Utah State University
Department of Mechanical and Aerospace Engineering
Academic year 2009-2010

Design and Testing of a Demonstration Prototype for Lunar or Planetary Surface Landing Research Vehicle *(LPSRV)*

Course Handbook

Instructor: Stephen A. Whitmore
Instructor Phone: 435-797-2951
Instructor Email: swhitmore@engineering.usu.edu
Office: ENGR 419F

Table of Contents

Section Name …………………………………………… Page number

Course Overview …………………………………………… 3

Assessment Materials …………………………………………… 6

Section 1
Introduction …………………………………………… 1-1
USA Space History Policy, and Organizations …………………………………………… 1-9

Section 2
Systems Engineering I ……………………………………………2-1
Systems Engineering II *Design Tools* ……………………………………………2-13

Section 3
The Space Environment ……………………………………………3-1
The Lunar and Martian Environment ………………………………………… 3-10

Section 4
Rockets, Past, Present And Future ……………………………………………4-1
Rocket Science 101 *Basic Concepts and Definitions* ………………………………………… 4-16

Section 5
Spacecraft Subsystems Overview ……………………………………………5-1

Section 6

Propulsions Systems ……………………………………………6-1
Overview

Propulsion Systems II …………………………………………… 6-18
Selecting the Right System

Section 7

Orbital Mechanics I ……………………………………………7-1
Kepler's Laws

Obital Mechanics II …………………………………………… 7-9
Visa Viva Equation
Describing Orbits in
3-Dimensions,
Orbital Maneuvering

Section 8

Flight Mechanics I ……………………………………………8-1
Launch Dynamics
Energy Analysis, and
Required ΔV

Flight Mechanics II …………………………………………… 8-20
Equations of Motion

Flight Mechanics III …………………………………………… 8-41
Motions in 6-degrees
-of-freedom

Appendix …………………………………………… 8-55
Introduction to
Geodesy

Section 9

Flight Controls I ……………………………………………9-1
Vehicle Stability,
Control Actuators
System Examples

Flight Controls II …………………………………………… 9-13
Feedback Control Systems

Section 10

Spacecraft Avionics I ……………………………………………10-1
Power and Thermal,
Management Systems

Spacecraft Avionics II …………………………………………… 10-16
Telemetry and
Communications Systems

Section 11

Spacecraft Structures ……………………………………………11-1
Structural Dynamics
Resonance

Mechanism*s* …………………………………………… 11-13

Section 12

Measurements and Uncertainty Analysis I *Error Classification, Calibration, and Data Presentation* ………………………………………… 12-1

Measurement and Uncertainty Analysis II *Probabilistic Description Of Error* ………………………………………… 12-16

Appendix *χ-2 Hypothesis Testing Example* ………………………………………… 12-31

Section 13

Technical Writing ………………………………………… 13-1

Course Overview

I) Synopsis: This Course is a two-semester sequence, with MAE 5930 Technical elective taught fall semester 2009, MAE 4800 Senior Design Class spring semester 2010.

Fall 2009

Course Title: ***Launch Systems Design***
Course No.: ***MAE 5930 (3 units)***
Class Times, Location: TBD
Office Hours: By Appointment
Prerequisites: MAE Senior with Good Academic Standing, Concurrent Enrollment in MAE 5420, Compressible Fluids

Spring 2010

Course Title: ***LLRV Design***
Course No.: ***MAE 4800 (3 units)***
Class Times, Location: TBD
Office Hours: By Appointment
Prerequisites: MAE 5930, Launch Systems Design, MAE 5420

Required texts:

Understand Space: An Introduction to Astronautics, Jerry Jon Sellers, 5th ed., McGraw-Hill, 2005., ISBN 9780073407753

Course Handbook, Class Notes Compendium *(Available in Student Book store)*, Published as NASA SP(?)

Maximum Class Size: 25

Suggested Teaching Assistants: 1 per Semester

II) Course Description:

This course is developed as partial fulfillment of the requirements of a grant funded by the NASA Office of Education. The final outcome is a "packaged" senior design course that can easily be "moved laterally" and incorporated into universities across the nation. The course materials must adhere to the standards of the Accreditation Board for

Engineering and Technology (ABET), and be relevant to one of four areas identified by NASA's Exploration Mission Directorate (ESMD):

i) *Spacecraft,*
ii) *Propulsion,*
iii) *Lunar and planetary surface systems,*
iv) *Ground Operations.*

This specific design project will target Item *iii) -- Lunar and Planetary Surface Systems* – and will develop senior design concepts for a Lunar or Planetary Surface Landing Research Vehicle *(LPSRV). (ESMD# DFRC1-15-SD)* Per NASA specifications concepts must account for reduced lunar gravity, and allow simulated terminal stage of lunar descent to be flown either by remote pilot or autonomously. The design project will challenge students to apply systems engineering concepts to define research and training requirements for a terrestrial-based lunar landing simulator. This Free-flying platform should allow for both sensor evaluation and pilot training. Selected concept must allow a small-scale prototype-demonstrator to be constructed within the time and budget constraints of a university-based senior design project. A prototype of the system concept will be constructed and flight-tested. Selected concept must be scalable to a full-size planetary landing research.

III) Significance of the Design Project

One of the many crucial points associated with NASA Constellations systems Lunar Landing mission is the portion from spacecraft separation in lunar orbit to descent and touchdown. Flight Training vehicles should be capable of rendering a realistic environment for both flight crew training and autonomous landing systems verification and validation. The Lunar Lander Training Vehicle (LLTV) developed for the Apollo program during the 1960's is considered to be a significant contributor to the success of the Apollo lunar program. Seven of the nine Apollo Astronauts that trained with the LLTV believe that such training was an important factor in increasing the probability of a successful landing and believe that such a vehicle is essential for future lunar missions.[1] As NASA's Constellation program prepares to send astronauts back to the lunar surface, a similar training vehicle, based on modern technologies, is required to ensure that astronauts develop skills at same high level of proficiency exhibited by the Apollo astronauts. Donald K. "Deke" Slayton, NASA's astronaut chief during the Apollo program, firmly believed there was no other way to simulate a moon landing except by flying the LLTV.[2]

Additionally, unlike the Apollo program the Altair lander will require a suite of sensors that reduce pilot workload and allow for Autonomous Landing and Hazard Avoidance (ALHAT). The potential role of an Earth demonstrator free flyer platform has been an ALHAT topic of discussion for quite a while. The general consensus among NASA researchers is that the most realistic and practical ALHAT approach is to pursue

---

[1] Proceedings, "Go For Lunar Landing, From Terminal Descent to Touchdown, Conference," Tempe, Arizona, March 4-5, 2008.

[2] Bennett, Floyd V., "Apollo Experience Report – Mission Descent and Ascent," NASA TN D-6846, 1972.

field testing on helicopters and airplanes, starting with sensor characterization flights and evolving towards more integrated testing with onboard processing. The consensus is that these component-level tests can bring the technology readiness level (TRL) to a level of approximately 5. However, to bring these components to a TRL that can be deployed on an operational mission a TRL of 7 or greater is required, and only closed-loop testing on a free-flying LLT/RV can achieve those results.[3]

III) Course Objectives and Deliverables:

Fall Semester 2009 will introduce students to design and systems engineering concepts, and will develop sufficient theoretical background to allow design and fabrication of a prototype demonstration vehicle. Apollo-era lunar mission designs will be examined in detail as a point of departure for this design. A minimum of 2 1-hour lectures will be delivered each week. As necessary design teams will break off into small development teams. At least 8 one-hour periods will be made available for "break off team" meetings.

- *i)* *Students will either use or develop simulation code required to fulfill team objectives as necessary.*
- *ii)* *Students will become sufficiently proficient in technical writing to deliver a professional grade final design report.*
- *iii)* *Students will learn the basics of team dynamics and teamwork.*
- *iv)* *The final outcome of the fall semester is a conceptual design roadmap including preliminary design reports, a test and measurements matrix, and sufficient engineering design drawings to allow construction to begin during the spring semester.*
- *v)* *A conceptual design review (CDR) will be performed during finals week of fall semester. This review will be made available as requested to NASA personnel via web cast, and will include faculty members within the college as peer reviewers.*
- *vi)* *As, required technical interchange videoconferences or web casts will be help with the NASA technical and administrative points of contact.*

Spring semester 2010 will emphasize detailed theory for specific sub-system relevant to the vehicle design, as well as fabrication and testing of the prototype article. Group lectures will be held at least one hour per week. Internal project design reviews will be held on a bi-weekly basis. As, required technical interchange videoconferences or web casts will be help with the NASA technical and administrative points of contact. A final report will be submitted for the NASA Systems engineering competition. *The final deliverable from this report is a* working LLRV prototype. A goal of a successful test flight before end of Spring Semester 2010 will be targeted.

All materials will be made available for interim review on the MAE 5930/4800 class web-based bulletin board. These materials include

[3] Email correspondence with Chirold Epp, NASA JSC ALHAT Program Manager, June 12, 2008.

i) Students will either use or develop simulation code required to fulfill team objectives as necessary.
ii) Assigned Homework and In-class Projects.
iii) All reviews and documentation required by NASA.
iv) Conceptual Design Report, Final Design Report.
v) Test reports for all critical developmental tests.
vi) As possible, students will be encouraged to submit papers to peer reviewed conferences and journals.

Assessment Materials

This Course is a two-semester sequence, with MAE 5930 Technical elective taught fall semester 2009, MAE 4800 Senior Design Class spring semester 2010. The proposed design course will incorporate of as many of the ABET-recommended[4] design issues as are possible. There is one specific requirement stated by ABET *"Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints."* In this design class the students will learn how to integrate their engineering skills to solve a complex engineering problem, present their engineering designs in an oral presentation, and document their design in a written report that is the basis of their engineering portfolio. This design experience is the final course that prepares students to enter the mechanical engineering profession.

The design course evaluation is a part of the overall USU MAE department plan for continuous improvement. Assessment measures will consist of student portfolios, student performance in project work and activity-based learning. Two particularly important assessments include *Success in NASA Systems Engineering Paper competition* and outcomes from the research aspects of this design study. These *research outcomes* include student conference presentations and published articles.

Grading: Homework Assignments will cover material presented in class, in the laboratory, plus material in the text covered by the assigned reading. Laboratory session s will be held as required to insure that the students are familiar with the testing and measurement techniques required for achieving the design objectives. Regular laboratory reports will be turned following laboratory period. Reports may include homework exercises. Laboratories may include simulation and modeling exercises. Student and faculty peer reviews and oral presentation evaluations will be an important part of the grading and assessment process.

MAE 5930 (Fall 2009)

[4] Criteria for Accrediting Engineering Programs, 2008-2009, ABET Engineering Accreditation Commission, http://www.abet.org/Linked%20Documents-UPDATE/Criteria%20and%20PP/E001%2008-09%20EAC%20Criteria%2012-04-07.pdf, (Retrieved: October 4, 2008).

i) 25% of student grades will come from individual homework assignments, laboratory reports, and class projects.

ii) 75% will be a weighted class grade, this grade fraction is scored as

Conceptual Design Report	50%
Conceptual design Presentation	25%
Student Peer Evaluations	25%

MAE 4800 (Spring 2009)

i) 40% will be a weighted class grade, this grade fraction is scored as

Critical Design Report	25%
Critical Design Presentation	25%
Student Peer Evaluations	25%
Systems Engineering Paper Submitted to NASA	

ii) 40% will be sub-system team grades, this grade fraction is scored as

Subsystems Final Design Report	50%
Interface Control Documentation	25%
Test and Evaluation reports	25%

iii) 20% Success of the flight test

Top-Level Objectives

Upon completion of this design class students will be able to synthesize mathematics, science, engineering fundamentals, and laboratory and work-based experiences to formulate and solve engineering problems in both thermal and mechanical systems areas. Students will have proficiency in computer-based engineering, including modern numerical methods, software design and development, and the use of computational tools. Students will be prepared to communicate and work effectively on team-based engineering projects. Students will recognize the importance of, and have the skills for, continued independent learning.

Desired Outcomes

Program outcomes are statements that describe what units of knowledge or skill students are expected to acquire during the achievement of this design. These outcomes are typically demonstrated by the student and measured by the program at the time of class completion. At the completion of this course each student is expected to have:

i) Ability to apply knowledge of mathematics, science, and engineering,
ii) Ability to design and conduct experiments, and analyze and interpret data,
iii) Ability to design a system, component, or process to meet requirements within realistic constraints
iv) Ability to function on multi-disciplinary teams,
v) Ability to identify, formulate, and solve engineering problems,
vi) Understanding of professional and ethical responsibility,
vii) Ability to communicate effectively,
viii) a knowledge of contemporary issues,
ix) Ability to use the techniques, skills, and modern engineering practice.

Contribution of course to meeting the requirements of ABET Criterion 5:

Professional Component Content			
Math & Basic Sciences	Engineering Topics	General Education	Engineering Design
✓	✓	✓	✓

Relationship of design course to desired USU MAE program outcomes:

		Course * Outcomes
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	✓
l)	an ability to work professionally in both thermal and mechanical system areas including the design and realization of such systems.	✓
*An ✓ indicates that this course helps the students to achieve the Program Outcomes.		

Specific Assessment Metrics

Course Objective	**Measurement Instrument**	**Self Assessment (A-F)**	**Student Assessment (A-F)**
Design component: Design must be the major component of the course. Student teams should explore and evaluate possible design alternatives. Each member of each team should play an active role in the design activities.	Project Reports, Interface Control Documents, Student and NASA Peer Reviews		

Ability to deal with realistic project constraints: These constraints may, for example, involve cost or performance considerations in the implementation or platform size restrictions imposed by the intended NASA. These issues will be addressed in the lectures, and students should be consciously aware of these considerations.	Project Reports, Interface Control Documents, Student and NASA Peer Reviews, Budget Analysis		
Knowledge of and ability to Apply Standards: Where appropriate, consideration of relevant standards should be applied. These considerations include NASA standard safety and consistency standards. As appropriate published NASA systems engineering documents and standards will be directly used as instructional materials.	Homework assignment, Project Reports, Interface Control Documents, Student and NASA Peer Reviews,		
Ability to Consider Ancillary Design Effects, e.g. Maintainability: The design should include consideration of how to make the system maintainable to accommodate changing requirements or to continue functioning in a somewhat different environment, e.g. planetary gravity fields and atmospheres.	Homework assignment, Project Reports, Interface Control Documents, Student and NASA Peer Reviews,		
Knowledge of Ethical, social, and professional issues: Issues relating to matters such as security, privacy, and intellectual property are often directly related to the general area of the capstone courses. Students should again be consciously made aware of these issues, perhaps via class discussions. Other professional issues include awareness of new methodologies, languages, tools and systems that may be used in industry and students' ability to learn about these on their own and capstone courses often present opportunities for students to develop these skills.	Project Reports, Student Peer reviews		
Thermodynamics: Students demonstrate ability understand basic physics and thermodynamics and equation of state and its relationship to compressible flow physics	Homework assignment, flow path modeling assignment		
Fluid Mechanics: Students demonstrate the ability to adapt apply integral form of conservation, momentum, and energy equations to one-dimensional flow problems; solve for isentropic flow properties in ducts, nozzles and diffusers.	Homework assignments, flow path modeling assignment		
Flight Mechanics and Payload Mass fraction Analysis: Students demonstrate the ability to analyze the required "DV" for a given rocket system payload, and to calculate the required propellant mass fractions based on the specific impulse of the system	Homework assignments, Programming assignments		

Propulsion System Sizing and Analysis: Students demonstrate the ability to design liquid and solid rocket systems, understand combustion processes, select a particular system design for a given mission requirement	Homework assignments, programming assignments		
Dynamics and Control: Students demonstrate Ability to model gravity-offset platform dynamics, and to design a simple regulator to maintain stability during flight	Homework assignments, programming assignments, test and evaluation		
Test and Evaluation: Students will demonstrate the ability to plan and execute the testing required for the development of a prototype test article. These skill include to make standard mechanical engineering measurements and apply calculus-based statistics in the interpretation of the resulting data.	Test readiness reviews, Test Result Reports, Systems Interface Documents, Final Design Report. First Flight test.		