FRAMES: A Structural Diagnostic for Resilience in Modular University Space Programs

(Framework for Resilience Assessment in Modular Engineering Systems)

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INTRODUCTION

University-based CubeSat programs are essential for training the future space workforce, yet 88% fail to persist long enough to achieve mission success (Pham, 2024). These failures are not a reflection of student capability; they are the result of programs operating in a boundary space where institutional classifications, funding categories, and embedded support are unclear or absent. This structural misalignment leads to high turnover, degraded relationships, and billions of dollars in potential workforce development and innovation capacity lost each year.

A small number of programs have successfully persisted in this environment. Bronco Space Lab (BSL) is one such exception. Its multi-generational history makes it an ideal diagnostic case study for identifying the structural mechanisms that allow university-based space labs to survive and scale. This study develops a diagnostic architecture designed to reveal where resilience is built or lost in programs like BSL. The approach focuses on mapping every internal and external interface in the lab's architecture which includes student cohorts, sub-teams, projects, partner institutions and more, and then systematically evaluating those interfaces for signs of fragility. Using six diagnostic dimensions this study identifies the patterns that cause disruption in knowledge transfer, such as knowledge silos, ambiguous outputs, or weakening connections across time. Findings from this research will inform a set of heuristics, evidence-based rules, that other space labs can use to anticipate fragility and design measures for resilience.

Literature Review

Classifications in CubeSat Technology and Engineering Education

In a CubeSat program, students build an actual spacecraft that will launch into space. It will either work or fail and it is very public and very expensive. It uses real flight hardware, has hard deadlines and offers no opportunities to try again if something goes wrong. This is fundamentally different from engineering coursework or typical hands-on-learning which involves theoretical learning, laboratory work, or projects that use equipment designed to be educational, mostly safe, predictable, and forgiving of student mistakes. Because CubeSat programs behave differently from traditional educational activities, universities struggle to classify them within existing funding categories. This classification problem helps explain their documented high failure rates.

When CubeSats were introduced by Stanford and Cal Poly in 1999, they were easily identified as educational tools. As Berthoud et al. (2019) document, a CubeSat had a purpose as "educational projects for engineering students." These projects could give students a semester or year-long project that gave them something real to build and teach them engineering skills. Without a thriving commercial CubeSat market and government demand for CubeSat expertise, expectations for student outcomes fit clearly into the capstone project category within aerospace engineering departments which required minimal external funding, operating within semester timelines, valuing student learning over mission success.

However, CubeSat technology has had a radical transformation within the space economy since and has become an essential part of space operations for government and commercial use.

Reports show that while NASA faces dramatic budget cuts, experiencing an 89% decrease in its share of the federal budget since 1966 (Edwards, 2019) and now receiving $24.9 billion in 2025, Department of Defense space funding is at an all-time high at $43 billion, nearly double NASA's budget, supporting national security initiatives like the "golden dome" missile defense system which relies on satellite-based defensive capabilities (FY2025 Federal Space Allocations). This trend shows a stabilization in workforce development centered on CubeSat educational experiences while exposing significant funding shifts within the space community.

The BIRDS program is an example of the challenges a CubeSat program faces in meeting the educational needs of evolving technology. As Cho et al. (2022) explain, "HORYU-IV was no longer a simple educational satellite" but instead "aimed to generate several research publications based on the results of in-orbit experiments" while serving capacity building for national space programs. University engineering education structures, rigid in nature, have not met the pace of this market transformation. Like NASA, as Edwards (2019) pointed out "has displayed relatively little innovation regarding its governance and management structures," universities by nature operate with the same institutional rigidity that limit rapid adaptability.

As Cho et al. (2022) observe about CubeSat resilience, "The program management, rather than the project management, becomes important. The program management tasks are the ones for faculty members or staff, not the ones for students because the tasks are more than building a satellite." The space program’s most challenging issues revolves around continuity in program management, in-house structures that keep their roles, relationships, documentation and coordination used to bridge otherwise disconnected organizations. These practices function as coordination mechanisms of an interface such as roles, tools, routines, or funding structures that preserve the continuity across modular organizations (independent) pursuing shared objectives. These functions and roles are fundamental to resilience in all organizations.

Universities are now facing the support of workforce development programs for technologies central to national security yet continue to classify and fund them as semester-long student projects. Cho et al. (2022) go on to note that sustaining these programs requires that "the principal faculty must work really hard to get the funding" because there is no clear institutional category that provides appropriate reliable support for what these programs do. This classification gap pushes programs into boundary spaces, operating outside traditional structures as hybrid autonomous organizations (HAOs). Students organize themselves into workforce development programs with multi-year timelines, industry partnerships, and government contracts, often functioning as independent organizations rather than recognized university entities. These structural conditions help explain the 88% failure rate among university CubeSat programs and the 40% failure rate even after launch (Pham et al., 2024; Berthoud et al., 2019). Programs are not failing because students lack capability, but because they must operate in a boundary space where institutional support, funding, and continuity mechanisms are fragile by design.

CubeSat Classification for the Innovation Market

Due to the nature of the rapidly evolving technology inside space markets, to further understand the persistence of space labs in university settings, it is necessary to examine how universities interact with new technologies in the innovation markets. Market innovation research has identified fundamental shifts in how technologies develop and secure institutional support. CubeSat technology exemplifies the transformation described by Mazzucato and Robinson (2017) from “mission-oriented” to “diffusion-oriented” innovation paradigms, where “distributed agency” replaces centralized institutional control. In the mission-oriented era of the mid-20th century, government agencies such as NASA set clear objectives and coordinated resources toward those goals. Universities built supporting programs such as aerospace engineering departments to train engineers for careers that matched NASA’s long-term missions. The career path was structured by a clear category set by a central organization and was mission oriented.

However, Mazzucato and Robinson (2017) document a “visible shift in US space policy” away from NASA-led projects toward a decentralized ecosystem that includes private firms, public agencies, and nonprofit actors. In this diffusion-oriented environment, agencies shape “framework conditions and market opportunities through policies and contracts” rather than directing which technologies are developed. Aerospace departments, designed for the mission-oriented era, left with rigid categories and structures are not set up to adapt to the unpredictable nature of this type of diffusion market. As new technology is introduced, and evolves quicker than the institutions can categorize, often other entities fill in the educational gaps left.

CubeSat technology, a central technology to modern university space programs, exhibiting features of “distributed agency” and “nonlinear development,” two hallmarks of rapidly evolving innovation markets (Sprong et al., 2021), now move faster than the institutions that originally supported it. Sprong et al. (2021) also predict that “emergent self-organization” will appear when an institution cannot adapt quickly enough to support a technology. Student-led space labs are an example of this response. Initially operating outside formal academic hierarchies, these organizations now coordinate complex missions: building satellites, managing external funding, and partnering with industry. Champenois & Etzkowitz (2018) call these types of organizations that emerge in boundary spaces between institutions hybrid autonomous organizations (HAOs). These organizations draw resources from multiple domains while remaining outside the control of any single one. They serve as informal infrastructure, a micro-level response to institutional inertia (Sprong et al., 2021).

Diagnostic Architecture

To understand how university space labs function and persist, this study uses two frameworks: Nearly Decomposable Architecture (NDA) and Hybrid Autonomous Organizations (HAOs). These frameworks can identify the key actors in a complex ecosystem, how they interact, and the points where knowledge transfers and make it possible to locate areas where systems are fragile and at risk of failure as well as areas where resilience is built and reinforced.

In 1962, Herbert Simon introduced NDA to describe how complex systems can remain functional without centralized authority. Simon explained NDA using a biological and molecular analogy: Modules act like cells or molecular groups. They perform most of their work internally and interact most frequently with components inside their own partition. Interfaces are like bonds or connective tissue linking modules together. Interfaces are the locations where the modules exchange information, resources, or coordinate actions. Coupling refers to the strength of these bonds: strong and resilient inside modules, weaker and more fragile across external interfaces.

This separation in coupling strength allows modules to adapt within themselves without destabilizing the entire system. Internal changes can happen quickly, while the larger system evolves more slowly. However, Simon noted that these weaker external bonds can erode if not reinforced, leading to fragmentation. Interface mechanisms are the specific roles, processes, and tools that maintain connections at an interface and prevent them from degrading. These mechanisms differ by level and context: external interfaces (e.g., between a university and a government agency) may rely on formal contracts and continuity roles, while internal interfaces (e.g., between student cohorts inside a lab) may depend on onboarding processes, leadership's technical knowledge and shared documentation.

This analogy makes it easy to visualize how modules adapt quickly within their partitions while external connections can degrade if their interfaces are not actively reinforced. It is particularly relevant to the modular, multi-actor nature of the CubeSat ecosystem, where universities, government agencies, and industry partners must coordinate without shared authority. The research by Klessova et al. (2022) shows that NDA uses temporary agreements, shared milestones, and interface roles instead of centralized oversight. While this architecture makes rapid adaptation possible, it also makes the larger system inherently fragile: integration is costly, timelines are often misaligned across actors, and external interfaces must be deliberately reinforced, or they will degrade. These qualities make NDA a architectural map of where fragility is most likely to emerge, and which interfaces and mechanisms must be examined first.

Boundary Spaces and Hybrid Autonomous Organizations (HAOs)

While NDA provides the system-level map, it cannot explain how units operating at the edge of institutional systems persist over time. To understand this, we turn to the concept of boundary spaces, introduced by Champenois & Etzkowitz (2018). Boundary spaces are at the intersection of institutional zones where domains overlap. Unlike boundary lines, which simply demarcate separate domains, boundary spaces integrate elements from each (Champenois & Etzkowitz, 2018). Within boundary spaces, hybrid autonomous organizations (HAOs) emerge. These independent entities draw resources, expertise, and legitimacy from multiple institutional domains while remaining outside formal control by any one of them (Champenois & Etzkowitz, 2018). They often arise in response to gaps in institutional capabilities or when existing actors cannot adapt quickly enough to changing market demands.

Student-led space labs exemplify HAOs. Operating outside traditional academic hierarchies, they integrate functions typically distributed across universities, government agencies, and industry: acquiring external funding, managing partnerships, and coordinating complex technical projects. Yet their lack of formal classification makes them vulnerable. They must constantly navigate misaligned institutional logics and maintain tenuous connections to their surrounding institutions.

Together, NDA and HAO theory provide a multi-level framework for understanding CubeSat ecosystems. NDA maps the system-level architecture, showing where fragile external interfaces are most likely to fail. HAO theory focuses on the unit-level dynamics within boundary spaces, showing how university space labs must continuously manage both their external interfaces to larger NDA modules and their internal interfaces across teams, cohorts, and projects. This layered perspective is essential for analyzing program resilience in student-led space labs and for identifying where interventions are needed to reinforce structural integrity.

METHODOLOGY

This study is a diagnostic single-case study of Bronco Space Lab, a university-based CubeSat program that has demonstrated resilience across multiple student cohorts and projects. The methodology emerged from a literature review on open access to space and university CubeSat program failure, which identified two persistent fragility points across the sector: (1) knowledge loss during transitions and (2) instability in funding continuity. These findings clarify that failures in such programs are mainly structural and not technical, prompting the need for systems-level framework to diagnose resilience. Bronco Space Lab was selected because it represents a hybrid autonomous organization (HAO) operating at the edge of institutional systems (university, government agencies, and industry), drawing on multiple domains while remaining outside formal control by any single actor. Its multi-generational history and involvement in complex, multi-institutional missions make it an ideal case for identifying the structural mechanisms that support or undermine continuity in this class of programs.

This study applies Nearly Decomposable Architecture (NDA) (Simon, 1962) as the foundational framework to map Bronco Space Lab's (BSL) position within the larger CubeSat ecosystem. NDA conceptualizes universities, government agencies, and industry organizations as modules that conduct most of their work internally and are connected through interfaces (e.g., grants, contracts, milestone reviews). These modules, like molecules in a complex biological system, contain strong internal bonds but are connected externally through weaker couplings that are prone to degrading over time.

To construct the system-level map, we examined how Bronco Space Lab interacted with surrounding institutional modules through external interfaces such as funding agreements, launch contracts, and industry partnerships. We documented the interface mechanisms (e.g., communication roles, documentation protocols, reporting procedures) that maintained or failed to maintain these external interfaces over multiple generations. This mapping allowed us to locate potential points of structural weakness and identify the mechanisms most critical to preserving resilience over time.

At the unit level, we analyzed Bronco Space Lab as an HAO that must integrate resources and legitimacy from multiple institutional domains while navigating misaligned timelines, competing priorities, and the absence of formal classification. We examined both external interfaces surrounding NDA modules and internal interfaces within the lab itself. Internal interfaces include coordination mechanisms across sub-teams, disciplines, and student cohorts. We evaluated whether internal and external interfaces were reinforced by robust interface mechanisms such as integrated design reviews, structured onboarding, and standardized documentation, and we examined how knowledge was transferred across interfaces, particularly during cohort turnover or project handoffs.

The NDA framework provided six diagnostic dimensions used to identify potential stress points in the system.

1. Actor autonomy: the degree to which different parts of interdependent project actors operate independently. Two actors may have conflicting objectives (project completion, student education, innovation etc.). How many conflicting objectives and to what extent are they diverging.
2. Partitioned knowledge domains: the extent to which knowledge is siloed across modules. Certain groups may not share knowledge over time if knowledge becomes too specialized

and knowledge gaps become larger. What integration mechanisms are in place to ensure knowledge is easily obtained.

3. Emergent or ambiguous outputs: how often do project goals shift or remain undefined during development?

4. Temporal misalignment: differences in timing across modules, such as academic calendars versus project cycles. What types of milestone alignments are there or other mechanisms to offset the losses created by turnover?

5. Integration cost: the effort required to coordinate and synthesize modular work. Is effort sustainable at each interface? Is effort sustained systemically by faculty, processes, or places?

6. Coupling degradation: the tendency for relationships between modules to weaken over time. Are the planned interfaces (e.g., milestone reviews, joint activities) still occurring? Are all modules participating, or are some disengaging?

Following the identification of the six NDA diagnostic dimensions, the analysis was structured around four core structural elements of the system:

1. Modules: Distinct, semi-autonomous groups or organizations participating in the CubeSat program. At Bronco Space Lab (BSL), these include sub-teams organized by function (e.g., mission operations, power systems, software), as well as institutional and external partners.

2. Couplings: The linkages that connect modules, which can be strong, weak, stable, or prone to degradation. Couplings determine the degree of coordination and the speed at which information or resources can move between modules.
3. Interfaces: Specific connection points where two or more modules interact directly to exchange information, transfer resources, or coordinate tasks.
4. Interface mechanisms: The formal or informal structures that sustain interface function, such as leadership roles, project management tools, meeting protocols, or shared documentation repositories.

Each structural element would be assessed with the following process and a focus on identifying points of potential knowledge loss, and where resilience mechanisms were in place to maintain coordination:

1. Locate all internal and external interfaces within the module being examined.
2. Apply the six NDA diagnostic dimensions to classify each interface.
3. Identify the mechanisms sustaining each interface.
4. Assess the coupling or bond strength of each mechanism to evaluate resilience or fragility.

During execution, it became clear that many interfaces could not be fully identified without first mapping what become known as “micro-modules.” An additional step of identifying and classifying rotational micro-modules was incorporated into the process prior to completing interface mapping.

Planned Procedure: The intended process for this study was to locate all internal and external interfaces within Bronco Space Lab, apply the six NDA diagnostic dimensions to classify each interface, identify the mechanisms sustaining them, and document coupling or bond strength to assess resilience or fragility.

Actual Procedure: In practice, interfaces could not be fully identified without first mapping the micro-modules they connected. This adaptive step provided the foundation for a more accurate classification of interfaces and their mechanisms. By incorporating micro-module mapping into the process, the study produced a more complete picture of the lab's interface architecture and resilience mechanisms than would have been possible under the original plan. The following analysis section presents the structural features revealed through this adapted methodology.

Data sources included peer-reviewed literature, internal program reports, mission updates, technical papers, conference proceedings, government and industry websites. We also reviewed gray literature, including student-authored reflections and lab documentation, and integrated qualitative data from interviews with coordinators, faculty, sponsors, and students when available.

Analysis

Assessing each module, coupling, interface, and interface mechanism against the six NDA diagnostic dimensions, three structural features emerged as central to Bronco Space Lab's resilience profile:

1. Rotational Micro-Module Structure: BSL operates through overlapping, temporary micro-modules that cycle in and out over 1–4 semesters. These micro-modules can be

classified by functional role and by temporal position in the rotation cycle. The rotational structure produces predictable knowledge-transfer vulnerabilities and drives the formation of distinct micro-module classes.

2. Multi-Level Interface Architecture: Mapping revealed three categories of interfaces between knowledge holders:

    I. Concurrent interfaces: between active modules working in parallel.

    II. External interfaces**:** connecting BSL to outside institutional modules.

    III. Intergenerational interfaces**:** linking outgoing and incoming cohorts.

    These interface types exhibit different resilience and fragility patterns, particularly where timelines and coupling strength differ.

3. Interface Knowledge Classification: Two primary knowledge-transfer types were identified at interfaces:

    I. Institutional knowledge: deeply embedded in individuals or cohorts, at risk when personnel rotate out.

    II. Codified knowledge: documented and transferable independent of individuals.

    Interfaces dominated by institutional knowledge were more prone to degradation in the absence of robust mechanisms, while codified interfaces demonstrated greater resilience.

These findings represent an ongoing investigation. Not all modules, couplings, interfaces, and interface mechanisms have yet been mapped against all NDA dimensions. The features identified here reflect a partial but significant understanding of BSL's system-level resilience profile.

1. Critical Feature #1: The Rotational Nature of Micro-Modules

In our diagnostic analysis, we observed that Bronco Space Lab functions as a hybrid autonomous organization (HAO) that maintains external interfaces with surrounding NDA modules (universities, government agencies, and industry partners). This boundary module is internally composed of overlapping, rotational micro-modules, such as student cohorts, sub-teams, and project groups, that cycle in and out over time. This internal structure is a source of both flexibility and fragility. Micro-modules allow the boundary module to adapt quickly to new technical needs and funding opportunities, but their continuous reconfiguration creates points where knowledge transfer can fail, and internal or external interfaces can degrade. These vulnerabilities are often not visible when the boundary module is viewed as a single, stable unit.

The micro-modules within BSL are inherently temporary because they are populated by undergraduate students who transition in and out of the lab as they progress through their academic programs. Unlike the permanent institutional actors (faculty leads, administrative staff, and university-level structures), these micro-modules are assembled and dissolved on a semester or project cycle.

1.1 Predictability

Each micro-module exists for a fixed period: typically, one to four semesters, depending on the student's availability and the project timeline. Overlapping cohorts create partial continuity, yet turnover is constant where seniors graduate, incoming students require onboarding, and middle cohorts shift to new roles. This rotation is structurally embedded because BSL operates inside the semester calendar, making micro-modules fragile by design.

These rotations create predictable knowledge transfer issues: Incoming cohorts often join mid-projects, receiving information they cannot immediately act on. Middle cohorts pass along knowledge tied only to their current project phase, which may not help future teams. Outgoing cohorts graduate before projects are complete, leaving incomplete work and undocumented context. Resilience at these points depends on permanent interface mechanisms such as faculty, staff, or structured processes that can align knowledge overall program goals. Where those mechanisms are missing, knowledge may not transfer, and continuity is at risk.

1.2 Classification of Micro-Modules

To better characterize their fragility, micro-modules can be classified along two dimensions: functional role (e.g., Electrical team, Power team, Mission Ops, CS team) and time position (e.g., Incoming, Established, Outgoing). This classification allows the analysis to better track interfaces and identify areas of risk.

2. Critical Feature #2: The Nature of the Interfaces and Knowledge Transfer

Initial observations suggest that special attention must be made to categorizing specialized knowledge to support interface structures Two interfaces were found that have different fragility types:

1. Codified interfaces: These can be supported through structured mechanisms such as walkthroughs, onboarding systems, documentation repositories, or integrated design reviews.
2. Institutional knowledge interfaces: These rely on tacit, experience-based knowledge held by individuals or groups. When these individuals rotate out, their knowledge is often lost.

The latter category poses significant challenges for knowledge transfer, particularly when compounded by the realities of academic schedules, physical distance, and time constraints. Hands-on learning is inherently tied to in-person experience and repetition, making it less accessible to newcomers and increasing the risk that critical knowledge will be lost when micro-modules turn over or knowledge must be transferred over distance and time. Understanding the relative importance of codified vs. institutional knowledge interfaces will be central to the next phase of the study. This will inform not only how internal and external interfaces are mapped, but also which interface mechanisms are most effective in mitigating fragility.

3. Critical Feature #3: Interface Mapping

Once the micro modules had been identified and interface nature is understood, each interface had to be captured to assess the full set of connections in the lab's architecture. This map will identify:

- Interfaces between micro-modules across generations (e.g., outgoing and incoming cohorts on the same project).
- Interfaces between concurrent micro-modules working on different projects.

- Interfaces to external NDA modules (e.g., universities, government agencies, industry partners).

Because most micro-modules operate on short 1–2 year timelines, these interfaces are frequently reconfigured, and knowledge transfer between them is inconsistent. Documenting these relationships will allow us to understand which interface mechanisms (e.g., continuity roles, onboarding systems, documentation repositories) are most critical to resilience, and which gaps lead to degrading in both internal and external coupling. A preliminary flow chart will be developed to visualize these interfaces, showing the rotational nature of the micro-modules and their points of contact. This chart will also capture external dependencies, such as multi-institutional projects where other universities bring their own micro-modules and unique funding pathways into the boundary module.

3.1 Failure Analysis and Backward Tracing

During the interface mapping process, it was found that backward tracing would be a critical validation of interface vulnerability. This approach involves documenting instances of unexpected confusion, project delays, or knowledge gaps among micro-modules, then tracing backward to identify where specific knowledge transfer should have occurred but failed. Examples of observable failures may be students repeating work already completed by previous cohorts, teams making decisions without awareness of prior technical choices, integration problems stemming from undocumented design rationale, or new cohorts unable to operate systems developed by outgoing teams.

To map failure backward, the analysis will identify: (1) what knowledge was needed, (2) where that knowledge should have been gained, (3) which interface mechanism was responsible for the transfer, and (4) why the transfer failed (weak coupling, missing documentation, temporal misalignment, etc.). These backward-traced failures will be matched to interface mechanisms to determine which are vulnerable to degradation or what interfaces are necessary in places that have been overlooked for support.

Ongoing Analysis

This analysis forms the basis for the next stage of analysis where the goal is to generate the complete architecture of the Bronco Space Lab using the NDA dimensions to identify the interface mechanisms that affect resilience and the conditions under which they fail. Each interface will be evaluated for the type of knowledge (codified, institutional, or both) it transfers. This architecture will then serve as the foundation for extracting a set of heuristics, the simple, evidence-based rules that predict where resilience and fragility emerge. These heuristics will be used to develop a diagnostic scaffold to anticipate fragility and design interventions that reinforce continuity in similar classification environments.

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