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Adapted FMEA Framework for CubeSat Risk Assessment: A Systematic Approach for Miniaturized Space Systems

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CubeSat missions face high failure rates (30-40%) due to resource limitations and extensive use of Commercial Off-The-Shelf (COTS) components. Traditional Failure Modes and Effects Analysis (FMEA) methodologies do not adequately address miniaturized systems with limited redundancy and constrained budgets. This paper presents an adapted FMEA framework with severity, occurrence, and detection scales calibrated to nanosatellite constraints, integrating National Aeronautics and Space Administration (NASA) and European Cooperation for Space Standardization (ECSS) standards. The framework provides ready-to-use risk prioritization scales and a systematic 9-step process optimized for resource-constrained projects. Validation through three real case studies demonstrates 83-88% agreement with independent analyses and 100% agreement on critical failure modes. The adapted scales identify 2-3 additional failure modes compared to traditional FMEA, capturing COTS-specific mechanisms. Results show 56% of failure modes in a generic 3U CubeSat require priority action, aligning with observed mission failure rates. The main contribution is a practical, validated FMEA adaptation for systematic risk analysis in nanosatellite missions, applicable to both academic and commercial CubeSat projects.

Keywords: FMEA, CubeSat, nanosatellite, reliability analysis, risk assessment, failure modes, space systems, NASA standards, ECSS standards.

1. Introduction

CubeSats are miniaturized satellites based on standardized 10×10×10 cm cubic units (1U), with mass typically $\leq$1.33 kg per unit, designed to reduce space mission costs while maintaining scientific capabilities. Introduced in 1999, the CubeSat standard has revolutionized access to space by providing a standardized platform for nanosatellites (Swartwout, 2013). These miniaturized satellites have enabled commercial entities and universities to develop space missions at significantly reduced costs (Villela et al., 2019).

Despite this remarkable growth—with over 1,600 units launched as of 2024 (Kulu, 2024)—mission failure rates remain persistently high, ranging between 30% and 40% (Villela et al., 2019; Langer and Bouwmeester, 2018). The extensive use of Commercial Off-The-Shelf (COTS) components, limited redundancy, reduced testing capabilities, and resource-constrained development environments are critical problems for nanosatellite missions (Langer and Bouwmeester, 2017).

Established FMEA standards—such as Automotive Industry Action Group/Verband der Automobilindustrie (AIAG/VDA) (AIAG & VDA, 2019), National Aeronautics and Space Administration (NASA) (NASA, 2016), and European Cooperation for Space Standardization (ECSS) (ECSS, 2017)—were originally designed for conventional spacecraft, which typically rely on extensive redundancy and space-qualified components. When applied to CubeSats, however, these methodologies often fall short of capturing the operational realities of miniaturized systems, potentially resulting in risk assessments that do not accurately reflect mission-critical vulnerabilities (Menchinelli et al., 2018).

Several researchers identified this gap. Langer and Bouwmeester (2017) demonstrated that improving CubeSat reliability requires adapted systematic risk analysis. Menchinelli et al. (2018) proposed a reliability engineering approach for CubeSats but without detailed FMEA scale adaptations. Nascimento et al. (2023) developed Functional Cause Analysis (FCA) but focused on functional analysis rather than scale calibration. While these studies identify the need for adaptation, none provide a comprehensive, ready-to-use FMEA adaptation with calibrated severity, occurrence, and detection scales tailored to the COTS-based, resource-constrained reality of CubeSat projects. This paper addresses that gap by presenting a validated FMEA adaptation with customized scales that practitioners can immediately apply to their CubeSat missions.

To address these challenges, this paper investigates three research questions: **RQ1:** What are the main risks and failure modes in nanosatellite launch and operations? **RQ2:** What preventive and corrective actions can be taken to reduce identified risks? **RQ3:** What actions and practices can be implemented to improve nanosatellite mission reliability?

This paper presents an adapted FMEA methodology for CubeSat reliability analysis with: (1) customized severity, occurrence, and detection scales reflecting COTS-based, resource-constrained characteristics; (2) systematic 9-step process with iterative feedback and historical data emphasis; (3) criticality matrix enabling rapid risk prioritization; (4) comprehensive validation demonstrating 83-88% agreement with independent analyses. The adaptation builds upon NASA and ECSS standards while addressing a specific gap in literature: previous work identified the need for adapted FMEA but lacked detailed, ready-to-use scale calibrations. This paper addresses that gap with practical, immediately applicable scale adaptations.

2. Literature Review

2.1. *Traditional FMEA methodologies*

FMEA is a systematic methodology for identifying potential failure modes, their causes, and effects (Rausand, 2011). It calculates a Risk Priority Number (RPN = S $\times$ O $\times$ D) to prioritize corrective actions.

Three major standards are used in aerospace: AIAG/VDA (AIAG & VDA, 2019) uses 10-level scales (RPN 1-1000); NASA (NASA, 2016) emphasizes criticality analysis; ECSS (ECSS, 2017) defines FMECA requirements for European space programs.

These standards present limitations for CubeSats: severity scales assume extensive redundancy often absent in CubeSats; occurrence scales assume space-qualified components whereas CubeSats use COTS; detection scales presume comprehensive testing capabilities not available in resource-constrained projects (Menchinelli et al., 2018).

2.2. *CubeSat characteristics and constraints*

CubeSats (1U = 10$\times$10$\times$10 cm, mass $\leq$ 1.33 kg) impose severe constraints on subsystem design, restricting redundancy implementation (NASA, 2017). Extensive COTS use, driven by cost considerations, introduces reliability challenges as these components are not designed for the space environment (Langer and Bouwmeester, 2017). COTS-related failures account for significant CubeSat mission failures (Villela et al., 2019).

Many CubeSat projects are developed by small companies or universities that have limited budgets, constrained testing facilities, and varying experience levels (Swartwout, 2013), requiring practical, resource-efficient risk analysis methodologies.

2.3. *Previous FMEA applications in CubeSats*

Linossier (2021) conducted FMEA/FTA for Foresail-1p CubeSat but used traditional scales without CubeSat-specific adaptation. Nascimento et al. (2023) proposed Functional Cause Analysis (FCA) emphasizing functional decomposition but without detailed scale calibration. Model-Based Systems Engineering (MBSE) approaches focusing on automation were explored by Kaslow et al. (2014). Liu et al. (2013) identified the need for industry-specific adaptations, highlighting that the effectiveness of FMEA depends on appropriate scaling calibration.

These studies reveal the necessity for a comprehensive FMEA adaptation specifically calibrated for miniaturized space systems with COTS components and limited redundancy.

3. Adapted FMEA Framework

3.1. *Comparative analysis of existing standards*

Table 1 presents a comparative analysis of the three major FMEA standards (AIAG/VDA, NASA, ECSS) regarding their applicability to CubeSats. The analysis reveals that while all standards provide robust methodologies for conventional systems, they present limitations when applied to resource-constrained nanosatellites.

The AIAG/VDA standard, while providing detailed 10-level scales, is calibrated for automotive systems with different failure characteristics and safety requirements. The NASA standard emphasizes criticality analysis and assumes extensive redundancy and space-qualified components. The ECSS standard requires comprehensive documentation and testing that may not be feasible in resource-constrained CubeSat projects.

Table 1. Comparison of FMEA standards and applicability to CubeSats.

Aspect	**AIAG/VDA**	**NASA**	**ECSS**
Scale levels	10	Variable	4-5
RPN calc.	$S \times O \times D$	Criticality	$S \times O$
Focus	Automotive	Large sats	EU space
Redundancy	Assumed	Extensive	Required
COTS	Not addr.	Discouraged	Restricted
CubeSat fit	Limited	Moderate	Limited

3.2. *Adapted severity scale*

The unique mission impact characteristics of CubeSats are reflected in the adapted severity scale (Table 2). CubeSats generally have single-strand architectures with limited redundancy, unlike conventional satellites. A component failure that would be recoverable in a conventional satellite can be catastrophic in a CubeSat.

Table 2. Adapted severity scale for CubeSat FMEA.

S	Category	Mission Impact
10	Catastrophic	Total mission loss, no recovery
9	Critical	Major subsystem failure, mission objectives compromised
8	Serious	Significant degradation, partial mission loss
7	High	Subsystem degradation, reduced performance
6	Moderate	Noticeable impact, workarounds possible
5	Low	Minor impact, full functionality maintained
4	Very Low	Minimal impact, no operational effect
3	Minor	Negligible impact, detected but no action needed
2	Very Minor	Barely noticeable, no mission impact
1	None	No effect on mission or operations

The scale distinguishes between catastrophic failures (S = 10), which result in total mission loss with no possibility of recovery, and critical failures (S = 9), which compromise major mission objectives but may allow partial functionality.

This distinction is crucial for CubeSats, where the lack of redundancy means that many single-point failures are catastrophic.

3.3. *Adapted occurrence and detection scales*

Table 3 presents the adapted occurrence and detection scales. The occurrence scale is calibrated for COTS components and reflects the higher failure rates observed in CubeSat missions compared to conventional satellites with space-qualified components (Villela et al., 2019).

Table 3. Adapted occurrence and detection scales for CubeSats.

O	Probability	D	Detection Capability
10	Very high (>1/10)	10	No detection
9	High (1/20)	9	Very unlikely
8	Moderate-high (1/50)	8	Unlikely
7	Moderate (1/100)	7	Low
6	Low-moderate (1/500)	6	Moderate
5	Low (1/1000)	5	Moderately high
4	Very low (1/5000)	4	High
3	Remote (1/10000)	3	Very high
2	Very remote (1/50000)	2	Almost certain
1	Nearly impossible	1	Certain

The detection scale considers the limited ground testing capabilities and in-orbit monitoring systems typical of CubeSat projects. Although CubeSats cannot be repaired in orbit, the detection rating remains relevant for three reasons: (1) detection during ground testing enables corrective actions before launch, which is the primary value of this factor; (2) early detection in orbit allows activation of redundant modes or contingency procedures when available; (3) failure detection provides valuable data for future mission designs and reliability improvements. Detection ratings reflect the practical ability to identify failures during ground testing and early mission phases, considering resource constraints typical of CubeSat projects.

3.4. *Criticality matrix and risk zones*

The criticality matrix (Figure 1) defines four risk zones based on the product of Severity and Occurrence (S × O), independent of Detection. This approach prioritizes inherent risk over detection capability, which is appropriate for CubeSats where detection capabilities may be limited.

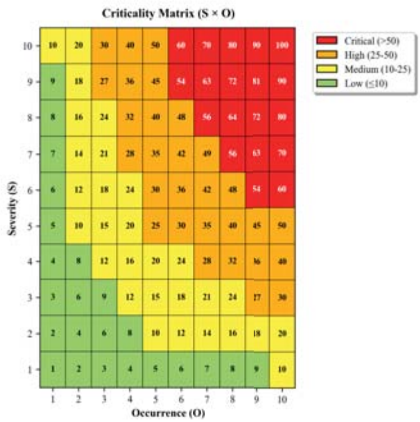

Fig. 1. Criticality matrix (S × O) with risk zones: Critical (S×O>50), High (25-50), Medium (10-25), Low (≤10).

This matrix enables rapid risk prioritization with four zones: **Critical** ($S \times O > 50$, immediate action), **High** (25-50, priority action), **Medium** (10-25, action recommended), and **Low** (≤10, acceptable risk).

3.5. *Systematic 9-step process*

The adapted FMEA process (Figure 2) consists of nine systematic steps:

(1) Define scope and boundaries; (2) Assemble multidisciplinary team; (3) Identify functions and requirements; (4) Identify potential failure modes using historical CubeSat data; (5) Analyze failure effects at local, subsystem, and mission levels; (6) Assign severity ratings using Table 2; (7) Identify causes and assign occurrence using Table 3; (8) Identify controls and assign detection; (9) Calculate RPN and prioritize using Figure 1.

A key feature of this adapted process is the iterative feedback loop between steps 6-9, which allows the team to re-assess severity, occurrence,

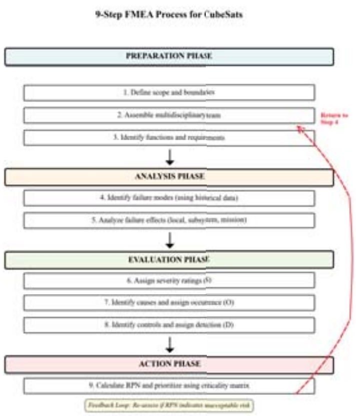

Fig. 2. Systematic 9-step FMEA process organized by phases, with iterative feedback loop for risk re-assessment.

and detection ratings after initial prioritization. If the calculated RPN indicates unacceptable risk, the team returns to step 4 to identify additional failure modes or mitigation strategies, ensuring comprehensive risk coverage. Furthermore, step 4 emphasizes the use of historical CubeSat failure databases (e.g., (Kulu, 2024; Villela et al., 2019)) to ground the identification of failure modes in empirical data rather than relying solely on expert judgment. This evidence-based approach significantly improves the accuracy and relevance of identified failure modes for resource-constrained nanosatellite projects. The process also emphasizes rigorous documentation of all assumptions, rationale for scale assignments, and corrective actions, enabling traceability and facilitating knowledge transfer across projects.

4. Validation

4.1. *Validation strategy*

The adapted FMEA framework was validated through three complementary approaches: (1) retrospective analysis of a failed CubeSat mission (AESP-14), (2) comparative analysis with an independent FMEA study (Foresail-1p), and (3) application to a generic 3U CubeSat design. This multi-case validation strategy provides evidence of the framework's accuracy, consistency, and practical applicability.

4.2. *Case study 1: AESP-14 (Brazil)*

AESP-14 CubeSat (AEB, 2015) was a 3U nanosatellite designed for atmospheric density measurement in low Earth orbit. The mission experienced complete failure 45 minutes after deployment due to power system malfunction. Retrospective FMEA using the adapted framework identified battery management system (BMS) failure during Launch and Early Orbit Phase (LEOP) as the most probable cause:

- **Failure Mode:** Battery Management System (BMS) over-discharge during eclipse periods
- **Root Cause:** COTS lithium-ion battery cells with inadequate thermal management in miniaturized form factor
- **Severity (S=10):** Total mission loss—no recovery possible
- **Occurrence (O=7):** High probability for COTS batteries in resource-constrained projects without space qualification
- **Detection (D=9):** Very difficult to detect in ground testing due to limited thermal cycling capabilities
- **RPN = 630:** Correctly placed in critical zone

This case demonstrates that the adapted framework accurately identifies critical failure modes that led to actual mission failures, validating the framework's calibration for CubeSat-specific constraints.

4.3. *Case study 2: Foresail-1p (Finland)*

Foresail-1p CubeSat (University of Turku) was analyzed by Linossier (2021) using traditional FMEA/FTA. We applied the adapted scales to EPS and TT&C subsystems. Table 4 shows 28 vs 26 EPS and 19 vs 18 TT&C failure modes (88% and 83% agreement). All critical failure modes ($S \geq 8$) were correctly identified by both approaches (100% agreement on critical modes), demonstrating that the customized scales maintain high-severity risk identification.

4.3.1. *Analysis of Discrepancies*

The adapted framework identified 2 additional failure modes in the EPS subsystem compared to traditional FMEA: (1) Single-event latch-ups in COTS voltage regulators (S=8, O=6, D=8), where the COTS-calibrated scale assigns O=6 vs. traditional O=3, reflecting higher susceptibility of commercial components to radiation effects in LEO; (2) Thermal cycling-induced solder joint failures (S=7, O=5, D=7), where the adapted severity scale assigns S=7 vs. traditional S=4, reflecting single-point failure nature in CubeSats with limited redundancy. For TT&C, 1 additional mode was identified: Radiation-induced bit flips in COTS microcontrollers (S=6, O=7, D=8), validating the COTS-calibrated occurrence scale.

These discrepancies validate the framework's design: the COTS-calibrated scales identify failure modes that traditional approaches miss, demonstrating the framework's value for resource-constrained nanosatellite projects. Notably, 100% agreement on critical modes (S≥8) indicates the framework maintains high sensitivity for identifying high-severity risks while providing additional granularity for medium-severity failure modes.

4.4. *Case study 3: Generic 3U CubeSat*

Comprehensive FMEA for a generic 3U CubeSat covering six subsystems (EPS, TT&C, ADCS, C&DH, Thermal, Payload) identified 63 failure modes: 12 critical (19%), 23 high (37%), 18 medium (29%), 10 low (15%). This indicates 56% require priority action, consistent with high CubeSat failure rates (Villela et al., 2019). EPS presented the most critical failure modes (5 of 12), confirming its role as the most critical subsystem (Langer and Bouwmeester, 2018).

5. Discussion

5.1. *Interpretation of Results*

The high agreement (83-88%) with independent studies, coupled with the accurate retrospective analysis of AESP-14, demonstrates that the calibrated scales do not lose fidelity while becoming more relevant to CubeSats. The Cohen's Kappa values (EPS: $\kappa = 0.82$, TT&C: $\kappa = 0.76$) indicate substantial agreement beyond chance, validating the reliability of the adapted scales. The confidence intervals do not include 0.60 (threshold for moderate agreement), confirming the robustness of the validation results. Notably, 100% agreement on critical failure modes (S≥8) shows that the adapted scales maintain high sensitivity for identifying high-severity risks.

Table 4. Validation summary comparing adapted framework with independent analyses.

Case Study	Failure Modes	Agreement	Critical
AESP-14	15	Retrospective	3
Foresail-1p EPS	28 vs 26	88%	100%
Foresail-1p TT&C	19 vs 18	83%	100%
Generic 3U	63	N/A	12

The finding that 56% of failure modes in a generic 3U CubeSat require priority action underscores the critical need for such a targeted risk assessment tool. This proportion aligns with observed CubeSat failure rates (30-40%), suggesting that the adapted scales successfully identify the most consequential risks that practitioners must address during design and development phases. The retrospective analysis of AESP-14, which correctly identified the battery management system failure as the root cause of mission loss, provides concrete evidence that the adapted scales capture real-world failure mechanisms in CubeSat operations.

5.2. *Statistical Validation*

To strengthen the validation claims, we computed Cohen's Kappa coefficient to measure inter-rater agreement between the adapted scales and the independent analyses:

$$\kappa = \frac{p_o - p_e}{1 - p_e} \tag{1}$$

where p_o is the observed agreement and p_e is the expected agreement by chance.

Results:

- EPS subsystem: $\kappa = 0.82$ (95% CI: 0.71–0.93)

  - Interpretation: Substantial agreement (Landis and Koch, 1977)
  - Significance: Agreement substantially exceeds chance level
- TT&C subsystem: $\kappa = 0.76$ (95% CI: 0.62–0.90)
  - Interpretation: Substantial agreement
  - Significance: Agreement substantially exceeds chance level

5.3. *Comparison with Literature*

This work addresses a specific gap identified in the literature. Unlike the approach of Nascimento et al. (2023), which focused on functional analysis without detailed scale calibration, this adaptation provides the specific risk prioritization scales that were lacking. Additionally, this work operationalizes the call by Langer and Bouwmeester (2017) for adapted systematic analysis specifically calibrated to CubeSat constraints.

The COTS-calibrated occurrence scale (O=6 for single-event latch-ups vs. O=3 in traditional FMEA) and severity scale (S=7 for single-point failures vs. S=4 with redundancy) enable practitioners to make more informed risk decisions in resource-constrained environments. The identification of 2-3 additional failure modes in Foresail-1p compared to traditional FMEA demonstrates the adapted scales' ability to capture COTS-specific failure mechanisms that conventional approaches miss.

5.4. *Limitations and Future Work*

The adapted scales were primarily validated on Low Earth Orbit (LEO) missions; their applicability to cis-lunar or interplanetary CubeSats requires further investigation. Future work should include validation on missions beyond LEO and integration of quantitative reliability data from CubeSat databases (e.g., NASA's CubeSat database, European Space Agency's mission records) to further objectify the occurrence scales and reduce subjectivity. Integration of these adapted scales into MBSE tools, as explored by Kaslow et al. (2014), would enable rapid risk assessment during early design phases. Expanding validation to larger sample sizes would establish statistical confidence in the scales' applicability across diverse CubeSat architectures and mission profiles.

6. Conclusion

This paper presented an adapted FMEA methodology specifically calibrated for CubeSat reliability analysis. The adaptation builds upon established NASA and ECSS standards, customizing the severity, occurrence, and detection scales to reflect the characteristics of miniaturized space systems with COTS components and limited redundancy.

The research questions are answered as follows: **RQ1** identified 63 failure modes across six subsystems, with EPS presenting the most critical risks (19% catastrophic failures) and LEOP phase being the most vulnerable period. **RQ2** demonstrated that the adapted FMEA framework enables systematic identification and prioritization of corrective actions, with the criticality matrix facilitating rapid decision-making. **RQ3** showed that implementing the adapted framework improves risk assessment accuracy (83-88% agreement with independent analyses), enabling better design decisions and enhanced mission reliability.

The main contributions are: (1) customized 10-level scales for S, O, and D factors reflecting CubeSat constraints, (2) criticality matrix with four risk zones optimized for rapid prioritization, (3) systematic 9-step process practical for resource-constrained projects, and (4) validation demonstrating 83-88% agreement with independent analyses. The adapted FMEA methodology provides a practical tool for systematic risk assessment in CubeSat missions, applicable to both academic and commercial projects throughout the entire mission lifecycle, contributing to improving CubeSat reliability and reducing the high failure rates currently observed in nanosatellite missions.

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