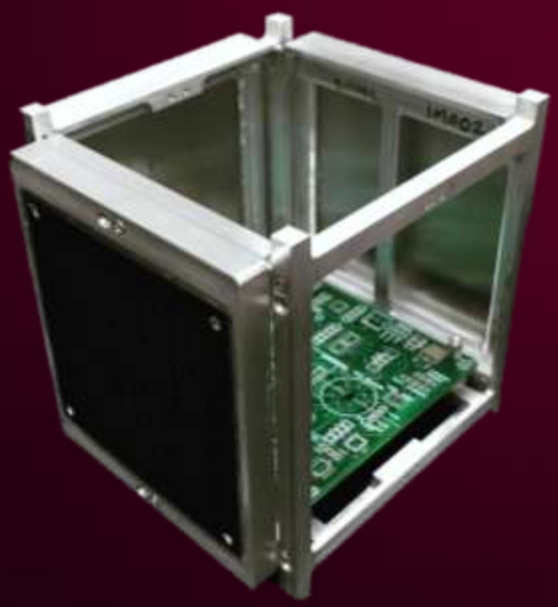
Dwight Look College of ENGINEERING TEXAS A&M UNIVERSITY

Mechanical Design and Optimization of a Standardized Cubesat



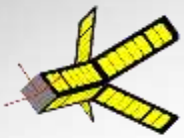
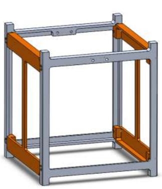
A Thesis by
David Malawey
2016.02.23

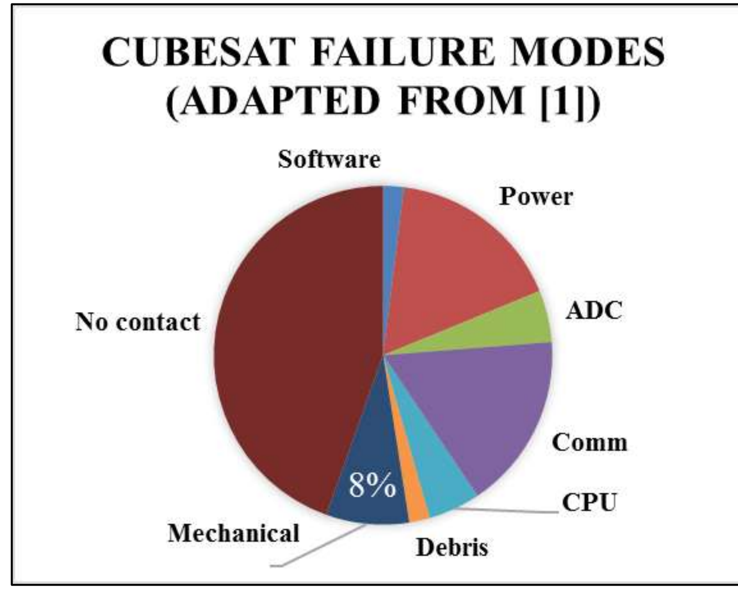
Outline

1. Background and Research Objectives
2. Multidisciplinary Optimization
   - Problem Setup
   - Sensitivity, Pareto Front
3. Mechanical Design and Prototyping
   - Design for Manufacturability
   - Finite Element Analysis
4. Results, Lessons, Suggestions
   - Machining results
   - MDO results
   - Overall Contributions
5. Questions & Extras

Term	Meaning
Power	electrical power
Batt	Batteries
Panel	solar panel
X_n	design variable
X^*	Optimal design at hand
P_n	Parameter
g(X,P)	Constraint function
J(X,P)	Objective function

Background

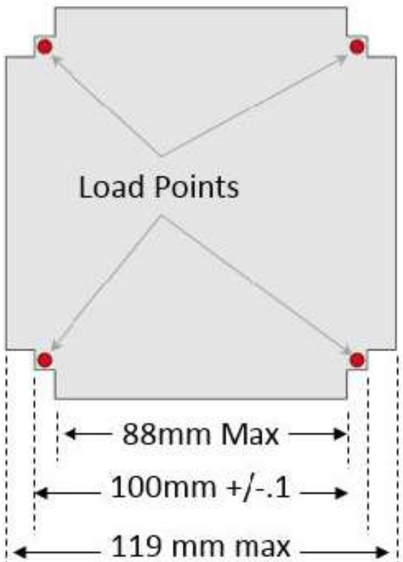
- MDO for Cubesats
  - “*Large Scale MDO of a Small Satellite…*” [1]
    
    - Maximizes power gen, data transmit
    - Extensive (attitude, communication, power)
    - Configuration of Existing satellite
  - “*Uncertainty-Based MDO of Lunar Cubesat…*”[2]
    
    - Maximize capability for lunar mission
    - Payload, propulsion decided
  - *“…Propulsion for Earth-Escape Missions”* [3]
    
    - Novel Thruster Feasibility
    - ΔV Maneuvers
  - *“Mechanical Design and Optimization…”*
    
    - Cost effectiveness
    - Varying missions



Background

- CubeSat Prototypes
  - Full design envelope, CDS [2]
  - Sheet metal: high investment
  - Extrusion: low flexibility
  - intricate machining: expensive

1



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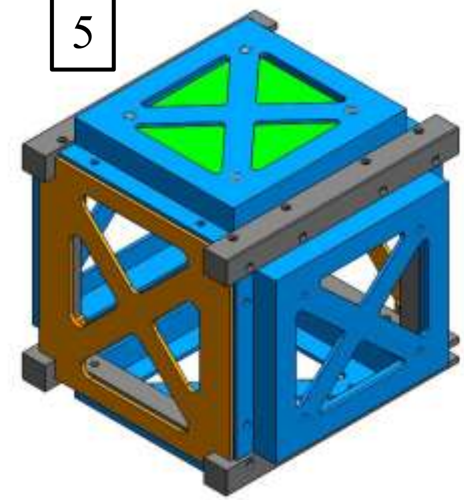
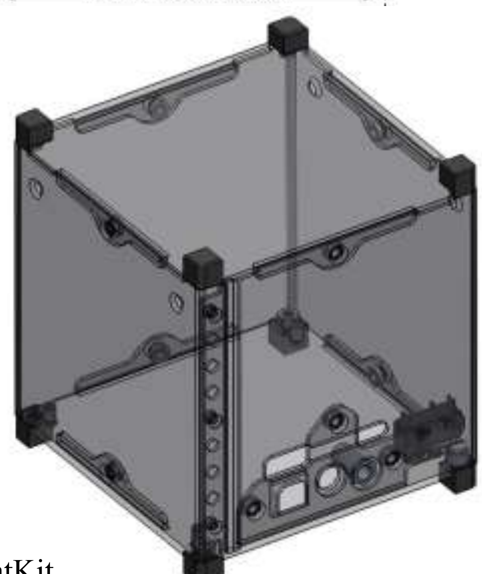


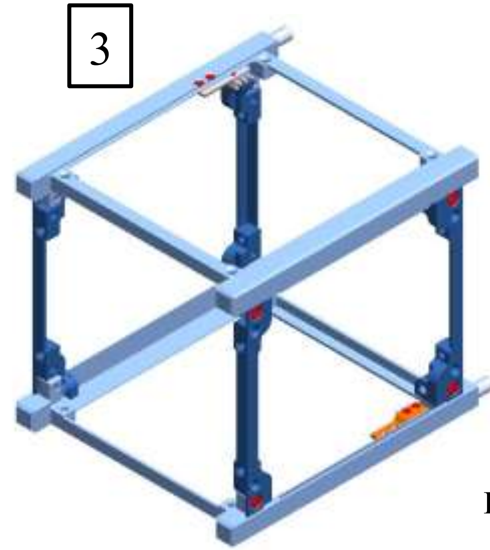
Unknown – Shared by NanoRacks

2



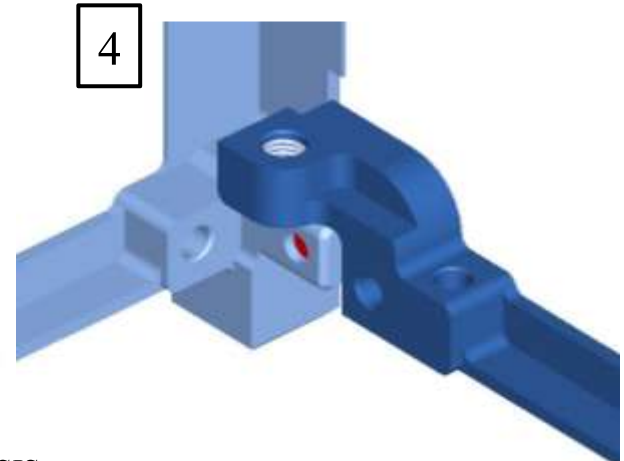
CubeSatKit

3



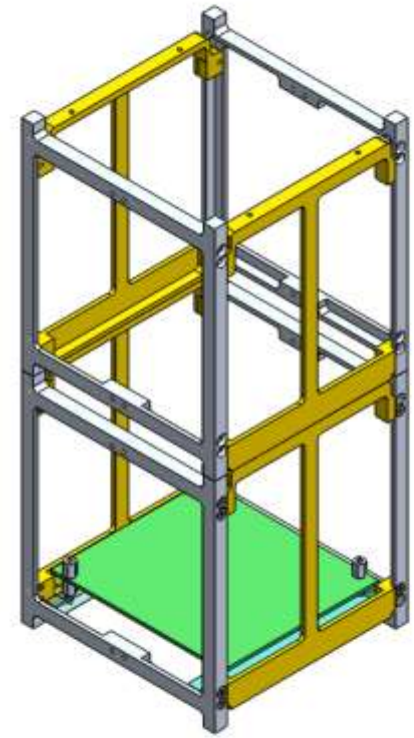
ISIS

4



Objectives of the research

- Maximize mission effectiveness, minimizing the mass of the critical functions.
- Optimize for cost effectiveness
  - Include commercial off-the-shelf components
- Maintain flexibility to reoptimize for different missions.
  - Take advantage of continuously growing body of data
  - Ability to expand to 3U, NU.
- Make a prototype that is fed by the optimizer and is designed for manufacturability
  - Make a CAD model and simple finite element analysis



2U configuration

Multidisciplinary Optimization

- Design Vector:
  - shown
- Objective function:
  - min. mass
  - min. cost
- Constraints (3)
  - Power demand is met by panels and batteries
  - Structure bending stiffness
  - Propellant is sufficient

Var	Description	Metric	Lower	Upper
X_1	Propellant type	Gas type	1	9
X_2	Thruster type	Model	1	3
X_3	Structure material	Material	1	3
X_4	Solar panels	Qty	0	4
X_5	Batteries	Qty	1	Inf.
X_6	Structure rail width	(mm)	3	20

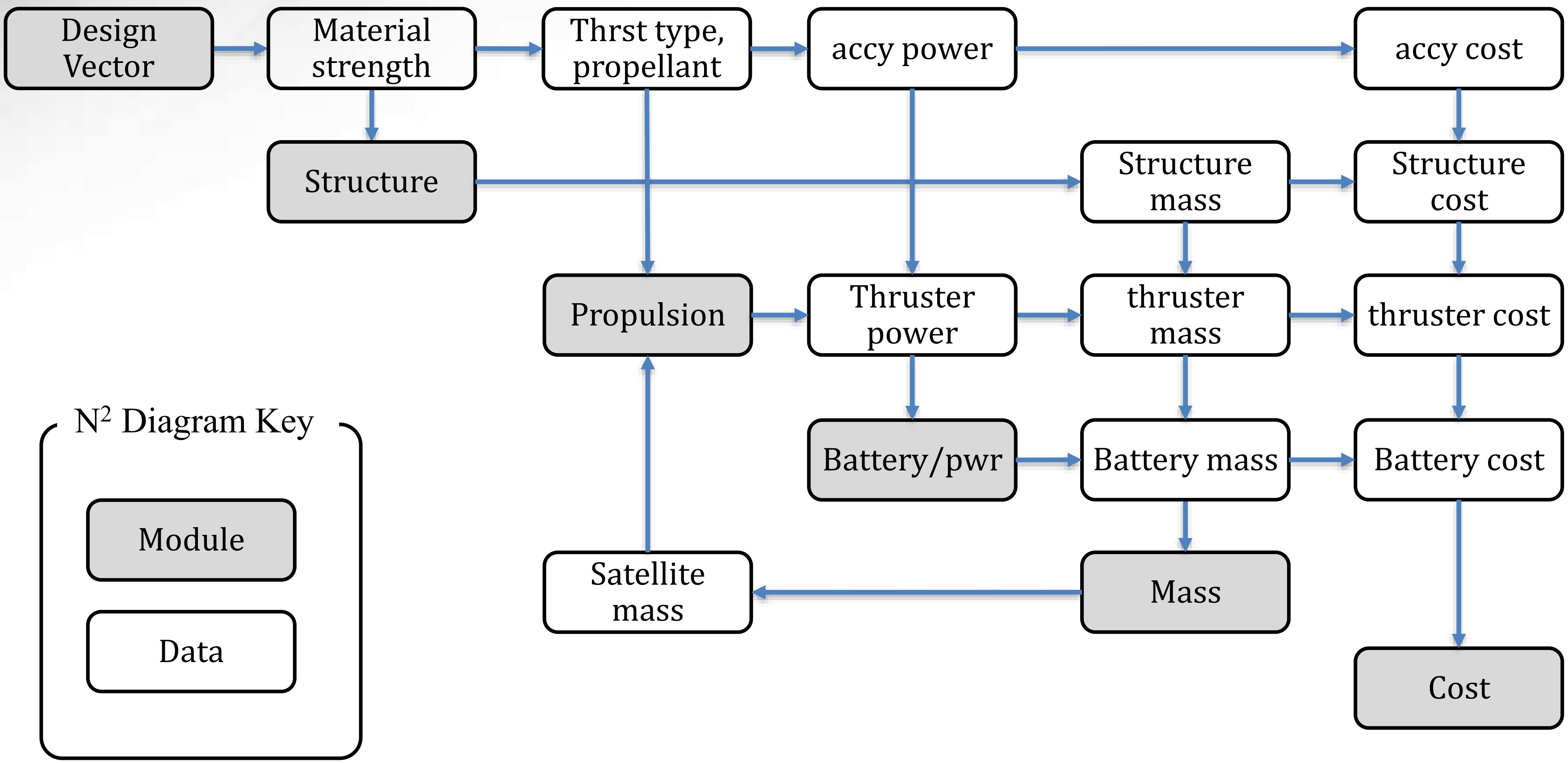
Power Constraint

$$\sum_{1}^{n}(I_n v_n D_n * 24P_1) - (X_5 v_b P_7 + X_6 P_3 P_8 * 24P_1) = 0$$

I_n= current
v_n= voltage
D_n= duty cycle
P_1= mission duration
n = no. devices

v_b= batt voltage
P_7= batt capacity (Ah)
P_3= panel power rating
P_8= sunlight ratio

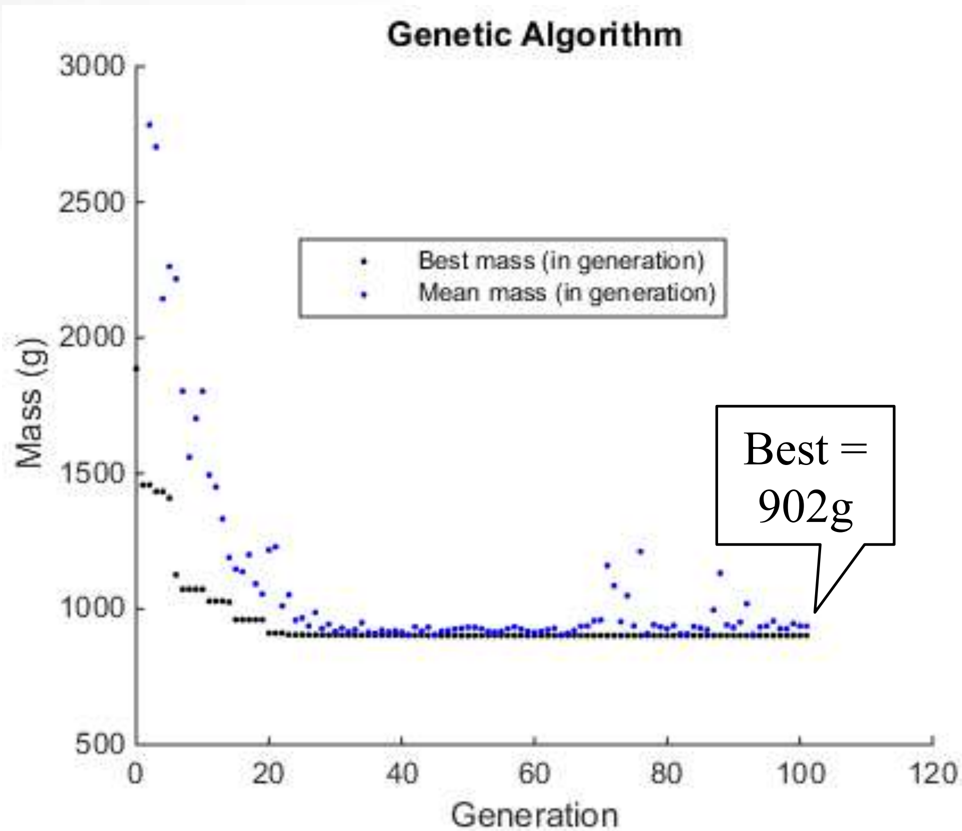
Multidisciplinary Optimization

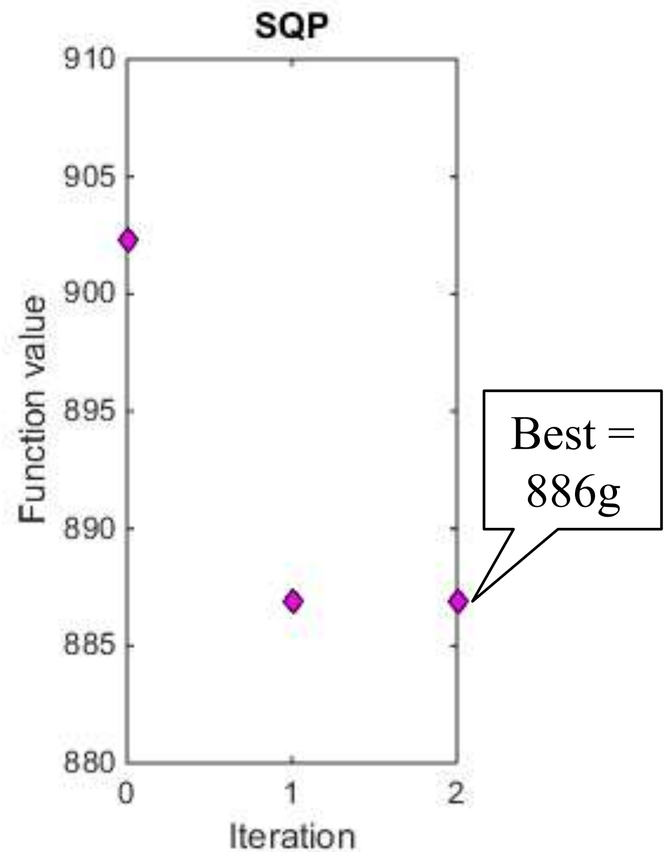


Multidisciplinary Optimization

- Novel "Heuristic + Gradient" combination
    - GA resolves all 6 variables
    - SQP refines 3 continuous variables
    - Fairly repeatable

$$\begin{aligned} &\min && J(X,P) = [mass(X,P)] \\ &s.t. && g(X,P) \leq 0 \\ &&& x_{L.Bound,i} \leq x_i \leq x_{U.Bound,i} \end{aligned}$$

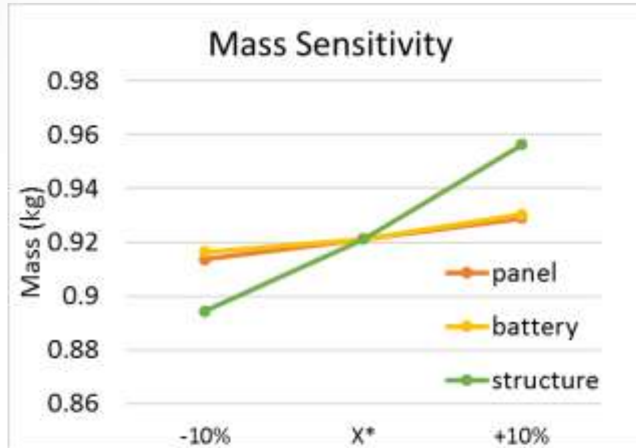




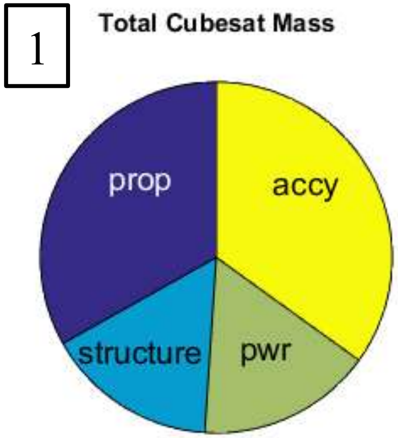
Multidisciplinary Optimization

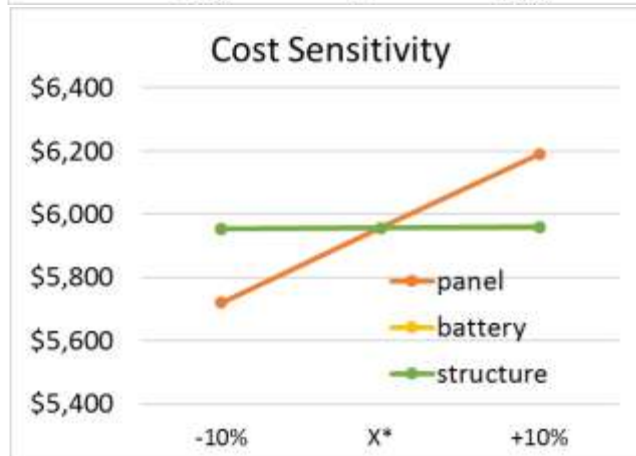
- Sensitivity Analysis
    - Sensitivity: continuous variables
    - Mass: subject to structure
    - Cost: subject to solar panels
- Also, Parameter Sensitivity

$$\text{Jacobean: } \frac{\%}{\%} = \begin{array}{c} \begin{array}{cc} \text{Mass} & \text{Cost} \end{array} \\ \begin{bmatrix} .084 & .395 \\ .075 & .003 \\ .336 & .006 \end{bmatrix} \end{array} \begin{array}{l} \\ \text{Panel} \\ \text{Batt} \\ \text{Struct.} \end{array}$$



1





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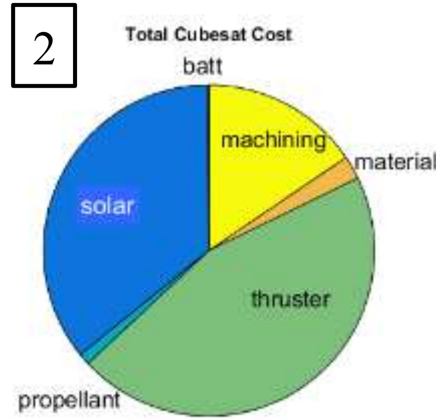
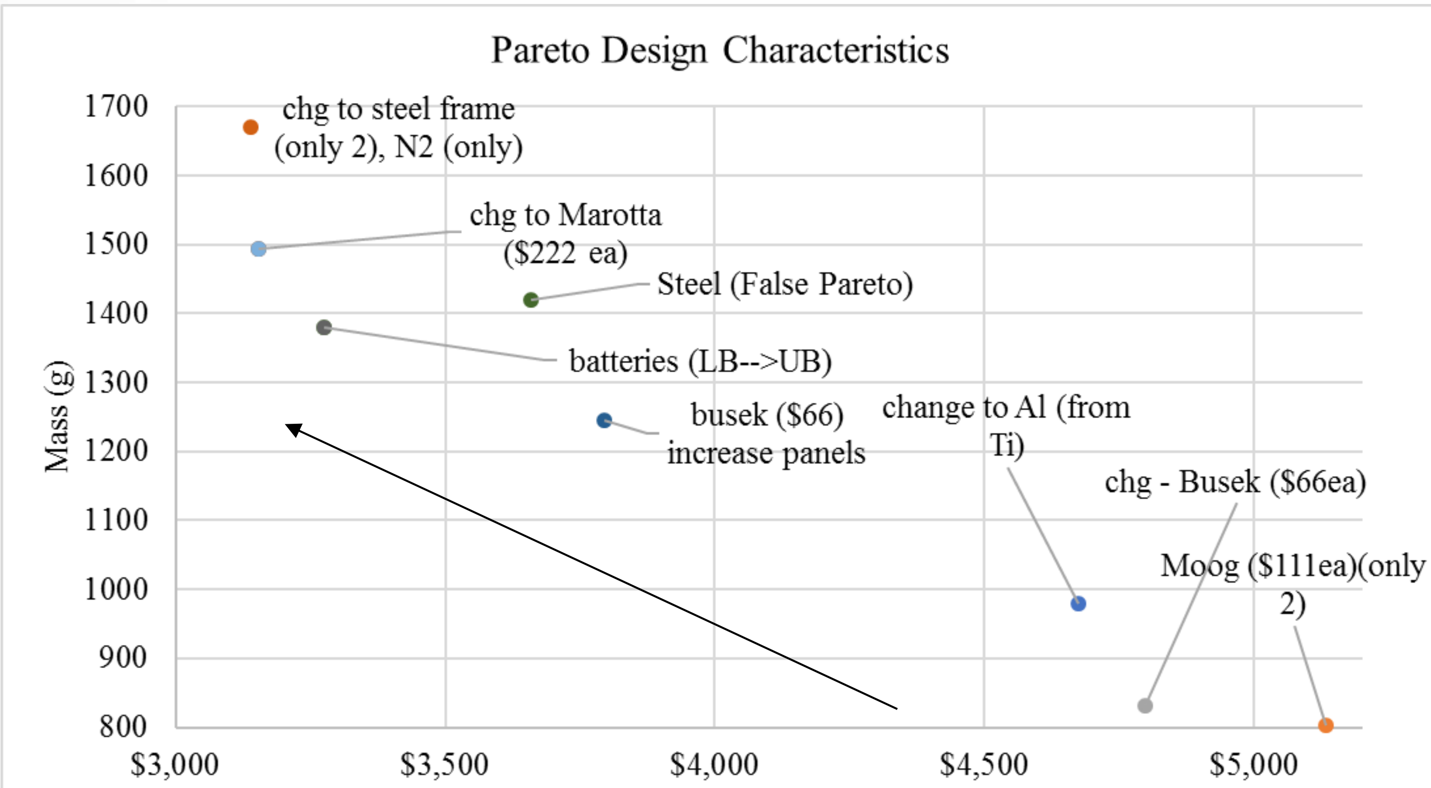


Multidisciplinary Optimization

- Pareto front
  - AWS – simplest method with 2-stage optimizer.
  - Difficulty with “bare” Pareto front
    - Increase lambda resolution
  - Investigate design decisions

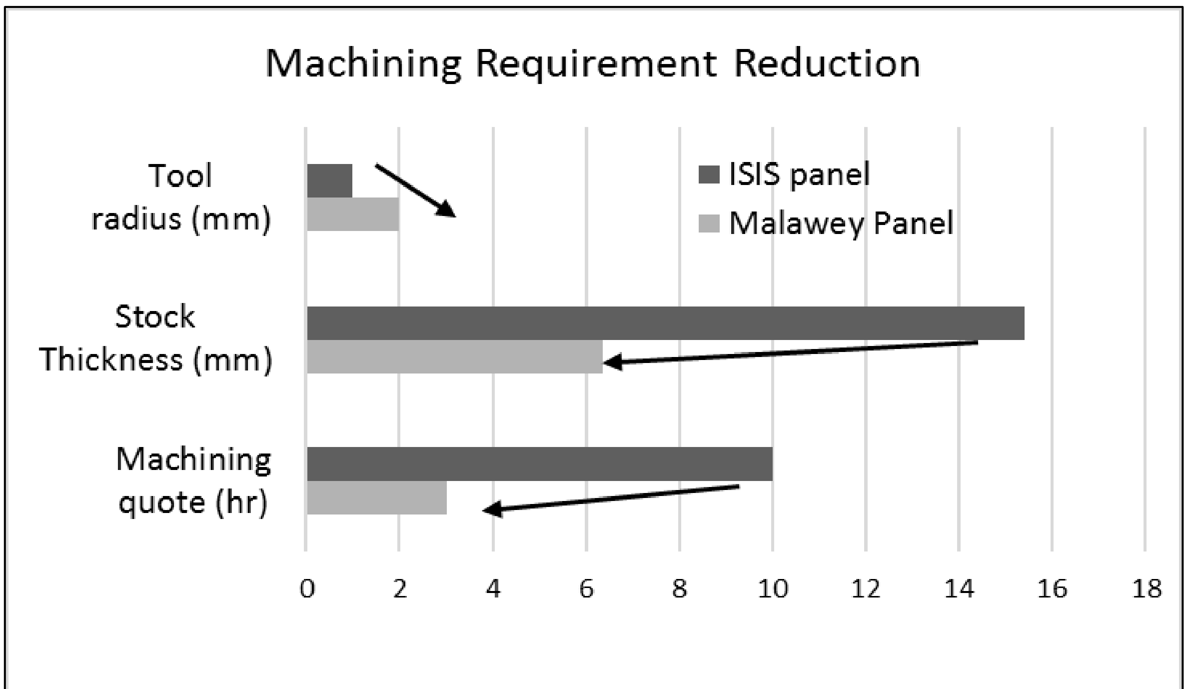
for i=1:N;
λ =(i/N)

$$J^* = cost(\lambda) + mass(1-\lambda)$$



Mechanical Design and Prototyping

- Begin with Benchmark
  - Reduce cost
  - Maintain function (mass, strength, features)
  - Make design fed by optimizer



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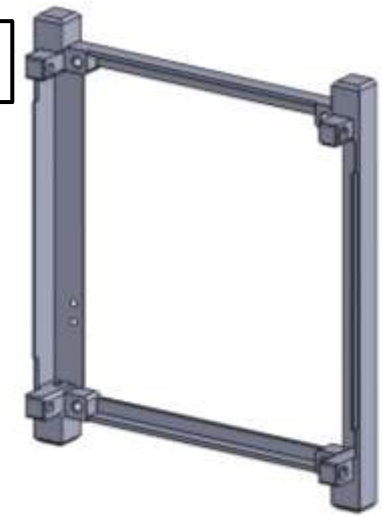

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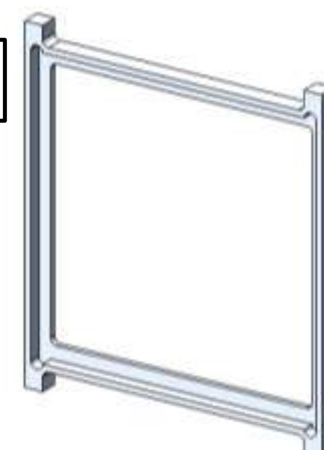
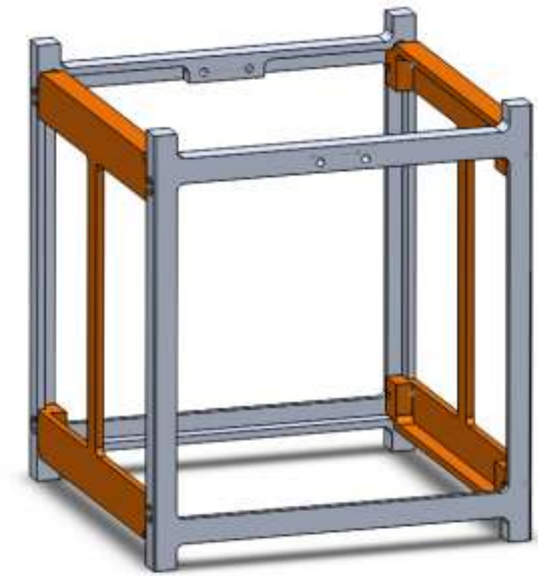
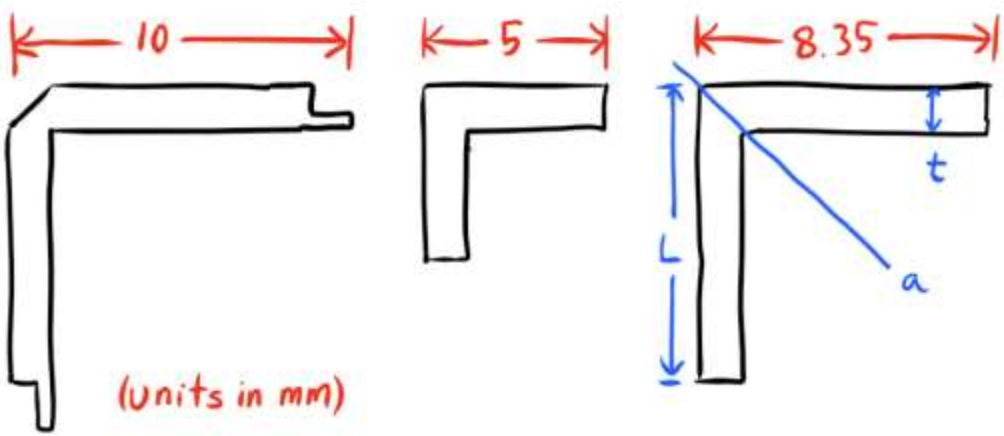


Mechanical Design and Prototyping

- Design takes results from the optimizer
- Bending stiffness constraint is met by adjusting length L
- Frame mass is proportional to x-sec area

1





Constraint

$$g_2(X,P) = EI_{x^*} - EI_{benchmark}$$

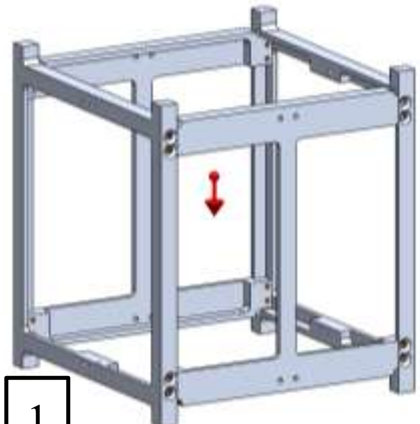
	ISIS1	ISIS2	DPM
$I_{a'}$ (mm^4)	61	10	78
I_a (mm^4)	239	35	270

Area Moment of Inertia

$$I_a = \frac{t(2L-t)(2L^2-2Lt+t^2)}{12}$$

Mechanical Design and Prototyping

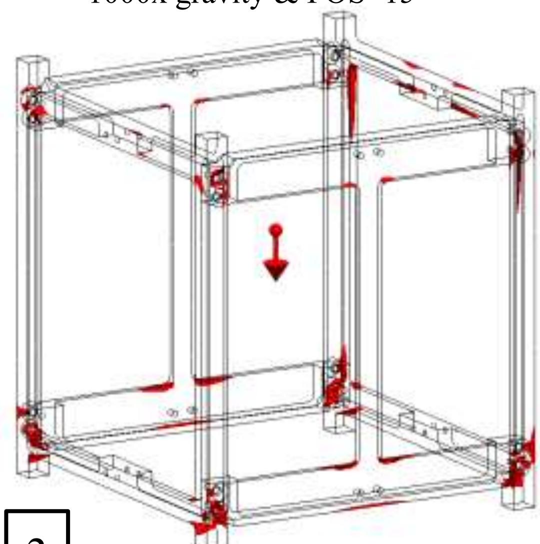
- Continue with Design
  - Build Models
  - Perform simple FEA
    - Consider: Moving from Benchmark to FEA as baseline.
    - Perform Convergence Study



1

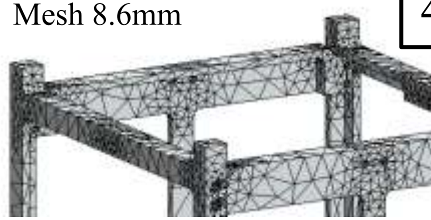
2

1000x gravity & FOS=15



3

Mesh 8.6mm

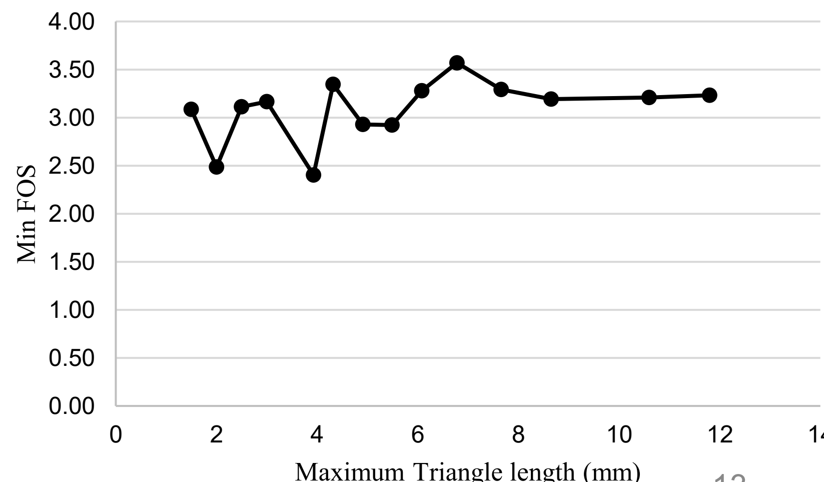


4

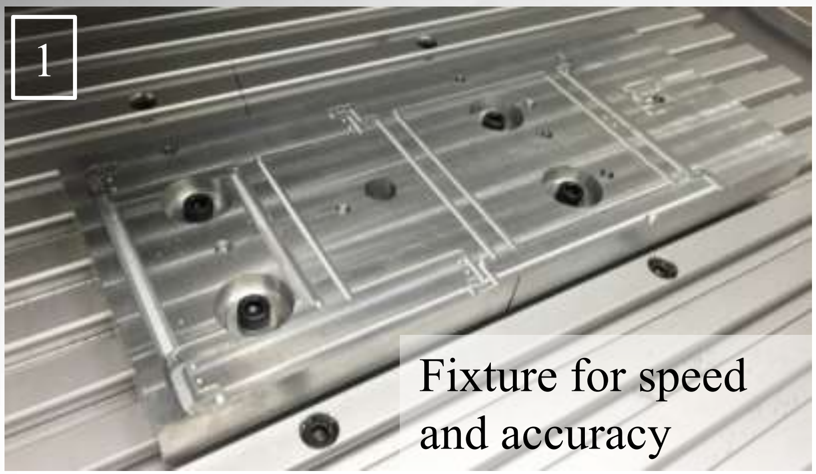
Mesh 1.5mm

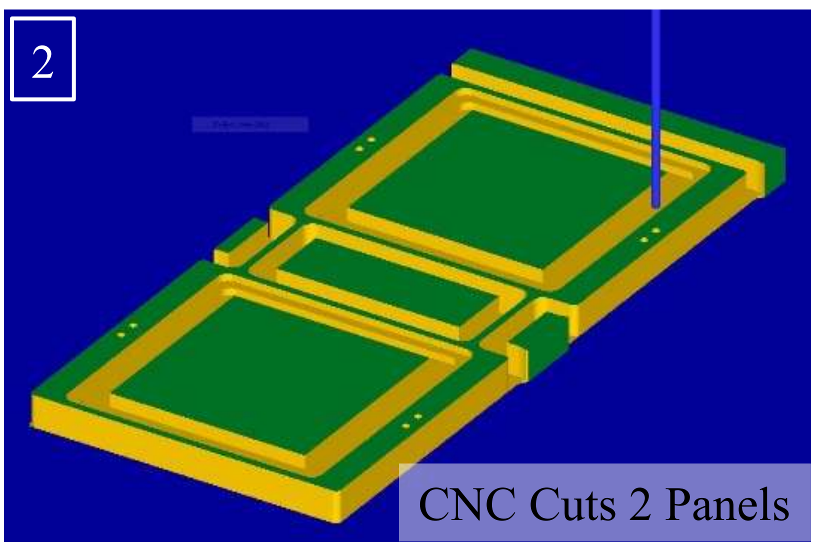
5

Factor of Safety (minimum)

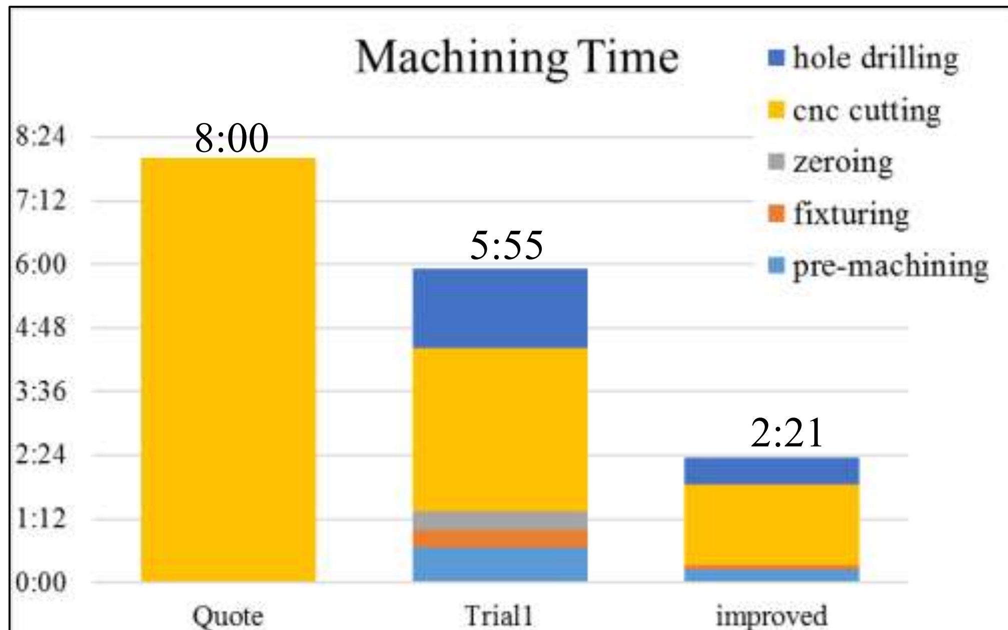


Prototyping Results

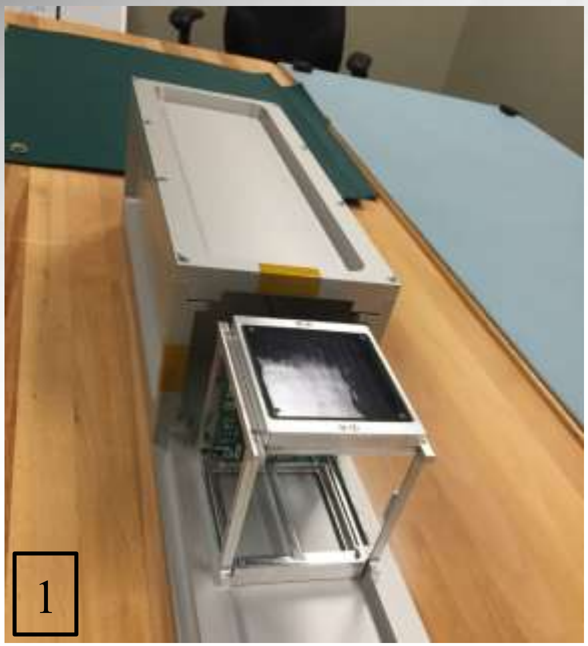




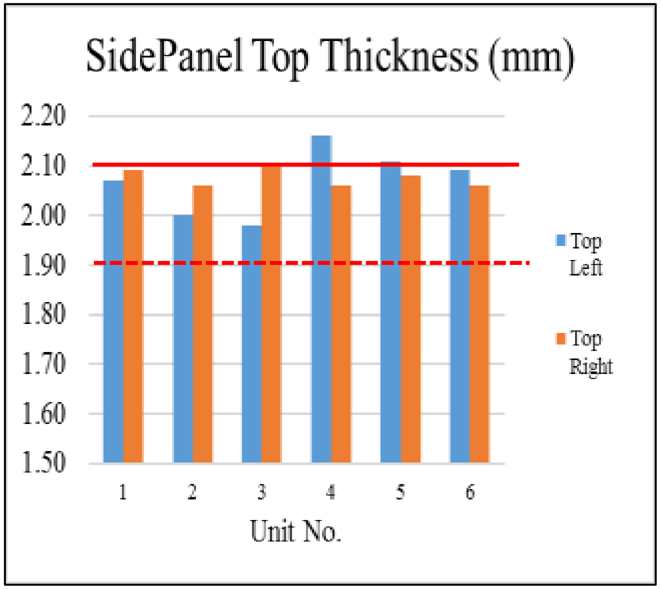
- Continue with prototyping
    - Meet the tolerances
    - Improve the speed by 62%
    - Find weaknesses in process
- Truly measure manufacturing time/cost

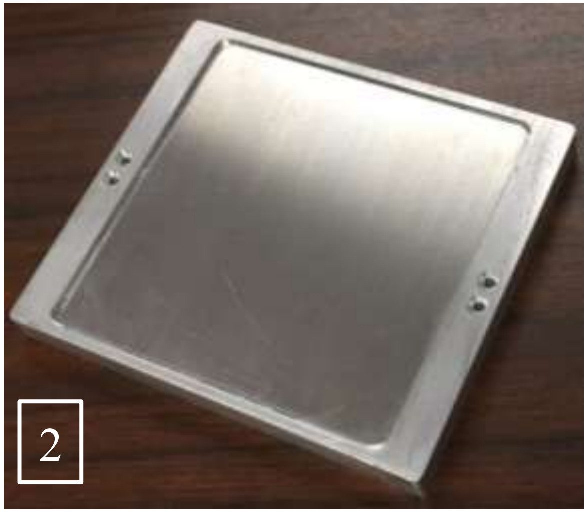


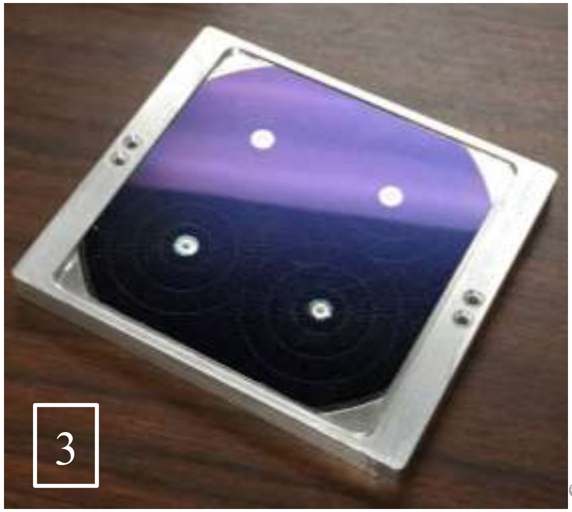
Mechanical Design and Prototyping

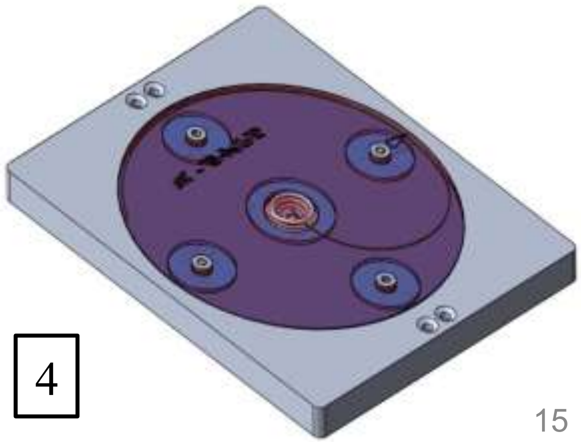


- Fitment into P-pod deployer
- Meeting tolerances
- Add modular components
  - Inert Fixed Panel
  - Solar Fixed Panel
  - Deployable Antenna FP



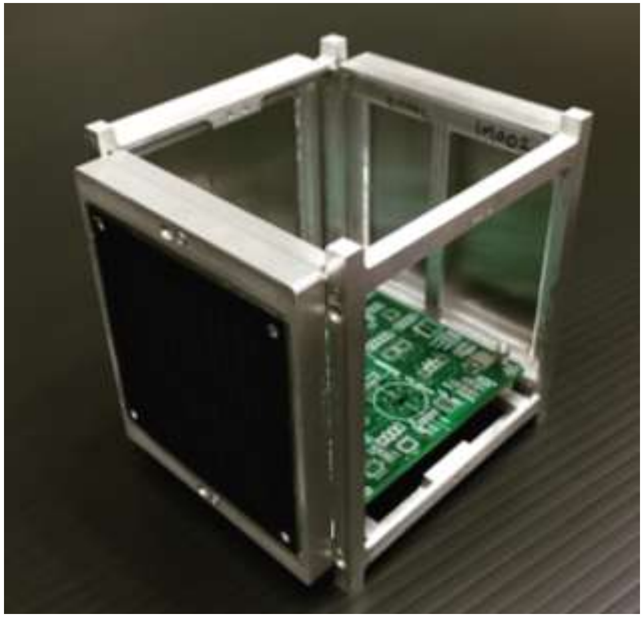


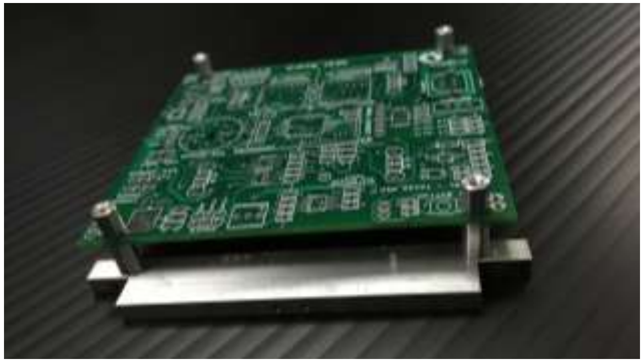




Conclusions

- Heuristic method is capable of optimizing a cubesat and is enhanced by a gradient-based function for continuous variables.
- More COTS subsystem data is required to make a truly usable
- Manufacturing cost can be lowered at least 50% from existing satellites while maintaining functionality.
  - (piece by piece evaluation)





Recommended Future Work

Future Item	Description
Validate X* Design with full prototype	Build a model with all subsystems. Determine feasibility and adjust parameters as needed.
Pareto Front – Add heuristic data	Populate the optimizer with more thruster designs and more metals to fabricate from. Add the option of using magnetorquers which have no cold gas and find the point of cost advantage
Add Multi-timescales	Ensure that the batteries are sufficient during high-draw period in shadow.
Details That Impact Performance	Account for heating requirements
Write CNC generating code	Find a way to generate G-code from the CAD model and integrate CAD model into optimizer.

References

[1] "CubeSat Design Specification (CDS)," California Polytechnic, San Luis Obispo, 2009.

[2] X. Hu, "Uncertainty-based Multidisciplinary Design Optimization of Lunar CubeSat Missions," University of Cambridge.

[3] S. Spangelo and B. Longmier, "Optimization of CubeSat System-Level Design and Propulsion Systems for Earth-Escape Missions," *Journal of Spacecraft and Rockets,* vol. 52, no. No.4, 2015.

[4] M. Swartwout, "The First One Hundred Cubesats: A Statistical Look," *Journal of Small Satellites,* pp. 213-233, 2013.

[5] J. T. Hwang, D. Y. Lee, J. W. Cutler and J. R. R. A. Martins, "Large-Scale MDO of a Small Satellite Using a Novel Framework for the Solution of Coupled Systems and their Derivatives," in *54th AIAA Structures, Structural Dynamics, and Materials Conference*, Boston, MA, 2013.

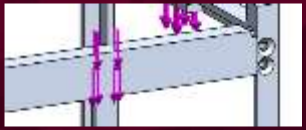
Questions or *Extras*?

- *Deployable antenna video* (youtube)

- *Propulsion Module Explained*

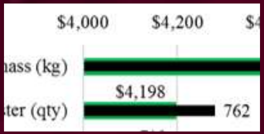
- *Prototype tolerance validation*

- *MDO Matlab code*
- *FEA with bearing stress*



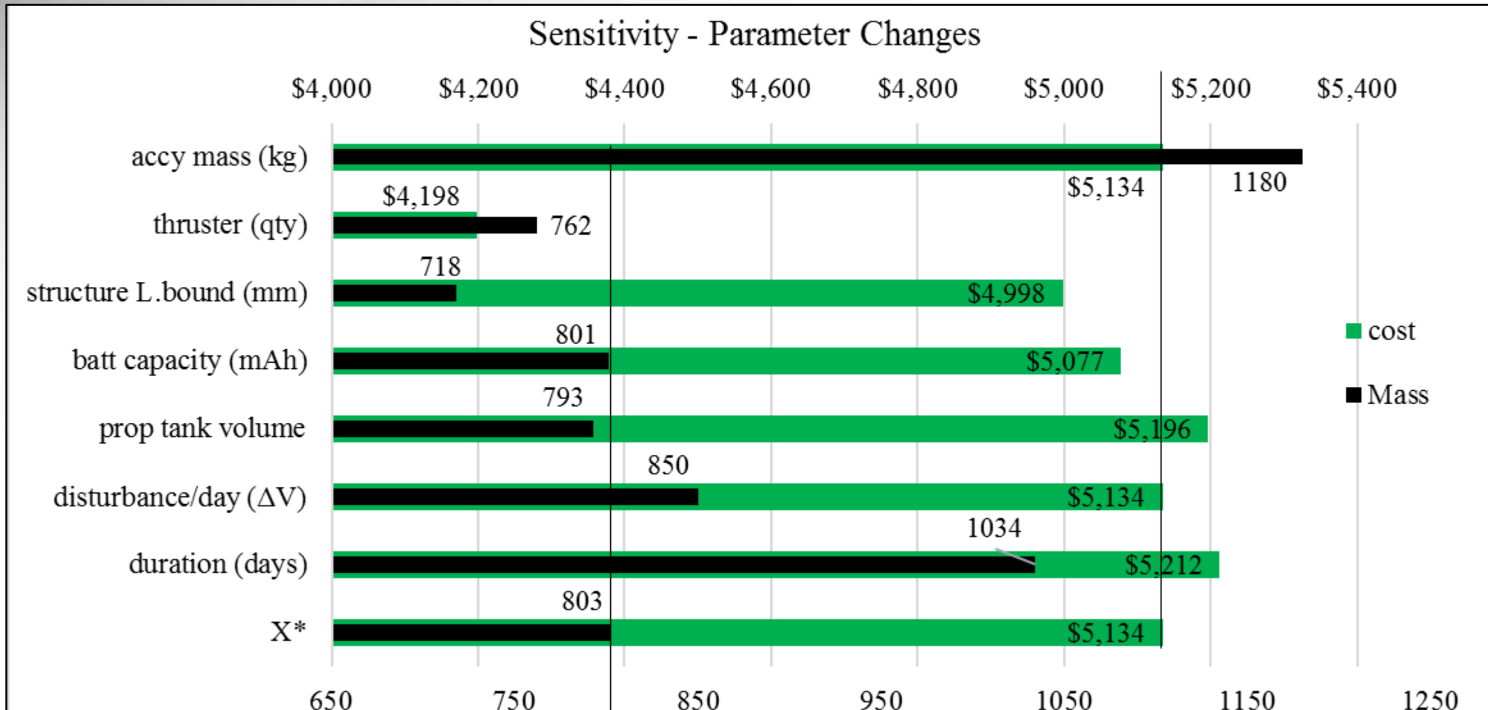
- *Pareto gradient misbehavior*

- *Sensitivity to parameters*



- *(give handout)*

Sensitivity to Parameters



Parameter	nominal	new	Effect
accy mass (kg)	0.33	0.66	mass increase only 337g
thruster (qty)	4	2	change from Moog (9g,1.0W) to Busek (17g,0.89W)
struct L.bound (mm)	3	1	1.66mm A36 steel
batt capacity (mAh)	3400	5000	from 2.39 --> 2.35 panels
prop tank volume	16.3	30	Xenon 1 tank
disturbance/day (ΔV)	0.5	0.75	30g Freon + 2tank, 43g Freon +3tank
duration (days)	30	60	58g prop + 4 tank, pwr cons increase to 746 but made by solar
X*	-	-	freon, titanium, Moog1W

Propulsion Module

- Impulse required (N·s) is a product of the required change in velocity and mass of satellite. When a propellant is selected, the specific impulse (units=seconds) of that propellant is used to determine the mass of that propellant required to achieve the Δv.
- Specific impulse roughly means the force (N) exerted by expelling a unit weight of propellant per second (N/s)
- The volume of the propellant is found using the density at which that cold gas might be stored.

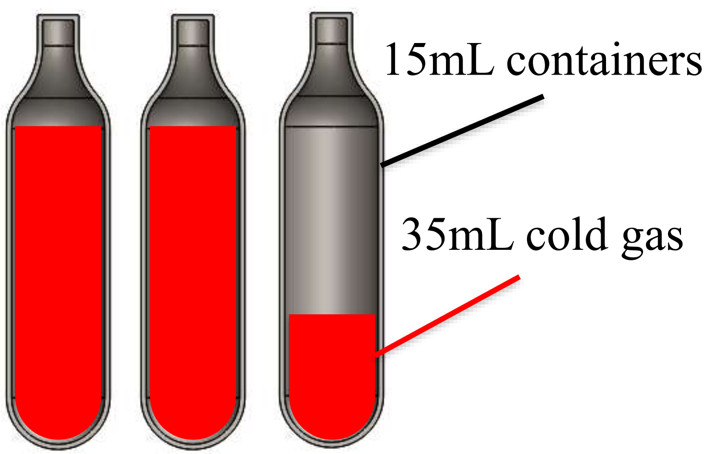
$$\Delta v_{required} = \Delta v_{initial} + P_9 P_1$$

$$m_{propellant} = \frac{I_{req}}{(I_{sp} * g)}$$

$$I_{req} = \Delta v_{req} m$$

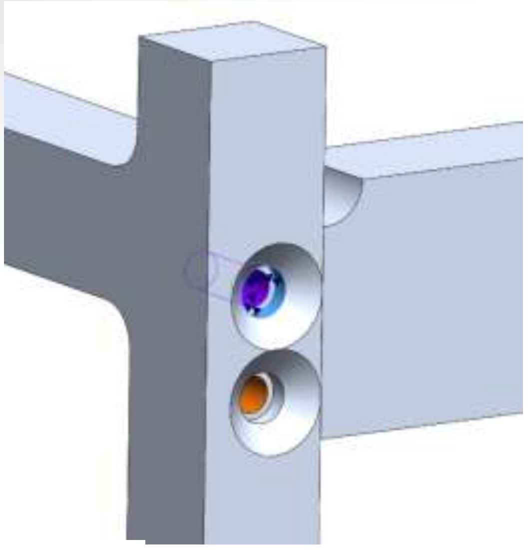
P_9= disturbance per day
P_1= mission duration
g = gravity
I_{sp}= specific impulse of propellant

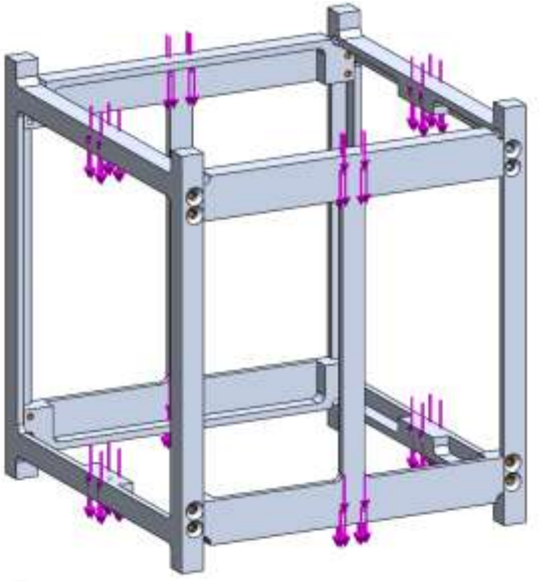
Propellant	Density (3500 psia, 0C) (g/cm3)	Specific Impulse (s)	Cost($/kg)
Hydrogen	0.02	296	120
Helium	0.04	179	52
Neon	0.19	82	330
Nitrogen	0.28	80	4
Argon	0.44	57	5
Krypton	1.08	39	330
Xenon	2.74	31	1200
Freon 14	0.96	55	10
Methane	0.19	114	10
Ammonia	0.88	105	10

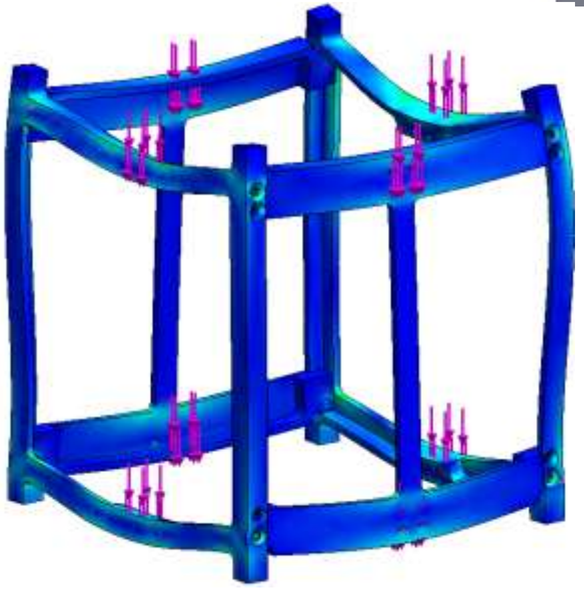


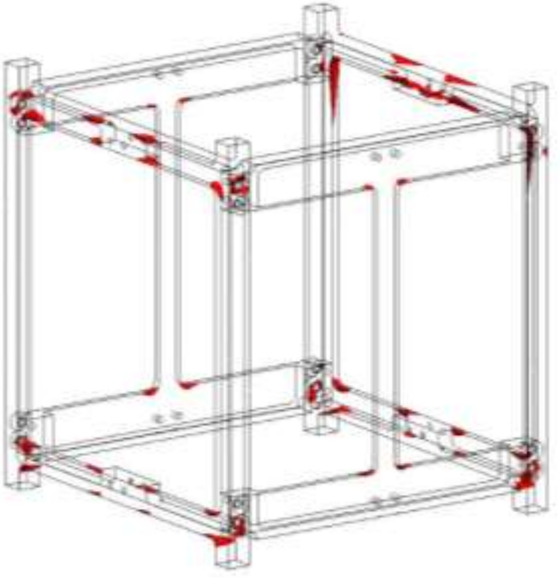
FEA – Bearing Stress

- 45lb load total
- yields a minimum factor of safety of 3.9 in all regions of the material

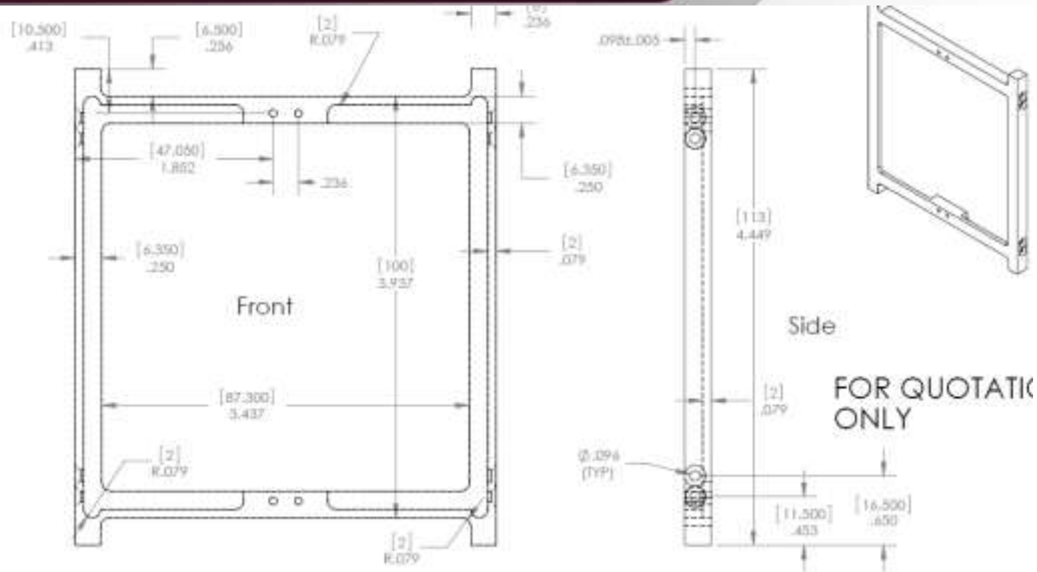


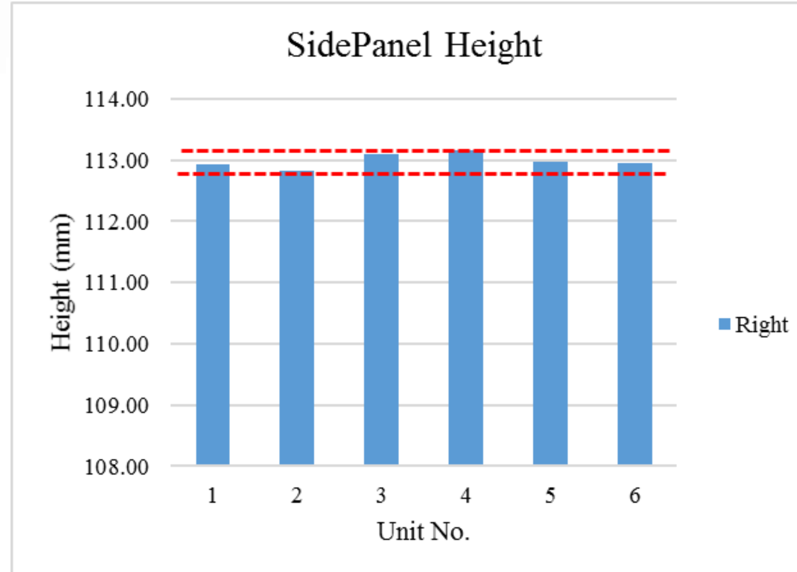


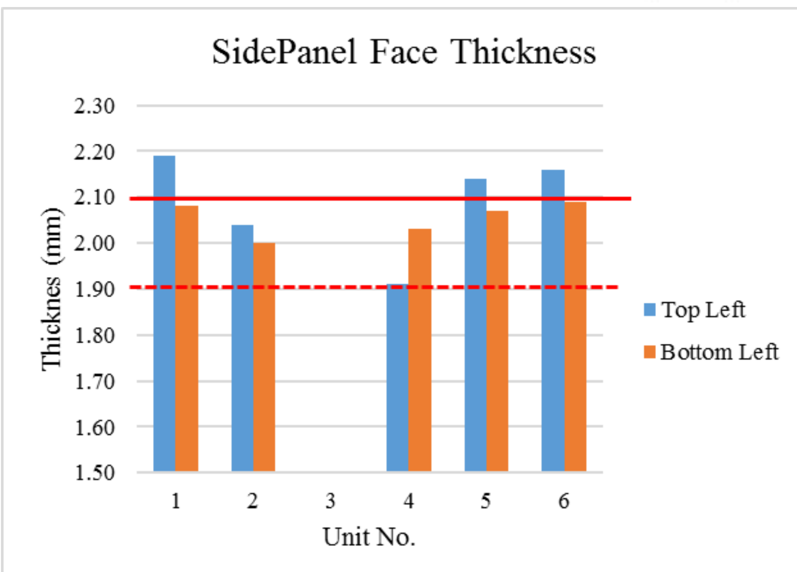


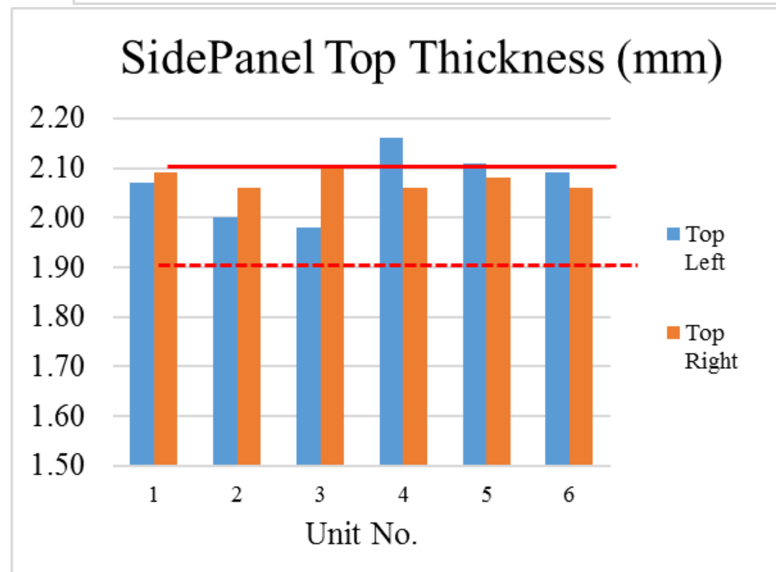


Prototype Tolerance Validation



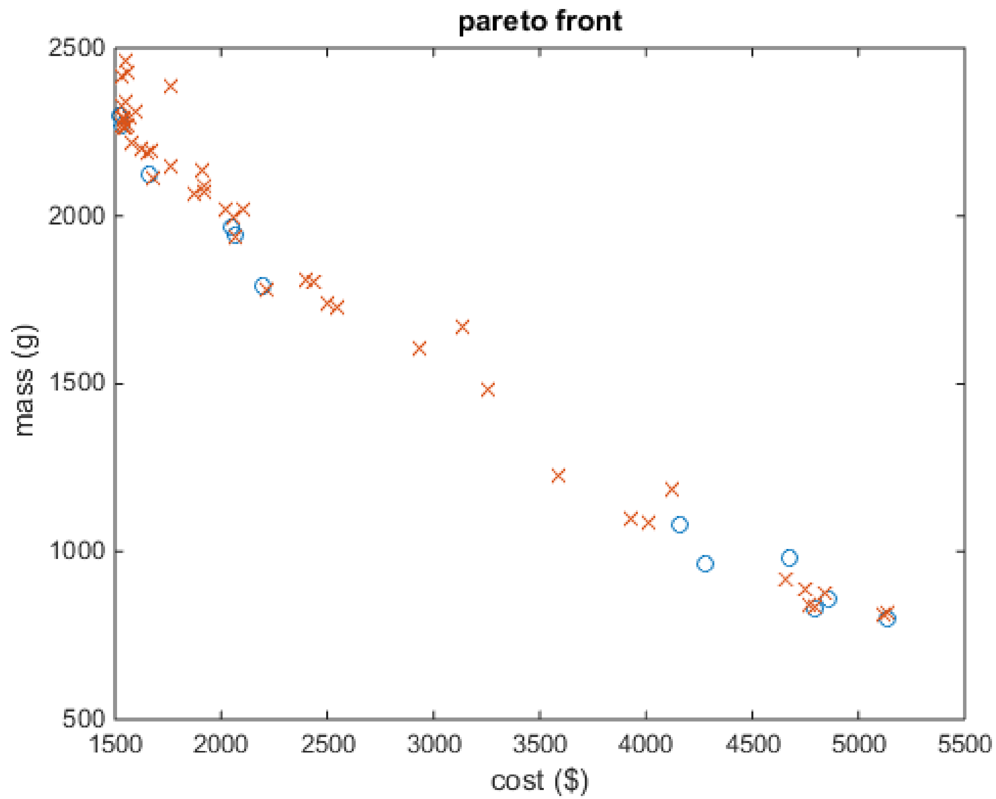




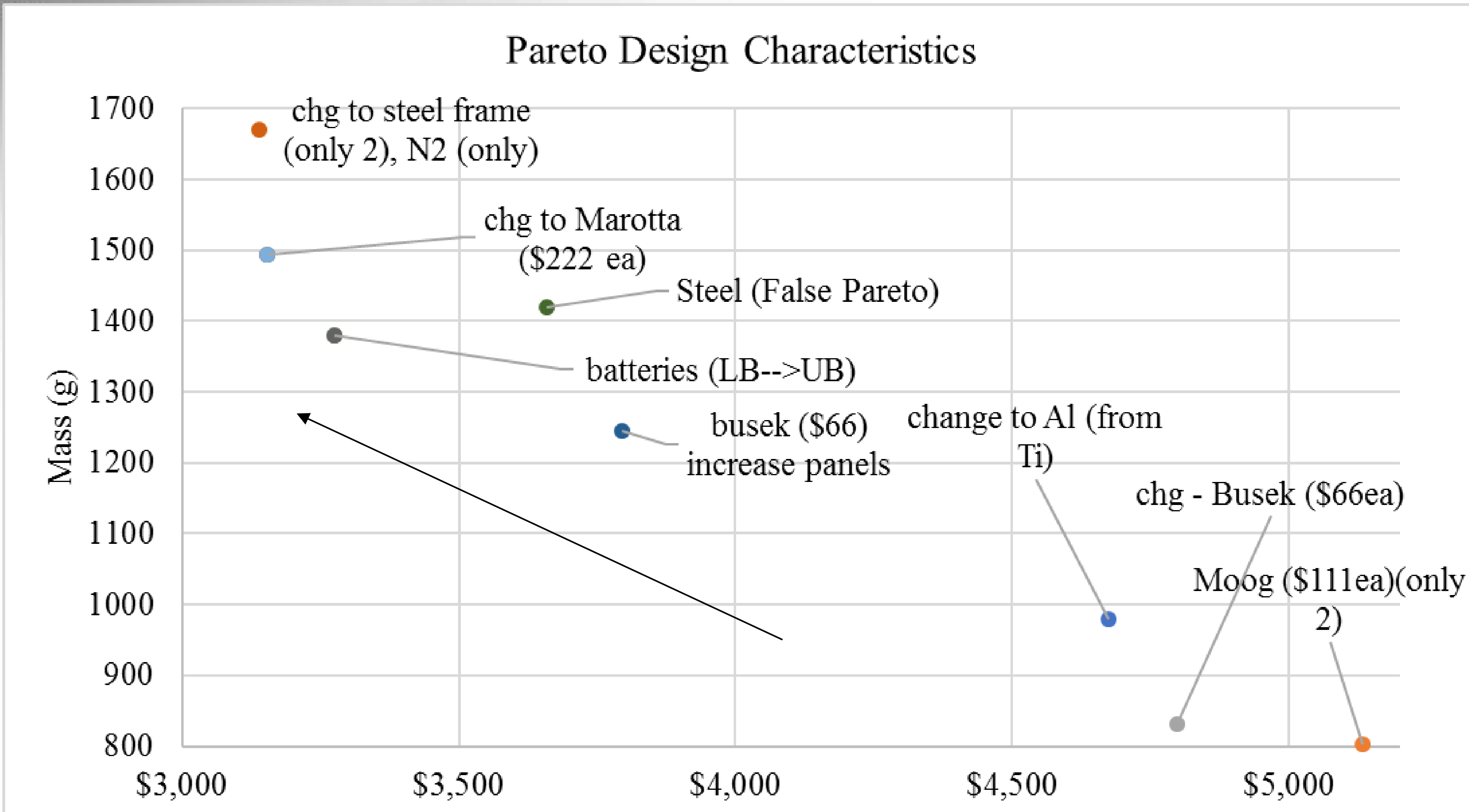


Pareto gradient misbehavior

- GA-only gives X points
- Adding SQP results in O’s
  - All X points converge to blue points
  - Sometimes this *increases* the objective function from the GA result.



Pareto Designs



Comparison of Thesis Scopes of Work

CubeSat MS Thesis Scopes of Work

David Malawey, 2/12/2015

			Design/analysis Tasks																		
Title	Level	1U, 2U, or 3U	FEA (sat or frame)	Mechanical drawings	Vibration/stress Simulation	Actual Vibration/stress test	test/experiment design	structure design	module selection	develop prototype	antenna mechanical design	FEA 1 or more components	frame manufacturing method	material selection, detailed	simulation design	Attitude control algorithms	ADC component integration	aerodynamic calculations	magnetic calculations	gravity calculations	TOTAL
David Malawey Thesis			1	1				1		1	1		1								6
Quick-Turn Finite Element Analysis for Plug-and-Play Satellite Structures	MS thesis	1U	1	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	5
Development of CubeSat Vibration Testing Capabilities for the Naval Postgraduate School & Cal Poly San Luis Obispo	MS thesis	1U	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Development of Composite and Polymer Material Cubesat Structure with focus on Materials	MS (1sem)	3U	0	1	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0	6
Desgn of a Cubesat Guidance, Navigation, and Control Module	MS thesis	1U	0	1	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	5
Structural Subsystem Design, Analysis, and Opitimization for a nanosatellite	MS thesis	1U	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	3
Passive Attitude Stabilization for Small Satellites	MS thesis	1U & 3U	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	6
Design, Analysis, Fabrication, and Testing of a Nanosatellite Structure	MS thesis	NA	1	0	1	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	6
Nanosat/Cubesat Constellation concepts	MS thesis																				
			3	3	2	2	1	4	1	2	1	1	2	3	2	2	1	1	1	1	

c = consideration

→ Propulsion Calculations

→ [very basic] propulsion controller design

→ 1U module optimization (3U consideration but not design)