Spacecraft Technology and Systems Architecture
Modified for COVID-19

Spring, 2020

General Course Information
MAE 4160/4161/5160: https://canvas.cornell.edu/courses/13649
T/Th 1:25-2:40pm **EST, Zoom**

Instructor Information
Hunter Adams vha3@cornell.edu

Office Hours:
Th, 3:00-5:00pm **EST, Zoom**
F, 8:00-9:00am EST, Zoom

Teaching Assistant Information
Dean Keithly drk94@cornell.edu

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Office Hours:
M, 4:30-6:00pm EST, Zoom

Message to students, and how to use this document

My goal, for the rest of this semester, is to provide you with the information that you enrolled in this class to learn while adding as little logistical stress as possible. We're in new territory, so please provide me feedback so that I can adjust as we go. My commitment to you all and to this class remains as high as it has ever been. Do not hesitate to contact me with any questions, comments, or feedback.

This is a modified version of the syllabus for this course. All modifications are highlighted in red. Please read through this, paying particular attention to the highlighted text. Please also pay particular attention to the modified schedule on the last page of this document.

Here are my promises to you:

- Regardless of your geographic location, you will have many opportunities per week to interact directly with me (in lecture/office hours), and with your TA's.
- You will receive the same quantity and quality of lecture content remotely that you would have received on campus.
- Expectations for class projects will be managed in light of the situation.
- We can expect some minor hiccups as we adjust to an online course. Please be patient with me as I discover and resolve any issues that may arise, and I promise that I will be very patient with you all.

General information

- **Zoom links for lectures and office hours will be located on Canvas, in the Zoom directory.**
- **All lectures will be recorded and posted on Canvas for students that cannot attend synchronously.**
- **All assignments will be turned in online via Canvas *as a single PDF file*.**
- **Our last day of instruction is now May 12 (see revised schedule at the end of this document)**.
- **Students may drop the course/change to S/U grading until 4/21.**

Course Description

This course is a survey of contemporary space technology from subsystems through launch and mission operations, all in the context of spacecraft and mission design. It focuses on the classical subsystems of robotic and human-rated spacecraft, rockets, planetary rovers, and habitats, as well as on contemporary engineering practice.

- MAE 4161 also includes a senior-design project option that fulfills the undergraduate requirement in this area.
- MAE 5160 includes an in-depth design activity suitable for M.Eng. study that maybe used to complement the 6-8 hour MEng project requirement but that does not meet that entire requirement on its own.

Topics covered include subsystem technologies and the systems-engineering principles that tie them together into a spacecraft architecture. Subsystem technologies discussed include communications, thermal subsystems, structure, spacecraft power, payloads (remote sensing, in-situ sensing, human life support), entry/descent/landing, surface mobility, and flight-computer hardware and software. A brief review of the theory and practice of guidance/navigation/control and space propulsion is provided, with the expectation that students have already encountered this material in the prerequisite courses (e.g. in MAE 4060 and 3260).

The final project consists of architecting a complete spacecraft system with appropriate subsystems, with designs supported by parametric analysis and simulation. This project will be matured throughout this semester, through a sequence of design reviews meant to resemble aerospace industry practice.

- MAE 4160 students (3 credits) engage in a multi-person space-system design project, with a single final report co-authored by all team members.
- MAE 4161 students undertake this project within such a team but with the reporting expectations of a senior-design project, namely a 20pp, separate report for each student that documents each MAE 4161 student's design, some of which may be included in the team's report.
- MAE 5160 students (4 credits) conduct an in-depth study of a space-technology problem that is integrated with one of these team design projects and forms part of the team's report.

Required Materials

Lecture notes and slides will be made available before or shortly after each lecture. These notes will draw from many sources, but principally from SMAD (listed below).

- *Space Mission Engineering: The New SMAD (Space Technology Library, Vol. 28*, Microcosm Inc., July 2011 Edition, ISBN: 1881883159.

Prerequisites/Corequisites

MAE 3260 and MAE 4060 or equivalent courses at another institution. Or come talk to me.

Course Objectives

1. Students will understand, at a higher systems level, space missions and systems, and how the space environment and mission requirements drive spacecraft design;
2. Students will understand the basic fundamentals of spacecraft subsystems, including propulsion, attitude determination and control, power, structures, thermal, communications, and command and data handling;

3. Students will understand typical practices for designing space systems in a contemporary context of US commercial space and government agencies;
4. Students will be able to simulate a spacecraft in operation at the level of a Preliminary Design Review (PDR) using state of the art tools, and identify and characterize subsystems for a preliminary spacecraft design.

Grading Policy

All grades will be posted to Canvas. The grade will count the assessments using the following proportions:

- **Project preference**: 2%
- **Homeworks ~~and in-class quizzes~~**: 14%
- **Prelim**: 15%
- **SRR Document**: 10%
- **SDR Document**: ~~10%~~ **15%**
- ~~**PDR Presentation**: 10%~~ **Eliminated.**
- **CDR Plan**: 10%
- **Final Design Report**: ~~25%~~ **30%**
- **Peer Evaluations**: 4%

Contact Hunter for all requests for homework re-grades. Numerical scores will be mapped to letter grades based on Hunter's perception of the difficulty of the material throughout the semester.

Group activity grading

For the grades that involve group activity, individual grades are assigned on the following basis:

1. Each design document is assigned a single grade X. Criteria for grading each document will be provided along with the specifics of the assignment. The total points (T) available to the N members of the team is given by $T = NX$
2. The default is that every student receives the grade given to the group's document. I.e., each student's individual grade is $X_i = X$ in the default case. This distribution of points reflects the case where each student contributes similar quality and quantity of work.
3. Students are asked to identify which portion of the reports they worked on. The TA's and instructor's assessment of these sections may alter the distribution of points among the team members so that each student's grade X_i differs from the overall document grade X, keeping T constant. If there is some redistribution so that the values of X_i differ, the total points remain the same: $T = \sum_i^N X_i = NX$

4. Detailed guidelines about expectations for these design documents will be made available on Canvas.

More details about each assessment

- **Homework**: Homework problems will be graded on an integer scale from 2 through 0: 2 indicates that the answer is correct or so nearly correct that it deserves full credit; 1 indicates that the effort toward solving the problem merits some partial credit; and 0 indicates that the problem was not attempted or that the solution is so far off the mark that no partial credit can be given.

  Consulting with classmates on homeworks is encouraged, even recommended. However, each student must turn in his or her own work, with no intentional duplication of other students' work. You will not learn the material and will be unprepared for the design activity if you merely copy others' homework.

- **Prelim**: There will be one ~~in-class~~ **take-home** prelim, as shown on the schedule. This test will be open books, open notes, homework, and any other paper you want to bring. No computers, phones, or other wireless devices may be used. **This will be on the honors system. The exam must be completed within a 24-hour window, and then submitted online *as a single PDF file*.**

- **Project Preference**: The first document to submit for a grade is a statement of your preferred project, along with a list of other students with whom you wish to work. Groups may not be larger than 4 students.

- ~~**In-class quizzes**: Occasional, brief in-class assignments (quizzes) will count toward the overall homework grade. These quizzes will be open books, open notes, homework, and any other paper you want to bring. No computers, phones, or other wireless devices may be used.~~ **Eliminated.**

- **Design Reports**: This course mimics U.S. industry and government practice in documenting spacecraft system architecture and analysis details in written reports or presentations that correspond to key decision points in the lifecycle of a spacecraft. The lectures include discussion of all aspects of this lifecycle. However, a single semester is simply not enough time to walk through a full-scale design process for a realistic system, regardless of size or complexity. So, design reports in this class require that the design be analyzed up to the "Preliminary Design Review" stage and include a plan for completing work up to the "Critical Design Review" stage. Additional work—e.g. completing more detailed analysis, building prototypes, etc.—is optional and is undertaken at the discretion of the student.

  The summary below is meant as an overview. Each assignment includes more explicit detail and draws from material provided in lecture:

  SRR Document - 10%: The **System Requirements Review** establishes the correctness of key requirements for the space system, including performance, functionality, and design processes. This written document shall be approximately 10 pages, consisting of precisely articulated requirements at the level of the mission, space and ground segments, and high-level subsystems.

SDR Document - ~~*10%*~~ ***15%***: The **System Design Review** is a milestone that confirms that the system architecture is solving the right problem: that the requirements are reflected in the basic choices that comprise the spacecraft to be analyzed in greater detail. The document to be completed is a roughly 10 page summary that explains the big picture: images of the spacecraft, high-level diagrams, the concept of operations, and a mission timeline, justified with elementary analyses.

~~*PDR Presentation - 10%*: The **Preliminary Design Review** documents the analyses that demonstrate the spacecraft as architected can feasibly meet the requirements. More detailed analysis will have to be performed before the spacecraft's components can be procured or built, but after PDR, there is no longer a question that the story holds together. At this point some "long-lead items" might be procured for a real spacecraft; so, some insight into possible vendors is required at the PDR level. This presentation will be scheduled for a time/day near the end of the semester and will offer an opportunity for the students on the team to receive critiques that can be incorporated into the Final Design Report. MEng students' detailed design material should be included in this presentation.~~ **Eliminated.**

CDR Plan - 10%: The Critical Design Review marks the end of design and analysis and the beginning of fabrication/procurement, assembly, integration, and testing. Unique to this class (i.e. not usually seen in practice), the CDR plan required here is a 5 page document that summarizes what analyses will be required if the project were to continue to CDR.

Final Design Report - ~~*25%*~~ ***30%***: This design report might be called a "PDR Analysis Book." It documents the details of the analysis presented at PDR. It takes the form of a design report, which begins with describing high-level requirements, the mission and spacecraft architectures that meet these requirements, and post-PDR activities. It is meant to stand on its own but likely will incorporate most of the material already submitted during the semester. Creating this report should be more of an exercise in organization of existing work into the form of a report and verifying completeness than generating new material. There is no specific length requirement.

Due dates for homeworks and design reports

Homework is generally due one week after it is assigned. Design Reports will be assigned farther in advance. The schedule (below) shows the precise due dates. Solutions will be posted and homework returned approximately one week after the homework is due.

All work is due on the indicated day by 1:25 pm ~~in the drop box on the second floor of Upson, near the classroom~~ **submitted online as a single PDF file**. Work submitted late but within one week of the due date/time will receive 50% of the credit they would have received if on time. For fairness to all students and administrative simplicity, no homework late by more than one week will be accepted. Feel free to submit it early.

Homework must be neat with boxed answers. Illegible homework will not receive credit, nor will individual problem solutions whose answers are not clearly indicated.

Homework is graded on a coarsely quantized scale. Each problem, no matter how simple or involved, will earn 2 points if it is mostly or entirely correct (corresponding to an A, B, or C grade). A problem will be given 1 point if the answer is profoundly flawed (D or F grade). A problem will receive 0 points if it is not seriously attempted.

Academic Integrity

Academic integrity is expected of all students of Cornell University at all times, whether in the presence or absence of members of the faculty. Violations of the code of academic integrity will be prosecuted through the Academic Integrity Hearing Board. For more information, see the following page on academic integrity: `http://cuinfo.cornell.edu/aic.cfm`.

Students with Disabilities

Please give me your Student Disability Services (SDS) accommodation letter by the second week of the semester so that I have adequate time to arrange your approved academic modifications. You may request a private meeting by email to help ensure confidentiality. If you need an immediate accommodation for equal access, please speak with me after class or send an email message to me and/or SDS at `sds_cu@cornell.edu`. If the need arises for additional accommodations during the semester, please contact SDS. It is your responsibility to verify that your accommodations are in place for exams—please check with me at least one week prior to all exams if you have any questions or issues. **For the take-home prelim, *all* students will be given extended test time greater than the maximum extended test time from SDS.**

Project Options

1. Artificial reef in Titan's mare

Key concepts:

- Entry, descent, and landing
- Interplanetary trajectory design
- Novel communications design

It is dangerous to make any assumptions about alien life, particularly life as alien as may be found in Titan's lakes, but perhaps there are a few that are reasonable. For example, it is likely safe to assume that life in Titan's lakes is the result of an evolutionary process, and it's likely safe to assume that the evolutionary process on Titan also produced predators and prey. If there are predators pursuing prey in Titan's lakes, then it is certainly the case that there are prey evading predators. On Earth, this means finding hiding places. It probably means the same thing on Titan.

You are tasked with designing a mission which places infrastructure in which Titanic prey species may hide into the mare, and then detecting the presence and properties of organisms using that infrastructure. Much like we put infrastructure in the Earth's oceans to seed coral growth and attract sealife, you will put infrastructure in the mare to seed and attract whatever lives there. You are also expected to relay basic information about the chemistry of the mare.

Mission objectives:

- Place a 1x1 meter, 150 kg artificial reef on the bottom of Kraken Mare (unknown depth, 2-15 meters) on Titan.
- Communicate data from sensors (cameras and chemistry sensors) on the reef to operators on Earth for a duration of not less than 4 weeks.

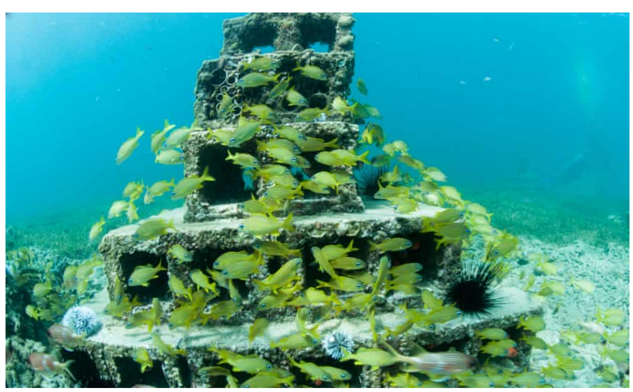

Figure 1: Artificial reef

2. A mysterious startup

Key concepts:

- Agility/pointing
- Remote sensing.
- Constellation design.

You've been approached by a startup that is developing a constellation of low-Earth spacecraft for tracking and gathering information about objects moving quickly through the Earth's atmosphere (jets, missiles, etc.). They won't tell you precisely what payload they're carrying, but they tell you that they need to be able to keep the boresight of an instrument trained on planes as fast as an SR-71 Blackbird. They want the constellation to provide persistent coverage of the entire globe, for aircraft at any altitude up to 26 km.

Mission Objectives:

- Design a spacecraft which can track an SR-71 Blackbird (i.e. keep the boresight of an instrument pointed at it).
- Design a constellation of such spacecraft to provide persistent global coverage for altitudes up to 26 km.

3. Car collector

Key concepts:

- Deep-space rendezvous.
- Entry, descent, and landing.

On Feb. 6, 2018, SpaceX performed their first test of the Falcon Heavy. As a test payload, they carried a Tesla Roadster. That Roadster is now orbiting the Sun on a trajectory that carries it from approximately 1AU to beyond Mars orbit.

You've been approached by a very wealthy car collector that would like to add that particular Roadster to his collection. You are tasked with rendezvousing with the Roadster and returning it to the Earth. This mission may take up to 30 years, but you may not damage the Roadster.

Objectives:

- Return the Tesla Roadster to the surface of the Earth without damaging it in 30 years or less.

4. Lunar termites

Key concepts:

- Entry, descent, and landing.
- Novel commmunications.
- Lunar trajectory design.

Kirstin Petersen's lab at Cornell (the Collective Embodied Intelligence Lab) builds robots that perform collective construction. Much like termites, which collectively build mound structures without any central control, Prof. Petersen's robots collectively build user-specified structures without a central controller.

Let us suppose that Prof. Petersen and her students have designed a collection of small robots that will build structures from lunar regolith (runways, habitats, etc.). If we get them to the right place on the Moon and we let them go, then we can leave them alone and they will begin building structures.

You are tasked with doing exactly that. You must land a mothership containing 100 of Prof. Petersen's robots (TERMES) at a particular location on the Moon, and you must do so softly enough that none of them break. Then, you must relay information about their progress.

Mission Objectives:

- Place 100 of Prof. Petersen's robots on the surface of the Moon without damaging them (assume fragility equivalent to Mars Exploration Rovers).
- Communicate sufficient information to ground operators to maintain knowledge of each robot's health and status, and their collective construction progress for not less than 1 year. This includes health and status information from each robot, and at least 10 4k photos of construction progress each day.

5. Martian Positioning System

Key concepts:

- Constellation design.
- Interplanetary trajectory design.

You are tasked with designing a martian positioning system. From any location on the surface of Mars, a receiver must be able to deduce its location to the same accuracy/precision as GPS on Earth. You may assume access to Superheavy/Starship/SLS.

Mission Objectives:

- Create a martian positioning system that enables receivers anywhere on the surface of the Moon to determine position/velocity at any time with accuracy/precision equal to that of GPS.
- Design the system such that the receivers are of equivalent size/power draw used for Earth's global positioning system.

Schedule

Lecture	Date	Topic	Items Due
1	1/21/20	Intro/Cassini case study	
2	1/23/20	Mission design process	
3	1/28/20	Requirements, trades, risks	
4	1/30/20	ADCS review	Project pref.
5	2/4/20	Orbit mech./design review	Homework 1
6	2/6/20	Propulsion/GNC review	
7	2/11/20	Communications (I/II)	Homework 2
8	2/13/20	Communications (II/II)	
9	2/18/20	The space environment	SRR Document
10	2/20/20	Avionics/flight software	
	2/25/20	February Break	
11	2/27/20	Estimation methods	
12	3/3/20	Power	Homework 3
13	3/5/20	Thermal	
14	3/10/20	Structures	Homework 4
15	3/12/20	Remote sensing & payloads	
	3/17/20	**COVID-19**	
	3/19/20		
	3/24/20		
	3/26/20		
	3/31/20		
	4/2/20		
16	4/7/20	Entry, descent, and landing (Zoom lecture)	
17	4/9/20	Rovers (Zoom lecture)	Homework 5
18	4/14/20	Organisms in space/ECLSS (Zoom lecture)	
19	4/16/20	Space suits (Zoom lecture)	
20	4/21/20	Funding and cost (Zoom lecture)	Takehome Prelim
21	4/23/20	Space policy and politics (Zoom lecture)	
22	4/28/20	Cubesats and smallsat architectures (Zoom)	SDR Document
23	4/30/20	Ground segment (Zoom lecture)	
24	5/5/20	Launch segment (Zoom lecture)	CDR Plan
25	5/7/20	Guest lecture: Dmitry Savransky (Zoom)	
26	5/12/20	Case study: Chipsats (Zoom lecture)	
	5/14/20	Study Period	
	5/16/20		Final report & peer evaluations