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Achieving Low-Cost, High-Reliability Payload Services Through a Collegiate Approach Using Standardized Satellite Bus Architectures

Nathan Drzadinski, Griffin Hentzen
Purdue Space Program
414-731-8220 | 414-344-8657
ndrzadinski@gmail.com | griffinhentzen@gmail.com

ABSTRACT

The space community is rapidly expanding, especially in the Small Sat sector. The incremental implementation of more compact technology and the decline of launch costs lowers the barrier to entry into space, allowing for new actors to expand into the market. Two important players in this incremental process are collegiate satellite programs and commercial satellite-as-a-service (SataaS) providers. Collegiate satellite programs have previously occupied the low-cost, low-reliability market. These are often in a one-time collaboration with a professor or company, always resulting in the design of a unique bus derived by mission-specific stakeholder needs. In contrast with university programs, current commercial SataaS providers occupy the medium/high-cost, high-reliability market. This reliability is accomplished by developing standardized satellite bus systems and implementing recurrent engineering. It would be highly desirable for a player to create a low-cost solution without sacrificing the high reliability that common industry entities provide. Such a solution would tremendously increase access to space for actors within industry, academia, and government.

This paper introduces the concept of a collegiate SataaS program, wherein student satellite teams develop a standardized bus to host a variety of customer payloads across separate missions. The paper features this type of program's life cycle, benefits, and trade-offs, as well as an example in Purdue Space Program's Boiler Bus program. These collegiate SataaS programs create and exclusively occupy a low-cost, semi-high-reliability market space by combining the inherent low cost of collegiate programs with the high reliability and quick development times brought about by standardization seen in industry. If widely adapted, this type of program could have substantial benefits for the space industry, lowering the barrier to entry for new players and allowing for further proliferation of scientific and industry driven progress.

1. INTRODUCTION

The global space economy is growing tremendously, with an expected $1.8 trillion market valuation by 2035, tripling from its current value.[1] This is mainly due to decreasing launch costs, investment diversification, and increased commercial innovation. Over the last few years, numerous modern launch systems have drastically reduced launch costs. For example, SpaceX's Falcon 9 system at $2,600 per kg and Falcon Heavy system at $1,500 per kg, compared to the Delta II system at $38,800 per kg and the Space Shuttle's $65,000 per kg.[2] This order of magnitude difference in cost is estimated to decrease steadily with next generation launch systems like Starship and New Glenn becoming operational. This decrease in cost significantly increases access to space. Also, a newfound breadth of investors are finding their way into private investment in the space industry. Despite setbacks due to Covid, the amount of money coming into the space sector continued to grow.[3,4] New actors are having an easier time addressing the large monetary hurdles they encounter. This decrease in cost and increase in revenue is allowing more work to be put into commercial innovation. Innovation then helps decrease the price of development, including non-launch costs and gets more attention from investors. Satellite-as-a-service providers are an essential catalyst for this innovation, offering standardized satellite bus platforms.

Satellite-as-a-service (SataaS) is becoming increasingly popular because it allows individuals or companies to focus on their mission without the complex, risk-intensive, and time-consuming process of designing a complete satellite. Commercial SataaS products are highly reliable due to their standardized architecture's repeated flight heritage. Utilizing SataaS solutions also lowers the time from mission conception to orbit, allowing companies to remain at the frontier of their field more aggressively. In addition, SataaS maintains a healthy level of mission implementation flexibility. Service providers may offer additional service options like system-level integration, testing, and mission operations, as shown in Table 1.[5] Not only does this service streamline the process to orbit, but it also supplies large programs with a more affordable way to test individual elements for iterative development. Many benefits are exemplified in the small satellite sector particularly, due to its higher affordability, lower development time, and increased flexibility.

Table 1: SataaS Mission Implementation Flexibility[5]

Option	Product or Service		
	Satellite Bus	**System-Level Integration and Testing**	**Mission Operations**
1	SataaS Provider	SataaS Provider	SataaS Provider
2	SataaS Provider	SataaS Provider	Customer/Partner
3	SataaS Provider	Customer/Partner	Customer/Partner

Collegiate satellite teams are a different type of bus provider, offering even lower costs and a potential pipeline of workforce ready professionals. Traditional collegiate satellite programs partner with a professor, organization or company, looking to put a payload on orbit. The team then creates a unique satellite bus to host said payload. Finally, the team and partner coordinate spacecraft integration, testing, launch, and operations. Once the payload's mission ends, the collegiate team starts this process again, usually with a new partner. Collegiate programs are inherently more affordable as they lack a profit motive and have access to institutional facilities. Additionally, collegiate programs are eligible for various grants and launch opportunities, including NASA's Small Business Technology Transfer (STTR) program and CubeSat Launch Initiative (CSLI).[6,7] A unique benefit of collegiate satellite teams is a partner's ability to recruit directly from talent they helped cultivate.

To better facilitate the growing space industry, it is imperative to explore new solutions. This paper explores how collegiate teams that utilize a standardized satellite bus architecture are capable of providing low-cost, high-reliability payload hosting to a wide variety of partners. The creation of a collegiate SataaS program is a difficult proposition; however, this model has the potential to provide great benefit to partners as well as the collegiate team. The life-cycle, advantages, trade-offs, and stipulations of such a program from a student and customer perspective are outlined using the following format: Section 2 provides an overview of a collegiate SataaS program's life-cycle and interface with external partners. Section 3 discusses the advantages and trade-offs of a collegiate SataaS program compared to traditional collegiate teams and industry alternatives from a customer perspective. Section 4 discusses advantages and trade-offs of a collegiate SataaS program compared to a traditional collegiate team from a student perspective. Section 5 provides a collegiate SataaS program example in Purdue Space Program's Boiler Bus Program. Finally, Sections 6 and 7 provide a conclusion and future developments.

2. COLLEGIATE SATAAS PROGRAM OVERVIEW

2.1 Collegiate SataaS Program Lifecycle

This subsection illustrates, in detail, the program life cycle of a collegiate SataaS team, as in Figure 1. This lifecycle is broken down into three main phases: Start-up, Continuous Development, and Steady-State. Each phase begins with the program reaching a significant milestone in development: Program Conception, Pathfinder Mission, and Nth Mission.

Start-up Phase

A collegiate SataaS program is conceptualized in one of two ways: a program created from scratch or an existing collegiate satellite team deciding to transition to the SataaS program structure. Regardless, once a team decides to develop a collegiate SataaS program, they start with background research and preparation. One part of this background research is determining payload bay design drivers for the standardized satellite bus architecture. Research to identify these design drivers includes determining groups of potential partners and their payload needs. Two possible sources of partner needs are historic payload requirements and current commercial SataaS alternatives. These design drivers must be constrained by the team's capabilities to ensure

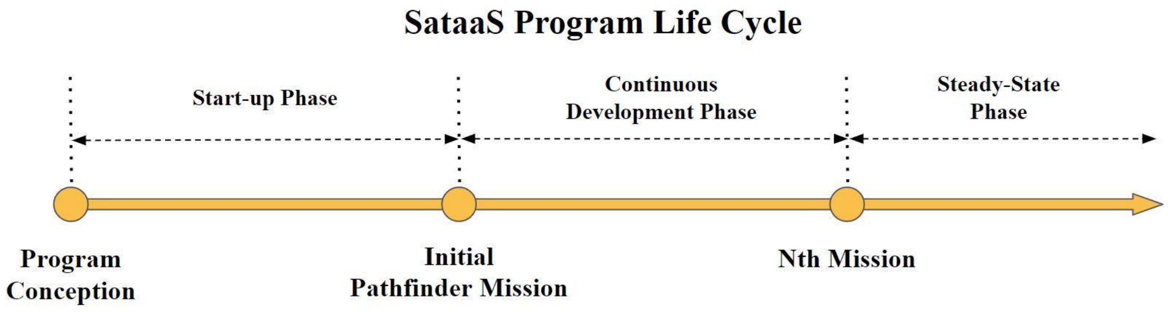

Figure 1: SataaS Program Life Cycle

an achievable first-generation architecture. Analyzing architecture feasibility is not typically a concern for traditional collegiate programs but is critical for the success of collegiate SataaS programs. Teams may assess their capabilities by polling student interest and compiling available resources such as university facilities, funding opportunities, and subject matter experts. This background research will inform the team's conceptual design and satellite bus requirements, including payload support capabilities.

The next stage of the process is designing the standardized satellite bus. While this paper does not delve into the engineering design process, which other groups have extensively covered,[8] it's important to note there are unique considerations for collegiate SataaS programs. One such consideration is that SataaS architectures accommodate a variety of payloads with different centers of mass and rigidity, a key differentiator from traditional collegiate programs. The testing regimen should ideally reflect this diversity by incorporating a variety of mass emulators. Given the high stakes of creating a successful first-generation bus, collegiate SataaS programs are likely to incorporate a significant portion of Commercial-Off-The-Shelf (COTS) components into their first-generation satellite bus. This may increase the cost per satellite, but it significantly enhances the satellite bus's reliability.

The start-up phase concludes with a pathfinder mission, which serves as the ultimate bus-level technology demonstration. It hosts a testing suite payload with the sole purpose of certifying the first-generation satellite bus architecture. For every given satellite bus requirement or advertised payload support capability, there would be a verifying instrument. For instance, the satellite bus may have a requirement pertaining to pointing stability. To test this requirement, the pathfinder payload may include an Attitude Control System (ACS) to perturb the satellite. This perturbation would simulate undesired momentum imparted by a customer payload onto the bus that would need to be counteracted. The pathfinder mission, therefore, plays a crucial role in verifying the satellite bus's capabilities and certifying its architecture.

Finding a launch provider for the pathfinder mission with no standalone scientific payload or customer funding is more challenging; however, the team has multiple paths to orbit. First, the team could apply through standard rideshare programs such as NASA's CSLI, which has continued to trend towards student learning experiences rather than strictly scientific payloads.[7] Programs like NASA CSLI have historically been the primary driver of academic access to space and are a viable route for collegiate SataaS programs. Another route is to acquire a secondary payload from a customer that could finance a launch opportunity, as the team may have otherwise done in a traditional structure. Although finding a customer could be challenging due to not having a flight-certified system, it will become increasingly feasible for future pathfinder missions. Finally, a collegiate team can receive a free launch opportunity from a launch provider or coordinator. However, it is difficult to find an opportunity like this; thus, this route should be independent of mission planning.

Once on orbit, the spacecraft would begin operations to certify the capabilities of the satellite. After the testing suite payload verifications have concluded for the first time, the team would operate any secondary payloads. The team would then intermittently repeat the testing suite payload verifications to certify the architecture's continued performance over the course of its life. This allows for data collection on the long-term survivability of the satellite bus and its constituent components. In addition to intermittent testing, the team would monitor the satellite through end of life for the pathfinder mission.

Continuous Development Phase

The success of the first-generation pathfinder mission would begin the continuous development phase. The collegiate SataaS team would start operating as a commercial SataaS provider, using the first-generation architecture for all subsequent missions and ensuring that all customer payloads are supported by a flight-proven satellite bus. A flight-proven architecture substantially increases reliability, which is discussed further in sections 2.2 and 3.2. During this time, the team would start developing a second generation of this architecture, presumably aiming to lower the cost per satellite as this is the best opportunity for improvement. Decreasing costs are most easily attained by migrating COTS components in-house. In-house components are inherently less expensive than COTS alternatives but have lower initial reliability. A primarily in-house architecture can gain the same system level reliability as a primarily COTS alternative through its pathfinder and subsequent missions providing flight heritage.

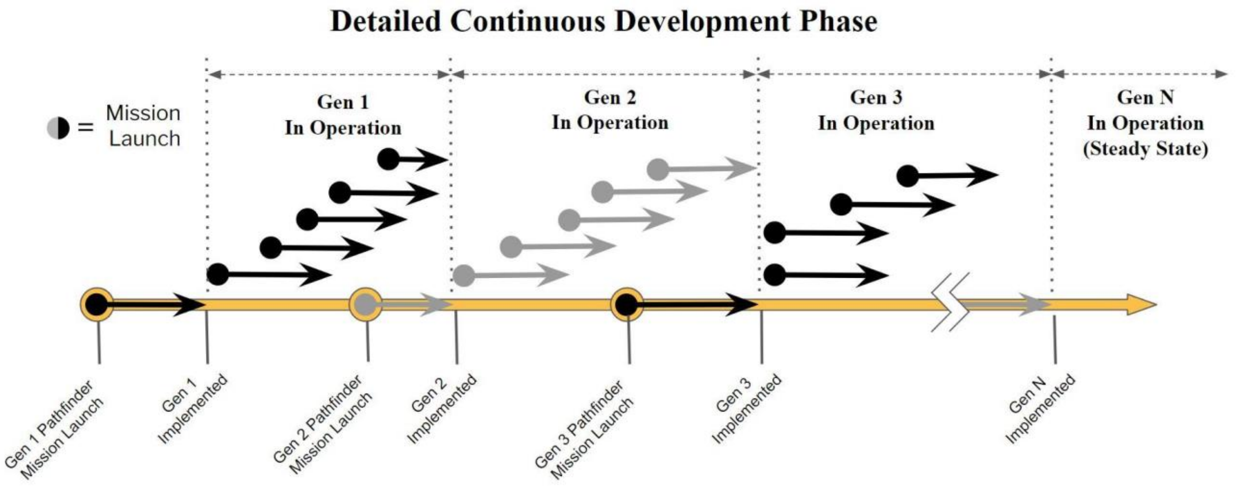

Figure 2: Detailed Continuous Development Phase

After a substantial number of advancements are ready to be incorporated into the architecture, the team would certify the second generation of the architecture through a second-generation pathfinder mission. As shown in Figure 2, this new generation would replace the first and become the baseline for all subsequent missions until the following generation is certified. The team would continue this approach with a third generation and onwards, with each generation migrating more components in-house, or upgrading in-house components. After several generations, the design will stagnate, and the team will enter the steady state phase.

Steady-State Phase

Once several generations of architecture have gone through certification and retired, the team will eventually reach a point where further iterations would see no increase in performance or affordability. This marks the beginning of the steady-state phase. In this phase, the team continues to host customer payloads on their now highly reliable and low-cost bus. The primary defining trait of this phase is that the team would no longer be developing a future generation of their existing architecture. Instead, the team will likely begin designing a new architecture with different capabilities and system design drivers. The development of this new architecture would follow a process similar to the original one, with key advantages. This new architecture could utilize many of the same components as the team's existing architecture and would have a shorter start-up phase. Furthermore, the system design drivers would utilize background information from the original architecture, but the team's capabilities would differ, allowing for a more capable architecture.

2.2 Collegiate SataaS Program Customer Interaction

With the successful demonstration of the satellite's architecture, the team would begin partnering with customers to place their payload on orbit. A customer and collegiate SataaS team could start a partnership at any stage in the customer's payload design-cycle. After discussing with the collegiate team whether the

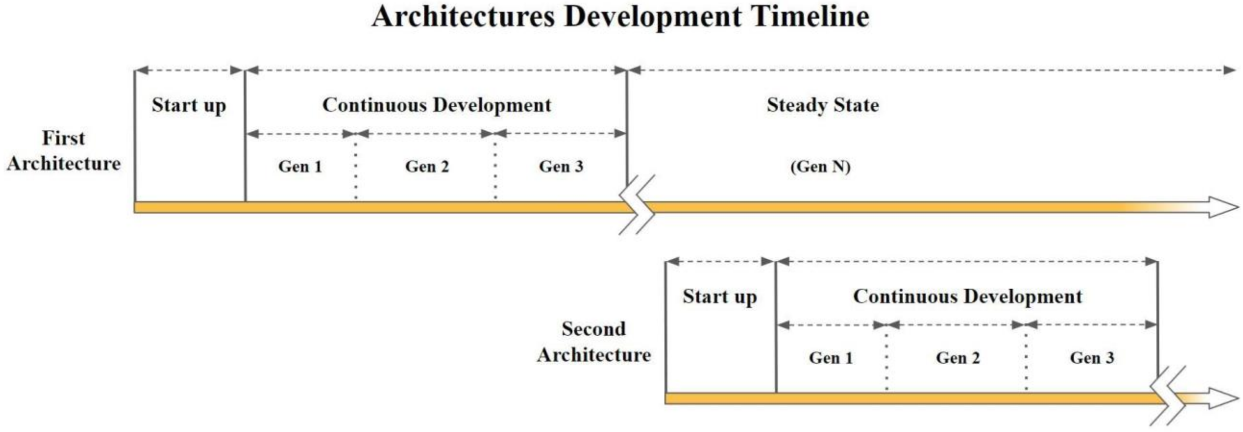

Figure 3: Architecture Development Timeline

capabilities offered by the satellite bus are suitable, the customer and team would officially form an agreement detailing their partnership. This partnership is very similar to how commercial SataaS providers operate, as outlined in the introduction, see Table 1. The partnership agreement would detail the roles and responsibilities of each party, including expected financial obligations, testing regimen, and launch coordination. This paper assumes that the collegiate team provides all these services in order to detail the collegiate SataaS program fully.

After forming an official agreement, the two parties would develop a mission plan. The collegiate SataaS team would then fabricate the satellite bus, and the customer would design and fabricate their payload, conforming to the standardized payload bay. Once the satellite bus and payload are fabricated, the customer hands over their payload to the student team for system-level integration and testing. The collegiate team would handle the logistics of finding and coordinating a launch opportunity. The collegiate team, in coordination with their payload partner, would facilitate spacecraft integration with the launch provider. Once on orbit, the collegiate team would operate the satellite and work with the customer to provide all payload data, which may be encrypted to meet specific customer needs. Numerous steps in the process offer low logistical overhead but allow for flexibility regarding customer involvement to provide a desirable customer experience.

3. PROGRAM IMPACT FOR CUSTOMERS

This section discusses the customer considerations for collegiate SataaS programs. Figures 4 and 5 illustrate the considerations when comparing a collegiate SataaS program to a commercial alternative or a traditional collegiate program. The Y-axis shows whether a given consideration of the SataaS program is advantageous or disadvantageous. These considerations evolve and are analyzed during the continuous development and steady-state phases. When comparing these different providers, there are numerous considerations to address.

3.1 Comparison of Collegiate & Commercial SataaS Providers.

Cost

A collegiate team can provide a lower cost per satellite than commercial providers due to the absence of profit motive, paid employees, taxes, or property expenses. Furthermore, collegiate SataaS programs have access to resources and funding opportunities such as on-campus makerspaces, labs, and university funds. As a result, the only expenses that collegiate SataaS teams would incur are the cost of materials to build each satellite bus, architecture development costs, and minor operational expenditures. A customer only needs to pay the required material cost to construct each satellite. The cost per satellite decreases substantially as further generations are developed.

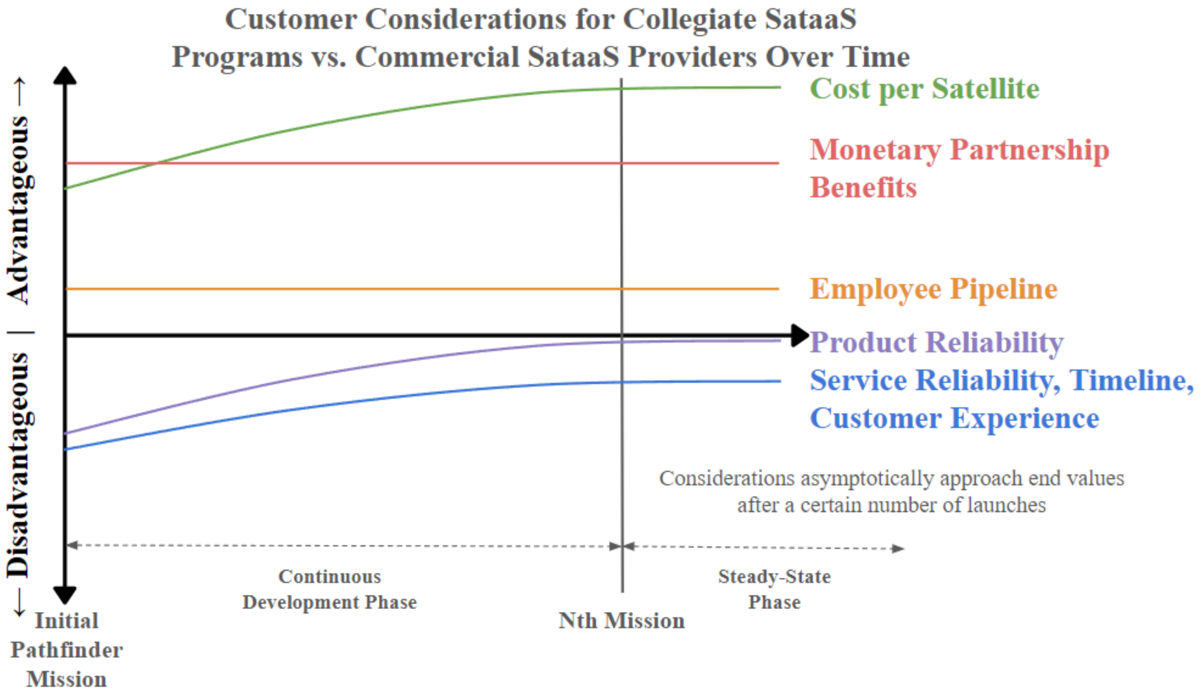

Figure 4: Qualitative Diagram of Customer Considerations for Collegiate SataaS Programs vs Commercial SataaS Providers Over Time

Monetary Partnership Benefits

In addition to receiving access to low-cost satellite services, companies that partner with collegiate programs are eligible for various monetary benefits. One such benefit is NASA's STTR program, which requires partnering with a non-profit research institution in order to receive funding for the maturation and commercialization of the company's technology.[6] Another substantial benefit is access to free launch opportunities such as NASA's CSLI program. This program accepts small satellites developed by educational and nonprofit institutions and offers a free launch to orbit.[7] While these opportunities are not necessarily as certain as other considerations, they can offer significant monetary benefits to a customer.

Employee Pipeline

A unique benefit of partnering with a collegiate program versus utilizing a commercial solution is that student workers can be hired directly from the program. After the start-up phase of the collegiate SataaS program, students can gain experience across the entire mission lifecycle. This includes developing a mission concept, creating a mission plan, interfacing with external partners, designing and manufacturing spacecraft hardware, performing spacecraft integration and testing, and operating spacecraft on orbit. These experiences enable the program to supply students to companies at any stage of development. Additionally, potential hires would have prior experience with an employer's specific product and team. Strong working relationships impart several benefits in the hiring process.

Product Reliability & Service Reliability

Initially, collegiate SataaS programs will have substantially worse anticipated product and service reliability than commercial alternatives since a single successful architecture demonstration by a commercial entity carries more weight than for a collegiate program. As time goes on, however, and the collegiate team continues to demonstrate success and increase the flight heritage of its architecture, the product reliability will tend to approach commercial alternatives. In contrast, collegiate service reliability will never truly equal industry due to the difference in experience and workmanship between the two entities, resulting in a higher risk of operational or manufacturing errors such as ESD events.

Timeline & Customer Experience

Timeline and customer experience for collegiate SataaS programs begin very low due to initial program turbulence and the inherent qualities of all student teams. As the cumulative experience of the program grows, the design process, manufacturing process, and all documentation become optimized, smoothing out turbulence and decreasing bus turnaround time. Furthermore, this iterative optimization would improve

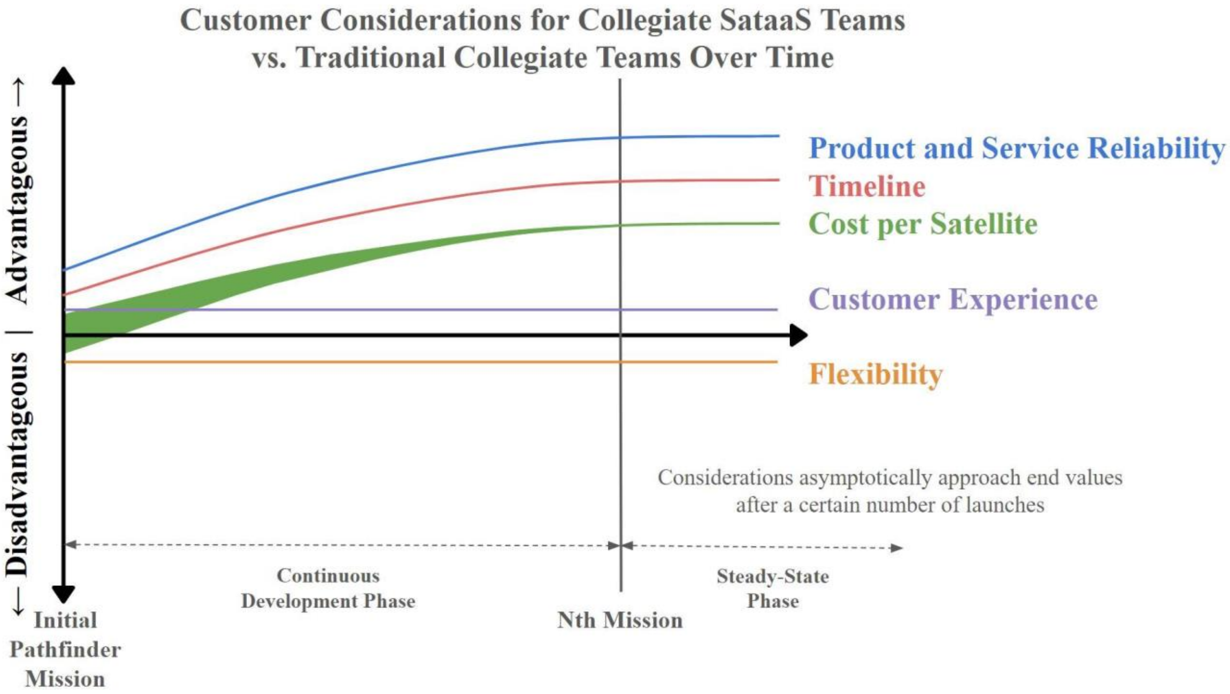

Figure 5: Qualitative Diagram of Collegiate Considerations for Collegiate SataaS Teams vs. Traditional Collegiate Teams Over Time

customer experiences as interfacing with external partners becomes more standardized. Despite improvements, students have other responsibilities and regularly cycle through the program. Therefore, collegiate teams will never operate as efficiently as full-time employees.

3.2 Comparison of SataaS & Traditional Collegiate Programs

Product & Service Reliability

Beginning immediately after the initial pathfinder mission, a standardized architecture with flight heritage will have higher product and service reliability than a traditional collegiate architecture. As launches continue, the team's ever-growing flight heritage and experience result in increasingly high product and service reliability. This reliability continues to grow before eventually asymptotically reaching a steady state.

Timeline

A SataaS team can provide a satellite in a substantially shorter period of time, as the team does not need to design a new satellite architecture for each mission as with a traditional team. As the team accumulates more experience with manufacturing and migrates components in-house, eliminating lead times, the timeline decreases.

Cost

The cost of a traditional collegiate satellite varies greatly. As a result, the difference in price between a traditional and a standardized satellite immediately following the pathfinder mission can be positive or negative. That being said, the cost per satellite of a first-generation architecture is expected to be higher than that of a traditional collegiate satellite due to the higher prevalence of COTS components. However, each satellite in a conventional program will likely require new prototypes, Flat Sats, and test articles, increasing the total mission cost. This contrasts with a standardized architecture, where subsequent satellites after the pathfinder mission would not necessitate repeating all exact development costs incurred previously. For example, each mission using a standardized bus requires no new prototype. The overall cost of a standardized satellite would be significantly lower than that of a traditional collegiate satellite after several generations due to the replacement of expensive COTS parts, in-house component upgrades, and the absence of developmental costs.

Customer Experience

The interfacing of customer and collegiate SataaS teams would be a standardized process and look similar from mission to mission. As a result, a SataaS collegiate team can operate with clearly defined, consistent expectations. This, combined with standard mechanical and electrical interfaces, creates a more desirable customer experience that changes very little with time.

Flexibility

The main drawback of collegiate SataaS programs is that the product cannot serve certain niche cases. If a customer's payload requires capabilities outside of the SataaS team's architecture(s), there is little flexibility in reaching a solution. For example, a payload requiring an orbit that experiences higher radiation than a SataaS product can support. For this consideration, a traditional collegiate solution is usually better, as they inherently tailor to unique payload requirements.

Employee Pipeline

Both traditional and SataaS programs allow partners to recruit students with general satellite design experience and experience working with their payload technology. However, a SataaS program provides a more well-rounded experience for students by enabling them to work on any part of the mission life cycle. In contrast, a traditional program runs on a step-by-step process, limiting the range of experiences available to potential employees.

4. DISCUSSION OF PROGRAM IMPACT FOR STUDENTS

4.1 Comparison Of Standardized & Traditional Collegiate Teams

Student teams considering switching to a standardized operation model from a traditional approach have a substantial amount to gain, but they should know all the advantages and disadvantages. Naturally, the benefits or drawbacks of specific considerations will change depending on the stage of the SataaS program. Figure 6 visually shows the advantages or disadvantages of a given consideration with respect to the three phases of the collegiate SataaS program lifecycle.

Credibility/Mission Success

Traditional collegiate missions generally utilize a mixture of COTS and in-house components. In contrast, the first generation of a standardized bus will likely use mostly COTS components, as discussed in section 2.1. For the initial pathfinder mission, this results in a higher expected mission success than traditional architectures. This advantage continues to grow as the architecture gains more flight heritage across several missions, ultimately plateauing at a reliability far above conventional architecture.

Programmatic Risk

SataaS programs carry significant programmatic risk because all development and investment in the first-generation architecture and pathfinder mission would suffer major setbacks if the initial pathfinder mission fails. Furthermore, pursuing a standardized architecture is a grand vision when compared with a traditional mission that usually has a specified scope and customer. This may initially cause low support from faculty, potential sponsors, and other parties; however, this consideration improves drastically after the first successful pathfinder mission. A team offering payload services with flight heritage is inherently more attractive to customers than a team offering to build an entirely new architecture. As a result, customers are more likely to partner with a SataaS program than with a team using the traditional model. With each completed mission and the continued growth of architecture flight heritage, the team can more easily secure future partnerships and operational funding.

Furthermore, traditional programs usually rely on a single partner for the mission and, as a result, are highly sensitive to mission cancellation. If that partner withdraws for any reason, all design work is negated, and the program faces substantial uncertainty. A SataaS program is more tolerant to mission cancellations since there are multiple missions in parallel, and while unfortunate, no design work is lost if a mission is canceled. As a result, SataaS teams will experience far less programmatic risk beyond their pathfinder mission, becoming more advantageous over time.

Work Desirability

As outlined in section 2.1, the collegiate SataaS team will need to invest more time into background research and high-level systems work than traditional teams. Despite its invaluable experience, this is generally undesirable work for students, and SataaS teams may find this detrimental during the first portion of the start-up phase. After this work has been completed, the SataaS team will design, fabricate, and test their architecture, making the desirability of work comparable to a traditional team for the remainder of the start-up phase. After a successful initial pathfinder mission, the desirability of work increases because multiple missions run concurrently, enabling students to engage in various aspects of the mission life cycle. This differs from traditional teams, which usually conduct missions sequentially. Furthermore, the shorter mission durations of a standardized team increase the likelihood that a student will see the mission from concept to end-of-life in a SataaS program. This experience enriches members and is not commonly provided by traditional teams, especially for complex missions.

Funding

Another temporary detriment to SataaS programs is the upfront funding required. Most initial pathfinder missions will need substantial investment from sponsors

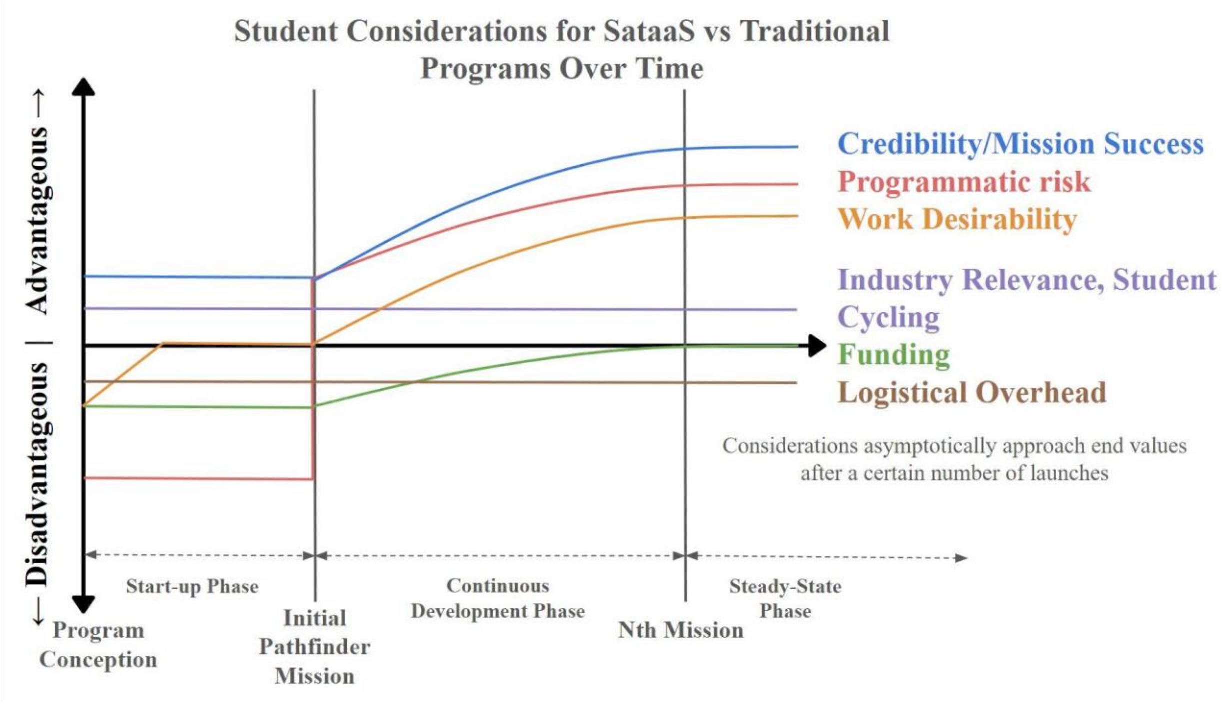

Figure 6: Qualitative Diagram of Student Considerations for SataaS vs Traditional Programs Over Time

and grants because there is no customer to fund the pathfinder. Furthermore, the program will have difficulty finding this investment due to a lack of program and partner credibility, and immediate mission impact. This is all in contrast to traditional teams whose projects are primarily funded by the customer and who benefit from partner credibility and mission inspiration. However, as with most other considerations, funding will become an advantage over time for SataaS teams. Following the initial pathfinder mission, SataaS teams will undertake multiple missions concurrently, becoming a credible, high-profile program with numerous partners. This facilitates easier and increased access to funds when compared to traditional collegiate teams.

Industry Relevance & Student Cycling

One consistent advantage of SataaS programs is industry relevance. Due to its higher nominal throughput, a SataaS program has a higher capacity to drive impact in the space industry than a traditional program.

Student cycling is detrimental to any collegiate program because of the resulting loss of knowledge and experience as members transition out without transferring all their knowledge to future members. Traditional teams attempt to smooth this transition by providing consistency in the design process; however, this is insufficient in many cases. For example, a member may gain exceptional experience in thermal analysis for one mission but subsequently leave without passing on their experience due to its irrelevance in the next developmental step. As a result, there would be no experienced student on the team for the thermal analysis needed in the next mission. A SataaS program allows for better transitioning of new members by ensuring there are experienced students working on all aspects of a mission lifecycle.

Overhead/Maintenance

One constant disadvantage that SataaS teams will need to face is the higher maintenance and logistical overhead associated with running a sustainable operation. SataaS programs demand continuous effort to sustain partner relations, ensure product and documentation quality, and meet general administrative needs. Partner relations for a SataaS program are more integral to its success and more numerous than those for traditional programs due to the fundamental structures of each program. Due to a higher level of documentation and higher emphasis on product quality, more effort will be needed to maintain SataaS program reliability. Finally, due to the parallel mission structure and subsequent program size, SataaS teams will assume more extensive administrative responsibilities.

4.2 Stipulations & Important Notes For Starting A Collegiate SataaS Program

While collegiate SataaS programs have many advantages, adapting a SataaS structure is not universally suitable for collegiate teams. Specifically, small teams, new teams, teams with poor documentation, and teams with limited networks are not well suited to this program structure. This section details these stipulations to guide collegiate readers considering implementing this program.

Collegiate programs with few members would need more labor to maintain the parallel mission structure in SataaS programs. Because of this, SataaS programs should be implemented at universities with sizable interested student populations that enable program growth. In addition, big drivers of this conclusion are the logistical overhead, initial programmatic risk, and initial systems work, which would hinder the program's ability to reach the continuous development phase.

For new collegiate satellite teams, it is highly advisable to establish a program with a traditional framework first, and then transition to the SataaS structure. This recommendation is primarily based on the significant logistical overhead, initial programmatic risk, and initial systems work that pose substantial barriers for teams in the start-up phase. With an existing program, the transition to the continuous development phase becomes more manageable, reducing the risk of dissolution or loss of members.

Documentation is the most critical part of a SataaS program since standardization is documentation at its core. If a team is unwilling to develop or maintain the thorough level of documentation required, the reliability of their architecture will decrease drastically, and they will lose much of the benefit that a SataaS structure offers.

Collegiate SataaS collegiate programs rely on their network to source payloads from a diverse range of interested parties. While not critical to the start-up phase of the program, having a robust and diverse network is a crucial factor in determining its success during the continuous development and steady-state phases. This network should encompass contacts throughout the entire space community and can be built using university avenues, program alumni, or traditional means.

5. THE BOILER BUS PROGRAM

Purdue Space Program’s Satellites (PSP-Sats) team is developing the Boiler Bus program, the pioneering example of the collegiate SataaS approach. Boiler Bus is envisioned to be a series of student-friendly, low-cost, and reliable universal satellite buses, with ground services, capable of hosting generic payloads for commercial, academic and government partners. This section seeks to present the program planning, background research and preparation, and system design work stages of the process, as well as reflect on lessons learned by the team. For this section it is important to note that the terms platform and architecture are used interchangeably.

Program Conception & Definition

Initially, PSP-Sats was operating as a traditional collegiate program. The team partnered with a professor looking to put a payload on orbit and began designing a satellite bus. However, during the conceptual design phase the mission was abruptly canceled due to unforeseen circumstances. Amidst obstacles searching for a new mission, the team decided to pivot the existing satellite bus design with a primary focus on supporting a variety of payloads. This concept was further refined to become the Boiler Bus program and has evolved to be the basis of the collegiate SataaS program model described in this paper.

The refined Boiler Bus program is built on core tenets that take the form of multiple minimum success criteria informing satellite bus platform design. These minimum success criteria are:

1. Boiler Bus platforms shall be Purdue student friendly.
2. Boiler Bus platforms shall be owned and dictated entirely by Purdue Space Program Satellites.
3. Boiler Bus platforms shall be a low-cost system.
4. Boiler Bus platforms shall be a reliable system.
5. Boiler Bus platforms shall be capable of supporting a wide range of generic payloads.

These minimum success criteria are broken down further into full success criteria that describe how the program's tenets dictate design in a more detailed manner. For instance, achieving full success criteria for being Purdue student friendly constitutes Boiler Bus platforms being designable, manufacturable, and operable by undergraduate students. The minimum and full success criteria are the driving factors for all current and future Boiler Bus platforms.

Background Research & Preparation

With the program framework and program design criteria, the team began background research and preparation for designing their first platform. The team was able to utilize prior work to accelerate this phase of the process. For instance, the capabilities of and resources available to the team had been firmly established through experience. However, this prior work also resulted in certain steps being taken out of order. One decision made out of order, the team decided the first platform should be sized as a 3U CubeSat supporting a ~2U payload, following the California Polytechnic State University - San Luis Obispo standard.[9] This early decision was justified by a 3U platform market existing, 3U being the optimal pairing of payload size with launch opportunity quantity, and the CubeSat standard was explicitly made for university students to help with initial development. The new background research focused on determining what payload bay design drivers would best serve the team's potential market. The team compiled the capabilities of commercial 3U platforms and historical 3U satellite buses. The team also looked at various standards used throughout the industry like common power lines and communications protocols.

This background research informed the initial platform's payload bay design drivers, which sought to provide a competitive alternative to market solutions. While this paper provides examples of payload bay design drivers, a comprehensive list or thorough explanation is not included. Some performance-based design drivers include maximum allowable mass and power draw, achievable point stability, and available payload data storage. Other design drivers meant to incorporate industry standards include power lines and communications protocols. Finally, certain design drivers are derived from a combination of performance and standards. For instance, the payload bay volume allocation of at least 96mm x 90mm x 200mm which is derived from being market competitive and allowing payloads to follow the CubeSat Kit Bus (CSKB) standard.[10]

Platform Design

The PSP-Sats team has derived system requirements, is currently finalizing its initial platform conceptual design, and has begun preliminary subsystem design. This section serves to describe example considerations unique to being a SataaS program. One example is that the electronics onboard the initial Boiler Bus 3U platform are being designed around the CSKB standard. While connection standardization is a system level design decision any team may make, the benefits of being able to interface with COTS components were a unique key consideration due to its effect on reliability of the initial pathfinder mission. A second example is the solar panel layout. While considering deployable solar panel layouts, the team accounted for space access geometry to accommodate the largest variety of payloads. The largest considerations for platform design have been reliability and cost, as these are the core aspects of a successful SataaS program. After a number of system level trades studies such as communications architecture, attitude determination sensor configuration, and deployable solar panel layout, the team's conceptual design has reached an estimated cost per satellite of $75,000-$85,000 while maintaining a high projected reliability.

Lessons Learned

Throughout the process of developing the Boiler Bus program, there have been numerous lessons learned specific to collegiate SataaS programs, helping inform a major portion of this paper. This section will serve to document the crucial lessons learned. First, PSP-Sats learned the importance of programmatic control and stability. The transition away from the team's primary mission was very disruptive and created a substantial amount of uncertainty regarding the team's future. This resulted in the team's foundational desire for program stability. Second, the team has faced significant disbelief that a program of this structure could succeed. Numerous entities including professors, potential customers, and non-stakeholders have expressed doubt in the program's ability to act as intended. While this has been the minority of interactions, it still represents an obstacle the team faces in acquiring funding, subject matter experts, and other resources, as well as maintaining high morale. Third, beginning as a traditional program and transitioning later benefited development greatly. The team was able to accelerate through multiple parts of background research and preparation, helping the team advance through the additional work necessary in a SataaS program. Finally, even with this acceleration, the team still had issues with work desirability, as described in Section 4.1, primarily affected recruiting and member retention. Despite all hardships faced, the program is currently on a strong upward trajectory, and has benefited greatly from these lessons learned.

6. CONCLUSION

In conclusion, a collegiate team utilizing a standardized bus approach can offer low-cost, high reliability satellite bus services, lowering the barrier to entry to space for a wide variety of customers. The collegiate SataaS team would begin by researching, designing, fabricating, testing, and flying a satellite bus housing a dedicated payload bay. The satellite bus's pathfinder mission would host an experimental payload designed solely to test and certify the architecture's design and advertised capabilities.

At this stage, the team begins working with customers to integrate and loft their respective payloads into orbit on subsequent satellites of the same architecture. These customers may include a professor with a scientific payload, a commercial entity seeking certification for a new product, or various other parties interested in LEO. A customer-developed payload integrates into the team's low-cost, flight-proven satellite bus to be launched on a rideshare program. Depending on the capabilities of both parties, the satellite can either be operated by the collegiate team or the customer. The collegiate team likely manages several missions with different customers running in parallel. This approach mirrors customer interaction with commercial SataaS providers but varies across universities.

There are several advantages, trade-offs, and other considerations for commercial customers considering partnering with a collegiate SataaS program. Holistically, collegiate SataaS programs are expected to achieve substantially higher affordability and comparable product reliability but a slightly lower service reliability and customer experience than commercial SataaS providers. Collegiate SataaS programs also allow for substantial monetary partnership benefits and provide a direct employee pipeline. An analytical comparison between collegiate SataaS programs and traditional collegiate programs shows that SataaS programs are more reliable, cost-effective, and expedient and offer a better customer experience than conventional programs. Despite these advantages, some customers may prefer a traditional collegiate team due to their higher flexibility or other extenuating circumstances. Ultimately, collegiate SataaS programs are a viable satellite bus provider.

Collegiate teams contemplating adapting the SataaS structure must consider numerous advantages, trade-offs, and stipulations. To start, collegiate SataaS teams may design for higher product reliability. Still, they would be challenged to find funding, carry high programmatic risk, have undesirable work, and need to maintain logistical overhead. Following the initial successful pathfinder mission, however, these challenges, except maintaining logistical overhead, become advantages along with a team's ability to handle student cycling. While SataaS programs are advantageous in the long term, they are not universally applicable and have several stipulations. Small teams, new teams, poorly documented teams, and isolated teams are likely not suited to implement this type of program.

PSP-Sats is proudly pioneering the collegiate SataaS model with their Boiler Bus program. Following the collegiate SataaS program lifecycle, the team has successfully gone through initial program conception and definition as well as finished background research and preparation for their first architecture, a 3U platform. Currently the team is working on completing their conceptual design and starting their preliminary subsystem design, taking into account the additional unique considerations of a SataaS program. Throughout the Boiler Bus development process, the team faced numerous hardships, but benefited greatly from lessons learned and are currently on an upward trajectory.

7. FUTURE DEVELOPMENTS

The authors desire to see numerous future developments of collegiate SataaS programs. One such development is the transition of several established traditional collegiate programs at large universities to the SataaS program model. Adapting this model would allow further programmatic insight by examining how programs evolve at different universities. Purdue Space Program is excited to pioneer this new collegiate model and looks forward to other universities adapting it as well. Another interesting development that could be explored is the potential of a distributed collegiate SataaS program. Small collegiate teams at separate universities could work together to act as a cohesive collegiate SataaS program. A few potential benefits could be access to resources and networks that provide additional funding avenues and the ability to find mission partners.

The authors envision the proliferation of collegiate SataaS programs driving significant impact in the space community. The widespread recognition of collegiate SataaS programs as viable, commonplace, and competitive with commercial alternatives is an inspirational notion. The possibility of students genuinely contributing to the space community and providing an educational workforce is an exciting prospect that the authors hope to see in the future.

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