From Ethical Frameworks to Engineering Practice: Student-Driven Aerospace Systems in the Emerging Space Economy

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The University of Colorado, Boulder

Author: Emma Herzog

Faculty Advisors: Sarah Stanford-McIntyre, Catherine Ambler, Barbra Sobhani

Abstract

The rapid growth of the global space economy has expanded technological capabilities while simultaneously raising concerns about equitable participation. In previous research, *Ethical Pathways to Integrate Earth and Space Economies* (Herzog, 2025), I argued that ethical governance frameworks, circular economic models, and collaborative public–private research partnerships are necessary to prevent the emerging space economy from reproducing the same structural inequalities seen in terrestrial industries. While these frameworks remain valuable, new developments in the aerospace sector suggest that additional pathways for expanding participation may be emerging from within academic and open engineering communities.

This paper explores how student-driven and open-source aerospace initiatives can function as practical mechanisms for expanding access to space development. By leveraging modular hardware architectures, open-source software platforms, and collaborative research networks, university-led projects are increasingly capable of developing mission-relevant technologies at significantly lower cost. These systems allow students, small research groups, and institutions with limited resources to participate in hardware development, systems engineering, and mission design—areas traditionally restricted to well-funded government agencies or major aerospace corporations.

Through an analysis of distributed satellite architectures, collaborative engineering ecosystems, and university-led technology demonstrations, this research examines how educational space systems can contribute to a more distributed innovation landscape within the broader space economy. These initiatives also serve as training grounds for the next generation of engineers while fostering interdisciplinary collaboration and knowledge sharing across institutional and national boundaries. Ultimately, this paper argues that student-driven and open-source aerospace development can complement existing ethical and governance frameworks by creating new entry points into the space economy, helping to cultivate a more resilient, inclusive, and globally collaborative model of space participation.

1. Introduction

The contemporary space economy is frequently characterized as entering a period of rapid democratization, driven by declining launch costs, the emergence of commercial providers, and the increasing availability of small satellite technologies. At first glance, these developments suggest that access to space is becoming more widely distributed, enabling new actors to participate in exploration, research, and infrastructure development. However, this perception of democratization masks a more complex structural reality. While access to space as a destination has become more economically attainable, access to space as a domain of participation, particularly in the design and development of mission-relevant technologies, remains unevenly distributed across institutional, national, and socioeconomic boundaries (OECD, 2019; Space Foundation, 2022; UNOOSA, 2021).

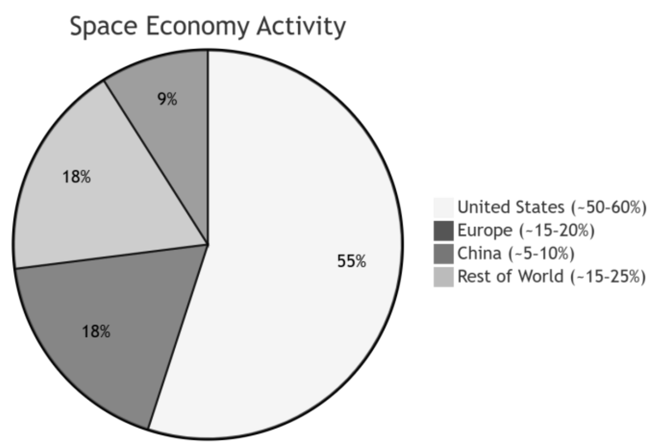


Figure 1: Global Distribution of Space Economy Activity (Source: Data adapted into pi-chart from OECD Space Economy Report (2019))

This distinction between access to space and access to participation is critical. The ability to launch payloads or purchase data does not equate to the ability to meaningfully shape the systems that define the space economy. Instead, participation at the level of engineering, systems integration, and mission design continues to be concentrated among well-funded government agencies and major aerospace corporations. As argued in prior work, this concentration reflects deeper structural inequalities embedded within both technological and governance systems, raising concerns that the emerging space economy may reproduce patterns of exclusion that have historically characterized terrestrial industries.

Previous research has approached this challenge primarily through the lens of governance, emphasizing the need for ethical frameworks that promote inclusivity, sustainability, and collaboration. Mechanisms such as public–private partnerships, circular economic models, and international regulatory coordination have been proposed as pathways for mitigating inequities and expanding participation (Herzog, 2025). While these approaches remain essential, they operate at a level that does not fully address how participation is enacted in practice. Policies can define who is allowed to participate, but they do not necessarily determine who is able to participate in a meaningful way.

A parallel transformation is occurring within academic institutions and open engineering communities, where student-driven aerospace systems are increasingly capable of producing functional and, in some cases, mission-relevant technologies. These systems leverage modular hardware architectures, open-source software ecosystems, and collaborative design practices to achieve outcomes that would have previously required significantly greater resources. As described in the submitted abstract, student-led initiatives allow individuals and institutions with limited access to capital or infrastructure to engage directly in engineering processes, thereby redefining participation within the space economy.

This paper builds on earlier work by shifting the focus from abstract ethical frameworks to the practical realities of engineering systems. It argues that student-driven space missions represent a convergence of economic efficiency and ethical design, functioning not only as educational tools but as distributed infrastructure that expands participation and reshapes innovation. By examining the economic structures, design methodologies, and collaborative dynamics of these systems, this research demonstrates that student missions provide a tangible pathway toward a more inclusive and resilient space economy.

2. Background and Context

2.1 Economic Concentration and Structural Barriers

The perception that the space economy is becoming more accessible is largely driven by advancements in launch technology and the growth of commercial providers. Companies such as SpaceX have significantly reduced the cost per kilogram to orbit, enabling a wider range of payloads to be deployed. However, focusing solely on launch costs overlooks the broader economic structure of space systems, which includes development, testing, regulatory compliance, and operations, as seen in figure 2 below. These components often represent the majority of total mission cost and remain largely inaccessible to smaller institutions (Space Foundation, 2022).

Furthermore, participation in the space economy is shaped by regulatory frameworks that are not evenly distributed across regions. Spectrum allocation, export controls, and licensing requirements can create significant barriers for emerging actors, particularly those operating outside established aerospace ecosystems (UNOOSA, 2021). These constraints reinforce existing hierarchies, limiting the ability of new participants to contribute to technological development.

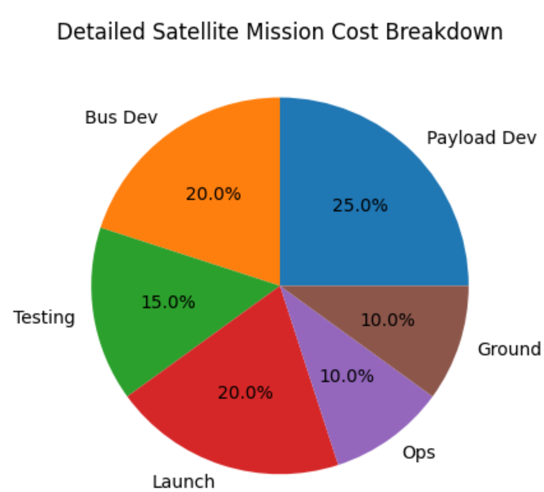


Figure 2: Breakdown of Satellite Mission Costs (Source: NASA Systems Engineering Handbook; Space Foundation)

This structural concentration is not merely an economic issue but also an epistemic one. When access to engineering processes is limited, so too is the distribution of knowledge and expertise. This creates a feedback loop in which established actors continue to dominate innovation, while new entrants face barriers to entry that extend beyond financial constraints.

2.2 Emergence of Small-Scale and Modular Systems

The development of CubeSat technology marked a significant shift in how aerospace systems are conceptualized and built. By standardizing form factors and simplifying integration requirements, CubeSats enabled universities and smaller organizations to participate directly in satellite missions (Heidt et al., 2000; Swartwout, 2013). This shift demonstrated that meaningful contributions to space-based research could be achieved at a fraction of the cost of traditional missions.

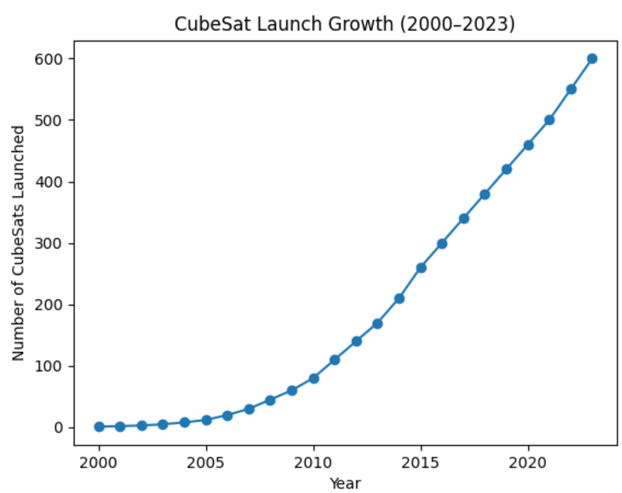


Figure 3: Growth of CubeSat Launches Over Time (Source: Swartwout CubeSat Database)

In parallel, advances in open-source software have further reduced barriers to entry. Platforms such as the Robot Operating System and GitHub allow developers to build upon shared frameworks, accelerating development, and enabling collaboration across distributed teams (Quigley et al., 2009). These tools have contributed to the emergence of a more accessible engineering ecosystem, in which knowledge and resources are shared rather than centralized.

Student-driven systems exist at the intersection of these technological and cultural shifts. By combining modular hardware with open-source software and collaborative design practices, they represent a form of engineering that is inherently distributed and accessible.

3. Methodology

This research adopts a multi-layered analytical methodology that integrates literature synthesis, systems engineering frameworks, and comparative case-based reasoning to examine how student-driven aerospace systems influence participation in the emerging space economy. This approach is intentionally interdisciplinary, combining perspectives from aerospace systems engineering, innovation theory, and science and technology studies to capture both the technical and structural dimensions of participation.

3.1 Literature Synthesis and Theoretical Framing

The literature synthesis draws from three primary domains: (1) economic analyses of the global space industry, (2) systems engineering methodologies, and (3) research on engineering education and open innovation ecosystems. Economic reports, including those from the Organization for Economic Co-operation and Development (OECD) and Space Foundation, provide insight into structural concentration and cost distribution across the space sector, highlighting persistent barriers to entry despite declining launch costs (OECD, 2019; Space Foundation, 2022).

To contextualize engineering practice, this research incorporates principles from the NASA Systems Engineering Handbook, which emphasizes lifecycle integration, verification and validation (V&V), and risk-informed design as foundational elements of aerospace system development (NASA, 2020). These principles serve as a baseline for evaluating how student-driven systems diverge from or approximate traditional aerospace development models.

Additionally, innovation theory and open systems research are used to frame student-driven systems as distributed knowledge networks. Concepts such as open innovation (Chesbrough, 2003) and collaborative design ecosystems (Klumpar et al., 2021) provide a theoretical basis for understanding how knowledge sharing and modular architectures enable participation beyond centralized institutions. This interdisciplinary synthesis allows the analysis to move beyond purely technical evaluation and consider broader systemic implications.

3.2 Systems-Level Analytical Framework

To evaluate student-driven aerospace systems, this research adopts a systems-level analytical framework that considers three interdependent variables: cost structure, accessibility, and participation outcomes. These variables are not treated as independent factors but as components of a feedback system in which changes in one dimension influence the others.

This framework is informed by systems engineering approaches that emphasize trade-space analysis and lifecycle considerations. In traditional aerospace development, cost, reliability, and performance are tightly coupled through optimization processes that prioritize risk mitigation (NASA, 2020). In contrast, student-driven systems redistribute these relationships by introducing iterative development cycles, modular architectures, and reduced upfront cost requirements.

The analytical framework therefore focuses on how design decisions, such as the use of commercial off-the-shelf (COTS) components, open-source software platforms, and modular subsystem integration, alter the system-level trade space. These decisions are evaluated in terms of their impact on both technical feasibility and accessibility, allowing for a comparative assessment of how different engineering approaches influence participation.

3.3 Case-Based Reasoning and Comparative Analysis

Rather than focusing on a single system, this research employs case-based reasoning to identify patterns across multiple student-driven aerospace initiatives. These include university CubeSat programs, student-built planetary rovers, and open-source satellite and robotics platforms. Case-based reasoning is particularly well-suited for this analysis because it allows for the identification of recurring design principles and structural characteristics across diverse implementations (Yin, 2018).

The selected cases are analyzed qualitatively, with attention to:

- System Architecture (modular vs. integrated),
- Development Process (iterative vs. sequential),

- Resource Constraints (budget, facilities, team expertise),
- and Knowledge-Sharing Practices (open-source vs. proprietary).

By comparing these dimensions across cases, the analysis identifies common patterns that define student-driven systems as a distinct mode of engineering practice. This approach enables the research to generalize beyond individual projects while still grounding conclusions in real-world examples.

3.4 Conceptual Modeling of Participation Dynamics

Building on the literature synthesis and case analysis, a conceptual model is developed to represent the relationship between cost, accessibility, and ethical participation. This model is not intended as a predictive tool, but as a heuristic framework for understanding how engineering decisions propagate into broader socioeconomic outcomes. This relationship is illustrated in Figure 4, which conceptualizes participation as an emergent property of engineering design decisions.

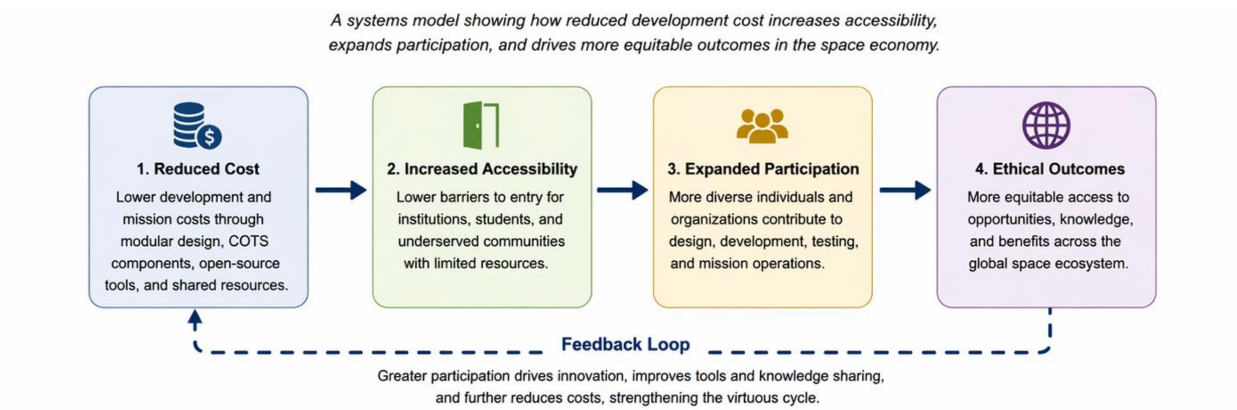


Figure 4: Conceptual model linking cost, accessibility, and ethical participation, adapted from systems engineering principles (NASA, 2020), open innovation theory (Chesbrough, 2003), and ethical framework research (Floridi et al., 2018).

The model conceptualizes participation as an emergent property of system design. Reductions in cost, achieved through modularization, iterative development, and shared resources, lead to increased accessibility, which in turn expands participation. Increased participation then contributes to more distributed knowledge production and more equitable access to engineering processes.

This approach aligns with research in sociotechnical systems, which emphasizes that technological systems are inseparable from the social structures in which they operate (Floridi et al., 2018). By framing participation as a systems-level outcome, the model connects engineering practice directly to ethical considerations, demonstrating that inclusivity is not only a policy objective but also a design outcome.

3.5 Limitations and Scope

It is important to note that this methodology emphasizes qualitative and conceptual analysis rather than quantitative modeling. While this limits the ability to produce numerical predictions, it allows for a deeper examination of structural relationships that are not easily captured through purely quantitative methods. Additionally, the focus on student-driven systems may not fully represent all emerging forms of distributed aerospace development, though it provides a representative and accessible subset for analysis.

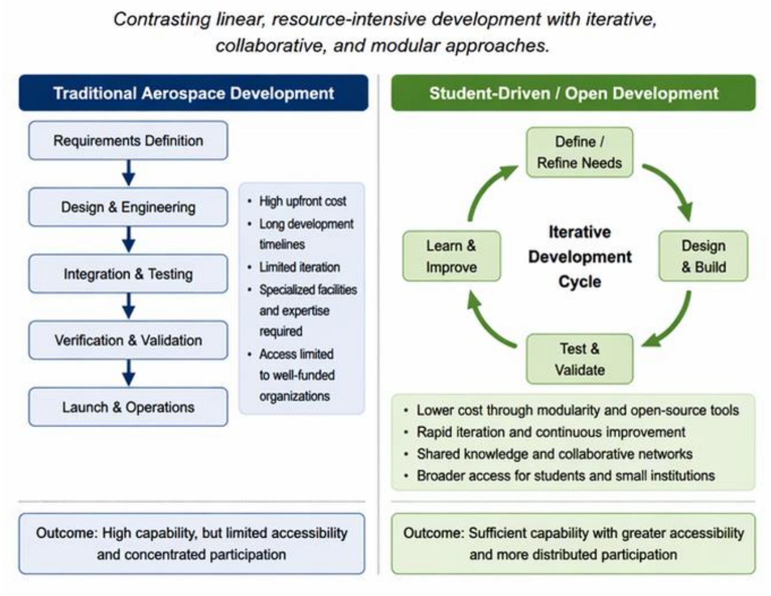
4. Results and Analysis

4.1 Cost Restructuring and the Reframing of Economic Access

One of the most frequently cited advantages of student-driven aerospace systems is their reduced cost relative to traditional mission architectures. While this observation is often presented as a simple comparison of budgets, it is more accurately understood as a restructuring of how cost functions within the engineering process itself. Traditional aerospace systems operate within a model in which cost is directly tied to reliability, redundancy, and risk mitigation, resulting in highly optimized but rigid systems that require extensive capital investment. In contrast, student-driven systems redistribute cost across time, labor, and iteration, allowing for functional systems to emerge through repeated refinement rather than upfront perfection (NASA, 2022; Space Foundation, 2022). This distinction between linear and iterative development models is illustrated in Figure 5 and reflects established differences between traditional aerospace systems and CubeSat-based development approaches (NASA, 2020; Heidt et al., 2000; Swartwout, 2013).

Figure 5: Lifecycle comparison between traditional aerospace systems and student-driven systems, adapted from NASA systems engineering lifecycle models (NASA, 2020) and iterative

design practices observed in small satellite and student-led missions (Source: Heidt et al., 2000; Swartwout, 2013).



This distinction is significant because it challenges the assumption that lower cost necessarily implies lower capability. Instead, student-driven systems demonstrate that capability can be achieved through alternative pathways that emphasize adaptability and modularity. The use of commercial off-the-shelf components, for example, is not simply a cost-saving measure, but a design philosophy that prioritizes accessibility and replaceability over bespoke optimization. Similarly, open-source software frameworks reduce development time while enabling collaboration across distributed teams, effectively lowering both financial and informational barriers to participation (Quigley et al., 2009).

When viewed through this lens, cost is not merely reduced, but redefined. It becomes less of a barrier to entry and more of a variable that can be managed through design decisions and organizational structure. This shift has broader implications for the space economy, as it expands the range of actors who can contribute to technological development. Institutions that would otherwise be excluded due to financial constraints are able to participate, not by competing directly with large-scale missions, but by operating within a different economic model altogether.

4.2 Innovation as an Emergent Property of Constraint

The relationship between constraint and innovation is often acknowledged but rarely examined in depth within the context of aerospace engineering. Student-driven systems provide a particularly clear example of how constraints can function as generative rather than limiting forces. Operating within environments defined by limited funding, evolving team expertise, and constrained access to facilities, student teams are required to engage in forms of problem-solving that prioritize flexibility and resourcefulness over optimization.

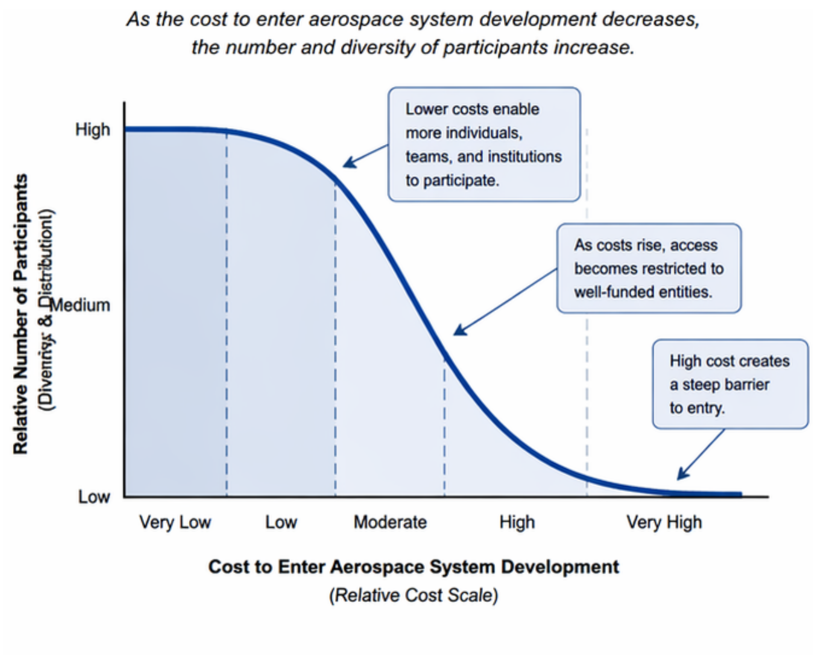
This dynamic produces a mode of engineering that is fundamentally iterative. Rather than attempting to eliminate uncertainty through extensive upfront analysis, student teams often engage with uncertainty directly, using testing and failure as mechanisms for learning and refinement. This approach aligns with research in design theory, which suggests that innovation frequently emerges from iterative engagement with constraints rather than from attempts to eliminate them entirely (Cross, 2001). In practice, this can lead to the development of hybrid systems, unconventional material choices, and adaptive architectures that would be less likely to emerge in environments where reliability and predictability are prioritized above all else.

It is also important to recognize that the lower stakes associated with student-driven systems enable forms of experimentation that would be difficult to justify in high-cost missions. The ability to test novel ideas without the risk of significant financial loss creates a space in which innovation can occur more freely. Over time, these experimental environments contribute to the broader innovation ecosystem, as successful concepts are identified, refined, and eventually integrated into larger-scale systems. In this way, student missions function not only as sites of learning, but as distributed research and development platforms that complement more traditional forms of aerospace innovation (Klumpar et al., 2021).

4.3 Ethical Participation as a Structural Outcome

The ethical significance of student-driven systems is often framed in terms of their educational value or their ability to inspire future engineers. While these aspects are important, they do not fully capture the deeper structural implications of these systems. The expansion of participation enabled by student-driven missions is not simply a byproduct of their existence, but a direct consequence of how they are designed and organized.

By lowering financial barriers and utilizing accessible tools, these systems enable individuals who might otherwise be excluded from aerospace development to engage directly in engineering processes. This has implications not only for workforce diversity, but for the distribution of knowledge and expertise within the field. University clubs and projects provide tend to attract a larger range of majors and disciplines as students seek out new opportunities. When participation is expanded, the range of perspectives and approaches to problem-solving also increases, contributing to a more robust and adaptable innovation ecosystem (Floridi et al., 2018). As illustrated in Figure 6, participation increases nonlinearly as cost barriers decrease, reflecting trends observed in global space economy data (OECD, 2019; Space Foundation, 2022; UNOOSA, 2021).



At the same time, the collaborative nature of student-driven systems fosters forms of interaction that differ significantly from those found in traditional aerospace environments. Rather than operating within rigid hierarchies, student teams often rely on fluid roles and shared responsibilities, requiring individuals to engage across disciplinary boundaries. This interdisciplinary collaboration not only enhances technical outcomes but also supports the development of communication and coordination skills that are essential for complex system design.

Figure 6: Relationship between cost of entry and participation in aerospace system development, based on economic analyses of the global space sector and access barriers (OECD, 2019; Space Foundation, 2022; UNOOSA, 2021).

Knowledge sharing further reinforces the ethical dimension of these systems. The use of open-source platforms and publicly accessible documentation, often associated with universities, allows knowledge to extend beyond individual teams or institutions, creating a network of shared resources that can be built over time. This stands in contrast to proprietary models of development, in which information is often restricted in order to maintain competitive advantage. In this sense, student-driven systems embody an alternative model of technological development, one that prioritizes accessibility and collective progress over exclusivity.

4.4 Reframing Student Missions as Infrastructure

Perhaps the most significant conceptual shift proposed in this paper is the reframing of student-driven systems as infrastructure rather than temporary educational tools. Infrastructure is typically understood as the underlying systems that support broader activity, often operating in the background and enabling more visible forms of development. When viewed through this lens, student missions can be understood as providing foundational support for the space economy in several key ways. First, they function as entry points, allowing individuals to gain the skills and experience necessary to participate in more advanced systems. This role is particularly important in a field where access to hands-on experience is often limited. Second, they serve as testing environments, enabling the exploration of new ideas and technologies in a context that allows for failure and iteration. Third, they contribute to a distributed network of innovation, connecting individuals and institutions through shared knowledge and collaborative projects.

This perspective challenges traditional hierarchies within aerospace engineering, which tend to prioritize large-scale missions as the primary drivers of innovation. While these missions are undoubtedly important, they are not the only sites of meaningful development. Student-driven systems operate in parallel, providing flexibility and accessibility that complement the scale and stability of institutional efforts. Recognizing this complementary relationship is essential for understanding the full scope of the space economy and for identifying pathways toward more equitable participation.

5. Discussion

5.1 The Interdependence of Ethics and Engineering Practice

One of the central insights that emerges from this research is that ethical participation in the space economy cannot be achieved solely through policy or governance frameworks. While such frameworks are necessary for establishing guidelines and constraints, they do not determine who is able to engage in the processes of design and development. That determination is shaped by access to tools, knowledge, and engineering environments, all of which are directly influenced by how systems are structured at the level of practice.

Student-driven missions occupy a critical position within this landscape because they operate at the intersection of accessibility and capability. They demonstrate that it is possible to engage in meaningful aerospace development without the resources typically associated with large-scale missions, thereby expanding the range of potential participants. At the same time, they embody ethical principles such as inclusivity and collaboration not as abstract ideals, but as practical outcomes of their design and organization.

This interdependence between ethics and engineering practice suggests that efforts to create a more equitable space economy must address both levels simultaneously. Policy can create the conditions for participation, but it is through systems like student-driven missions that participation is realized in practice. Without such systems, ethical frameworks risk remaining theoretical, disconnected from the realities of how engineering work is conducted.

5.2 Tensions Between Accessibility and Reliability

While the advantages of student-driven systems are substantial, it is important to engage critically with their limitations to avoid oversimplification. One of the most significant challenges associated with these systems is their relative lack of reliability compared to traditional aerospace missions. Limited resources, shorter development timelines, and evolving team expertise can all contribute to variability in performance and outcomes.

However, this tension between accessibility and reliability should not be understood as a binary tradeoff. Rather, it reflects different priorities and operational contexts. Traditional missions prioritize reliability because the cost of failure is extremely high, both financially and scientifically. Student-driven systems, by contrast, operate in environments where failure is not only expected but incorporated into the learning and development process.

This distinction allows for a more nuanced understanding of how different types of systems contribute to the overall space ecosystem. Rather than attempting to replicate the reliability of large-scale missions, student-driven systems can focus on their strengths, including adaptability, experimentation, and accessibility. Over time, improvements in tools, infrastructure, and support systems may help to bridge some of these gaps, further enhancing the impact of student missions.

5.3 Implications for the Future of the Space Economy

As the space economy continues to evolve, the role of distributed and accessible systems is likely to become increasingly important. The expansion of satellite constellations, the development of in-space manufacturing, and the growing interest in planetary exploration all point toward a future in which participation will need to be more broadly distributed in order to sustain innovation.

Student-driven systems provide a model for how this distribution can be achieved. By enabling participation at smaller scales and across diverse contexts, they contribute to a more resilient and adaptable ecosystem. This is particularly relevant in the context of global collaboration, where differences in resources and infrastructure can create barriers to participation. By lowering these barriers, student missions create opportunities for engagement that extend beyond traditional centers of aerospace development.

At the same time, realizing this potential will require intentional support from institutions, governments, and industry. Funding, mentorship, and access to facilities are all critical factors in determining the success of student-driven projects. Integrating these systems into broader frameworks of support can enhance their impact while ensuring that they remain aligned with both economic and ethical objectives.

6. Reflection

Engaging with this research has shifted my understanding of what it means to participate in the space economy in ways that extend beyond technical considerations. Initially, my focus was primarily on large-scale structures such as policy frameworks, economic models, and institutional systems. While these remain important, this work has highlighted the extent to which participation is shaped by everyday engineering practices and the environments in which those practices occur.

Student-driven systems have revealed a different way of thinking about engineering. In these environments, the boundaries between learning and doing are often blurred, and the process of building systems becomes a collective effort that is shaped by collaboration, iteration, and shared problem-solving. This stands in contrast to more traditional models of engineering, which can be highly structured and hierarchical. At the same time, this research has also made it clear that accessibility is not evenly distributed even within student systems. Access to resources, institutional support, and mentorship continues to influence which projects are able to succeed. This highlights the importance of connecting grassroots engineering efforts with broader support structures to ensure that opportunities for participation are truly expanded.

Perhaps the most significant takeaway from this work is the realization that ethics in engineering is not something that can be added after the fact. It is embedded in the decisions that shape how systems are designed, who can contribute, and how knowledge is shared. Student-driven missions provide a tangible example of how these ethical considerations can be integrated into the engineering process itself, offering insights that extend beyond the context of aerospace.

7. Conclusion

The expansion of the space economy presents a unique opportunity to rethink how participation in technological systems is structured. While advancements in launch capabilities and satellite technologies have made space more accessible in certain respects, they have not fully addressed the deeper question of who is able to engage in the processes that drive innovation. This paper has argued that student-driven aerospace systems represent a critical mechanism for addressing this gap, providing a model of development that is both economically efficient and ethically grounded.

By restructuring cost, these systems lower barriers to entry and enable participation from a broader range of actors. By operating within collaborative and open frameworks, they promote knowledge sharing and interdisciplinary engagement. And by functioning as distributed infrastructure, they contribute to a more resilient and adaptable innovation ecosystem. These characteristics position student-driven missions not as peripheral educational tools, but as integral components of the broader space economy.

At a time when the future of space development is being actively shaped, the importance of inclusive and accessible systems cannot be overstated. If the goal is to create a space economy that reflects shared human values rather than existing inequalities, then participation must be expanded atits foundation. Student-driven systems offer a practical and immediate pathway toward achieving this goal, demonstrating that the way we build systems can fundamentally influence who is able to be part of them.

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