Deterministic Design Optimization of Structures in OpenMDAO Framework

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Overview

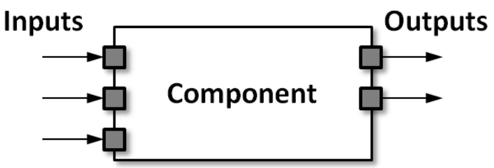
- Development of OpenMDAO Framework led out of NASA Glenn Research Center with support from NASA Langley Research Center
  - Can be used to develop an integrated analysis, optimization and design environment for engineering challenges. Hosting site: http://openmdao.org
- Demonstrate and verify OpenMDAO implementation by analyzing a set of widely used benchmark structural design problems and realistic cases
- Nonlinear Optimization Programing Techniques
  - NEWSUMT
  - CONMIN
  - NLPQL
  - Ipopt
  - NSGA-II

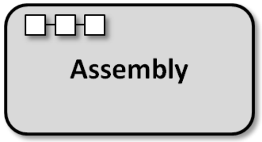
  } OpenMDAO
- Compare results of OpenMDAO with CometBoards (Comparative Evaluation Test Bed of Optimization and Analysis Routines for the Design of Structures)
- Summary and Future Plans

Basic Features

- OpenMDAO is an open source framework, easily available on http://openmdao.org
- Based on Python programming language; high level, interpreted language
- Provides a common platform to develop, test, and apply state-of-the-art optimization techniques for analyzing/optimizing MDAO problems
- Users can solve complex problems by linking together analysis and optimization codes from multiple disciplines & multiple architectures
- Structural Analysis Discipline: MSC/NASTRAN & closed form analysis
- Optimization Capabilities: Single-objective, Multi-Objective Techniques & Cascade Strategy
- Stochastic Optimization Capability: NESSUS/FPI - Initial version
- OpenMDAO is flexible and robust because it separates the flow of information (dataflow) from the process in which analyses are executed (workflow)

Component – a computational engineering application that accepts input and returns output





Assembly – a container object which houses sub-components, defining data connections between them

Driver – an object that controls process iteration (solvers, optimizers, iterators, etc.)

Workflow – an object that specifies execution order of components for a driver

Ref. Kenneth T. Moore, “OpenMDAO Development and Usage”, July 2012

OpenMDAO: Components (Solvers) Drivers (Optimizers) and Plugin Library

Components:

- adpac_wrapper
- excel_wrapper
- flops_wrapper
- nastran_wrapper
- nessus_stochastic
- ommodel_wrapper
- overflow_wrapper
- pareto_filter
- pdcyl_comp
- vsp_wrapper

Drivers:

- COBYLA
- CONMIN
- DOE
- FixedPointIterator
- Genetic
- Ipopt
- NEWSUMT
- NLPQL
- pyOpt
- Sensitivity
- SLSQP

Other Plugins:

Surrogate Models:

- Neural_net

DOE Generators:

- Monte Carlo

Resource Allocators:

- NAS_access

Differentiators:

- Chain Rule
- Analytic
- Finite Difference

- Users Guide and Developers Guide Documentation; Forum; Screencasts; Cookbook; Publications
- Plugin Installation Tool
- All of the official plugins can be found at: https://github.com/OpenMDAO-Plugins
- Users are encouraged to contribute their own plugins as well

Deterministic Design Optimization

- Casted as a nonlinear mathematical programming problem:

  Find x that minimizes $\boldsymbol{W}(x)$ subject to $\mathbf{g}(x) \leq \mathbf{0}$, $\mathbf{h}(x) = \mathbf{0}$ and $x_{lb} \leq x \leq x_{ub}$

  where $\boldsymbol{W}$ is an objective, x is a vector of design variables, **g** is a vector of inequality constraints, **h** is a vector of equality constraints, and x_{lb} and x_{ub} are vectors of lower and upper bounds on the design variables.
- Applications of nonlinear programming include: aerospace engineering, aircraft and spacecraft design, automobile design, naval architecture, electronics, computers, etc.
- Component used in OpenMDAO Framework:
  - MSC/NASTRAN is the analyzer
- Optimizers used in OpenMDAO Framework:

  1) NEWSUMT – Sequence of Unconstrained Minimizations Technique - *Miura, H. and Schmit, L. A. Jr.*

  2) CONMIN – CONstraint function MINimization - *Vanderplaats,G.N.*

  3) NLPQL – Non-Linear Programming by Quadratic Lagrangian - *Schittkowski, K.*

  4) Ipopt – Interior Point OPTimizer - *https://projects.coin-or.org/Ipopt*

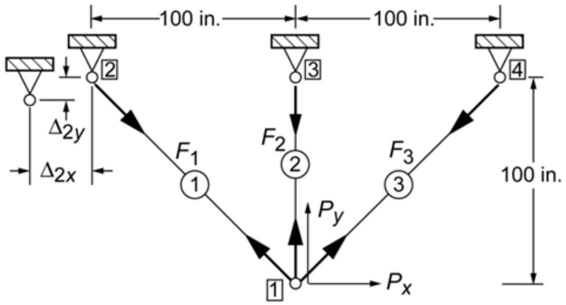
  5) NSGA-II – Nondominated Sorting Genetic Algorithm - *Deb K.*
- CometBoards (NEWSUMT)

Description and Results of Demonstration Cases

Case 1: Optimization of a Three-Bar Truss

- Design Variables:
  - Areas of the three rod elements
- Objective:
  - Minimize the weight of the truss
- Constraints: $|\sigma_i| \le \sigma_{allow} \quad i = 1,2,3$

  $\delta_i \le \delta_{max} \quad i = 1,2$



OpenMDAO Model Variables Specification			
Variable Name	**Data type**	**Default Value, I/O type**	**Description, Units**
bar1_area	Float	0.0, input	cross-sectional area for bar1, inch*inch
bar2_area	Float	0.0, input	cross-sectional area for bar2, inch*inch
bar3_area	Float	0.0, input	cross-sectional area for bar3, inch*inch
bar1_stress	Float	0.0, output	stress in bar1, lb/(inch*inch)
bar2_stress	Float	0.0, output	stress in bar2, lb/(inch*inch)
bar3_stress	Float	0.0, output	stress in bar3, lb/(inch*inch)
displacement_x_dir	Float	0.0, output	displacement in x_direction, inch
displacement_y_dir	Float	0.0, output	displacement in y_direction, inch
weight	Float	0.0, output	weight of the structure, lbs

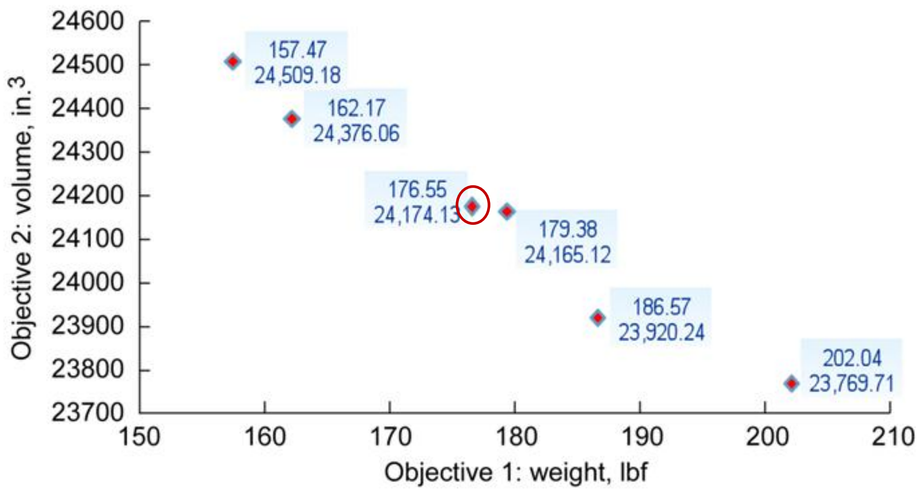
Three-Bar Truss Results

Problem	**OpenMDAO Optimization Methods**				
3-bar truss Design variables:3 Constraints: 3S, 2D	**NEWSUMT**	**CONMIN**	**NLPQL**	**Ipopt**	**CometBoards (NEWSUMT)**
Optimal Weight, lb	237.115	237.151	237.101	237.357	237.194
Optimal Design(in^2):	3.5356 3.3382 0.0101	3.5343 3.3380 0.01	3.5330 3.3380 0.0100	3.5346 3.3425 0.0116	3.5334 3.3394 0.0105
Active Constraints **S: Stress; D: Displacement**	1S, 1D	1S, 1D	1S, 1D	1S,1D	1S,1D
Number of Iterations	33	17	9	101	31
CPU time (mins)	33.191	6.183	4.231	93.320	180.0

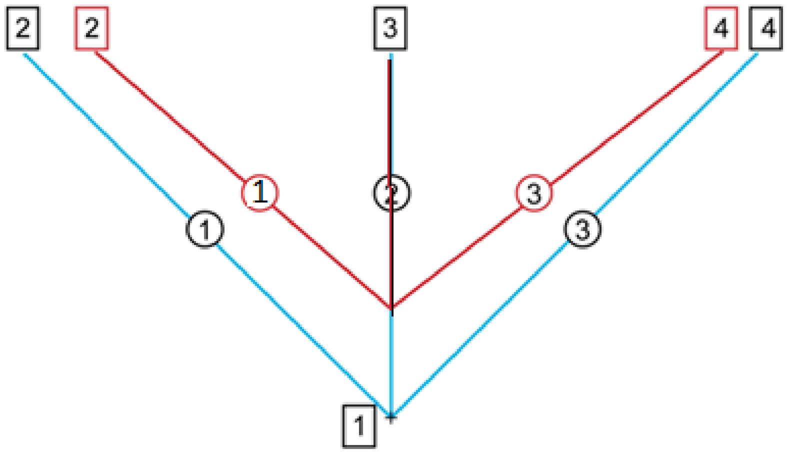
- Variation in solutions: Weight: 0.03% (NLPQL) to 0.07% (Ipopt)
- CPU time: NLPQL 42 times faster than CometBoards with fewer iterations
- OpenMDAO NEWSUMT reduced solution time by a factor of 5.4
- Performance: Acceptable by all methods

Multi-Objective Shape Optimization of the Static 3-Bar Truss

- Objective 1: Minimize the weight
- Objective 2: Minimize the enclosed volume
- Design Variables: cross-sectional areas of the bars, position of node 1(y-dir), position of nodes 2 and 4 (x-direction)
- Behavior constraints: stress and displacements
- NSGA-II Algorithm: population size = 80; generations = 50; crossover probability = 1.0; mutation probability = 0.5; distribution index = 20 and 50



Pareto optimal front for the 3bar truss



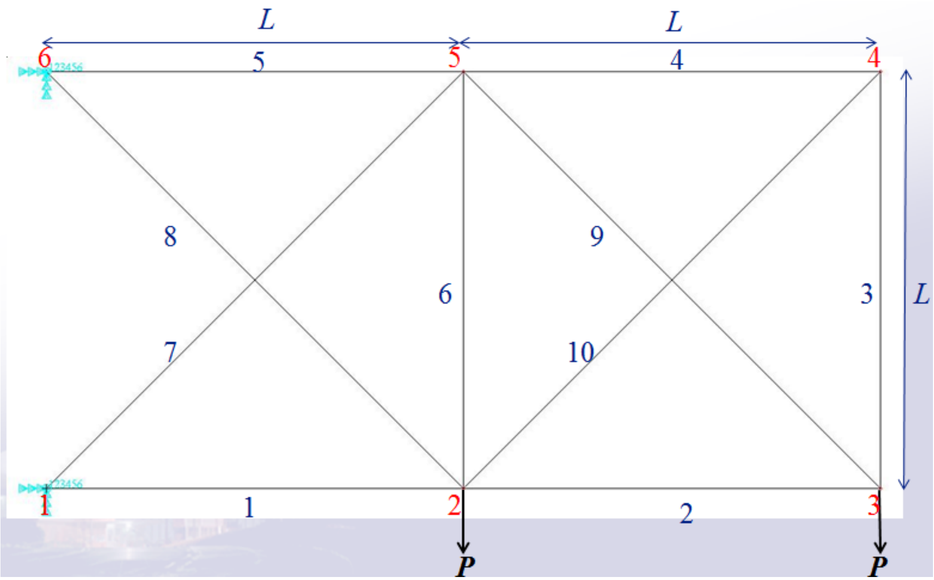
Initial (blue) and optimal shape (red)

Case 2: Design of a Ten-Bar Truss

- Objective:
  Minimize the weight of the truss
- Design Variables:
  Areas of the ten rod elements
- Constraints:

$$|\sigma_i| \le \sigma_{allow} \quad i = 1, 10$$

$$\delta_i \le \delta_{max} \quad i = 1, 2$$



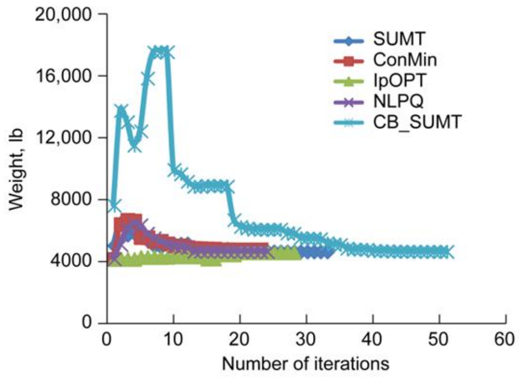
$L = 360$ inch
$P = 100$ kips
$E = 10$ Msi
$\rho = 0.1$ lb/in^3
$\sigma_{allow} = 25$ ksi
$\delta_{max} = 2$ inch

OpenMDAO Model Variables Specification

Variable Name	I/O Type	Data type; Description	Units	MDAO Type
bar_i_area, i = 1 to 10	input	Float; Cross-sectional area for bar_i	inch^2	Design variable
bar_i_stress, i = 1 to 10	output	Float; stress in bar_i	psi	Constraint
displacement1_y_dir	output	Float; displacement in y_direction, POINT ID:3	inch	Constraint
displacement2_y_dir	output	Float; displacement in y_direction, POINT ID:4	inch	Constraint
weight	output	Float; Weight of the structure; float	lbs	Objective

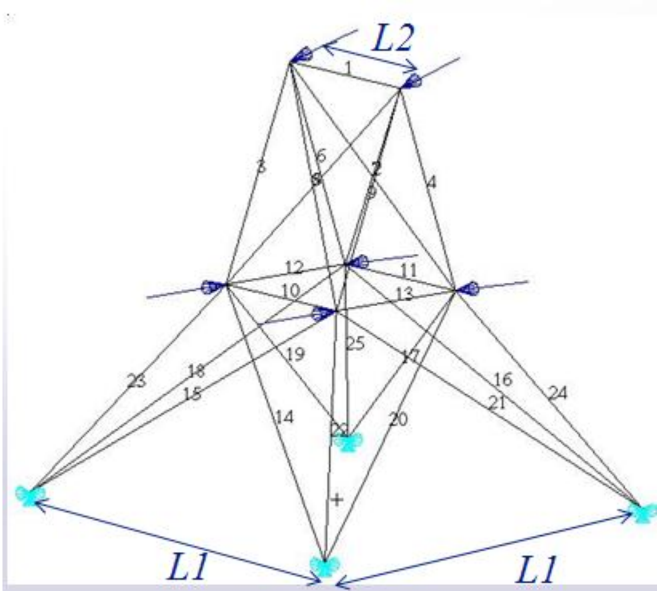
Ten-Bar Truss Results

Optimizers	Weight, lb	Design variables, sq. in.			Active constraints		CPU, min.
		Mean value	Variation		Stress	Disp.	
			Min.	Max.			
NEWSUMT	4677.48	11.15	0.10	25.22	2	1	92.36
CONMIN	4806.92	11.48	0.10	27.99	1	1	19.05
NLPQL	4673.89	11.13	0.10	26.06	2	1	27.0
Ipopt	4620.88	11.06	9.94	13.48	Infeasible	---	67.44
CometBoards (NEWSUMT)	4678.36	11.10	0.10	25.28	2	1	600.0



- Variation in solutions : Weight: -0.09% (NLPQL) to 2.7% (CONMIN)
- Design: Infeasible for Ipopt
- CPU time: CONMIN 32 times faster than CometBoards but heavier
- OpenMDAO NEWSUMT reduced solution time by a factor of 6.5
- Performance: Acceptable by 3 methods (NEWSUMT, CONMIN, NLPQL)

Case 3: Design of a 25-Bar Antenna Tower Truss



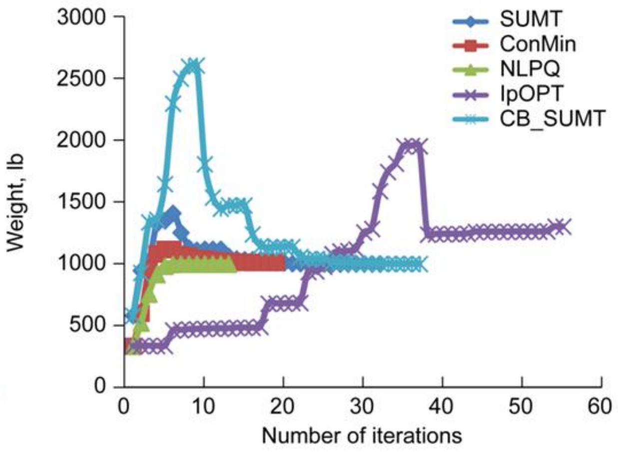
$L1 = 200$ inch
$L2 = 75$ inch
$E = 10$ Msi
$\rho = 0.1$ lb/in^3
$\sigma_{allow} = 40$ ksi
$\delta_{max} = \pm 0.35$ inch

- Objective:
  Minimize the weight of the truss
- Linked Design Variables:
  Areas of the 8 rod elements
- Constraints:
  8 stress and 2 nodal displacement constraints on element 1

Linking of the design variables		
Problem	Design variable	Members grouped
25-bar antenna tower (8LDV)	1	1
	2	2,3,4,5
	3	6,7,8,9
	4	10,11
	5	12,13
	6	14,15,16,17
	7	18,19,20,21
	8	22,23,24,25

Results of a 25-Bar Antenna Tower Truss

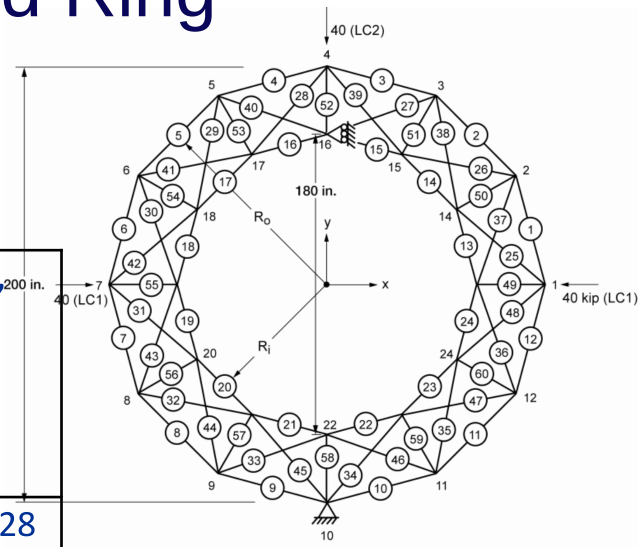
Problem	OpenMDAO Optimization Methods				CometBoards (NEWSUMT)
25-bar antenna tower Design variables: 8 LDV Constraints: 8S, 2D	NEWSUMT	CONMIN	NLPQL	Ipopt	
Optimal Weight, lb	998.194	1011.804	998.084	1301.144	998.482
Optimal Design (in²):	0.3015 2.8265 5.4753 1.8049 0.1119 2.9120 2.9482 3.0179	0.6688 3.2492 5.2978 1.9988 0.7026 2.8756 2.7997 2.9805	0.3070 2.8287 5.4726 1.8091 0.1199 2.9104 2.9450 3.0182	1.3877 6.4425 4.9730 5.2028 1.5624 3.3168 3.2615 3.0693	0.2992 2.8280 5.4766 1.8136 0.1175 2.9109 2.9477 3.0194
Active Constraints **S:Stress; D:Displacement**	5S	5S	5S	Infeasible	6S
Number of Iterations	32	17	13	58	37
CPU time (mins)	62.718	12.337	26.9	133.731	397.0



- Variation in solutions : Weight: -0.04% (NLPQL) to 1.33% (CONMIN)
- Design: Infeasible for Ipopt
- CPU time: CONMIN was 32 times faster than CometBoards but heavier
- OpenMDAO NEWSUMT reduced solution time by a factor of 6
- Performance: Acceptable by 3 methods (NEWSUMT, CONMIN, NLPQL)

Case 4: Sixty-Bar Trussed Ring

- Objective: Minimize the weight of the truss
- The 60 areas were linked into 25 variables
- 25 stress and 24 displacement constraints



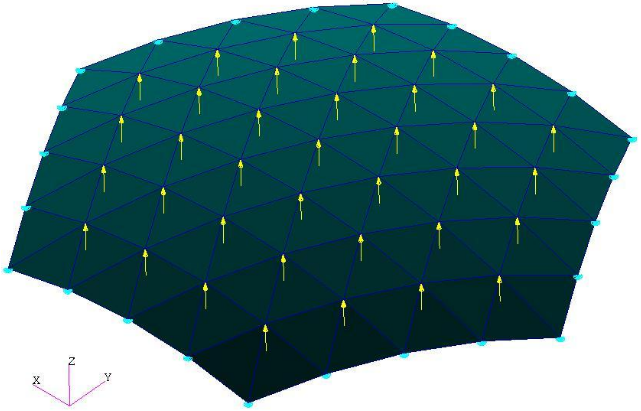
Optimizers	Weight, lbs	Design variables, sq. in.			Active constraints		CPU, min.
		Mean value	Variation		Stress	Disp.	
			Min.	Max.			
NEWSUMT	308.62	1.24	0.5	2.03	12	1	123.28
CONMIN	312.75	1.21	0.5	2.02	1	1	43.93
NLPQL	308.55	1.24	0.5	2.03	12	1	59.0
Ipopt	340.02	1.36	0.55	2.23	1	1	764.67
CometBoards (NEWSUMT)	308.67	1.24	0.5	2.03	12	1	810.0

$R_i = 90$ inch
$R_o = 100$ inch
$E = 10$ Msi
$\rho = 0.1$ lb/in^3

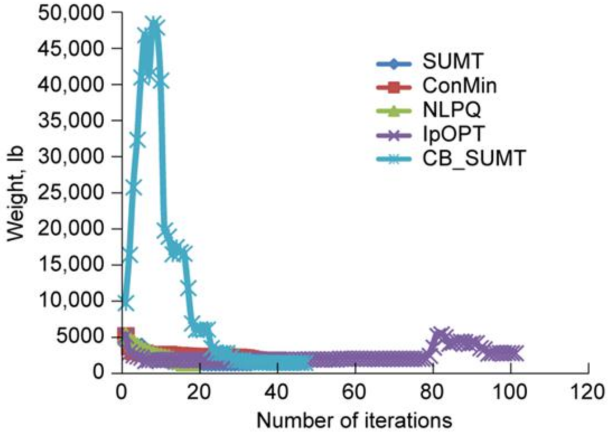
- Variation in weight about 10% (Ipopt)
- CONMIN least CPU but heavier and fewer number of active constraints
- OpenMDAO NEWSUMT reduced solution time by a factor of 6.5
- Performance: Acceptable by all methods

Case 5: Optimization of a Membrane Structure (Geodesic Dome)

Problem	OpenMDAO Optimization Methods				CometBoards (NEWSUMT)
Geodesic dome Design variables: 12LDV Constraints: 252S, 1D	NEWSUMT	CONMIN	NLPQL	Ipopt	
Optimal Weight, lb	1539.597	1929.653	1539.517	2229.409	1540.02
Optimal Design (in^2):	0.3015 2.8265 5.4753 1.8049 0.1119 2.9120 2.9482 3.0179	0.6688 3.2492 5.2978 1.9988 0.7026 2.8756 2.7997 2.9805	0.3070 2.8287 5.4726 1.8091 0.1199 2.9104 2.9450 3.0182	1.3877 6.4425 4.9730 5.2028 1.5624 3.3168 3.2615 3.0693	0.2992 2.8280 5.4766 1.8136 0.1175 2.9109 2.9477 3.0194
Active Constraints	120 S	Infeasible	119 S	Infeasible	120 S
Iterations	33	38	17	111	48
CPU time (mins)	79.753	39.315	26.0	390.488	643.0



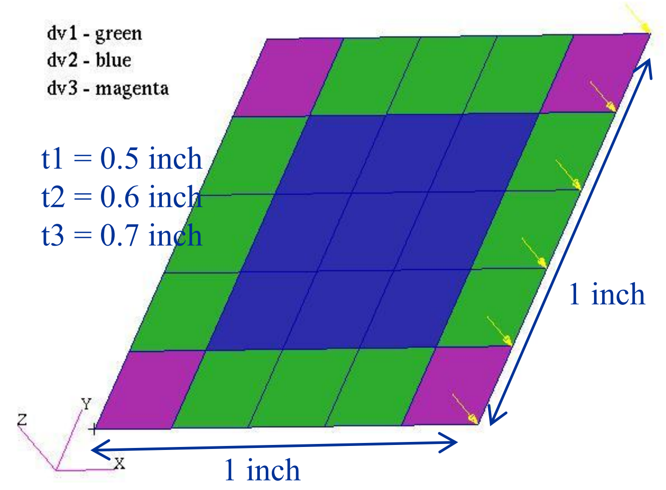
D = 240 inch; H = 30 inch; P = 925 kip
Bars = 156; Triangular = 96



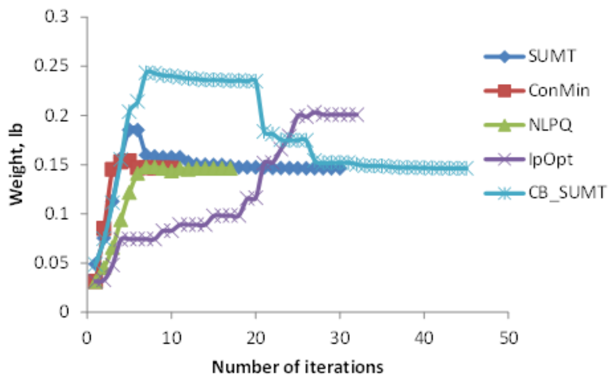
- Variation in solutions : Weight: -0.02% (NLPQL)
- Design: Infeasible for CONMIN & Ipopt
- CPU time: NLPQL 26 times faster than CometBoards and lighter design
- OpenMDAO NEWSUMT reduced solution time by a factor of 8

Case 6: Optimization of a Composite Plate with Strain and Displacement Constraints

Problem	OpenMDAO Optimization Methods				
Composite plate Design variables: 3LDV Constraints: 3Strain, 1D	**NEWSUMT**	**CONMIN**	**NLPQL**	**Ipopt**	**CometBoards (NEWSUMT)**
Optimal Weight, lb	0.146	0.146	0.146	0.201	0.146
Optimal Design, (in³):	2.6829 2.4288 3.0934	2.7137 2.4066 3.0920	2.6782 2.4332 3.0921	4.6486 3.1416 1.7898	2.6819 2.4308 3.0935
Active Constraints	3Strain, 1D	3Strain, 1D	3Strain, 1D	Infeasible	3Strain, 1D
Iterations	30	8	16	36	45
CPU time (mins)	51.49	2.74	15.0	35.72	193.0



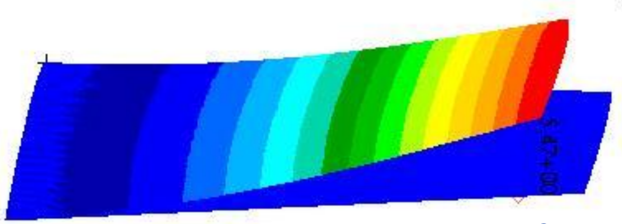
Ply lay-up: [0/-45/45/0]
Material: graphite/epoxy tape
$\varepsilon_{allow} = 4x10^{-3}\mu s$
$\delta_{max} = \pm 0.04$ inch



- Variation in solutions
  - Weight: no variation
  - Design: Infeasible for Ipopt
- CONMIN faster convergence by 98%
- Performance acceptable by 3 methods

Case 7: Minimize the Weight of a Ceramic Matrix Composite Blade

CQUD4= 25,945; Nodes = 26,026; DOF = 129,330; RPM = 8490

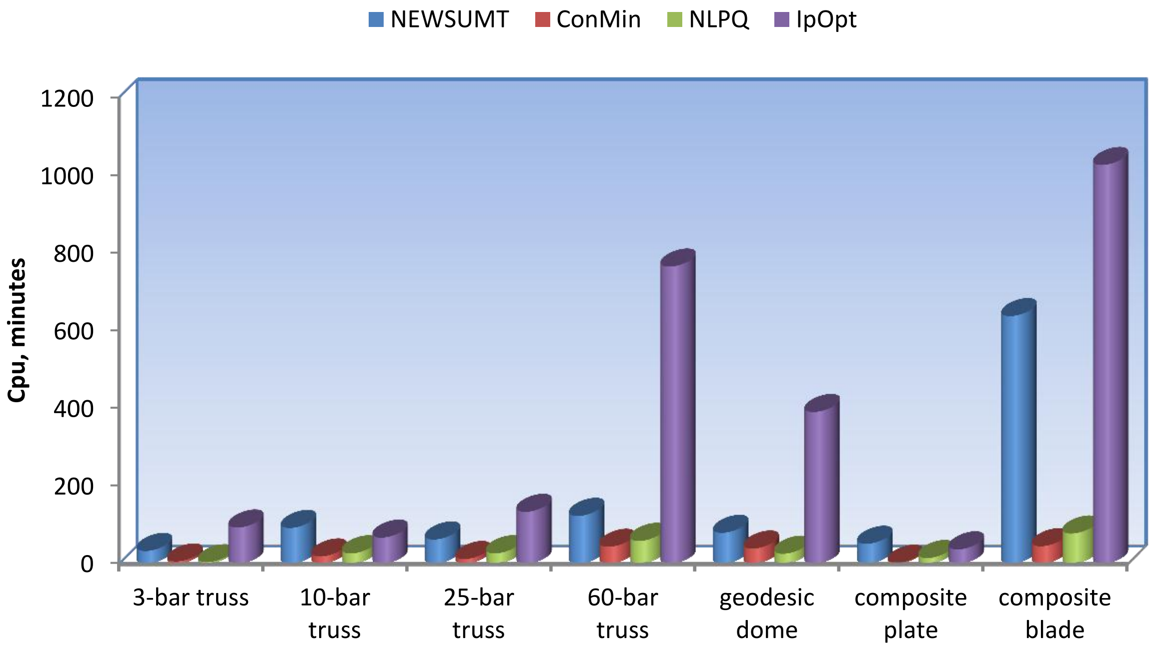


Fundamental mode shape on the deformed mesh

Design	Weight (lbs.)	Fund. Freq. (Hz)	dv1(in^3.) cap	dv2 (in^3.) wall	Iter	CPU (min)
Initial	0.123	13.48	0.5	0.03		
NEWSUMT	0.037	15.98	0.01	0.01	36	637.2
CONMIN	0.037	15.98	0.01	0.01	5	45.26
NLPQL	0.037	15.97	0.01	0.01	4	78.02
Ipopt	0.037	15.98	0.01	0.01	30	1026.26

- Increase of 18.5 % in the fundamental frequency is achieved while the weight is minimized by 70%

CPU Comparison for the Seven Cases



	NEWSUMT	CONMIN	NLPQL	Ipopt	CometBoards
Average (minutes/iteration)	4.5	2.0	4.1	7.4	11.2
Minimum	1.0	0.3	0.5	0.9	4.3
Maximum	17.7	9.1	19.5	34.2	21.3
Improvement factor	8.1	70.5	42.5	8.9	1.0

- Average solution time is in favor of CONMIN followed by NLPQL

Summary & Future Plans

- All four optimizations methods in OpenMDAO Framework produced acceptable solutions with some variation which may be due to the setting of the parameters and control options of the optimizers
- Overall, variation of weight was modest for all methods. Number of Active constraints was almost identical for NEWSUMT and NLPQL, but Ipopt produced infeasible designs for 4 problems
- Computing time of OpenMDAO optimizers was improved drastically by up to 87% difference in CPU time for NEWSUMT for the geodesic dome and 96% for NLPQL. Overall, OpenMDAO NEWSUMT reduced solution time by a factor of 8
- Future plans: Use OpenMDAO Framework for Stochastic Analysis of the MMSEV (Multi Mission Space Exploration Vehicle)


QUESTIONS?