Modular Rocket Design for Rapid and Reconfigurable Experimentation

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Abstract

Aerospace experimentation is often limited, not by ambition, but by the cost of repeatedly designing and manufacturing new launch vehicles. Whereas many advancements have been made in propulsion and materials, the structural design of rocket launch vehicles has remained comparatively static. For a single mission or experiment, an entire rocket must be built and designed from the ground up. Moreover, the majority of the launch vehicle is discarded after flight, with reusability not even considered. As such, many modern aerospace experiments are heavily constrained by two key factors: inefficiencies in development time and an increase in material cost. To overcome these inefficiencies, the Oconee County Rocketry Association (OCRA) explored an alternative approach to launch vehicle design through the incorporation of modular and reconfigurable threaded interfaces between structurally segmented rocket components. This report details the implementation of the design methodology into the launch vehicle design to support modularity and reconfigurability. In doing so, the conclusions of different experiments (or missions) detailed in the report support a design that favors efficiency in both time and material cost. As a whole, it studies the trends observed and challenges faced throughout the design, simulation, and assembly process in favor of achieving conclusive results in efficient experimentation methods. This has strong implications for the use of threaded modularity at a smaller scale to limit both high manufacturing costs and high experimentation timeframes. The conclusions also suggest a practical and scalable application of this vehicle design in the aerospace industry, especially alongside the growing use of 3D printing technologies in airframe manufacturing.

I. Introduction

Aerospace experimentation has long served as a means of exploring new environments and expanding scientific understanding. As missions grow more complex in their scope, however, launch vehicle development costs increase accordingly. In many cases, each new mission requires its own unique launch vehicle, both in design and manufacturing. This process can be incredibly inefficient as it drives up two key costs: money and time. Without consideration for reconfigurability in launch vehicle designs, key components of the rocket are simply discarded after a single launch, eliminating any chance for reuse. As a result, all material costs are blown on a one-time, single-mission use, and the time to design and manufacture another launch vehicle for another mission remains frustratingly static. These various limitations create a barrier for student and research teams looking to test multiple experimental concepts within constrained timelines and budgets.

To overcome the limitations of traditional single-use rockets, this work explores a modular and reconfigurable approach to launch vehicle design. Modularity is first achieved through structural segmentation. Rather than relying on long, pre-fabricated airframes, the launch vehicle is divided into smaller sections, allowing each component to be manufactured in-house using additive manufacturing techniques, namely 3D printing. The second aspect of modularity is implemented through threaded interfaces between each section, creating a repeatable and mechanically secure joint architecture. This design methodology not only simplifies assembly but also enables mission teams to focus solely on the development of experiment-specific components. As a result, manufacturing time and material costs are significantly reduced as shared components, such as the airframe, avionics bay, and booster, can be reused across multiple missions, allowing unique mission components to be integrated onto a common base rocket.

To implement the design methodology in real launch applications, the Oconee County Rocketry Association was tasked with developing different missions to be designed and launched on modular launch vehicles. Each subteam was responsible for designing a unique component or payload that connects seamlessly to the base rocket while pursuing a distinct experiment. Parker Timberman's Mission Air-Driven Gyroscopic Stabilizer (ADGS) introduces a duct in the nose cone to channel airflow into an internal turbine, focusing on increasing moment of inertia through rotational inertia and measuring stability through angular momentum analysis. Saahil Doshi and Sihoo Kim's mission titled Botanical Experiment on Aeronautical Mechanical Stress (BEAMS) focuses on a layered payload system designed to house bean samples and study how high-power flight stresses affect plant growth and health. George Gao, Emily Peng, and Benjamin Sayers' Mission Neredis-1 launches a multi-chamber biological payload to evaluate seedling resilience under high-altitude pressure and vibration. Cashton Isaac and Victor Piercy's Mission CC-9 tests a pendulum-driven spherical rover intended to help onboard "astronauts" quickly assess unfamiliar terrain conditions. Dimitri Do's Mission GYRO (Torquero-1) investigates passive spin generation through angled fin roots to evaluate its effectiveness and potential drawbacks. Finally, Daniel Donchenko and Janelle Davantes' Mission TuberRocket incorporates whale-inspired semicircular tubercles along fin leading edges to test their effects on stability, spin, ascent performance, and descent behavior. Together, these missions demonstrate how the modular design methodology results in rapid and reconfigurable experimentation.

This paper presents the design methodology of structural segmentation and threaded interfaces used to develop a modular, additively manufactured launch vehicle for rapid and reconfigurable experimentation. The proposed system is evaluated through OpenRocket-based aerodynamic and stability simulations. While full flight validation remains in progress, manufacturing and assembly testing demonstrate the feasibility of a reusable base launch vehicle capable of supporting a multitude of mission-specific configurations.

II. Design Methodology

Structural segmentation is the first aspect of modularity implemented into our launch vehicle design. Traditional high-power rockets often rely on long, pre-manufactured composite airframes that require specialized and expensive manufacturing processes. To avoid complex, out-of-house manufacturing, the base rocket was segmented into approximately 10-inch-long segments. This segmentation design allows for the entire rocket to be fully manufactured in-house using additive manufacturing methods. As a result, each segment of all mission-specific rockets was able to be fully manufactured out of Acrylonitrile Butadiene Styrene (ABS) filament with public-market 3D printing machinery. Not only does this make manufacturing simpler and more cost-effective, but it also allows for rapid prototyping with more cost-efficient filaments, such as Polylactic Acid (PLA).

Fig. 1 Modeled Launch Vehicle (A) and Exploded View of Structural Segmentation (B)

The second aspect of modularity is integrated into the launch vehicle design via threaded interfaces. Each segment of the launch vehicle incorporates a uniform threaded joint that secures tight connections between adjacent airframes. This method of fastening not only reduces assembly time but turns the rocket design into a reconfigurable vehicle. Because each segment is joined by the uniform threaded interfaces, mission-specific components can be easily exchanged out depending on the criteria of the mission. As a result, rockets do not need to be entirely redesigned to accommodate different experiments, but rather reconfigured as if each component were a simple building block that could be swapped and attached anywhere along the rocket. Along with increased efficiency, this design methodology also enables rapid experimentation. Because each base rocket section is kept uniform across all mission launch vehicles, this only requires one to two of the base rockets to be manufactured. When it comes time to launch each mission, the base section can simply be reused and reflown with new mission-specific components each time. Not only does this save time, but it also saves the material costs of manufacturing entirely new rocket bodies for each individual mission.

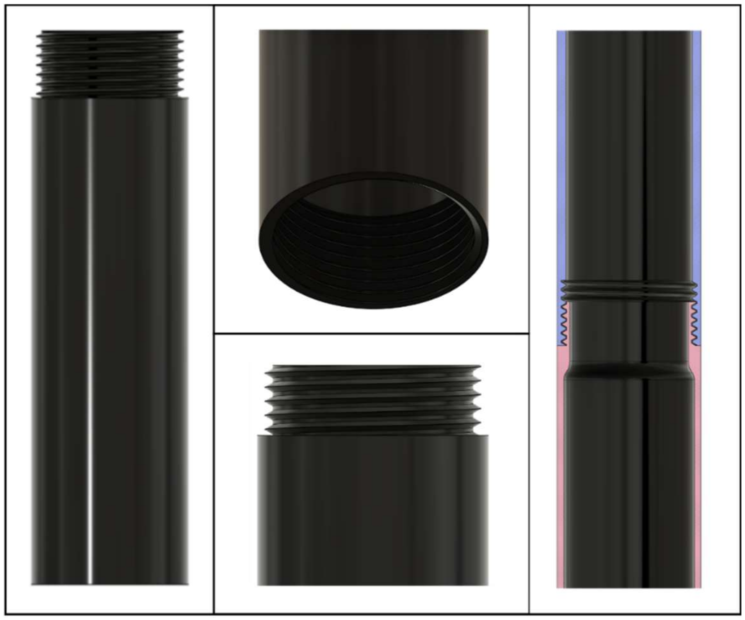

Fig. 2 Threaded Interface CAD Design and Integration

This design methodology is demonstrated through OCRA's mission launches, where each team implements structural segmentation and threaded interface joints into their mission-specific components. In doing so, the different missions highlight the wide range of applications supported by this modular framework.

The first example of modularity in the rocket is the way the body tube is assembled in separate threaded sections (Fig. 3). Rather than functioning as one continuous piece, the airframe is divided into individual segments. This structure allows sections to be added, removed, or replaced depending on the needs of a given experiment, providing flexibility without requiring a complete redesign of the vehicle.

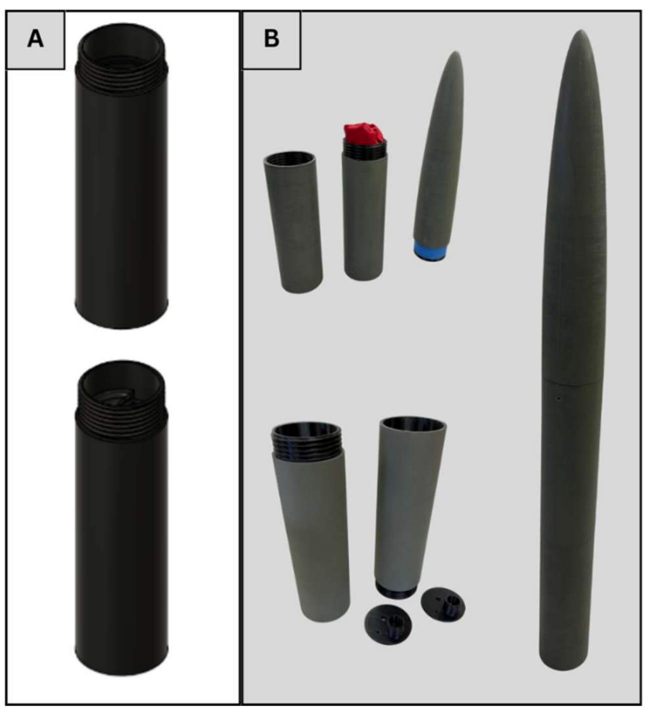

Fig. 3 CAD Airframe Segments (A) and ABS Printed Airframe (B)

Another example of modularity is seen in the rocket's ability to transition between larger and smaller diameter sections (Fig. 4). These transition components are designed to connect body tubes of different diameters, allowing the vehicle to accommodate varying payload volume requirements. By incorporating standardized transition pieces, specific sections of the rocket can be expanded to provide additional internal space for larger payload missions.

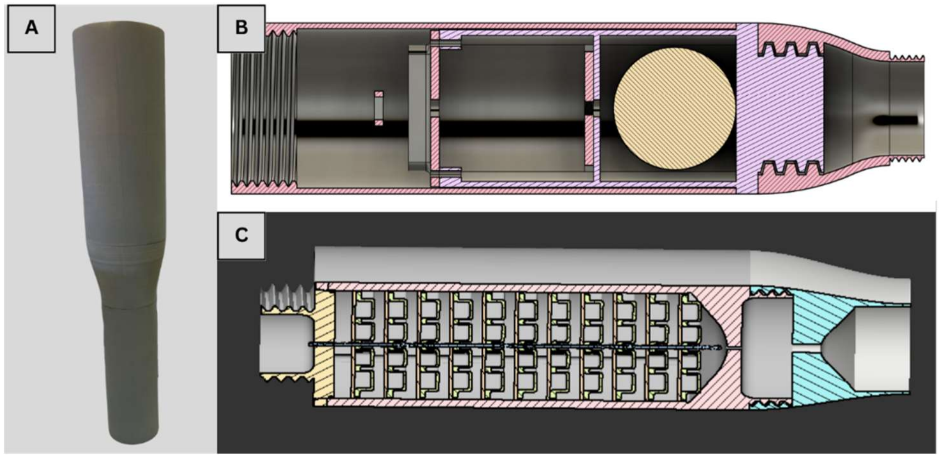

Fig. 4 3D-Printed Transition Airframe (A), CAD Model of Mission CC9 Transition Airframe (B), and CAD Model of Mission BEAMS Transition Airframe (C)

A third example of modularity is found in the fin can assembly (Fig. 5). The fin can is able to be exchanged independently of the main airframe, allowing fins to be angled or modified without altering the rest of the rocket. In addition, the fin mounting system enables different fin shapes to be swapped onto the same fin can structure. This design allows aerodynamic configurations to be adjusted without manufacturing an entirely new rocket body, while also supporting flexibility in motor selection and propulsion testing.

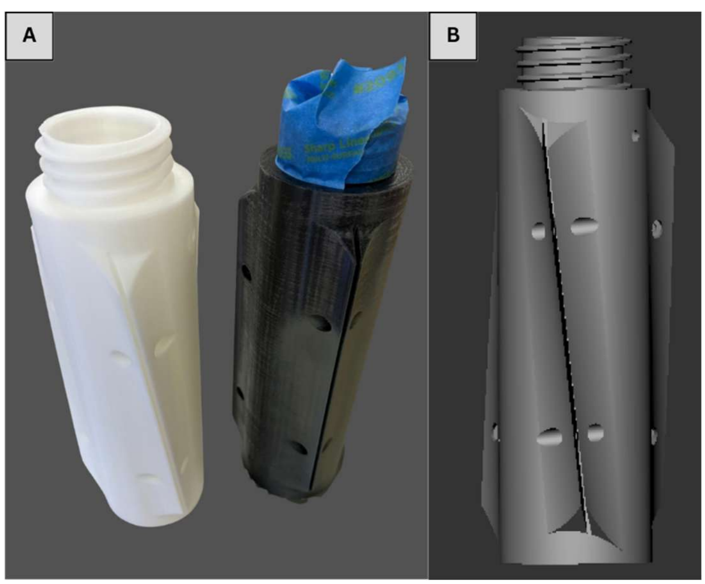

Fig. 5 3D-Printed, Mission-Specific Boosters (A) and CAD Model of Angled-Fin Booster (B)

III. Simulation and Performance Modeling

To validate the aerodynamic performance of each rocket developed under the modular methodology, every mission conducted OpenRocket simulations prior to launch preparation. Simulating each vehicle required a complete structural recreation of the rocket from standard CAD software into the OpenRocket platform (Fig. 6). In doing so, each team implemented its structurally segmented design directly into the simulation environment for performance validation. Once each rocket was fully reconstructed and weighed with all mission-specific components included, teams evaluated various H-Class motor options, nose cone geometries, and fin configurations to optimize performance during ascent. These simulations generate key flight data, such as projected apogee, stability, CP, and CG. From these data points, each team was able to verify that its rocket met the criteria for a successful and stable launch (Fig. 7).

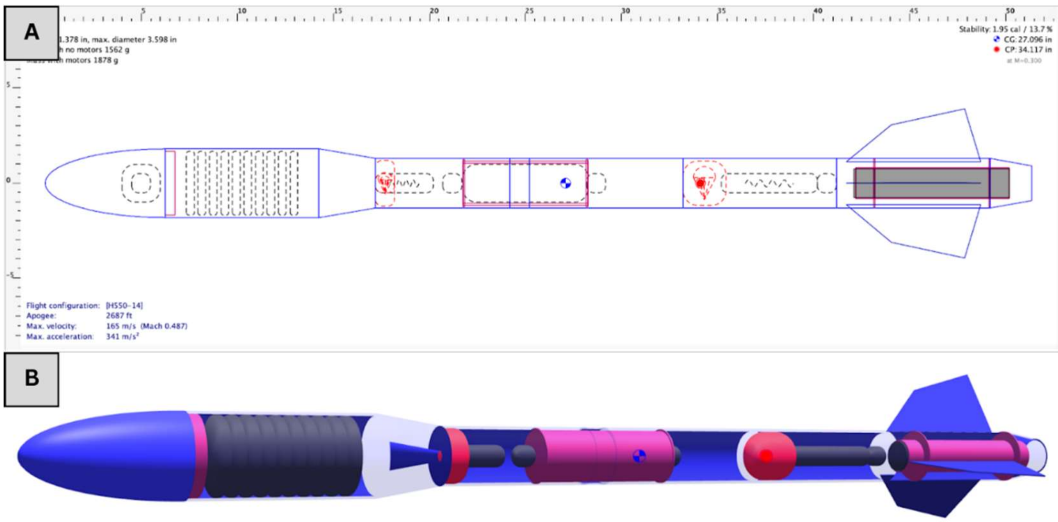

Fig. 6 OpenRocket 2D Configuration View of BEAMS Rocket (A) and OpenRocket Isometric View of BEAMS Rocket (B)

A **Mission CC-9:** Apogee: 1626 ft Stability: 1.6 cal / 10.2% Length: 61.166 in Center of Gravity: 33.215 in Center of Pressure: 39.441 in	B **Mission BEAMS:** Apogee: 2687 ft Stability: 1.95 cal / 13.7% Length: 51.378 in Center of Gravity: 27.096 in Center of Pressure: 34.117 in	C **Mission GYRO:** Apogee: 2449 ft Stability: 1.6 cal / 7.9% Length: 52.549 in Center of Gravity: 32.434 in Center of Pressure: 36.585 in
D **Mission Neredis-I:** Apogee: 2732 ft Stability: 2.13 cal / 10.1% Length: 54.675 in Center of Gravity: 29.493 in Center of Pressure: 35.033 in	E **Mission ADGS:** Apogee: 2102 ft Stability: 2.03 cal / 13.7% Length: 48.961 in Center of Gravity: 24.173 in Center of Pressure: 30.906 in	F **Mission TuberRocket:** Apogee: 2928 ft Stability: 2.18 cal / 11% Length: 52.675 in Center of Gravity: 29.04 in Center of Pressure: 34.822 in

Fig. 7 OpenRocket Simulation Performances for Missions: CC-9 (A), BEAMS (B), GYRO (C), Neredis-I (D), ADGS (E), and TuberRocket (F)

IV. Manufacturing and Assembly

Due to the core idea of modularity, 3D printing was decided as the best method of manufacturing. Whereas originally 3D printing was often viewed as more of a tool for rapid prototyping and less as a manufacturing method for final products, in recent years, 3D printing has become a widely accepted and invaluable method to manufacture parts in a cheaper, more efficient manner. Specifically in the field of rocketry, there are often large time inefficiencies and material costs due to the common obsolescence of launch vehicle parts, requiring new components to be designed and manufactured with each new launch. The use of 3D printing as a manufacturing method allows for reduced costs as well as more efficient manufacturing, especially over a prolonged period of time. This is due to the reusability that comes with the inherent modularity in a process that allows for rapid adjustments to be quickly translated to real-world components. In using 3D printing to manufacture parts, rockets are able to be designed with modularity and reusability in mind, meaning common segments shared across a variety of rocket designs are able to be reused in multiple rockets. Hence, over multiple launches, rather than having to remanufacture the same components, they can simply be reused and connected with new, rocket-specific components.

Most widely available 3D printers use thermoplastics as common filaments. Thermoplastics have the property of melting at feasible temperatures and solidifying into bound layers. These plastics can further reduce the manufacturing costs of using 3D printers, as some can be cheap and easy to find. Given the high temperatures and large forces that rockets endure, the plastic filament used will have to withstand thermal expansion and stress. For those reasons, acrylonitrile butadiene styrene (ABS) was preferred. ABS has a low thermal expansion coefficient (TEC), making it tolerant to strain from temperature changes. Due to ABS having a low thermal conductivity and a Flammability Hazard rating of 1 from the National Fire Protection Association, the material can endure the temperatures of K-class motors. ABS is also resistant to deformation and mechanical stress, so it can handle the forces of our rockets. As an added benefit, ABS is cheap and easy to acquire, helping to reduce costs.

For fin material, the used material must be highly tolerant to stress. When the rocket descends and hits the ground, there will be a large impulse applied to the rocket in a short time interval. Given the thin shape of the fins, this impulse will break fins made of inadequate material. If the fins break on descent, then the launch is considered a failure. To prevent this, G12 fiberglass sheets will be used to craft the fins. G12 is laminated fiberglass bonded with high TG epoxy resin. Due to its intertwined structure, G12 has a high tensile and compressive strength. This will enable the fins to be able to survive the impact during descent.

Fig. 8 Examples of Manufactured/Assembled Rocket Components

V. Anticipated Validation

To ensure that our modular rockets are launched in a standardized manner, all vehicles are designed and flown to meet Level 1 (L1) High Power Rocket certification standards as defined by the National Association of Rocketry (NAR) and the Tripoli Rocketry Association (TRA). L1 certification provides an objective engineering benchmark requiring safe flight on an H- or I-class motor, stable ascent, reliable recovery deployment, and post-flight structural integrity. By designing within this framework, each mission validates not only its experiment but the integrity of the modular airframe itself.

Each rocket is configured for an H-class motor certification flight, satisfying the propulsion requirement while maintaining structural margins for the ABS-CF airframe and fiberglass fins. Stability was verified in OpenRocket prior to manufacturing.

All rockets fall within accepted L1 stability ranges (~1.0–2.5 calibers). This ensures that there is a low risk of oscillation or instability during boost.

Recovery systems are standardized across all configurations and validated through ground separation testing. For certification approval, each rocket must:

1. Launch safely on a certified H motor.
2. Demonstrate stable, controlled ascent.
3. Deploy recovery at apogee via motor delay.
4. Land without structural failure (no fin loss, airframe rupture, or zippering).

Pre-flight procedures include CG verification against simulation, inspection of threaded interfaces, motor retention checks, and recovery packing verification. A certified L1 observer inspects the vehicle prior to launch and evaluates the post-flight condition before granting certification.

Although each mission carries a unique payload, our flights will prioritize compliance with L1 standards over experimental success. Because all rockets share a standardized modular airframe, successful L1 flights are validating the structural reliability of the threaded system across multiple configurations. This ensures that our modular design meets the nationally recognized high-power rocketry standards and that each launch is conducted within a standardized engineering and safety framework. Results of performance testing and validation beyond simulation and manufacturing remain to be explored, and could open up future publications or addendums of design methodology implementation.

VI. Conclusion

Between structural segmentation and threaded interface integration, the design methodology presents a modular and reconfigurable design. With OCRA's work in exploring missions using this methodology, simulations and assembly strongly support a method of design that enables rapid and reconfigurable experimentation.

Current applications of rocket technology use specialized lift vehicles that specifically meet the needs of a mission. Whereas this ensures that the payload will succeed on its flight, it also makes the design process for the rest of the rocket body highly dependent on the characteristics of the payload. Any alterations made to the payload during the design process will require further adjustments to other sections of the rocket in order to remain within mission parameters. Because every payload requires a unique rocket, the material, time, and labor costs of assembly are high. In addition, the failure of any component before launch will require a scrubbed launch and additional assembly. This tightly coupled design approach limits flexibility and slows the pace of experimental iteration.

Through the use of modular rocket parts, several mission payloads can be launched with minimal preparation delay, and the reuse of shared components between different rocket designs reduces the amount of assembly required per payload. While a modular rocket design is not suitable to replace all conventional rocket applications, there are some areas that could benefit greatly. Applications for rocket payloads meant to operate in the atmosphere to gather data or perform experiments, and then be recoverable with no damage to the airframe, are an ideal use case for modular designs. In these scenarios, a reusable and reconfigurable architecture allows teams to iterate rapidly, reduce cost, and focus design effort on the payload itself rather than repeatedly reconstructing the launch vehicle. In improving efficiency in these areas, this modular design methodology presents a viable path for educational and research teams to conduct aerospace experiments at both faster rates and lower costs.

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