16.810
Engineering Design and Rapid Prototyping

Lecture 1

Introduction to Design

Instructor(s)
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Teaching Assistants:
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January 9, 2007
Happy New Year 2007!

We won’t be designing White Knight or SpaceShipOne this IAP, but ...

You will learn about “the design process” and fundamental building blocks of any complex (aerospace) system
“The scientist seeks to understand what is; the engineer seeks to create what never was”

- Von Karman
Outline

- Organization of 16.810
  - Motivation, Learning Objectives, Activities

- (Re-) Introduction to Design
  - Examples, Requirements, Design Processes (Waterfall vs. Spiral), Basic Steps

- “Design Challenge” - Team Assignments
  - Previous Years (2004, 2005)
  - This Year: MITSET (30 min), VDS (30 min)
  - Deliverables Checklist, Team Assignments

- Facilities Tour
Organization of 16.810
Expectations

- 6 unit course (3-3-0) – 7+1 sessions
  - TR1-5 in 33-218, **must** attend all sessions or get permission of instructors to be absent
  - This is for-credit, no formal “problem sets”, but expect a set of deliverables (see √-list)
  - Have fun, but also take it seriously
  - The course is a 3rd year “prototype” itself and we are hoping for your feedback & contributions
- Officially register under 16.810 (Jan 2007) on WEBSIS
## History of this Course

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
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<tbody>
<tr>
<td>December 2002</td>
<td>Undergraduate Survey in Aero/Astro Department. Students expressed wish for CAD/CAE/CAM experience.</td>
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<td>April 4, 2003</td>
<td>Submission of proposal to Teaching and Education Enhancement Program (“MIT Class Funds”)</td>
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<td>May 6, 2003</td>
<td>Award Letter received from Dean for Undergraduate Education ($17.5k)</td>
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<td>June 5, 2003</td>
<td>Kickoff Meeting</td>
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<td>Sept 18, 2003</td>
<td>Approved by the AA undergraduate committee (6 units)</td>
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<td>Fall 2003</td>
<td>Preparation</td>
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<tr>
<td>Jan 5, 2004</td>
<td>First Class (Topic: Bicycle Frame Design)</td>
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<tr>
<td>Fall 2004</td>
<td>Preparation</td>
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<tr>
<td>Jan 4, 2005</td>
<td>Second Class (Topic: Race Car Wing Design)</td>
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<tr>
<td>Jan 2007</td>
<td>Third Class → Focus on helping student projects</td>
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see: [http://ocw.mit.edu](http://ocw.mit.edu)
A 2001 survey of undergraduate students (Aero/Astro) – in conjunction with new Dept. head search

- There is a perceived lack of understanding and training in modern design methods using state-of-the-art CAD/CAE/CAM technology and design optimization.

- Individual students have suggested the addition of a short and intense course of rapid prototyping, combined with design optimization.
Boeing List of “Desired Attributes of an Engineer”

- A good understanding of engineering science fundamentals
  - Mathematics (including statistics)
  - Physical and life sciences
  - Information technology (far more than “computer literacy”)

- A good understanding of design and manufacturing processes (i.e. understands engineering)

- A multi-disciplinary, systems perspective

- A basic understanding of the context in which engineering is practiced
  - Economics (including business practice)
  - History
  - The environment
  - Customer and societal needs

- Good communication skills
  - Written
  - Oral
  - Graphic
  - Listening

- High ethical standards

- An ability to think both critically and creatively - independently and cooperatively

- Flexibility. The ability and self-confidence to adapt to rapid or major change

- Curiosity and a desire to learn for life

- A profound understanding of the importance of teamwork.

* This is a list, begun in 1994, of basic durable attributes into which can be mapped specific skills reflecting the diversity of the overall engineering environment in which we in professional practice operate.

* This current version of the list can be viewed on the Boeing web site as a basic message to those seeking advice from the company on the topic. Its contents are also included for the most part in ABET EC 2000.
An engineer should be able to ...

- Determine quickly how things work
- Determine what customers want
- Create a concept
- Use abstractions/math models to improve a concept
- Build or create a prototype version
- Quantitatively and robustly test a prototype to improve concept and to predict
- Determine whether customer value and enterprise value are aligned (business sense)
- Communicate all of the above to various audiences

- Much of this requires “domain-specific knowledge” and experience
- Several require systems thinking and statistical thinking
- All require teamwork, leadership, and societal awareness
Develop a holistic view and initial competency in engineering design by applying a combination of human creativity and modern computational tools to the synthesis of a simple component or system.
“Holistic View” - of the whole. Think about:
- requirements,
design, manufacturing,
testing, cost …

“Engineering Design” - what you will likely do after MIT

“Human Creativity and Computational Tools”: design is a constant inter-play of synthesis and analysis

“Competency” - can not only talk about it or do calculations, but actually carry out the process end-to-end

“Rapid Prototyping” - a hot concept in industry today.

“Components / Systems”: part of all aerospace systems, But must be “easy” to implement in a short time
Course Concept
Course Flow Diagram (2007)

Learning/Review
- Design Intro / Sketch
- CAD Introduction
- FEM/Solid Mechanics
- Avionics Prototyping
- CAM Manufacturing
- Fabrication, Assembly, Testing

Problem statement
- Hand sketching
- Initial CAD design
- FEM analysis
- Optimization
- Revise CAD design
- Parts Fabrication
- Assembly
- Test

Deliverables
- (A) Requirements and Interface Document
- (B) Hand Sketch
- (C) Solidworks CAD Model, Performance Analysis
- (D) Manufacturing and Test Report with Cost Estimate
- (E) CDR Package

+ Guest Lectures
Learning Objectives

At the end of this class you should be able to …

(1) Carry out a systematic design process from conception through design/implementation/verification of a simple component or system.

(2) Quantify the predictive accuracy of CAE versus actual test results.

(3) Explain the relative improvement that computer optimization can yield relative to an initial, manual solution.

(4) Discuss the complementary capabilities and limitations of the human mind and the digital computer (synthesis versus analysis).
Grading

- Letter Grading A-F

- Composition
  - Design Deliverables* 70%
    - Requirements Document, Sketch, CAD Model & Analysis, Test & Mfg Report, Final Review Slides
  - Final Product 20%
    - Requirements Compliance
    - “Quality”
  - Active Class Participation 10%
    - Attendance, Ask Questions, Contribute Suggestions, Fill in Surveys

*see checklist
(Re-)Introduction to Design
Product Development - Design

Improved time-to-climb
Performance of F/A-18 in
Air-to-Air configuration by ~ 20%

Development
of Swiss F/A-18 Low Drag
Pylon (LDP) 1994-1996

“design” –
to create, fashion, execute,
or construct according to plan

Merriam-Webster
Design and Objective Space

**Design Space**

**Design Variables**
- Wing Area: 31.5 [in²]
- Aspect Ratio: 6.2
- Dihedral Angle: 0 [deg]

**Fixed Parameters**
- Air density
- Properties of balsa wood

**Objective Space**

**Performance**
- Time-of-Flight: 5.35 sec
- Distance: Ca. 90ft

**Cost**
- Assembly Time: 87 min
- Material Cost: $4.50

Remember Unified …?
Basic Design Steps

1. Define Requirements
2. Create/Choose Concept
3. Perform Design
4. Analyze System
5. Build Prototype
6. Test Prototype
7. Accept Final Design
Typical Design Phases

- General arrangement and performance
- Representative configurations
- General internal layout

- Systems specifications
- Detailed subsystems
- Internal arrangements
- Process design

- Sophisticated Analysis
- Problem Decomposition
- Multidisciplinary optimization

- General arrangement and performance
- Representative configurations
- General internal layout
Phased vs. Spiral PD Processes

Phased, Staged, or Waterfall PD Process
(dominant for over 30 years)

1. Product Planning
2. Product Definition
3. System-Level Design
4. Detail Design
5. Integrate and Test
6. Product Launch

Spiral PD Process
(primarily used in software development)

1. Product Planning
2. Define, Design, Build, Test, Integrate
3. Define, Design, Build, Test, Integrate
4. Define, Design, Build, Test, Integrate
5. Product Launch

Process Design Questions:
- How many spirals should be planned?
- Which phases should be in each spiral?
- When to conduct gate reviews?
Stage Gate PD Process

Planning

Concept Design

System-Level Design

Detailed Design

Integration & Test

Release

Cross-Phase Iterations (unplanned)

Within-Phase Iterations (planned)

Reviews

Spiral PD Process

- Planning
- Detailed Design
- System-Level Design
- Concept Design
- Integration & Test
- Reviews
- Cost (Cumulative Effort)
- Release

Rapid Prototyping is typically associated with this process.
Basic Trade-offs in Product Development

- Performance - ability to do primary mission
- Cost - development, operation life cycle cost
- Schedule - time to first unit, production rate
- Risk - of technical and or financial failure

Ref: Maier, Rechtin, “The Art of Systems Architecting”
Key Differences in PDP’s

- Number of phases (often a superficial difference)
- Phase exit criteria (and degree of formality)
- Requirement “enforcement”
- Reviews
- Prototyping
- Testing and Validation
- Timing for committing capital
- Degree of “customer” selling and interference
- Degree of explicit/implicit iteration (waterfall or not)
- Timing of supplier involvement
Hierarchy I: Parts Level

- deck components
  - Ribbed-bulkheads
  - Approximate dimensions
    - 250mm x 350mm x 30mm
    - Wall thickness = 2.54mm

- frame components
  - Ribbed-bulkheads
  - Approximate dimensions
    - 430mm x 150mm x 25.4mm
    - Wall thickness = 2mm

- keel
  - Ribbed-bulkhead
  - Approximate dimensions
    - 430mm x 660mm x 25.4mm
    - Wall thickness = 2.54mm
Hierarchy II: Assembly Level

- Boeing (sample) parts
  - A/C structural assembly
    - 2 decks
    - 3 frames
    - Keel
  - Loft included to show interface/stayout zone to A/C
  - All Boeing parts in Catia file format
    - Files imported into SolidWorks by converting to IGES format
### Product Complexity

How many levels in drawing tree?

Assume 7-tree

\[
#\text{levels} = \left\lfloor \frac{\log(#\text{parts})}{\log(7)} \right\rfloor
\]

<table>
<thead>
<tr>
<th>Item</th>
<th>Parts</th>
<th>Levels</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screwdriver (B&amp;D)</td>
<td>3</td>
<td>1</td>
<td>simple</td>
</tr>
<tr>
<td>Roller Blades (Bauer)</td>
<td>30</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Inkjet Printer (HP)</td>
<td>300</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Copy Machine (Xerox)</td>
<td>2,000</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Automobile (GM)</td>
<td>10,000</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Airliner (Boeing)</td>
<td>100,000</td>
<td>6</td>
<td>complex</td>
</tr>
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“Design Challenge” and Team Assignments
Project Description – IAP 2004

Model Bicycle Frame on 2-D plate

Material: Al 6061-T6
Thickness ¼”
Scale ca. 1:5
Phase 1

Problem Statement → Sketch → CAD Model → CAE → Rapid Prototyping Validation

Phase 2

Design Optimization (Trimming!) → CAD Model V2 → CAE V2 → Rapid Prototyping V2 Validation V2
**Project Description – IAP 2005**

**maximize** \[ F = L - 3D - 5W \]

Where:
- L = measured downforce (negative lift) at specified speed [N]
- D = measured drag at specified speed [N]
- W = total weight of the assembly (not including test fixture) [N]

The nominal speed is 60 mph
Project Deliverables – IAP 2005

Phase 1

Problem Statement ➔ Hand Sketch ➔ Initial CAD ➔ CAE (FEA) ➔ CAE (CFD)

Phase 2

Weight vs Wing Segment Angle

Design Optimization

Prototype Testing and Validation
Optimization – 2004 & 2005

- Manual Iteration
  - Design loops (Spiral method)

- Software
Learning from Mistakes

- Carrying out a full lifecycle creates memorable learning experiences
- Don’t prevent students from making mistakes
- Example: bi-wing configuration
- Excerpt from Student Reflective Memo:

  “I learned the value of constantly checking simulations against reality ..... My rear-wing design used a biplane setup, ...due to a huge oversight, the wings were actually arranged in an incorrect orientation which incurred a large drop in down force. ....This experience taught me a great lesson - always triple check your assumptions against your design. I spent hours and hours optimizing a design that was never constructed, simply because I was told to assume that the down force bonus would be experienced. I never bothered to verify this myself, and this disconnection had dire consequences.”
IAP 2007 Challenge

- Focused on Student-Driven Teams
  - VDS Vehicle Design Summit
  - MITSET Space Elevator Team
- Define/pick the current baseline configuration
- Create a performance model of the baseline configuration
  - VDS: miles-per-gallon [mpg]
  - MITSET: time-to-climb [sec]
- Pick 4-5 most critical components and subsystems based on performance sensitivity
- IAP 2007
  - assign 2-3 students per component/subsystem in the 1st session of IAP
  - design/redesign those components during weeks 2-3
  - manufacture and reintegrate during week 4
  - CDR at the end of IAP 2007 – look at performance improvement
Team Presentations (30 min each)

- MIT Space Elevator Team (MITSET)
  NASA Centennial Challenge
  Power Beaming

- Vehicle Design Summit (VDS)
  Assisted Human Power Vehicle (AHPV)
  Image: VDS 1.0 - Summer 2006
Facilities Tour
Facilities Tour

* Design Studio (33-218)
- 14 networked CAD/CAE workstations that are used for complex systems design and optimization.

* Machine Shop
- Water Jet cutter, Wing cutter

* Wind Tunnel
- Subsonic aerodynamic testing

* Software to be used:
  - Xfoil
  - Solidworks
  - Cosmos
  - Omax
  - Matlab
  - Altium

Next Steps

- Form a Team
  - Pick MITSET or VDS
  - Pick a component/subsystem
  - Give your team a distinctive name

- Study the following
  - 16.810 documents: schedule, deliverables checklist, project description, Register on WEBSIS if not already done

- Get username and passwd on AA-Design LAN

- Complete Attendance Sheet

- Prepare for Thursday’s lecture:
  - Look at CAD/CAE/CAM manual (Sample Part)
  - Go through step-by-step
  - Signup for a machine shop slot for Waterjet Manufacturing (OMAX)