A Framework for “Small” Satellite Architecture Design

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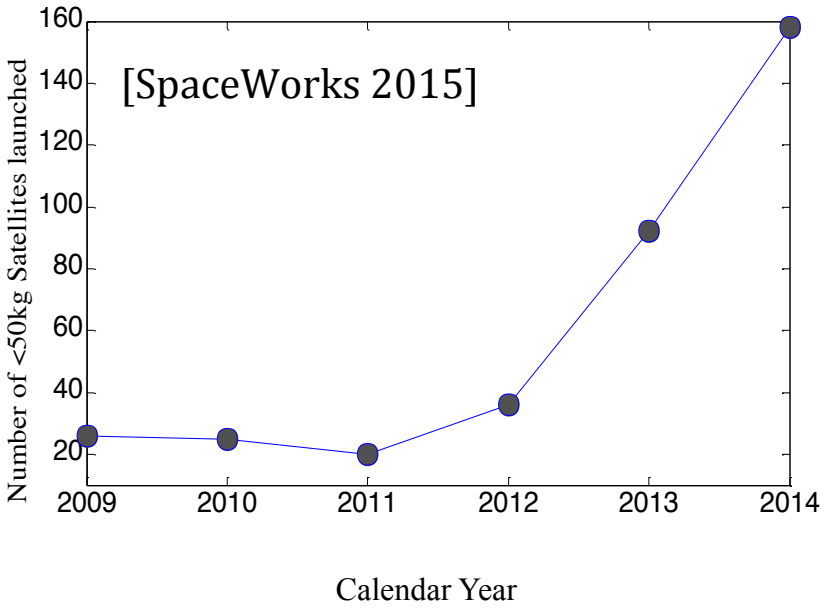
Research Scenario & Motivation

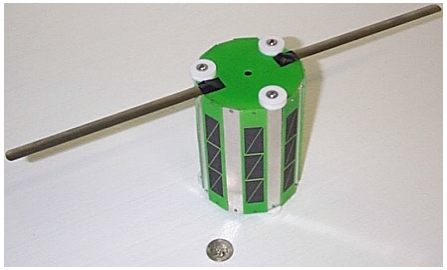
Small Satellites

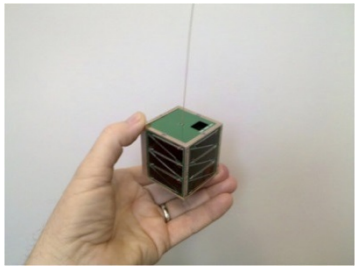
- Interest in small satellites has grown significantly in recent years
- Building, launching and operation of small satellite constellations is becoming increasingly feasible
  - Miniaturization of satellite components
  - Standardization of many satellite parts



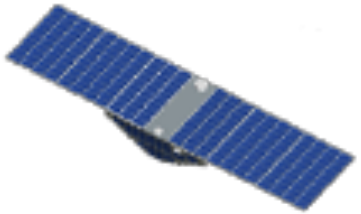
Category	Satellite Mass (kg)
Large	1000
Medium	500 to 1000
Mini	100-500
Micro	10-100
Nano	1-10
Pico	0.1-1
Femto	<0.1

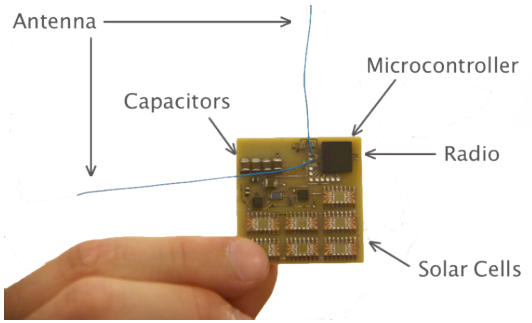
Examples of Recent Small Satellite Missions



- Google and Fidelity Investments have made a $1 Billion investment in SpaceX
- OneWeb Ltd to provide global internet service on a network of 648 lightweight LEOs through Air Bus
- CyGNSS: NASA Weather Predictions
- SNaP: US Military Nanosatellite UHF Constellation
- Small satellite startup Satellogic is on its way to building and orbiting a constellation of 300 Earth Observation (EO) satellites to provide near-real time imagery





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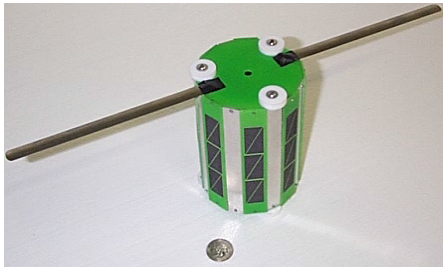

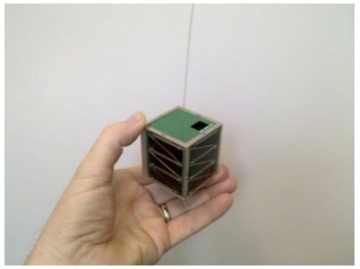

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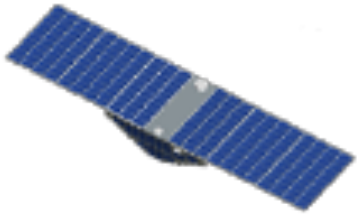
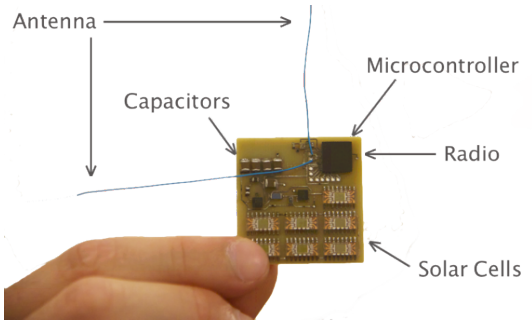
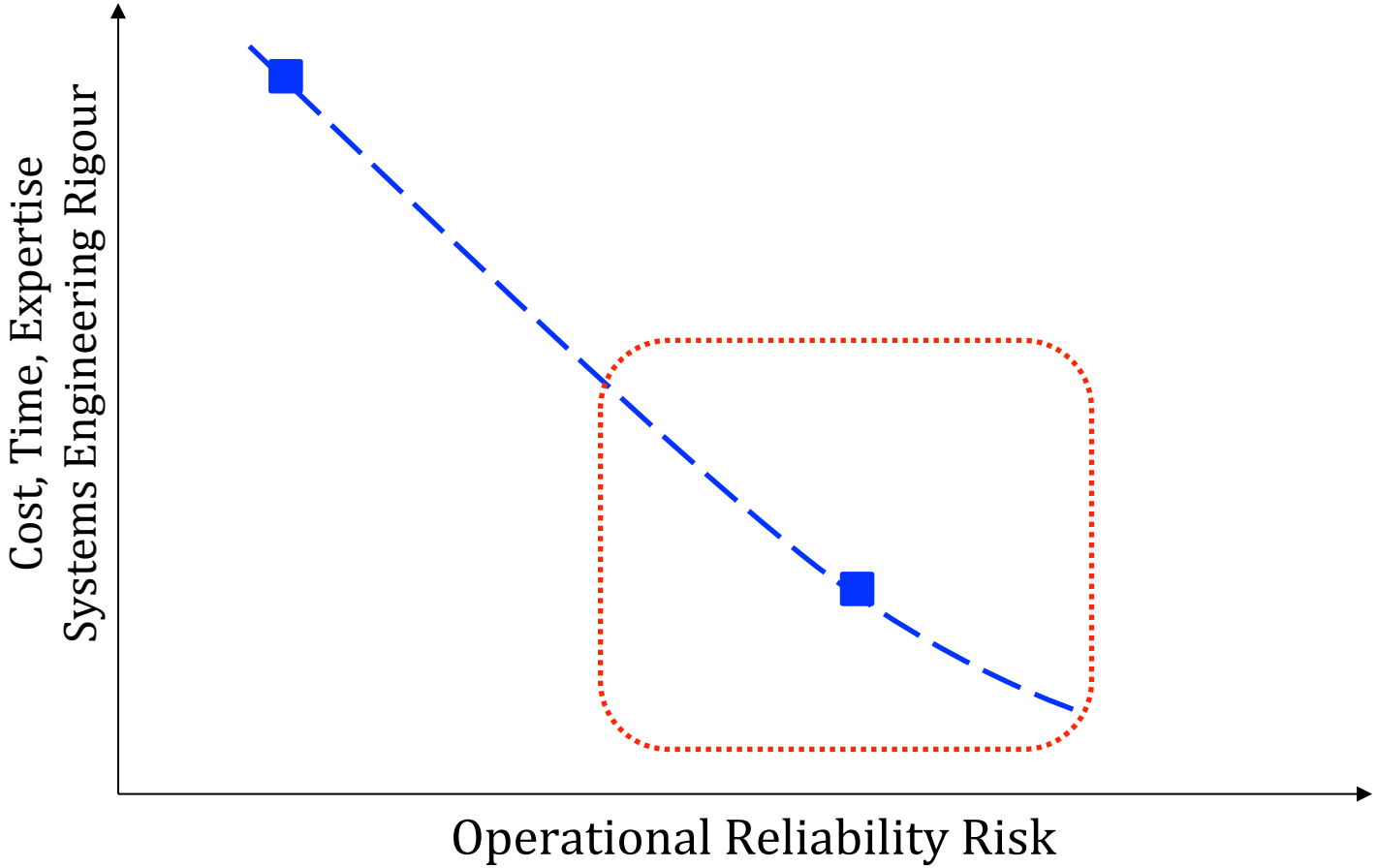




High-resolution earth imaging, space-based internet, atmospheric modelling, on-demand coverage

“Small”—A specific class of satellites

Relatively low resources and proportionally increased risk



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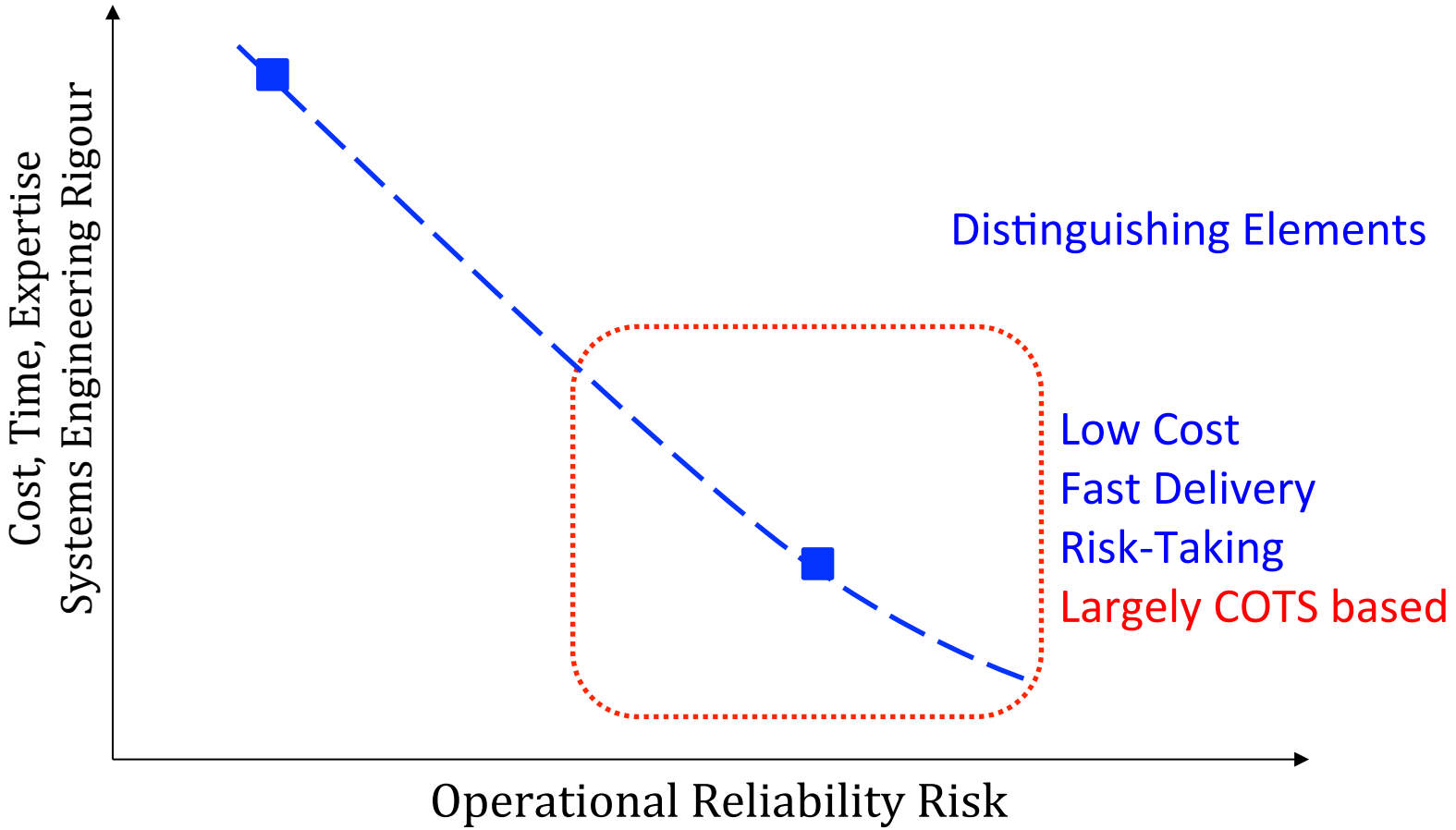


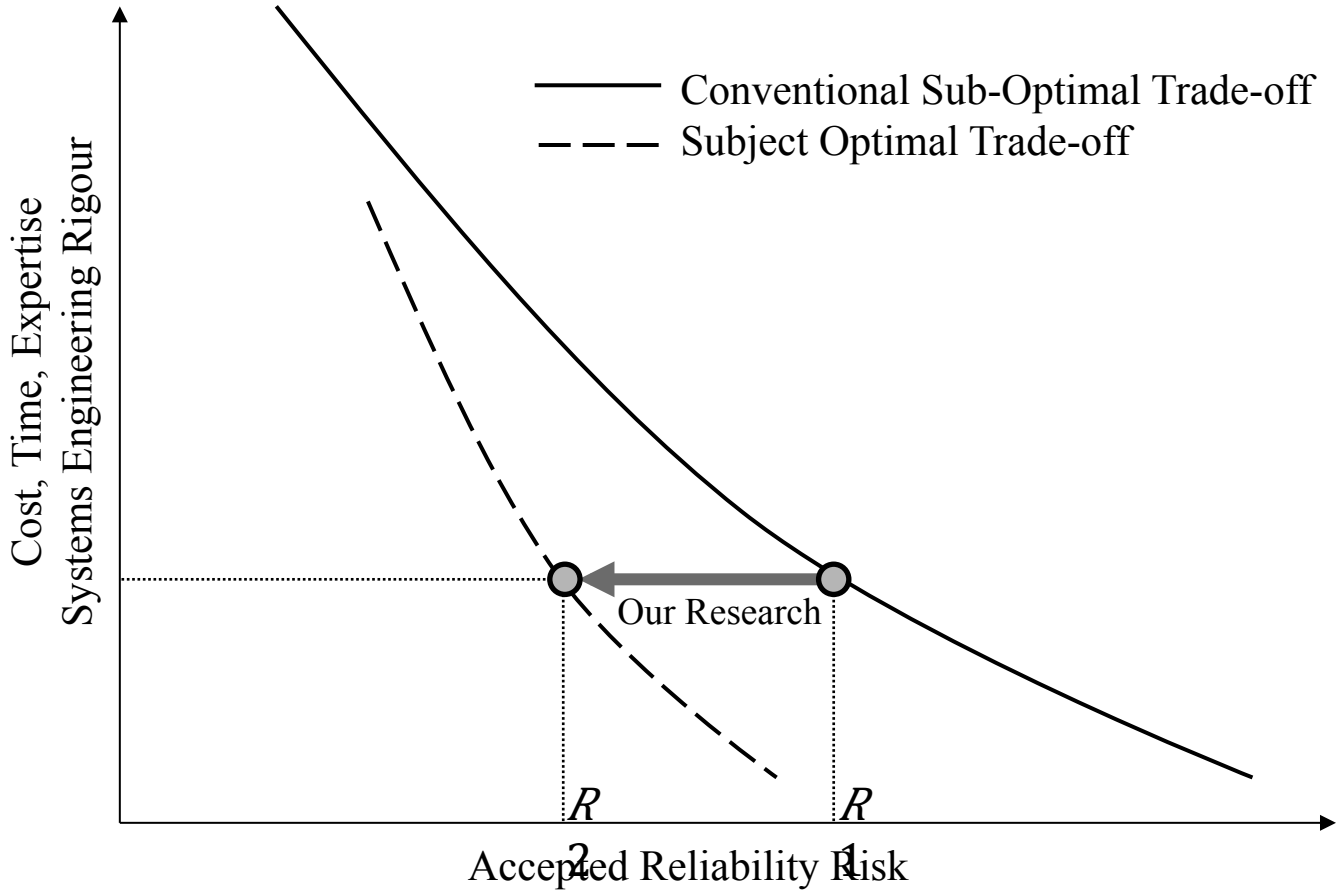
Standardization Efforts

- ISO TC20/SC14 (Space Systems and Operations)
- International Academy of Astronautics IAA Study Group 4.18
- Considering the term “Lean Satellite” to reflect the low-cost and fast delivery attributes rather than satellite size or mass
- Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery
- ISO/19683 Design Qualification and Acceptance Tests for Lean Satellite
  - COTS to comply before sold as space units

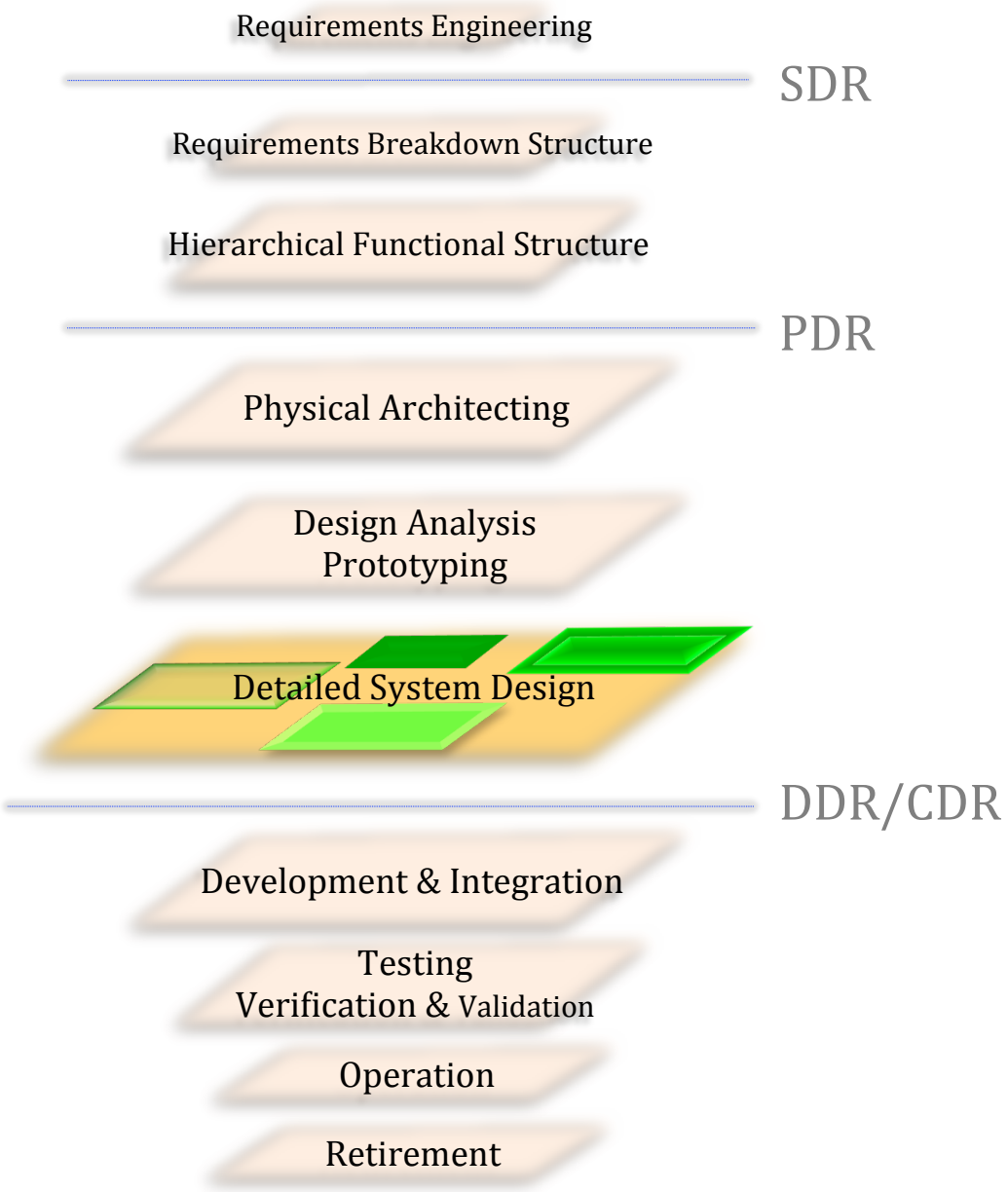
Aspects under Discussion—Lean Definition

Total cost including infrastructure investment, launch and operation	3M to 10M USD
Time from the contract to delivery	6-months to 3-years
Number of mission payloads	1 to 5
Number of persons needed to operate per satellite pass	1 to 5
Number of people engaged in satellite development	10 to 30 persons
Percentage of non-space qualified COTS parts/material usage	10% to 90%
Mission down time allowed	90-min to 1 week
Satellite mission duration	1 to 3 years

Challenge—Reducing Risk for Same Resources

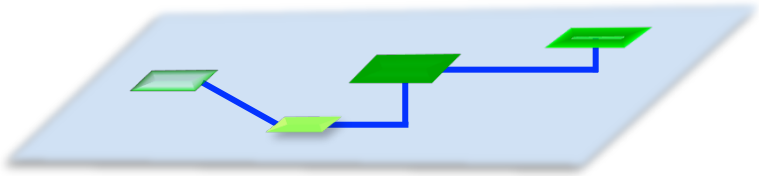


Traditional Systems Engineering Lifecycle

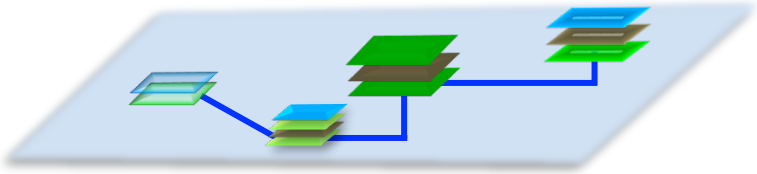


Lean Satellite—Largely COTS based

Various physical elements are connected together in a specific way to perform the required functions

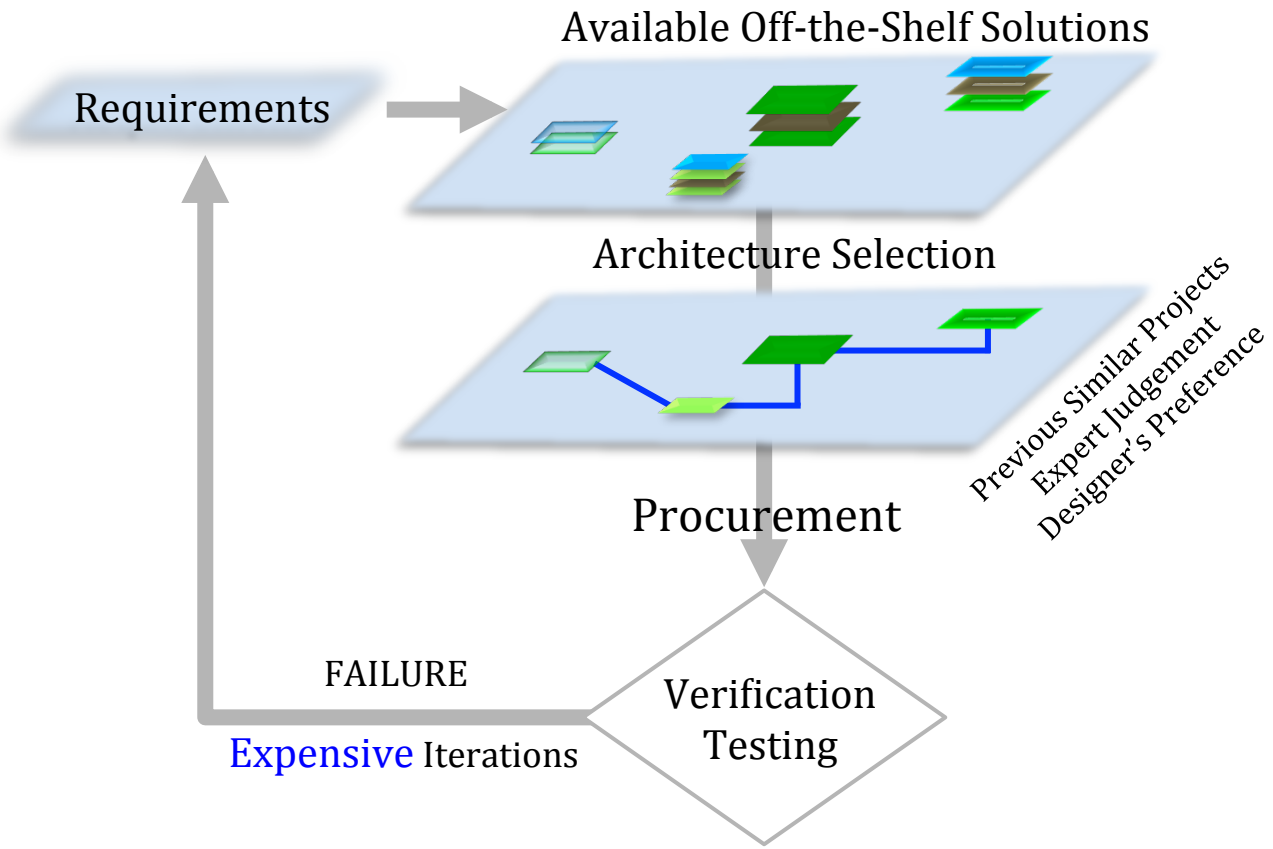


Largely driven by availability and compatibility of COTS alternatives of each element



Selection of preferred COTS alternatives of each element

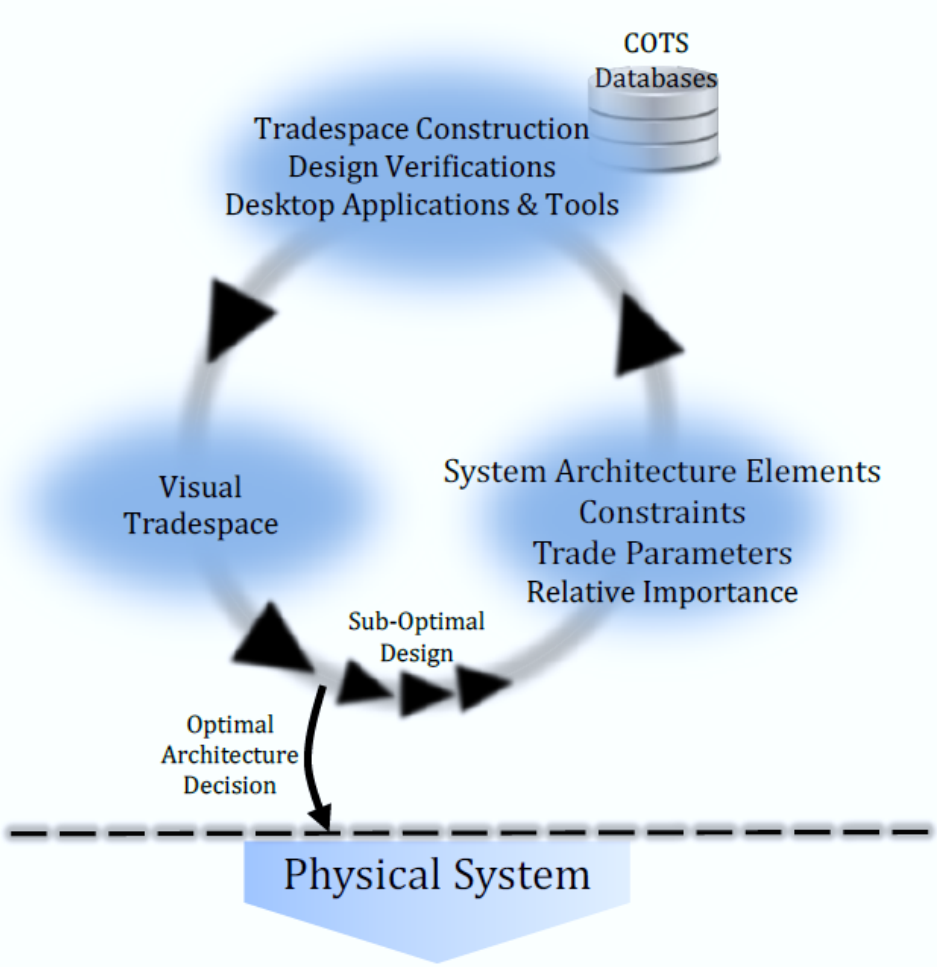
Decide-Build-Test



Making the decision first and then testing a physical design to receive feedback

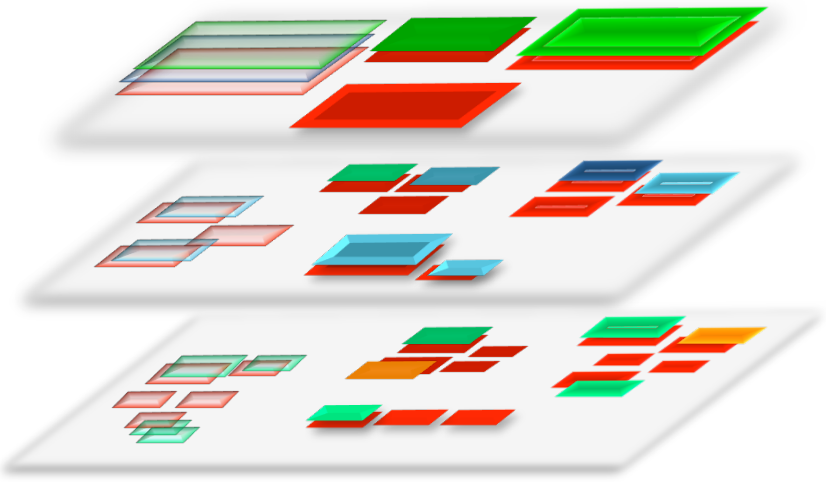
Proposed Approach
Lean Satellite Architecture Design

Elements of Proposed Framework



Proposed TSE—Explore-Test-Decide

Requirements



Explore the Design Hierarchy

Explore all potential architectures

Combinations of available component alternatives

Tradespace Exploration

Assessing against the Objective Function

To address the Lean Satellite challenges
e.g. Improving Reliability

Opportunity Identification

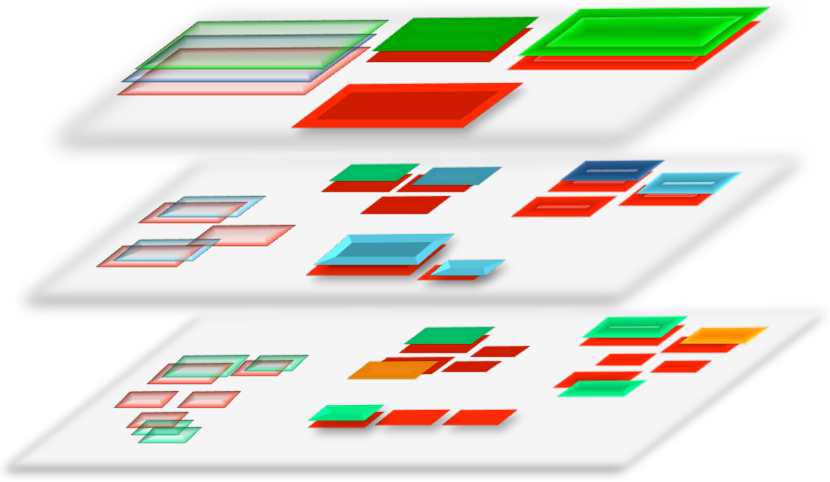
Design Verification

DDR

Physical Development

Proposed TSE—Explore-Test-Decide

Requirements



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Combinations of available component alternatives

Tradespace Exploration

Assessing against the Objective Function

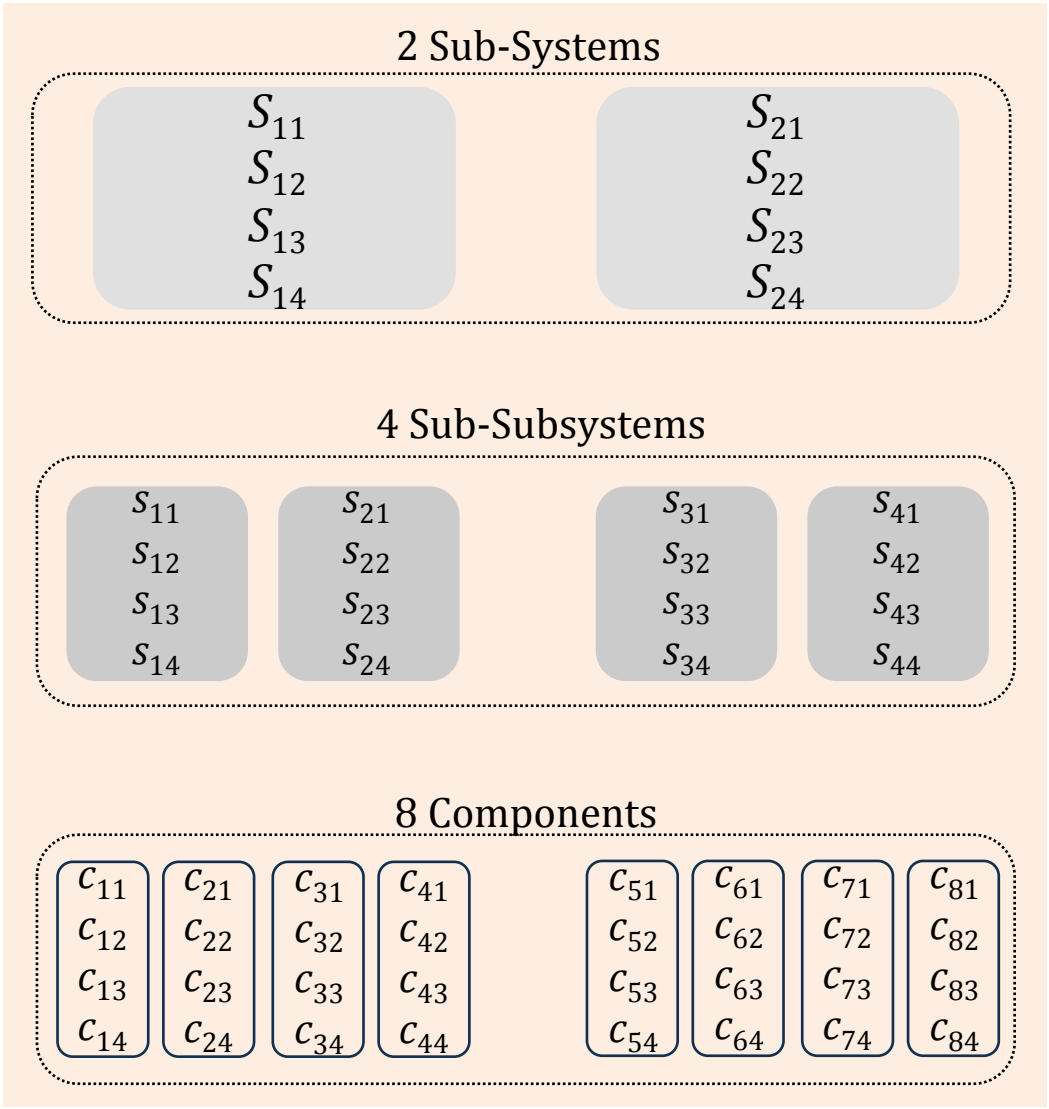
To address the Lean Satellite challenges
e.g. Improving Reliability

Opportunity Identification

Design Verification

Design decisions are delayed until the feasibility and optimality are proven prior to physical development

Exploring the Design Hierarchy
Off-the-shelf Solutions



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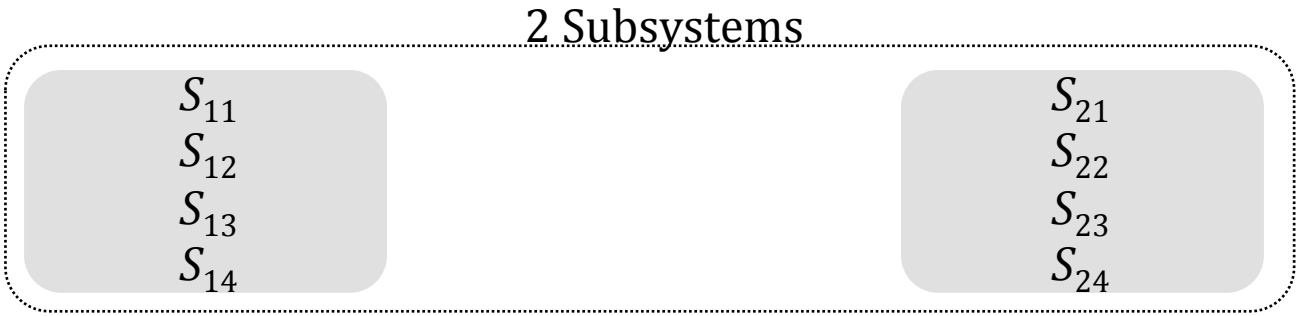
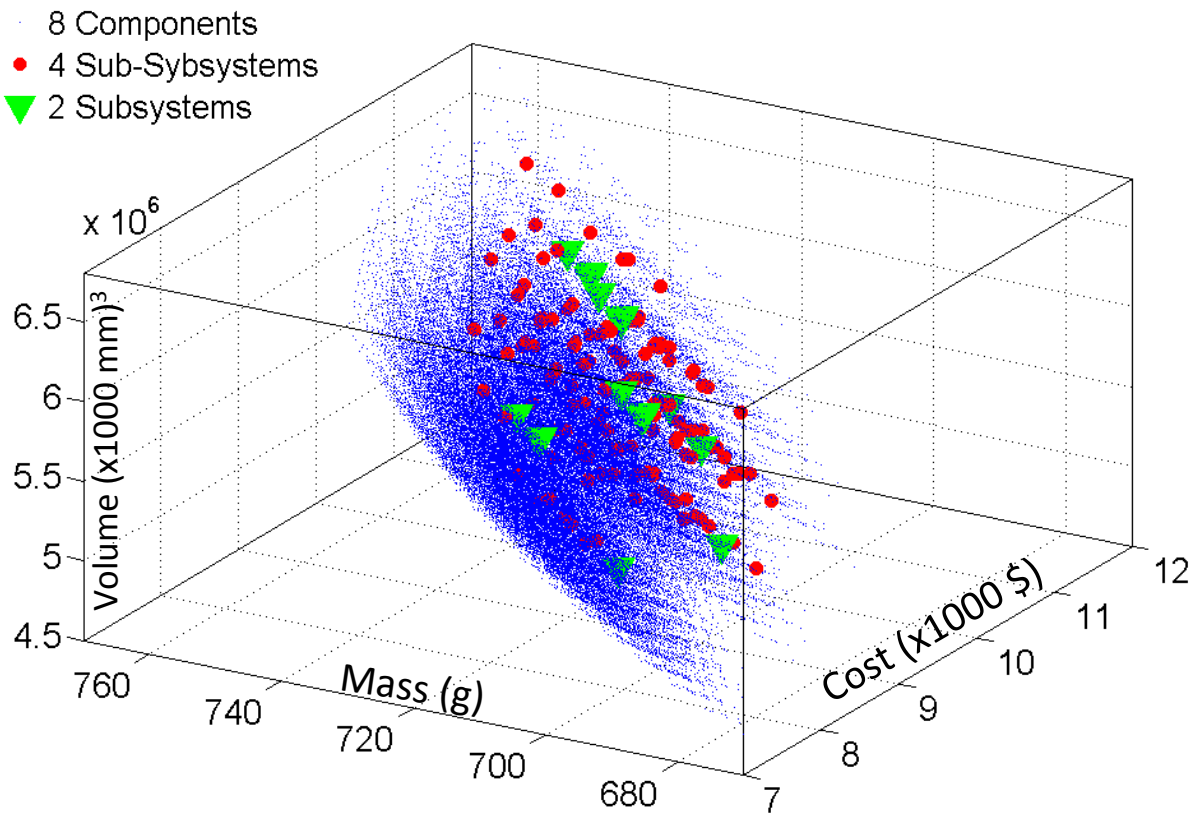


Design Alternative	Mass (g)	Volume $\times 10^6 (mm)^3$	Cost k$
S_{11}	343.55	2.5373	3.4772
S_{12}	363.16	3.0021	4.1302
S_{13}	362.57	3.0036	4.0663
S_{14}	366.94	3.1067	4.1529

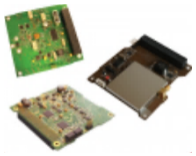
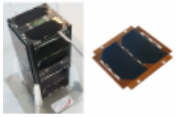
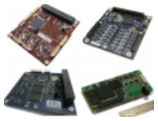
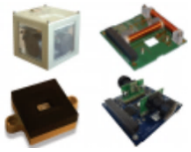
Design Alternative	Mass (g)	Volume $\times 10^6 (mm)^3$	Cost k$
S_{21}	348.99	2.7455	5.1664
S_{22}	353.80	2.8243	4.2446
S_{23}	361.87	3.0125	5.9877
S_{24}	368.73	3.1705	6.1676

Exploring the Design Hierarchy
Off-the-shelf Solutions



Considering lower layers of design decomposition (or hierarchy) is likely to disclose non-intuitive designs of interest

CubeSat System Example

i	k	K_i
Communication		4
Power		4
Solar Panels		3
Attitude Control		4
Command & Data-Handling		4
Antenna		2

$$\sum_{i=1}^{N} c_{i,k} \quad 1 \le k \le K_i$$

http://www.cubesatshop.com/

Design Space of Example CubeSat System

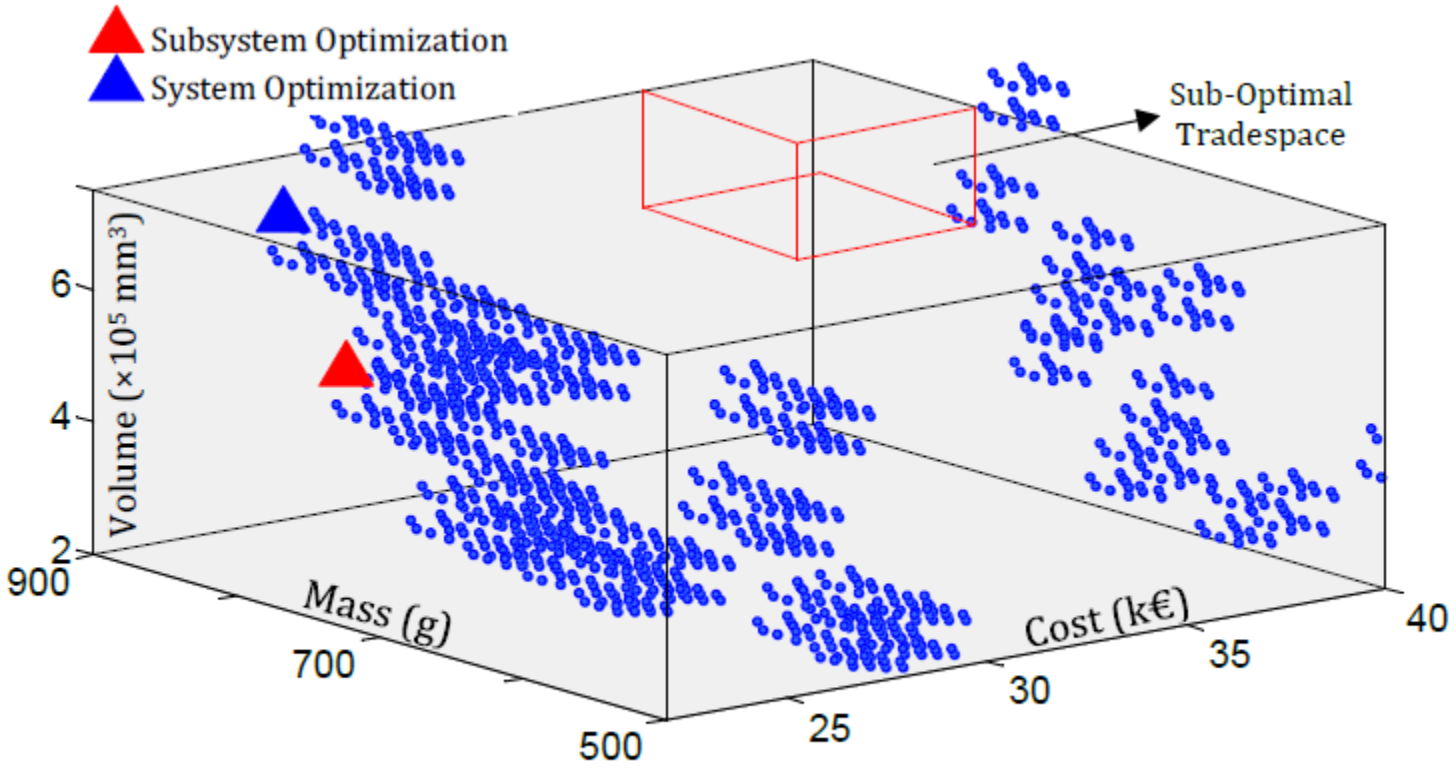


Figure 4. Volume-mass-cost tradespace for the example CubeSat system

Design Space of Example CubeSat System

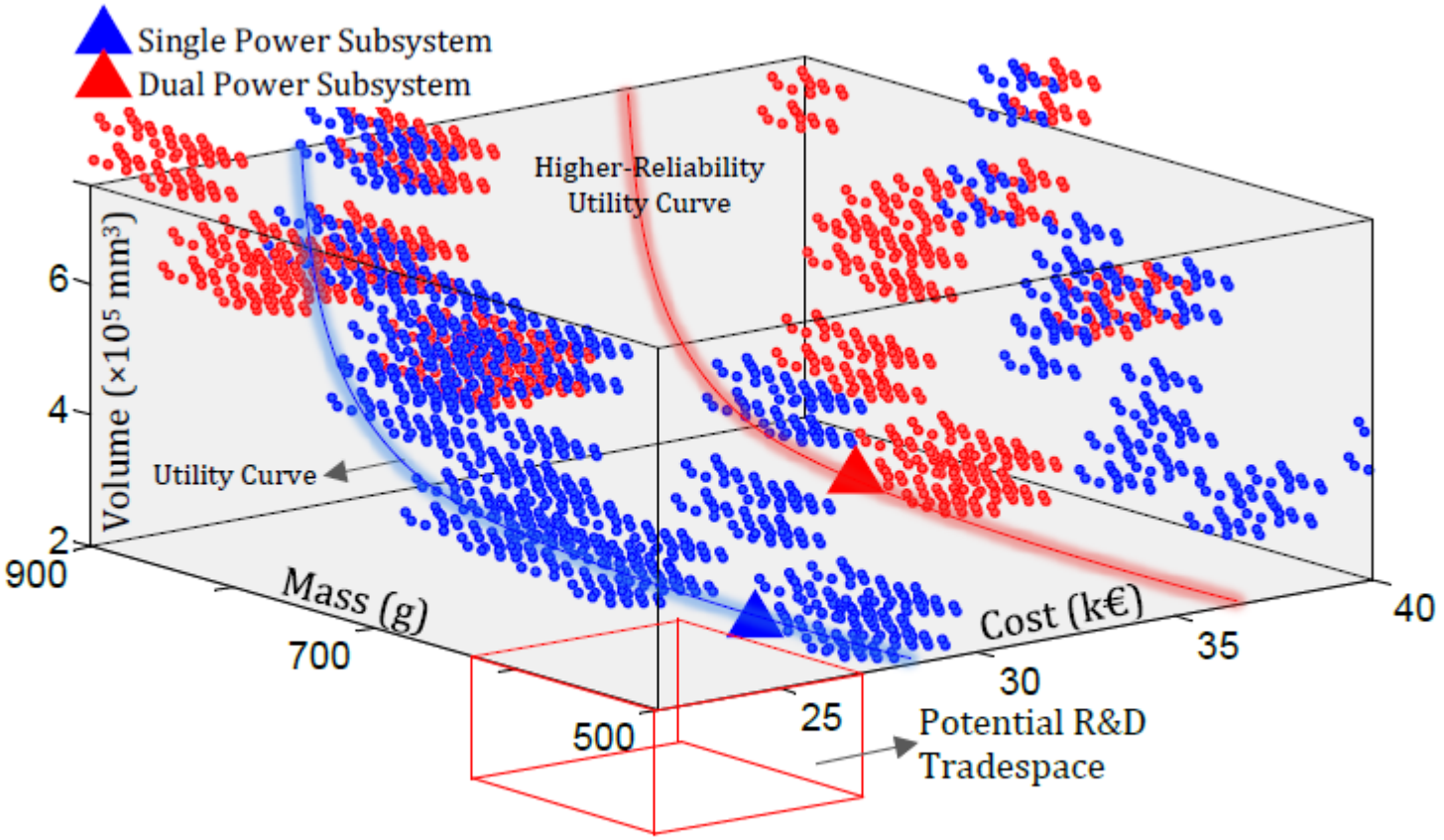
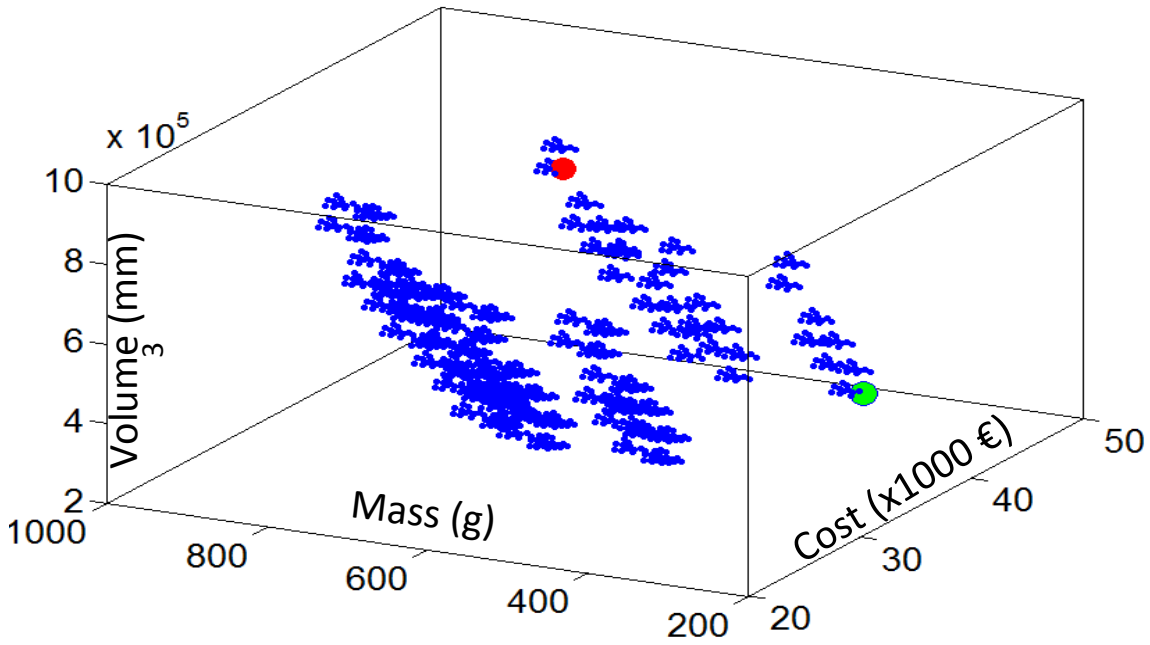


Figure 5. Tradespace of example CubeSat system including improved reliability designs

Design Space of Example CubeSat System



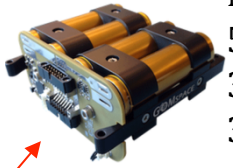
Difference
Cost 5550€
Mass 450g
Volume 351x105mm^3

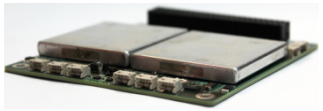
Net difference in the mass, volume and cost budget of the two highlighted design

- An opportunity to improve reliability through redundancy

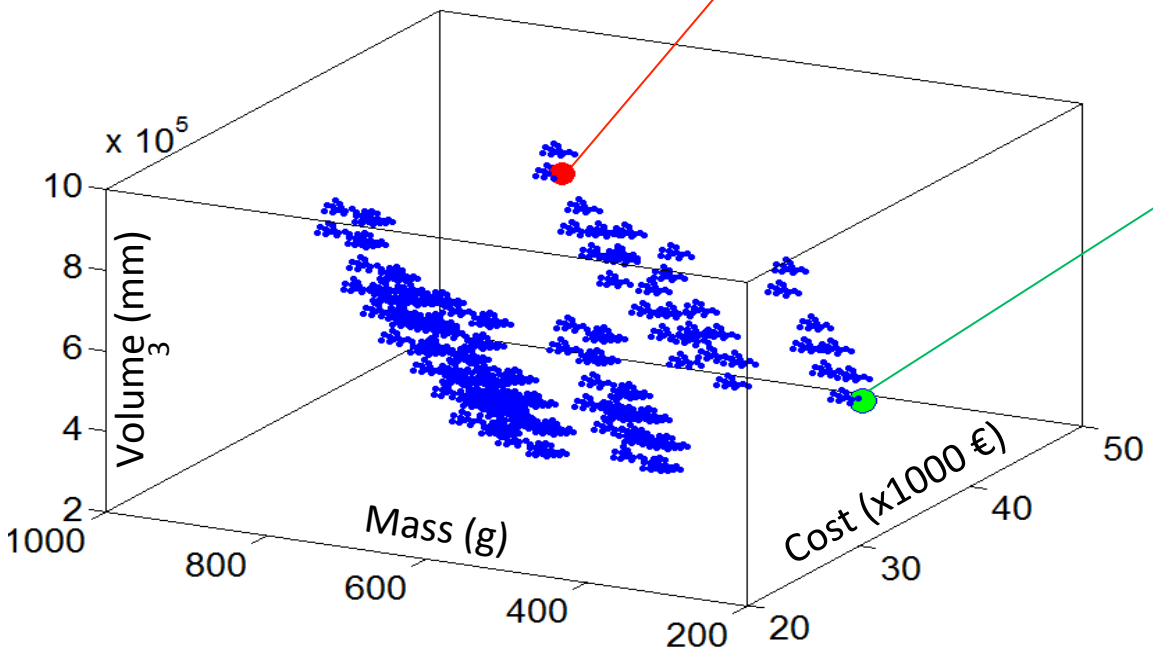
Value of Exploration

Power Subsystem in this design
NanoPower P31U Power Supply
5500€
370g
$316x10^5$





Power Subsystem in this design
Crystalspace P1U "Vasik"
5400€
80g
$60.48x10^5 mm^3$



Difference
Cost 5550€
Mass 450g
Volume $351x105mm^3$

Net difference in the mass, volume and cost budget of the two highlighted design

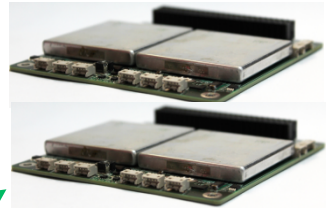
- An opportunity to improve reliability through redundancy
  - A more reliable single power subsystem is not available

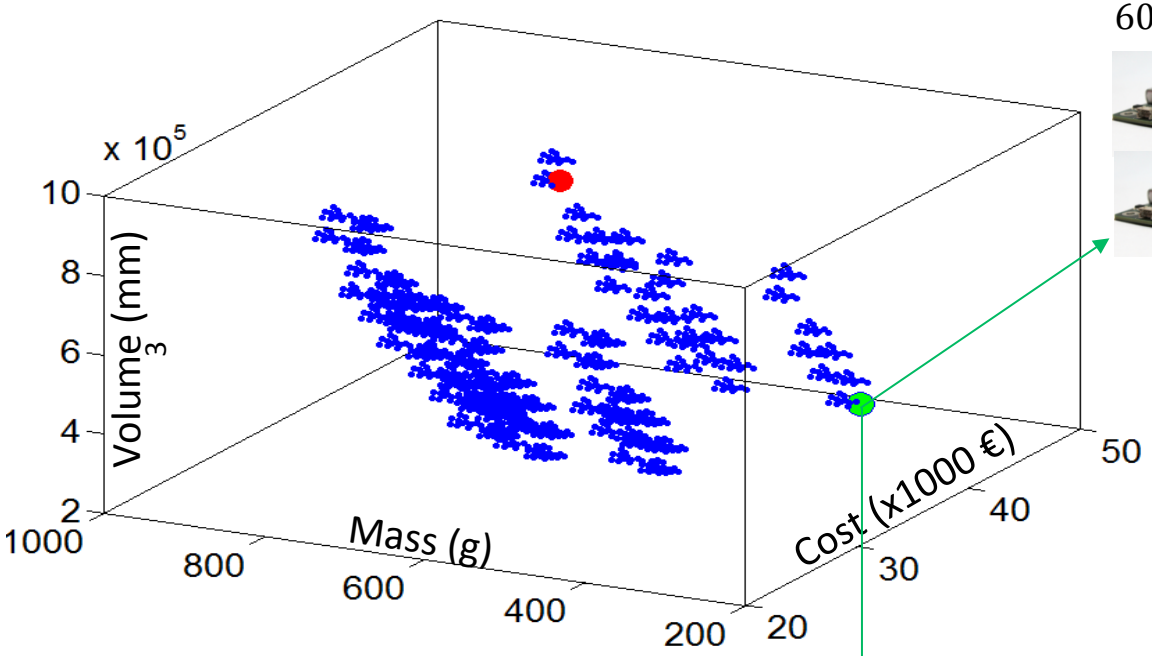
Designing for Reliability

The Difference allows for redundancy, through either power subsystem, to improve the reliability as:

$$R_c = 1 - (1 - R_d)(1 - R_d)$$

Power Subsystem Specifications
Crystalspace P1U "Vasik"
5400€
80g
$60.48 \times 10^5 mm^3$





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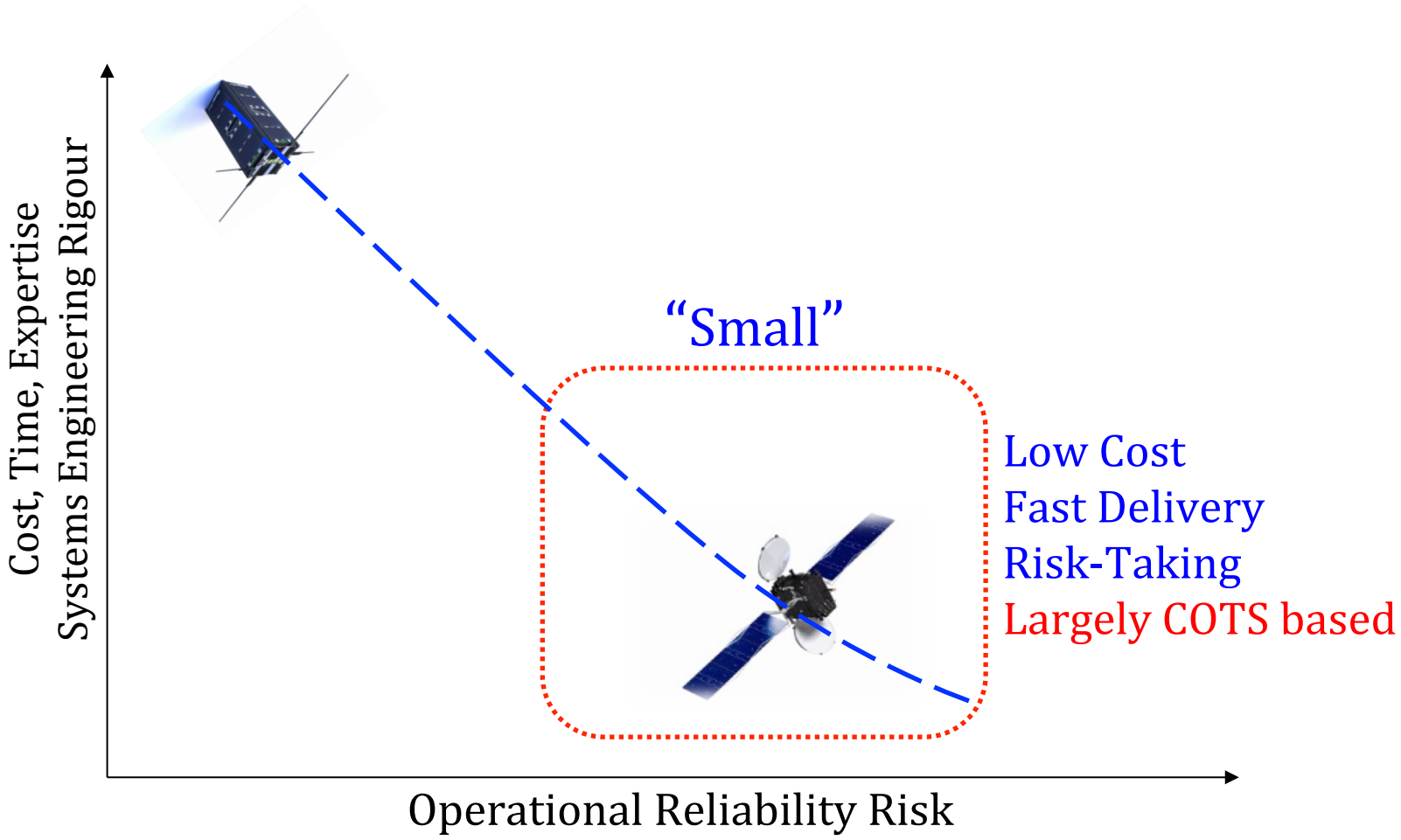
Conclusions



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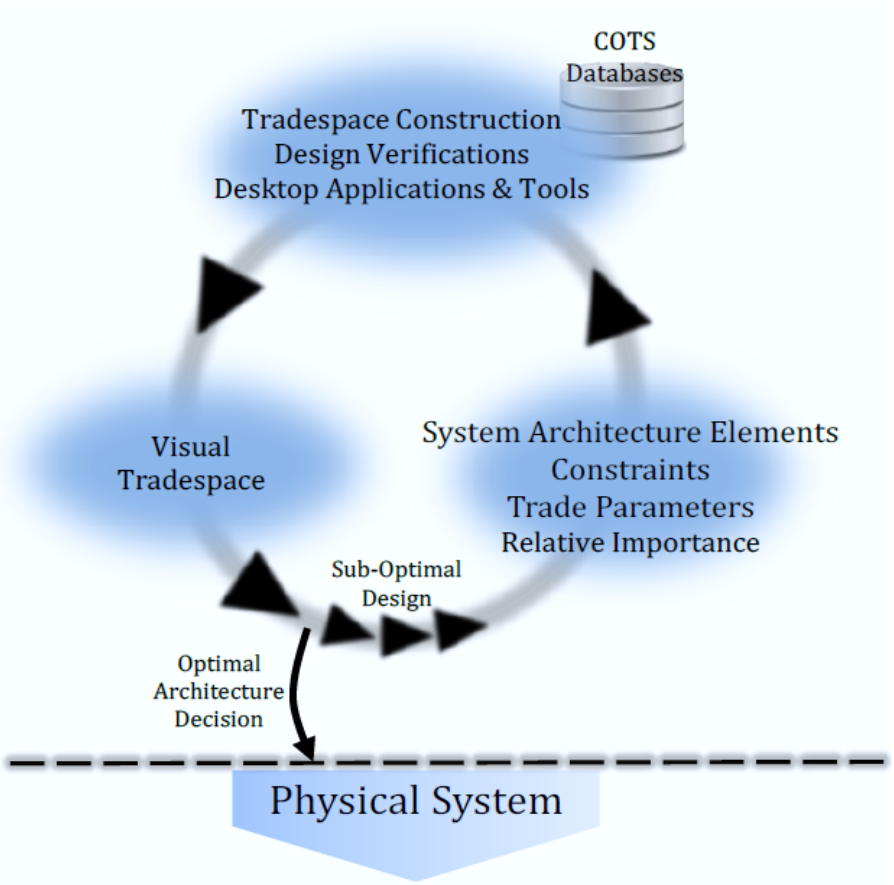
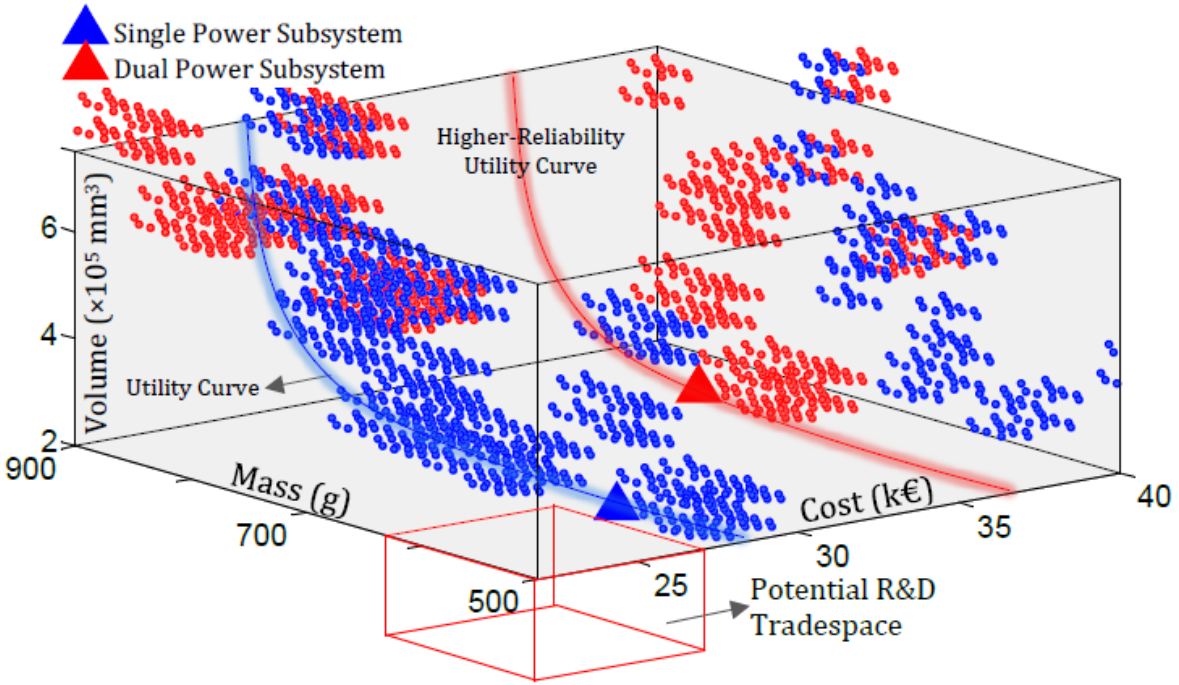


✗ Decide-Build-Test

✓ Explore-Test-Decide

Conclusions



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