Multidisciplinary System Design Optimization (MSDO)

Introduction
Lecture 1
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Prof. Olivier de Weck
Prof. Karen Willcox

Introductions

Olivier de Weck, Ph.D. – Lecturer
Assistant Professor, deweck@mit.edu

Karen Willcox, Ph.D. – Lecturer
Assistant Professor, kwillcox@mit.edu

Il Yong Kim, Ph.D. – Assistant Lecturer
Postdoctoral Fellow, kiy@mit.edu

Jackie Dilley – Course Assistant
jdlley@mit.edu
Today's Topics

- Course Rationale
- Role of MSDO in Engineering Systems
- Learning Objectives
- Pedagogy and Course Administration
- A historical perspective on MDO
- MSDO Framework introduction
- The “dairy farm” sample problem

Course Rationale

- Computational Design and Concurrent Engineering (CE) are becoming an increasingly important part of the Product Development Process (PDP) in Industry
- MIT offerings strong in linear programming and constrained convex optimization (single objective)
- However, there is a perceived gap at MIT:
  - mostly management, not design focus
  - multiobjective optimization
  - MDO vibrant research field
    but no course to represent it
- This is NOT a traditional optimization course: M-S-D-O
Role of MSDO in Engineering Systems

Goal: Create advanced and complex engineering systems that must be competitive not only in terms of performance, but also in terms of manufacturability, serviceability and overall life-cycle cost effectiveness.

Need: A rigorous, quantitative multidisciplinary design methodology that can work hand-in-hand with the intuitive non-quantitative and creative side of the design process.

This class presents the current state-of-the-art in concurrent, multidisciplinary design optimization (MDO)

Product Development Process

The Environment: technological, economic, political, social, nature

The System: creativity, architeacting, trade studies

The Enterprise: manufacturing, assembly, integration

The System: virtual, real

"Turn information to matter"

"Process information"

The Product Development Process:
1. Beginning of Lifecycle
2. Conceive
3. Design
4. Implement

SRR: - Mission - Requirements - Constraints

PDR: choose

CDR: iterate

SRR: create

PDR: virtual

CDR: real

Massachusetts Institute of Technology - Prof. de Weck and Prof. Willcox
Goal: Find a “balanced” system design, where the flexible structure, the optics and the control systems work together to achieve a desired pointing performance, given various constraints.
Automotive Example

Ferrari 360 Spider

Goal: High end vehicle shape optimization while improving car safety for fixed performance level and given geometric constraints


Course Objectives

The course will

- fill an existing gap in MIT’s offerings in the area of simulation and optimization of multidisciplinary systems during the conceive and design phases
- develop and codify a prescriptive approach to multidisciplinary modeling and quantitative assessment of new or existing system/product designs
- engage junior faculty and graduate students in the emerging research field of MDO, while anchoring the CDIO principles in the graduate curriculum
Learning Objectives (I)

The students will

1. learn how MSDO can support the product development process of complex, multidisciplinary engineered systems

2. learn how to rationalize and quantify a system architecture or product design problem by selecting appropriate objective functions, design variables, parameters and constraints

3. subdivide a complex system into smaller disciplinary models, manage their interfaces and reintegrate them into an overall system model

Learning Objectives (II)

4. be able to use various optimization techniques such as sequential quadratic programming, simulated annealing or genetic algorithms and select the ones most suitable to the problem at hand

5. perform a critical evaluation and interpretation of simulation and optimization results, including sensitivity analysis and exploration of performance, cost and risk tradeoffs

6. be familiar with the basic concepts of multiobjective optimization, including the conditions for optimality and the computation of the pareto front
Learning Objectives (III)

(7) understand the concept of design for value and be familiar with ways to quantitatively assess the expected lifecycle cost of a new system or product.

(8) sharpen their presentation skills, acquire critical reasoning with respect to the validity and fidelity of their MSDO models and experience the advantages and challenges of teamwork.

How to achieve these learning objectives?

MSDO Pedagogy

e.g. A1 - Design of Experiments (DOE)

e.g. "Genetic Algorithms"

e.g. "NASA LaRC"

Guest Lectures

Assignments A1-A5

Lectures

Class Project

Lab Sessions

Readings

e.g. "iSIGHT Introduction"

e.g. "STSTank"

e.g. "Principles of Optimal Design"
Assignments

Part (a)
Small, simple problems to be solved individually, many just by hand or with a calculator. Goal is to ensure learning of the key ideas regardless of chosen project.

Part (b)
Application of theory to a project of your choice from either existing class projects or a project related to your research. Solution individually or in teams of two or three.

- Assignments A1-A5 scheduled bi-weekly.
- Usually handed out Monday, Tutorial on Friday, due on a Monday two weeks later.

Lectures

Lecture schedule in separate document.

Module 1: Problem Formulation and Setup
Module 2: Optimization and Search Methods
--- Spring Break ---
Module 3: Multiobjective and Stochastic Challenges
Module 4: Implementation Issues and Applications
Class Project

Option A – Use a pre-existing project
These are prepared simulation codes that you can use as your class project for solving part (b) of the assignments in lieu of a personal research-related problem:
\AERO-ASTRO\16.888\AIRCRAFT (C-Code)
\AERO-ASTRO\16.888\COMSATS (MATLAB)
\AERO-ASTRO\16.888\SHUTTLETANK (Excel)
\AERO-ASTRO\16.888\SUPersonic (Excel)

Option B – Formulate your own project
- This is an opportunity to push your research forward
- Form teams of 1-3 students
- Must be a design problem, must be multidisciplinary
- Write 1 page project proposal in A1

Lab Sessions

This room is the “Design Studio” …. NOT just another computer cluster. There is a lot of thought behind the façade. “Complex Systems Development and Operations Laboratory”

Result of the most recent strategic plan of the Dept. of Aeronautics and Astronautics at MIT. New Focus:
- CDIO
- System Architecture and Systems Engineering
- Aerospace Information Engineering
Tools and Infrastructure

- **Physical Infrastructure:** Design Studio 33-218
- **Computational Infrastructure:**
  - **Class folder:** `\AERO-ASTRO\16.888`
  - Located on AA-DESIGN PC network
  - Will setup individual usernames and passwords
- **Software Infrastructure:**
  - Matlab, Excel, C-compiler
  - iSIGHT - donated by Engineous Software Inc.
    (Participate in iSIGHT academic BETA test program)
  - CO - donated by Oculus Technologies Corp.

Readings


  will assign at the end of each lecture
Guest Lectures

Guest Lecture 1:
3 Mar  Dr. Jaroslaw Sobieski, NASA LaRC
Overview of MDO, Video Lecture

Guest Lecture 2:
14 Apr  Dr. Peter Fenyes, General Motors Research Center
IFAD/CDQM – MDO in vehicle development

During the semester:
- Dr. Cyrus Jilla: Simulated Annealing
- Dr. Rania Hassan: Particle Swarm Optimization
- Dr. Il Yong Kim: Design Space Optimization
- Prof. Dan Frey: Robust Design

Grading

Assignments A1-A5* 50%
Project Presentation 20%
Final Report (Paper) 20%
Active Participation 10%

100%

No mid-term or final exams

* Each Assignment counts 10%
Introduction to stellar.mit.edu

Historical Perspective on MDO

The need for MDO can be better understood by considering the historical context of progress in aerospace vehicle design.

- 1903 Wright Flyer makes the first manned and powered flight.
- 1927 Charles Lindbergh crosses the Atlantic solo and nonstop
- 1935 DC-3 enters service (12,000 to be produced)
- 1958 B707 enters service
- 1970 B747 enters service
- 1974 A300 enters service
- 1976 Concorde enters service
1970-1990 Cold War and Maturity

- **Big slump** in world economy ("oil crisis" 1973), airline industry and end of Apollo program leads to a reduction of engineering workforce around 25%

- Two major new developments: Computer aided design (CAD), Procurement policy changes for airlines and the military

- Earlier quest for maximum performance has been superseded by need for a "balance" among performance, life-cycle cost, reliability, maintainability and other "-ilities"

- Reflected by growth in design requirements, see next slide. Competition in airline industry drives operational efficiency.
Multidisciplinary design extended to other industries: spacecraft, automobiles, electronics and computers, transportation and energy/power suppliers

Thrusts in government and industry to improve productivity and quality in products and processes

Design process: Globalization results in distributed, decentralized design teams, high performance PC has replaced centralized super-computers, disciplinary design software (Nastran, CAD/CAM) very mature, Internet and LAN’s allow easy information transfer

Advances in optimization algorithms: e.g. Genetic Algorithms, Simulated Annealing, MDO software, e.g. iSIGHT

Goal of MDO: Gain design knowledge earlier and retain design freedom longer into the development process.
Key motivation: Control of Lifecycle costs

- Control of Lifecycle costs
- Actually incurred costs

Definitions

**Multidisciplinary** - comprised of more than one traditional disciplinary area described by governing equations from various physical, economic, social fields

**System** - A system is a physical or virtual object that exhibits some behavior or performs some function as a consequence of interactions between the constituent elements

**Design** - The process of conceiving and planning an object or process with a specific goal in mind. In the context of this class this refers to the conceiving of a system that will subsequently be implemented and operated for some beneficial purpose.

**Optimization** - To find a system design that will minimize some objective function. The objective function can be a vector comprising measures of system behavior (“performance”), resource utilization (“time, money, fuel…”) or risk (“stability margins…”).
Problem Formulation and Setup

(NLP)

\[ \begin{align*}
\min & \quad J(x, p) \quad \rightarrow \text{objective} \\
\text{s.t.} & \quad g(x, p) \leq 0 \quad \rightarrow \text{constraints} \\
& \quad h(x, p) = 0 \\
& \quad x_{i, LB} \leq x_i \leq x_{i, UB} \quad \rightarrow \text{bounds} \\
\text{where} & \quad J = \begin{bmatrix} J_1(x) & \cdots & J_z(x) \end{bmatrix}^T \\
& \quad x = \begin{bmatrix} x_1 & \cdots & x_i & \cdots & x_n \end{bmatrix}^T \quad \rightarrow \text{design vector}
\end{align*} \]

MSDO Framework

Design Vector

Simulation Model

Objective Vector

\[ \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \rightarrow \text{Discipline A} \rightarrow \text{Discipline B} \rightarrow \text{Discipline C} \rightarrow \text{Output} \]

\[ \begin{bmatrix} J_1 \\ J_2 \\ \vdots \end{bmatrix} \]

Coupling

Multiobjective Optimization

Numerical Techniques (direct and penalty methods)

Heuristic Techniques (SA, GA)

Approximation Methods

Sensitivity Analysis

Isoperformance

Special Techniques

Tradespace Exploration (DOE)
Challenges of MSDO

- Deal with design models of realistic size and fidelity that will not lead to erroneous conclusions
- Reduce the tedium of coupling variables and results from disciplinary models, such that engineers don’t spend 50-80% of their time doing data transfer
- Allow for creativity, intuition and “beauty”, while leveraging rigorous, quantitative tools in the design process. Hand-shaking: qualitative vs. quantitative
- Data visualization in multiple dimensions
- Incorporation of higher-level upstream and downstream system architecture aspects in early design: staged deployment, safety and security, environmental sustainability, platform design etc...

Simple example (I)

"Dairy Farm" sample problem

L - Length
N - # of cows
R - Radius

Goal: maximize Profit P
Simple example (II)

Agricultural Model:

- **Area**: \( A = 2LR + \pi R^2 \) [m²]
- **Fence Perimeter**: \( F = 2L + 2\pi R \) [m]
- **Milk Production per Cow**: \( M = 100 \cdot \sqrt{A / N} \) [liters]

Economic Model:

- **Cost**: \( C = f \cdot F + n \cdot N \) [$]
- **Income**: \( I = N \cdot M \cdot m \) [$]
- **Profit**: \( P = I - C \) [$]

**Parameters**:
- \( f = 100 \$/m \)
- \( n = 2000 \$/cow \)
- \( m = 2 \$/liter \)

**Constraint**: \( C \leq 100,000 \$ \)

Get same results analytically?

Summary

- **Learning Objectives**:
  - decompose and integrate multidisciplinary design models
  - formulate meaningful problems mathematically
  - explore design space and understand optimization
  - critically analyze results, incl. sensitivity analysis

- **Understand current state of the Art in MSDO**
  - see depth and breadth of applications in industry & science
  - get a feel for interaction of quantitative-qualitative design
  - understand limitations of techniques
  - good overview of literature in the field

- **Benefit your research** directly … and have fun!
• Read Course syllabus carefully by 2/6/2004

• Read Chapter 1
  – Papalambros, “Principles of Optimal Design”
  – Before: Monday – February 9, 2003

• Read 1991 MDO White Paper
  – Before: Monday – February 9, 2003