE: SCIENCE AND TECHNOLOGY SERIES: VOLUME 31: by Saul (Editor) Ferdman
- The Lunar Base Handbook (Space Technology Series) by Peter Eckart (Paperback - Dec 1, 1999)
- Technologies of manned space systems (Space flight technology series) by Aleck C Bond (Unknown Binding - 1966)
- Metallurgical Assessment of Spacecraft Parts, Materials and Processes (Wiley-Praxis Series in Space Science and Technology) by Barrie D. Dunn and M. Phil (Paperback - Jun 1997)
- Satellite Control: A Comprehensive Approach (Wiley-Praxis Series in Space Science and Technology) by John T. GarnerIntroduction to space communication systems (McGraw-Hill series in missile and space technology) by George NKrassner
- Robots in Space: Technology, Evolution, and Interplanetary Travel (New Series in NASA History) by Roger D. Launius and Howard E. McCurdy (Hardcover - Jan 7, 2008)
- Recent Developments in Space Flight Mechanics (Science and Technology Series Volume 9) by Paul B. (editor) Richards (Hardcover - 1966)
- The Lunar Sourcebook (Heiken et al) is a good reference. Chapter 3 covers the lunar environment.
- http://insa.netquire.com/docs/Lessons_Learned_Fina.pdf

Facilities

- Students need facilities to conduct team meetings without being interrupted, to conduct phone/video conferences with sponsors, to fabricate their prototypes/deliverables, and to do assembly and testing
- Do not underestimate the resources for this
  - Space for projects
  - Personnel for a safe fabrication shop

Fabrication

- This course is not a course in how to use a fabrication shop
- That is an important class for engineers, but it is expected that students have completed such a course beforehand
- It should be possible for them to complete their project (and product) within the university, but it is not required
- Depending upon the project's budget, work can be done "out of house"
- Working with contract fabrication allows students to learn much more about engineering communication

Syllabus

- A sample syllabus will be included here based upon the test implementation this fall

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Grading

- Each sponsor and advisor will expect a finished, documented project completed to his or her expectations
- It is important to grade against those expectations as well as the students' use of a structured design process and the tools therein

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Roles

Student Role in Projects

- Each student will participate in a team project
- This is the most important element of the class
- The project is designed to be their first project outside of school and should be treated as a job
- The goal is to give them that experience with fewer ramifications for project failure
- Each person will be expected to participate in the team and work on the project professionally
- Each sponsor and advisor will expect a finished, documented project completed to their expectations

Advisor

- The advisor and sponsor are also responsible for project success
- The role of the advisor is to help guide the team through the design process, offer advice when appropriate, steer when necessary, and help find information when necessary
- This is accomplished through at least one weekly, hour-long meeting
- The advisors should not be expected to be the sole source for technical information nor necessarily the primary source

Sponsor

- The advisor and sponsor are also responsible for project success
- The sponsors represent their own interests
- The team is expected to serve those interests within the guidelines set by the advisor
- Groups should meet frequently with their sponsors – in person and by teleconferencing or videoconferencing

Projects

Why a Sponsored Project?

- This course is developed around having sponsored projects
- Ideally the projects are paid for by an outside group that is truly committed to the project
- This commitment gives the project financial resources as well as a "customer"
- Even if there is no financial commitment, each project should have a customer that is external to the class that "needs" the final product
- It is important to remind sponsors that not all student projects are successful

Project Description

Project Concept Statement

Design of a Lunar Penetrator to collect one meter of regolith sample

Surface penetrators have been launched in the past by NASA space missions to Mars, which have failed to provide the intended outcome. According to the investigation results from the Mars mission, the failure is attributed to the inability of the communication system to transmit mission data to earth stations via the orbiting satellite. This may be due to the failure of the penetrator and communication hardware to survive impact.

The internal structure of the moon is still not well understood. Acquisition of further knowledge about the lunar core can help us to understand the moon's early history. The regolith sample can provide us with information on the presence of water and other organic volatiles which is relevant to assess lunar evolution and the possibility of future lunar resources. This information reflects the core interests of NASA's lunar missions, making them the main sponsor for this project to coordinate the primary design requirements and specifications.

Our main objective is to design and possibly test a sub-scale prototype of a lunar penetrator that demonstrates key attributes including survival of great impact forces, compliance with weight and dimensional constraints, and the ability to interface with various scientific instruments. The objective will be achieved by following a structured design methodology, progressing from the design problem analysis stage through the optimized parametric design stage. During this entire design process, various design tools will be used to achieve the desired objectives and minimize the risk of failure. Detailed design drawings and specifications will be delivered by February 2009, possibly followed by the fabrication of a sub-scale prototype.

Issues

Instructor Background

- Instructors (lecturers) MUST have a solid background in the fundamentals of the structured design process as well as design experience
  - This is often a shortcoming of some faculty that are asked to teach capstone design
  - I will make it clear in Module 00 along with what type of course this will support

Student Capability

- There seems to be significant concern with the level of the material and students' capabilities
  - We have taught most of this material to senior undergraduates in the past (even juniors)
  - This is material that many will need to become design engineers
  - Faculty can choose to omit topics if their students are having difficulty

Amount of Material

- There was considerable concern that there is more material than can be taught in a course
  - I agree, use this as a text and pick and choose which topics you feel are necessary
  - I will include 'A' and 'B' topics in Module 00
- Course is designed as three hours of class (lecture) time per week for two semesters

NASA Examples

- NASA examples WILL be added following the pilot course
  - We will follow the one project (done by one or two groups) through each module and use their deliverables as examples
  - These will be in the appendix of each module

Course Syllabus

- We will include one to give an example of how we chose to structure the pilot course
  - I don't feel that any two courses end up the same as the differences in curricula, project structure, faculty experiences, *etc.* are too extreme

Additional Topics

- Based upon our assessment and what we hear from reviewers, we are planning to add additional topics
  - Risk
    - In Module 00 we will discuss the difference between regular and high risk design in space-based projects and what tools are used to help mitigate that risk
  - Systems Integration
    - We will be more explicit in discussing systems integration as a standalone topic, we have found a new resource for this information
  - Technology Assessment
    - We need to do a better job of teaching TA and TRL
    - We are looking for material resources – suggestions?

Additional References

- Based upon reviews, we will group pertinent references for each module and put them with descriptions at the end of each module
- These would be geared towards instructors
- There was also a comment on the need for a descriptions slide with each module that we did not understand, but might go into this additional instructor material

ESMD Lessons Learned

- What have you learned in projects that would help in this course?
  - Additional tools

Project/Meeting Hours

- There was some concern about whether the capstone projects can be completed in a year and the number of meeting hours required
  - From our experience projects can go from needs definition to finished quality hardware in 25-28 class weeks
  - Student groups should be self-managed to some degree and meet with their advisor for roughly one hour a week
  - Groups should also meet with their sponsor for roughly one hour per week, ideally with their advisor present
  - Sponsor and advisor involvement are key to project success

Appendices

http://www.nasacapstonedesign.m
tu.edu/

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