CDIO SPACE SYSTEMS PRODUCT DEVELOPMENT

PROGRAM PLAN

Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

Revision 2.1
February 19, 2002

Configuration Control as of 2-19-02
Author, Control Authorization

David W. Miller
Chief Systems Engineer

Table of Contents

1 GENERAL DESCRIPTION: 16.684 CDIO

CDIO: Conceive, Design, Implement, and Operate will take you through all the activities required to create a final aerospace product. In this context the goals of CDIO are:

- To educate students to master a deeper working knowledge of the technical fundamentals
- To educate future engineers to lead in the creation and operation of new products/systems
- To educate future researchers to understand the importance and strategic value of their work

Our vision is to provide students with an education that stresses the fundamentals and is focused on real world systems and products. It will provide an integrated education that provides experiential learning through a rich offering of team-based design-build-operate projects; both in the classroom and a state-of-the-art Learning Laboratory.

For every product there is a concept, a vision of something new. The design of the project creates a user's manual for the implementation. Each part of this manual must be self-consistent; each section must allow physical implementation. 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, careful design, and precise implementation will translate into success.

In this class, each of you will be part of one team, the CDIO team. We will analyze the requests from our 'customer'; design a product to meet all the specified requirements; implement our design in a working, final product; and operate it to evaluate its performance in a controlled environment.

As part of the Systems Engineering and Architecture (SE&A) curriculum, the class will put emphasis on the design process. While there are many definitions of SE&A, one definition, closest to the philosophy behind CDIO, 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 customer's needs and why the mission is worth conducting.

- *Which:* The trade analysis compares different mission architectures and determines which architecture best meets the requirements and therefore the customer 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 and operations facilities.

CDIO, as 16.684, is an educational experiment. The course aims to provide each of you a lifecycle experience with a hardware-related, complex aerospace system. You will be part of a large team environment, which emphasizes communication, teamwork, planning, and responsibility. In addition, you will also be individually responsible for designing, building, operating, and analyzing a specialized subsystem in a laboratory setting. In this way you will be exposed to the interfaces between the needs of the team and the responsibilities of the individual team members. Further, it is the first time that an undergraduate class will have to deliver a final product to a major outside organization. We will have a fixed delivery schedule, strict requirements and restrictions, and several reviews.

At the end of the course each of us, including the students, will assess the merits of integrating this class into the standard academic program. At any time during the course you should feel free to contact Dr. Doris R. Brodeur (with any feedback on the pedagogic aspects of the class. She will be the liaison between you, the students, and the board of faculty, which will review the course as a whole. We believe that these experiences will be of great educational value, and hope each of you will both learn and enjoy it.

2 THE PROJECT

Formation flight of satellites is a concept that has been proposed for many purposes, including space interferometry. Unlike monolithic telescopes, interferometers are based on the concept of combining light from multiple apertures spaced a distance apart. Just as a monolithic telescope's angular resolution improves with aperture size, an interferometer's resolution improves with increased distance between apertures. Hence formation flight of separated spacecraft appears to be a useful tool in implementing space interferometry.

Until now, traditional thrusters have been proposed for formation flight attitude and positional control. However, there are several concerns with the use of thrusters, including plume contamination of neighboring spacecraft and sensitive optics, and the use of fuel as a nonrenewable energy source. Rather than thrusters, *electromagnets* could be used for formation flight control. Electromagnetic formation flight control has the potential to:

A. eliminate concerns about thruster plume impingement and optics contamination

B. control *relative* degrees of freedom, as opposed to the *inertial* degrees of freedom controlled by thrusters, and

C. rely on electricity provided by solar arrays, a renewable energy source, as opposed to thrusters whose finite fuel supply often limits the life of the spacecraft.

Therefore, the objective of this class is to demonstrate the feasibility of an electromagnetically controlled array of formation flying satellites. This objective is cast as the following **Mission Statement**:

Demonstrate the feasibility of electromagnetic control for formation flying satellites.

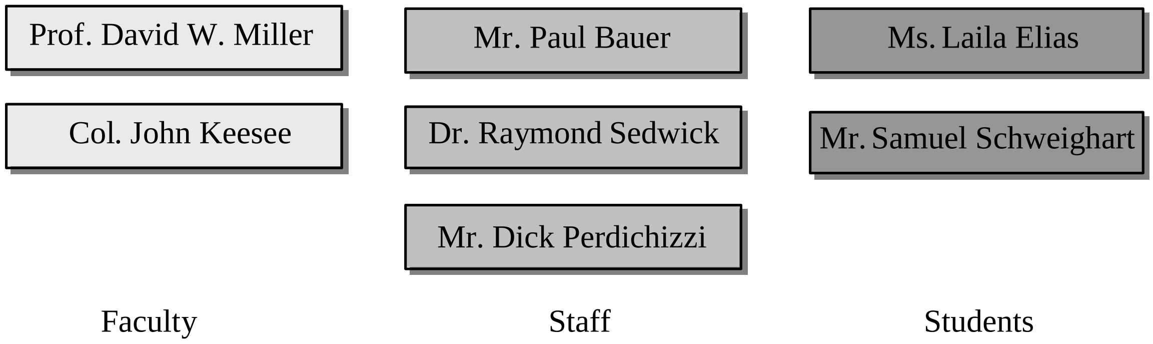
Specifically,

- Demonstrate implies operating an electromagnetic formation flight testbed in a mode representative of a real world application, or "scaled" to demonstrate real-world feasibility.
- Electromagnetic control implies the design and implementation of a controller using electromagnets as actuators to control relative position and attitude.

- Formation flying satellites implies a testbed composed of multiple rigid bodies that must exhibit the functionality of a real cluster of satellites in formation flight.

3 ORGANIZATIONAL STRUCTURE

CDIO is a three-term class. The first two terms will be twelve units; the third term six. As we progress through the project, more time will be allotted to laboratory time (the implementation stage). Recall that CDIO corresponds to 16.83, 16.621, and 16.622; therefore it includes teaching on both Space Systems Engineering and Laboratory practice. Details on class organization and each of the terms follow below.



Faculty: Prof. David W. Miller, Col. John Keesee

Staff: Mr. Paul Bauer, Dr. Raymond Sedwick, Mr. Dick Perdichizzi

Students: Ms. Laila Elias, Mr. Samuel Schweighart

4 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 4.1 shows the schedules for CDIO as they exist on the first day of classes. The individual sections describe each term in more detail. These may change as needed by the various demands that will be placed on the program.

4.1 Overall Program Schedule

As mentioned, the course will be conducted over three semesters: Spring CY02, Fall CY02 and Spring CY03. The total number of units will be thirty (30) with Spring CY02 being 4-4-4, Fall CY02 being 2-6-4, and Spring CY03 being 1-5-0. The overall hardware development and test and operations plan consists of the following:

- *System Conceptualization*. For the period starting on 2/5/02 and ending 3/21/02, the class will organize into system conceptualization teams. These teams will be responsible for defining requirements, downselecting to a candidate mission architecture, trading sub-system components and formalizing hardware development processes.
- *Prototype Hardware*. Following Spring Break in the Spring of CY02, students will organize into sub-system teams and develop sub-system prototypes in the laboratory. While the teams will need to adhere to interface allocations and requirements, the laboratory work of each sub-system team is primarily performed in isolation from the other teams. During the Fall CY02 semester, prior to CDR, sub-system benchtop prototypes will be brought together and integrated into a system prototype that will be tested by CDR. The design presented at CDR must reflect lessons learned through the sub-system and system prototypes.
- *Flight Hardware*. Following successful completion of CDR in the Fall of CY02, the flight system will be developed. It is envisioned that those components of the system prototype that have not undergone design modification will be used in the flight system in order to save schedule and cost. Flight hardware fabrication and verification will be complete by the Acceptance Review in CY03 after which it will be operated in the field.

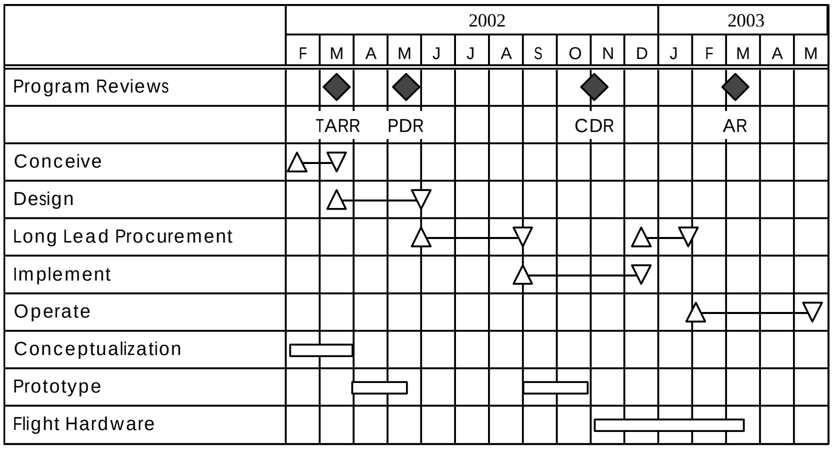


Figure 4.1 Program Schedule

4.2 Spring 2002: Conceive & Design

The weekly schedule for 16.684 Space Systems Product Development consists of two lectures of two hours each. These lectures will take place Tuesdays and Thursdays from 1:00 p.m. – 3:00 p.m. In addition, laboratory sessions are encouraged on Friday afternoons or at other times convenient for all group members, for a total of four hours per week.

The laboratory facilities have been assigned to 16.684. Documents, software etc. may be left in this room throughout the course. The rooms have PCs installed and are usable immediately.

See Section 9.2 for details on the facilities, which can be used by this class. Together with the four hours of homework/preparation this results in the 4-4-4 assignments of the 12 units for Spring 2002.

Table 4.1 16.684 Weekly Schedule Spring CY2002

	Monday	Tuesday	Wednesday	Thursday	Friday
9-10					
10-11					
11-12					
12-1					
1-2		Lecture		Lecture	Lab
2-3		Lecture		Lecture	Lab
3-4					Lab
4-5					Lab
5-6					
6-7					
7-8					

The following table contains the detailed schedule for each session in the semester. The key milestones are the **TARR on March 19, 2002** and the **PDR on May 7, 2002**. All absences need to be cleared ahead of time with one of the graduate assistants (GAs), Laila Elias or Samuel Schweighart. The schedule is subject to change,

since the needs of the program and the availability of individual lecturers might change. Changes will be communicated by email.

Table 4.2 Spring CY2002 Conceive and Design Schedule

Tue	**1-3**	**Thu**	**1-3**	**Fri**	**1-5**
Feb 5	Class Introduction, Requirements	**Feb 7**	Requirements, EM Design	**Feb 8**	Team Activities
Feb 12	Team Plans, System Management	**Feb 14**	Mission Design, Teamwork	**Feb 15**	Team Activities
Feb 19	Presidents' Day, Monday Schedule	**Feb 21**	Team Presentations, Form. Flight Control	**Feb 22**	Team Activities
Feb 26	Team Presentations Cont Trade Analyses	**Feb 28**	Individual Prog.Repts, Presentation Planning	**Mar 1**	TARR Preparation
Mar 5	Sub-System Planning Real Time Software	**Mar 7**	Team Progress Repts, TARR Preparation	**Mar 8**	TARR Preparation
Mar 12	TARR Preparation	**Mar 14**	TARR Preparation	**Mar 15**	TARR Dry Run
Mar 19	TARR (1-5) in 33-116	**Mar 21**	Lab Introduction Requirements Doc.	**Mar 22**	
Mar 26	Spring Break	**Mar 28**	Spring Break	**Mar 29**	Spring Break
Apr 2	Reliability & Ops, Sub-System Design	**Apr 4**	Design Document	**Apr 5**	Sub-System Prototyping
Apr 9	Sub-System Design	**Apr 11**	Sub-System Reports	**Apr 12**	Sub-System Prototyping
Apr 16	Patriots' Day Holiday	**Apr 18**	Manufacture & Test	**Apr 19**	Sub-System Prototyping
Apr 23	Presentation Planning	**Apr 25**	Sub-System Design	**Apr 26**	Sub-System Prototyping
Apr 30	Sub-System Reports	**May 2**	PDR Preparation	**May 3**	Sub-System Prototyping
May 7	PDR (1-5) in 33-206	**May 9**	PDR Action Items	**May 10**	Design Document
May 14	Design Document	**May 16**	Design Document Social		

Lectures Laboratory Reports

Presentations Holidays

Curriculum

Table 4.3 Spring 2002 Curriculum

Date	Topic	Objective
2/5	Class Introduction & Requirements	Introduce the programmatics of the class and describe the mission. Understand concisely what the customer needs and how that impacts the functions that each element of the design must perform.
2/7	Requirements Discussion & EM Design	Discussion of requirements application to EMFF. Also, introduction to fundamental concepts of electromagnetics and EM design.
2/12	System Engineering Management	Present the various activities associated with managing the system engineering process of an aerospace product.
2/14	Mission Design	Walk through the basic steps and processes involved in designing a mission.
2/14	Teamwork	Dr. Andrea Mckenzie speaks on teamwork and the dynamics of working in a group.
2/21	Formation Flight Control	Understand the fundamentals of formation flight control, including modeling of the system and selection of sensors and actuators.
2/26	Architecture Trade Process	Enumerate options for implementing each function and learn how to compare options in a quantitative fashion.
2/28	Presentations & Documentation	Learn the major ideas behind a great and successful presentation. This lecture will be mostly focused on the upcoming TARR presentation.
3/5	Sub-System Planning	Define the organization and goals of the sub-systems to maximize the “buy down” of program risk
3/5	Real Time Software	Understand the role of device drivers, interrupt handlers, timing, and I/O control in the operation of active systems
4/2	Reliability & Operations	Understand the reliability requirements for space flight, and learn about interfaces and other aspects of the operation of the system.
4/4	Design Document	Define the role of the document, organize the structure, and allocate responsibilities.
4/18	Manufacturing, Testing & Validation	Learn the differences between the design phase 'breadboard' design and the requirements for manufacturing and testing of space viable products. Understand the need and concepts behind the validation process.

Description

The Spring 2002 program consists of two formal presentations (milestones): the Trade Analysis and Requirements Review (TARR) and the Preliminary Design Review (PDR). The work for this term is mainly concentrated on the Conceive and Design stages of the project. Lectures will concentrate on the design process and team and intercommunication skills. Still, we expect that each sub-system team will have some part of their design implemented by the end of the term.

The objective of the Conceptual Design Phase (start to TARR) is to arrive at a mission architecture, which meets the needs of the customer better than other candidate architectures. To this end, several tasks must be completed, which are described below, and the class will be divided into four teams: Requirements and Scaling, Architectural Options, Databasing, and Processes. The relevant document is shown in parentheses:

1. *Requirements and Scaling:* The requirements task involves understanding and analyzing top-level system requirements, flowing those requirements down to sub-system requirements, and capturing the requirement traceability and validation in the requirements document.

   1.1. Extract Customer Requirements: The mission is being designed for a customer. It is essential that the team understand the needs of the customer through the scientific advisors, as well as the published literature. 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]

   1.2. System Functional Requirements and Scaling: 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. They should be scaled from the dimensions of a real-world mission to those of your testbed, while still demonstrating the feasibility of the real-world mission. The functional requirements are stated in engineering terms. [Requirements Document]

   1.3. Sub-System Requirements. The sub-system requirements are extracted from the system functional requirements and provide the specifications to which each sub-system team needs to design.

2. *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 that 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]

2.1. *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 downselect 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]

2.2. *Conceptualization:* Identify those attributes of an architecture that must be understood in order to allow one to judge the merits of that architecture against the metrics. Conceptualization specifically pertains to the manner in which "understanding" is achieved. High fidelity models, fundamental design relations, engineering experience, etc., can all be used but entail different levels of effort and uncertainty.

2.3. *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]

2.4. *Evaluation:* A formal downselect must lead to an architecture that merits 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, it represents a de-scope, or it is deemed comparable to the first architecture. [Design Document]

3. *Databasing:* Obviously, many components will need to be procured from vendors in order to save cost and schedule. Therefore, there is a need to generate a database of components and their specifications that are candidates for use in our system.

3.1.1. *Component Class Identification*: Identify different classes of components that will probably be needed by the system. This can often be done without knowledge of the final architecture.

3.1.2. *Database Commercial-Off-the-Shelf (COTS) Components*: Through web searching and other avenues, acquire specifications for candidate components and vendors within each component class. This information should be archived either electronically or in hardcopy (file cabinet).

3.1.3. *Make/Buy Criteria*: Define criteria based upon requirements and cost constraints that will allow the future sub-system teams to make decisions on whether the team should buy or fabricate a particular component.

3.1.4. *Procurement*: Initiate the procurement of long-lead items so that they will be in the laboratory by the time that the class needs them.

4. *Processes*: Well thought-out processes are essential to ensure that requirements are met, interface definitions are adhered to, and programmatic budgets (schedule, cost, etc.) are not exceeded.

   4.1. *Budgets*: Develop a process that will be used by the Systems Team to track budgets (mass, power, cost, volume, flops, etc.).

   4.2. *Verification*: All requirements need to be measurable so that one can verify that the requirements have been met. Therefore, define the requirements verification process.

   4.3. *Configuration Control*: Develop a process for managing interfaces and configuration. If left untracked, the process of integrating the sub-system prototypes into the system prototype will be a painful process.

   4.4. *Mission Timelining:* Any mission will not only have a design but also a chronology of events through which elements of this design are implemented. Timelining focuses on the proper sequencing of these events and helps to identify technical options for implementing these events. It is similar to program scheduling. [Design Document]

It is important to realize that decisions made during the Conceptual Design Phase, a phase that 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 (TARR to PDR) is to take a "strawman" mission architectural concept and develop the design in more detail. Functional requirements are flowed down to technical sub-system requirements. The design explains how the system achieves its requirements and how the sub-system functions are allocated. The tasks for each sub-system during the preliminary design phase (after Spring Break CY2002) 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 electromagnetics, power, software, 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. [Interface Control Document]
4. *Sub-system Trade Analysis and Preliminary Design:* Each sub-system group will conduct trade analyses during the preliminary design phase. For example, one can calculate the impact of variations in power consumption, hardware mass, or number of units on the system cost, performance, or reliability. This is a highly interactive process and works best if conducted concurrently among the team members. [Design Document] Software modules that relate sub-system performance and cost to sub-system requirements will be developed to aid in this task. 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. *Budget Development:* The systems group will use the 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]
6. *Detailed Timelining:* The details of the chronology of events also impact the design and warrant further analysis. [Design Document]
7. *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. Often 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.

4.3 Student Laboratory Objectives

For the purpose of fulfilling the laboratory requirement, it is envisioned that the class will be divided into five sub-system development teams. Each team will consist of several undergraduate students who will flow down requirements to their sub-system, develop a design that optimizes performance while meeting carrier and interface constraints, formulate fabrication and procurement plans, fabricate the prototype hardware and software, conduct tests, compare with models, and alter flight hardware designs as appropriate. Suggested teams are:

1. *Electromagnetic (EM) and Reaction Wheel Assembly (RWA) Design*: Design EM dipole configurations and hardware, and size RWA to meet requirements while staying within mass and power budgets.
2. *Structure and Air Carriage*. Define mechanical interfaces for subsystems, minimize frame mass, etc. Model and measure system inertias and model system. Complete CAD and FEM models of system with static, dynamic and thermal loads analysis. Integrate model of structure prototype built with CNC and/or rapid prototyping machine. Design or modify existing air carriage for longer-duration operations.
3. *Communications and Operations*: Create the operations plan that allows the testbed to verify that it is meeting requirements. Also develop the system that allows wireless and autonomous operation of the "satellites."
4. *Power, Avionics and Software*. Define electrical power system and electrical interfaces, optimize system electrical efficiency, and manage battery hazard control, analog signal conditioning, touch temperature control, analog device drivers, etc. Also responsible for on-board software device drivers, real-time control software operating system, data handling and temporary storage, and control loop design.
5. *Systems*. The role of the Systems Team will change each semester, as will its student composition. It is desired that the Systems Team be composed of one member from each of the sub-system teams so that each sub-system have representation in the Systems Team. Membership turnover will attempt to accommodate all students who wish to serve on the Systems Team. This team is responsible for mass, power, error and cost budgets, verification and validation plan, configuration management of CAE drawings, documentation and presentation preparation, etc.

Formal laboratory notebooks will be maintained during the second half of the Spring CY02 semester. These notebooks will be used to archive design decisions, test results, observations, important parameter values, vendor phone numbers, etc. Periodically, key information from these notebooks should be transferred to the Design Document. Laboratory notebooks will be graded about every two weeks (three times over the semester). Details on laboratory notebook grading are provided in Section 8.6.

4.4 Fall 2002: Implement

Welcome to the Implementation portion of CDIO. It is time to make our designs work. This is the most difficult of the three semesters but hopefully the most rewarding in terms of accomplishment. The semester starts with prototype subsystems and ends with the arrival of some of the flight hardware. In between, the class must complete sub-system testing, assemble and test the prototype, successfully complete the Critical Design Review, and initiate flight hardware procurement. This section discusses the organization of the Implementation phase (Fall semester CY02).

The Fall of 2002 will be mainly dedicated to implementation. As part of this, the group will reach the Critical Design Review (CDR). 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." At this point detailed designs of the sub-systems will be required. These must be sufficiently detailed so that implementation of each system is possible and the integration of each sub-system becomes a reality. The specific tasks are described below:

1. Most of the tasks started during the Preliminary Design Phase are continued in more detail during the Critical Design Phase.
2. Program Plan: The Program Plan, as part of the Design Document, 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."

4.5 Spring 2003: Operate

The customer's requirements plan for a first test in early April, 2003. As such, this term will be greatly dedicated to ensure that the test occurs. The first part of the term will continue with implementation. Towards the initial test, the group will start to concentrate on validation strategies. Initial planning calls for (a) initial tests on a flat surface at MIT and (b) if the system performs satisfactorily, field operations at Lockheed Martin's flat-floor facility in Denver.

5 DELIVERABLES

The description of the deliverables is given below. Please read the individual descriptions to familiarize yourself with the several presentations and documents that individuals and the class, as a whole, will turn in during the course of the program.

Phases

PDP	Preliminary Design Phase
CDP	Critical Design Phase

Presentations

TARR	Trades Analysis and Requirements Review
PDR	Preliminary Design Review
CDR	Critical Design Review
AR	Acceptance Review

Documents

RD	Requirements Document
DD	Design Document
IP	Implementation Plan (Part of Design Document)
OP	Operations Plan (Part of Design Document)

The deliverables for each student during Spring CY2002 are:

1. Weekly assignment.
2. One formal oral presentation.
3. Written contributions (viewgraphs and annotations) to two formal presentations.
4. Two oral progress review presentations.
5. Written contribution to one progress review presentation.
6. Development of their respective sub-system, including analysis and hardware.

7. Laboratory notebook documentation (See Section 8.6.).

The deliverables for the class as a whole for Spring CY2002 are:

1. The formal presentations, with annotated viewgraphs.
2. The Requirements Document, Design Document, TARR presentation, PDR presentation.

5.1 Weekly Assignments

Each of the following weekly assignments is due in hardcopy at the beginning of the lecture period (1pm) on the date indicated. Some assignments are individual (with individual work performed by the student), while others are team efforts (with individual contributions indicated by initialing sections). Students should be prepared to engage in discussions related to the assignments from 1pm to 2pm on the due date. Please remember that the more complete the delivered documentation, the better able you will be to incorporate it into the TARR and PDR presentations, as well as into the Design Document. This will save you time and effort in the long run.

2/7/02 [Individual] A draft motivation for the class project, mission statement, and high-level functional requirements. Prepare these using the proposal, requirements lecture, and other material handed out on the first day.

2/14/02 [Team] A plan for your team up to the TARR, detailing the team's objectives, tasks, schedule, and individual team-member assignments. Drafts will be reviewed on 2/12/02.

2/21/02 [Team] A PowerPoint viewgraph presentation (~6-8 slides) of your team's concept of the final product. Include mission statement, requirements flowdown, trades, concept design (Use drawings with key features highlighted.), operations concept, and assessment of key advantages and disadvantages of your design. Be prepared to give a fifteen-minute informal presentation in class.

2/28/02 [Individual] A progress report on the individual assignments described in the assignment due on 2/14/02. Be prepared to give a brief summary in class.

3/7/02 [Team] A team progress report that shows how individual progress is meeting the objectives and schedule of the team. Be prepared to give a brief team report.

3/14/02 [Team/Individual] Draft of the TARR viewgraphs due with individual contributions indicated by initials.

3/19/02 [Team] TARR presentation.

4/4/02 [Team] Sub-system plan, including sub-system responsibility, objectives, requirements, schedule, assignments, and budgets. Emphasis should be placed on elements relating to PDR.

4/11/02 [Individual] Define individual tasks leading to PDR. For prototyping activities, describe measurements, noise sources, prototype design, cost, and success criteria.

4/18/02 [Individual] Progress reports.

4/25/02 [Individual] Progress reports.

5/2/02 [Team/Individual] Draft PDR viewgraphs due.

5/7/02 [Team] Preliminary Design Review.

5/16/02 [Team/Individual] Design Document due.

5.2 Presentations

High-quality presentations are important for communication of what you are doing. Every student is expected to make one formal oral presentation per term. The systems group will be responsible for arranging all presentations. The formal presentations are listed below. Part of the grade for each student will be based on his or her technical contribution to all formal presentations, as well as on the delivery of his or her portion of the presentations. Each of the presentations will be accompanied by one or more documents. (Each presentation description lists the relevant documents that should accompany the presentation. Descriptions of the documents, themselves, are given in the following section.)

1. *Trade Analysis and Requirements Review (TARR):* The objectives of the TARR are threefold. First, to formally accept and place under configuration control the Requirements Document. Customer, functional and highest level systems requirements are placed under control. Second, the rationale for selection of the mission architecture that is to be carried forward is presented and formally accepted. Third, the plan for executing the Preliminary Design Phase is presented and captured in the PDP ICD.
2. *Preliminary Design Review (PDR):* The objectives of the PDR are threefold. First, it provides a formal opportunity to present the status of the design (and budgets) down to the requirements and associated functions of the various sub-systems. Second, it provides an opportunity to present the design to an audience that is not part of the design team. This aspect of the PDR is often called a Non-Advocate Review (NAR) since it provides the customer with a critical “sanity check” before substantial program resources are spent on the design. Third, the plan for executing the Critical Design Phase is presented. This plan is captured in the CDP ICD.
3. *Critical Design Review (CDR):* The objectives of the CDR are threefold. First, the CDR provides an opportunity to present the completed design. Second, it is the first review in which the entire Program Plan for implementing and deploying that design will be presented. Third, it provides an opportunity to “sell” the design and program plan to an audience that is comprised of the customer and funding agencies. In typical programs, successful completion of a CDR leads immediately into flight hardware fabrication (i.e., “cut metal”). Therefore, a strong CDR presentation is essential for ensuring that the large resources required for the fabrication phase are made available.
4. *Acceptance Review (AR):* The objectives of the AR are threefold. First, the IDF is used as an opportunity to put the higher-level portions of the mission design under configuration control. This helps the team to focus on the details without concern that major design assumptions are going to change and thereby invalidate their work. Second, it provides an intermediate opportunity to review progress on the Program Plan for developing and deploying the design. Third, it provides a critical opportunity to refine the CDP ICD based upon the accomplished work, remaining work, and remaining time.

Presentation Guidelines

Remember that there are two ways to sink an idea: have a bad idea or have a good idea that is poorly presented.

- All presentations will have a duration of three (3) hours, where 2.5 hours is spent on the presentation and half an hour is devoted to questions and answers. All presentations will be accompanied by annotated viewgraphs.

5.3 Documents

All the documents in the class have a specific purpose, and are essential to the success of the project. Recall that each document must be self-sufficient, factual, and accurate. Therefore, attention must be paid to each of them. The description for each document is given below.

1.0 *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.

1.1 Revision 1.0 will be placed under Configuration Control at the TARR. It will therefore require the signature of the Chief Systems Engineer for modifications to the customer, functional or top level subsystem requirements to be made.

2.0 *Design Document:* captures the "build-to" specifications for the mission. 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 sub-system 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 sub-system is facing particularly stringent requirements while others face more lenient requirements. This allows proper balancing of the allocated requirements.

2.1 Revision 1.0: At this stage, the Design Document consists of portions of text and portions that are in outline form. The text portion identifies the subsystems, discusses the subsystem trades conducted, and justifies the selected subsystem implementation. This discussion will reference the Requirements Document on which it is based. The outline portion identifies the locations in the design document where requirements are presented, designs are developed, and budgets are kept.

3.0 *Implementation Plan:* describes how the design will be developed and deployed. Since this document is placed under configuration control at the CDR, it describes all events subsequent to CDR. These include the schedule, funding, suppliers, hardware flow, sub-system integration, flight hardware validation and verification, etc. for the fabrication, qualification, acceptance, and operations phases of the mission. For a commercial venture, it may be tightly coupled to the Business Plan, which also captures the "return" or profit along with a market risk analysis and contingency plan.

4.0 *Operations Plan:* outlines the procedures and dates for operation of the satellite. This plan must be self-sufficient from a user point of view. It must clearly define startup, operation, and shutdown methods. It should also have a plan on the dates for testing, validation, and future operation of the satellite.

Document Guidelines

- All the documents will enter under "Configuration Control" after they have been submitted to the staff. After submission, the Chief Systems Engineer (Professor Dave Miller) will sign the document, which indicates that it can no longer be changed. In order to modify the document after submission, the changes must be authorized by the Chief Systems Engineer. Note that there will be a complete lecture on this topic, where you will get details on the system and understand the ideas behind it.
- All documents will be developed in the software specified the first week of class (most likely: MS Word). This way we ensure that all members of the CDIO team will have access to the information in a timely manner.

6 MODULE DEVELOPMENT

In order to perform trade analyses and design, students will develop and utilize software modules. These modules describe the particular disciplines for which the students are responsible and mathematically capture the relationships between that discipline's inputs and outputs. There will be times during the class 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 a group. First, they force the students 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.

The Modules can be created in several software packages, as long as they contain the full mathematical description and behavior of the sub-system. If codified in Matlab, for example, 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 real time on the screen. In this way, design spaces can be explored and compared in fractions of the time conventionally required. 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 attributes are suggested for each module:

1. Definition of interfaces (inputs and outputs) and module content (i.e., module requirements).
2. Module development: mathematical relationships, software code, and code validation.
3. Contribution to the Integrated Concurrent Engineering exercises.
4. Module refinement: list features to be refined, mathematical alterations, software code, and code validation.

Additionally, the following **deliverables** must be included in the Design Document appendix: module requirements, mathematical relations, code, validation, and use history.

7 COMMUNICATIONS

7.1 Daily Communications

An email list has been established. It should be used to augment communication between individuals and groups in the class. The GAs will be on the list but the faculty will not be on the list. The GAs will keep the faculty and staff informed of all important issues that arise. A separate list, with just the staff has also been setup. Be sure to only use the staff list if absolutely necessary, since the professors get too many e-mails already!

7.2 Weekly Communications

The faculty, staff and GAs will meet every Monday at 10am to discuss progress in the class. Representatives from the class will on occasion be asked to come and talk with the faculty and staff at this meeting. Almost every Tuesday will start with a 20-minute review of action items and the last 20 minutes of Thursday will end with the assignment of action items. The review will consist of email memos (in standard CDIO memo format) as well as a brief verbal description by the cog-e.

8 GRADING

Grading for CDIO is 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 during the term, after each major presentation/due date.

Table 8.0: Grading Categories and Weights for Spring CY02

Criteria	Grader	Weight	# per student
Colleague Reviews	16.684 Students	20%	2
Progress Presentations & Weekly Assignments			
Written	Faculty, Staff & GAs	10%	1
Oral	Faculty, Staff & GAs	5%	2
Formal Presentations			
Written	Faculty, Staff & GAs	10%	2
Oral	Faculty, Staff & GAs	5%	1
Design & Documentation	Faculty, Staff & GAs	20%	2
Laboratory Performance			
Participation/Attendance	Faculty, Staff & GAs	10%	6 weeks
Notebooks	Faculty, Staff & GAs	10%	3
Design Validation	Faculty, Staff & GAs	10%	1

Description of Grading Criteria:

1. *Colleague reviews:* the students will submit colleague reviews to the Graduate Assistants (GAs) around the times of TARR and PDR. Students' reviews will include evaluations of their student colleagues, as well as themselves. The format of this evaluation will be discussed later.
2. *Progress Presentations*: Throughout the term, several opportunities will exist for informal presentations on either individual or team progress. These presentations will be mostly guided to interface design, ensuring that all sub-systems will be able to come together. They will include both written updates and oral presentations and are listed in the weekly assignments schedule in Section 5.1. Each student will give two oral progress reports, at least one of which must be an individual report. For team reports, all members of the groups will be involved in the written part, but individual students will present orally.
3. *Formal presentations:* Each student will present at one of the two formal presentations during the Spring of CY02. The formal presentations will be the TARR and PDR. Each formal design review presentation will be accompanied by annotated viewgraphs

provided electronically and in written form by the students to the faculty, staff and GAs. Each student's contribution to the written presentation will be indicated by initials. The faculty and staff will grade and the students will hand in critique sheets.

4. *Documentation*: At the end of the semester the following documents should have contributions from all students: Requirements Document and Design Document. Each student's contribution to the documents will be indicated by initials.
5. *Laboratory Participation and Attendance:* Any systems engineering organization depends upon teamwork and access to colleagues. Best access occurs during class and lab time. The Graduate Assistant will take attendance and report it to the faculty and staff. Obviously, there may be a class that the student cannot attend. Contact Professor Miller for semester-long conflicts. Clear other conflicts with one of the Graduate Assistants.
6. *Laboratory Notebooks:* The notebooks will be kept by each individual student to fully document all designs for the project. Each lab session should have an entry for the progress made during that session. Each entry should not only document the design, but should also explain its function and operation, since this will lever down the work on the formal documents. The notebooks will be reviewed three times during the semester by the faculty and staff. Each time a grade will be assigned based on the correct use of the lab book (not on the success of the design, since the design process is iterative we don't expect a full working solution the first time around).
7. *Design Validation:* By the end of the semester each sub-system should have a working design. This 'prototype' is to be tested by the students to demonstrate how it meets the requirements set forth in the Requirements Document.

9 RESOURCES

9.1 Textbooks

The following textbooks provide resource material for this course:

1. **Required**: Space Mission Analysis and Design (SMAD), Larson & Wertz, available at the COOP. Formal Reference: James R. Wertz and Wiley J. Larson, "*Space Mission Analysis and Design*", Third Edition, Space Technology Library, Space Technology Series, Microcosm Press and Kluwer Academic Publishers.
2. Optional: Space Systems Engineering, Pisacane & Moore, available in the Aero & Astro library.
3. Optional: Augustine's Laws, Augustine, available in the Aero & Astro library.
4. Optional: Physics, Halliday, Resnik, & Krane, John Wiley & Sons, Inc.

9.2 CDIO Design Room and Facilities

The Design Studio is a computer and laboratory facility dedicated to CDIO. This room has computers, Internet access, software applications, presentation material, filing cabinets, etc. All the computers in the room are identical, to provide with easy of use. Further, the computers have been networked in order to provide better communication between the teams. Every computer should have access to all the information at all times, therefore, we ask that all your work always be placed in the shared drive. Make sure that you fill in the form passed around during the first day of classes, such that your number will be programmed in.

The laboratory facilities have been assigned to 16.684. Documents, software etc. may be left in this room throughout the course. The rooms have PCs installed and are usable immediately.

Be sure to contact the staff with any questions about the computers or the software in them. Specifically the system administrator for setting up your user accounts, class accounts, user privileges / permissions is Fred Donovan. He can also show you how to operate the equipment (projectors, audio-visuals etc…). Further, be sure to follow the guidelines regarding documents and presentations. Especially, be sure to use the software provided in the CDIO room.

9.3 Funding

The project has been given to MIT by several outside companies and agencies. As such, the project is funded. Yet, the funding is not unlimited, therefore, careful studies must be made before purchasing products. Once a trade analysis has been made on the necessary materials to complete the project (Databasing), then the students should contact Paul Bauer in order to initiate procurement. He will then review the proposals together with the rest of the staff, and a purchase order will be obtained if the proposal is approved.