Analysis of CubeSat Reliability


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CubeSat reliability (and by extension, constellation reliability) is a key parameter informing the design of the constellation. A quantitative assessment of CubeSat constellation reliability was developed based on multiple databases of historical performance. Databases and reliability models are now sufficiently mature to produce useful statistics.
Outline

• Review of Science Performance
• Overview of CubeSat Failure Models
• Simulation Approach and Tailoring for this Analysis
• Mathematical Implementation Details
• Results
• Summary
Science Performance vs. Constellation Size

- Median revisit requirement: 1 hour (baseline), 2 hour (threshold)
  - Four satellites meet baseline revisit requirement
  - Three satellites meet threshold revisit requirement

- Strategy: Maximize probability of meeting baseline requirements
  - Maximize probability of at least four satellites operating concurrently though 18-month mission life
Constellation Reliability versus Single Sat Reliability

Desired Reliability for Constellation

Probability of functioning constellation of four satellites at end-of-life vs. Probability of a single satellite working to end-of-life.
Outline

• Review of Science Performance
• **Overview of CubeSat Failure Models**
  • Simulation Approach and Tailoring for TROPICS
  • Mathematical Implementation Details
  • Results (TROPICS Project & NASA/ESSP)
• Summary
Overview of CubeSat Failure Modeling

• There has been an energetic sector of recent CubeSat research devoted to failure database development, parametric modeling, and statistical analyses


  – Swartwout Database and Analysis: https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

Some Distinctions and Observations

- Munich model has $R(t)$, but lumps all satellites together into a “universal class”
- Swartwout database does not have $R(t)$, only $R(90^{th}$ day), but breaks up the data in many useful quantitative ways (e.g. subdivision of “university” and “professional” class builds)
  - Shows failures dominated by bus, not payload (86% bus)
  - “University class” CubeSat failures occur more frequently by a factor of 23/8 relative to “professional class” CubeSat failures
- Richardson analysis identifies “fly-learn-refly” as the single most dominant predictor of CubeSat reliability and cites quantitative statistical improvement for up to five cycles
- 2016 NRC CubeSat report (“Thinking Inside the Box”) makes two interesting statements:
  - Historical success rate of NASA Class C/D missions is ~80% (Class A/B is ~90%)
  - CubeSat failure rate halved in the last eight years (“maturation effect”)
Breakdown of CubeSat Classes

- Universal Class ("Everything")
- University Class
- Professional Class
Simulation Approach

• Use a hybridization of the Munich and Swartout models and make adjustments to predict the reliability of:
  – Originally proposed 12-satellite “universal class” constellation
  – Currently proposed 6-satellite “professional class” constellation

• Assume four satellites are needed for 18 months to claim baseline science success for either scenario

• Adjustments:
  – “Maturation effect” (Across-the board-improvement in CubeSat reliability in 2017 relative to database completed in 2014)
  – Additional fly-learn-refly cycles
  – “Universal” vs “Professional” class

“Universal Class” = University + Professional
Implementation Notes

• “Maturation” adjustment
  – Conservatively assume that future improvements will yield a halving of failure rate in 12 years (not 8). Thus failure reduction from 2014 to 2017 is $0.5^{(3/12)} = 0.84$.

• Fly-learn-refly adjustment
  – Swartwout statistics show a failure reduction ranging from approximately 0.6 to 0.7 over the course of five cycles. Conservatively choose 0.75 as the failure reduction factor for all cycles up to five.
  – Relative to baseline Munich database, assume one additional cycle for payload maturity and three additional cycles for bus maturity.

• “Professional” class adjustment
  – To convert Munich “total” population to “professional” population, we need to know relative amount of each population (79/35 for u/p) and the ratio of failure rates (23/8 for u/p), thus:
  – Failure reduction factor = $(79+35)/(79*23/8 + 35) = 0.43$
• “Maturation” adjustment = 0.84
  – At the 90th day, 84% fewer failures than before

• Fly-learn-refly adjustment = 0.75 per cycle
  – At the 90th day, 75% fewer failures than before for one cycle
  – At the 90th day, 42% fewer failures than before for three cycles

• “Professional” class adjustment = 0.43
  – At the 90th day, 43% fewer failures than before
Adjustment of the Wiebull Parameters

• All Wiebull parameters are updated with each adjustment.

• The Wiebull parameters are all scaled by the same single multiplicative factor to achieve the desired failure adjustment at the 90\textsuperscript{th} day to be consistent with Munich model.

• This has the effect of narrowing the R(t) distribution as reliability improves (consistent with Langer, Figure 14, for example).
Summary of Results

• Original 12-sat constellation of “Universal” class:
  – Add adjustment for failure reduction due to CubeSat maturation
  – Add adjustment for one additional fly-learn-refly cycle
  – Results: single-sat reliability at 18 months: 0.49, 12/4 constellation reliability at 18 months: 0.9165

• Upgraded 6-sat constellation with “Professional” class bus:
  – Add adjustment for failure reduction due to CubeSat maturation
  – Add adjustment for three additional fly-learn-refly cycles
  – Add adjustment for “professional” class CubeSat design and parts
  – Results: single-sat reliability at 18 months: 0.82, 6/4 constellation reliability at 18 months: 0.9194

• Curves on next chart
Plot of Results

- **Solid lines:** Probability that four vehicles from the constellation survive for a given time.
- **Dashed lines:** Probability that a single vehicle survives for a given time.

Legend:
- **Six choose four reliability (professional class)**
- **12 choose four reliability (universal class)**
- **Adjusted for "professional class" design/parts (Current 6)**
- **Adjusted for two additional bus fly-learn-refly cycles**
- **Adjusted for one additional bus fly-learn-refly cycle (Original 12)**
- **Adjusted for Moore's law for cubesat reliability**
- **Munich model adjusted for "fully successful"**
Summary

• Results indicate a higher probability of baseline mission success for the upgraded 6-CubeSat constellation relative to the “as proposed” 12-CubeSat constellation

• Results indicate >90% probability of baseline mission success for the current 6-CubeSat constellation

Reliability of 6 “professional” CubeSats > reliability of 12 “university” CubeSats
Munich Model


• “CubeSat Failure Database” of 178 CubeSats, latest launch date of June 30, 2014

• Percent Non-Zero (PNZ) to handle DOA cases

• 2-Wiebull mixture function with seven parameters:

\[ P(t) = PNZ \left\{ \alpha_1 \exp \left[ - \left( \frac{t}{\theta_1} \right)^{\beta_1} \right] + \alpha_2 \exp \left[ - \left( \frac{t}{\theta_2} \right)^{\beta_2} \right] \right\} \]