Development of a Light-Weight, Reliable, Booster System for SHELS-Launched Payloads

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Abstract

Small satellite missions are often used to support low-cost space missions demonstrating new technologies. An economical source of low-cost space lift is to fly these satellites as secondary payloads aboard the Space Shuttle. The Shuttle has accommodations for flying these payloads using the Shuttle Hitchhiker Experiment Launch System (SHELS). While the relative costs for a Shuttle launch are at least an order of magnitude below the cost of a dedicated Expendable Launch Vehicle (ELV), final orbit altitude selection is limited to Shuttle mission goals. The Air Force Space Test Program (STP) is responsible for flying the Space Experiments Review Board (SERB) recommended experiments on a level-of-effort basis. Low-cost space lift is crucial to maximizing the number of SERB payloads that STP can support. Unfortunately, the typical Shuttle orbit does not provide a high enough orbit to guarantee the one-year orbital lifetime required to meet STP mission objectives. A low-cost, autonomous STP Transfer Upper stage, Guided (TUG) that can boost an STP payload from a typical Shuttle orbit to a higher, longer duration orbit would allow STP to take advantage of the low-cost space lift provided by the Shuttle and still meet their mission requirements. The Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) is pursuing a solution to fulfill STP's satellite lifting requirements by developing a low-cost, lightweight, reliable, strap-on propulsion module using several Small Business Innovative Research (SBIR) contracts focused on various parts of the TUG system. The Shuttle Expendable Rocket for Payload Augmentation (SHERPA) program will integrate all of these SBIR programs to meet the STP TUG requirement. The TUG system would be composed of several technologies being developed or already developed by AFRL/VS such as separation systems, guidance systems, propulsion modules, and modular bus architecture. The TUG would be re-startable for multiple orbit changes, station keeping, or de-orbiting at the completion of a mission.

Three versions of the TUG are envisioned. The first is a simple propulsion module that uses the satellite's Attitude Control System (ACS) and Guidance, Navigation, and Control (GN&C) to provide stack guidance. The second is a fully autonomous TUG that lifts the payload to the higher orbit as cargo, separates from the payload, and then accomplishes a collision avoidance maneuver and propellant burn after payload separation. The third configuration is an autonomous TUG with a long duration module that allow experiments to use the TUG's ACS, GN&C, and power systems in the intended final orbit.

There are many challenges in the development of this vehicle. The most difficult of these is meeting the man-rating requirements of the Shuttle. All critical systems must have triple redundancy to ensure that the system does not threaten the Shuttle, its crew, or its mission. Another complication is producing a structure that meets the strict mass and volume restrictions of the SHELS system. Integration is also a challenge, as many contractors and technologies are brought together under this program.

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Introduction

The United States Air Force is pursuing many different options for access to space quickly and reliably from payloads massing from a few to thousands of kilograms. The Space and Missile Center's Space Test Program (Detachment 12/ST) is responsible for launching small experimental SERB payloads. These payloads are often demonstration technologies that support future USAF space initiatives. The STP employs a variety of methods to fly its payloads. Expendable Launch Vehicles (ELV) are used for launching satellites as a primary or secondary payload. The Space Shuttle is also used to launch Air Force payloads using the SHELS system or mid-deck experiments inside the Shuttle cabin. Typical launch cost for a secondary payload launch using the SHELS system is about $500K. This attractive space lift cost is balanced by the low priority given to secondary payloads on the Shuttle, strict man-rating requirements for a Shuttle lift, and inability to choose the final orbit of the secondary payload. The issue of final orbit is exacerbated by the fact that initial Shuttle orbits tend to be low in altitude where atmospheric drag causes short on-orbit lifetime issues. The obvious solution is to develop a low-cost STP TUG sized to boost the STP payloads to a higher orbit while still meeting the rigorous Shuttle safety requirements and the mass and volume requirements of the SHELS system.

Concept of Operations

The STP has a need for a flexible propulsive spacecraft to transfer small satellites from the Shuttle orbit to a higher orbit. To meet this need, the STP TUG would consist of the following major elements:

1. A Shuttle-safe Propulsion Module (PM): Candidate systems are being developed under two SBIR contracts with SpaceDev and Busek. The goal is to develop a compact propulsion module; that can be used as part of all three STP TUG configurations; that has adequate thrust/volume characteristics necessary to support the STP mission while meeting the rigorous Shuttle requirements.

2. The Attitude Control System (ACS): This system is currently undefined. The basic requirements of the system are well understood. The exact nature of the system to achieve the pointing requirements of the STP TUG is still in work. Under a SBIR contract covering systems integration and design for a vehicle such as this one, AeroAstro is working with AFRL/VS to define this system. Elements of the system will include a low-cost attitude control sensor suite with capabilities sufficient to ensure accurate final orbital injection, and three-axis actuation capabilities to minimize the impact of the STP TUG on the design of the payload it is transporting.

3. The Guidance, Navigation, and Control (GN&C) System: Several small GN&C systems are under development at AFRL. These systems are lightweight (~1-3 lbs.), low-cost ($100k), and reliable. A guidance system developed by the Avidyne Corporation has been selected as the GN&C system for the TUG.

4. Satellite Bus Systems (power, thermal, communication, etc.): The AFRL/VS currently holds a SBIR contract with AeroAstro to develop innovative satellite bus technologies such as modular "plug and play" avionics assemblies. Our current intent is to use this contract as a vehicle to ensure that all the various technologies mesh together as well as to develop the innovative technologies that are the goal of the SBIR. A separate SBIR was recently awarded to AeroAstro to develop and implement systems engineering innovations and highly flexible systems integration, test, and operations procedures for a rapidly responsive orbital maneuvering vehicle. These SBIR innovations will be flight-demonstrated through the Shuttle TUG program. Bus systems not covered through other technology efforts will include a power system using primary batteries and optimized for a short-duration propulsive mission, and a low-cost, highly miniaturized TT&C system leveraging terrestrial wireless technology and components to enable high capabilities in a very small package. The thermal system on the spacecraft is designed to be passive and will be effective in either a short-duration or long-duration mission configuration.

5. Long-duration Electrical Power Systems: The requirement to use TUG system to support individual experiments for up to one year drives a modular addition to the standard TUG power systems that allow the TUG to operate on orbit for up to one year.

6. Auxiliary Equipment (low-shock, spacecraft separation systems, etc.): The AFRL/VS has already developed several innovative low-shock separation systems as well as other appliances that support TUG operations with almost no modification.

7. Lightweight, low-cost, adaptable structures for satellite buses and arrays: This modular architecture and diverse development team structure allows maximum efficiency in meeting STP TUG requirements by combining several SBIR development projects into a viable TUG. For example, the STP might elect to integrate the PM directly to a satellite that already has existing bus, ACS, and GN&C systems. This configuration (see Figure 1) is the simplest configuration of the TUG, consisting of the Shuttle-safe PM integrated with the satellite payload. This configuration is designated the Mark I TUG. Its mission would start after the Shuttle deployed the satellite and PM on orbit and moved away to a safe distance. The satellite would position the stack at the correct attitude and then command the PM to fire. This maneuver would insert the satellite on a transfer orbit where the satellite would coast to the desired final orbit. A second propulsive maneuver would insert the satellite into the desired orbit.

The next envisioned TUG configuration is the stand-alone STP TUG (Mark II) that includes propulsion, ACS, GN&C, low-shock separation systems, and short-duration power/support systems. This configuration of the STP TUG is a free-flying spacecraft in its own right albeit with a limited design lifetime on orbit. This configuration will be used to boost a small satellite to a higher orbit, drop the satellite off at the final orbit, then separate the TUG and perform a clearance maneuver away from the orbit of the satellite payload. Ideally, the TUG would transfer the satellite to the desired orbit using two propulsive maneuvers, then perform a clearance/collision avoidance maneuver followed by the TUG expending all remaining propellant by flying to the lowest orbit possible. This tactic ensures that no pressurized tanks with propellant are left on orbit and ensures the TUG re-enters the atmosphere as soon as possible.

The final TUG configuration (Mark III) would be used to support several experiments on orbit using the existing support hardware on the TUG. This configuration is similar to the Mark II TUG with the addition of communications and long-duration power systems. In this case, the TUG remains at the final orbit and provides housekeeping functions for the STP experiments. The mission duration for this version of the TUG is up to one year.

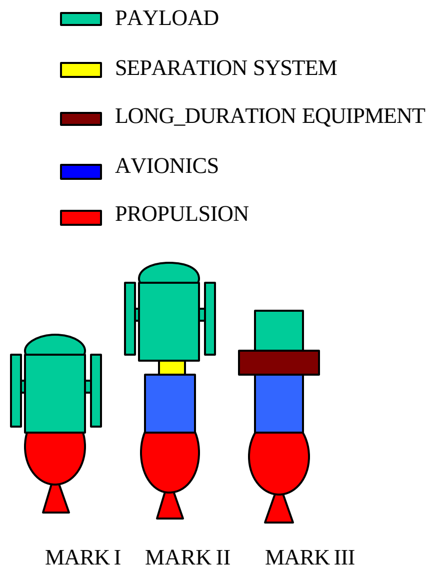

Figure 1. STP TUG Configuration Diagram

System Elements

Shuttle-safe Propulsion Module (PM): This system is being developed under a SBIR contract with SpaceDev. The goal is to develop a PM that will provide a ΔV of ~ 200m/s to a 181 kg initial spacecraft weight. Of this weight, 125 kg is devoted to the payload and 56 kg to the TUG. The PM will be the majority of this 56 kg mass. The PM is required to be highly reliable and affordable, utilizing non-toxic propellants for Shuttle safety. The PM is also required to be functionally compatible with all three STP TUG configurations. Additionally, propellant density considerations are important due to fixed volume constrains imposed within the SHELS environment.

The baseline SpaceDev PM solution is a small bipropellant hybrid motor using self-pressurizing liquid nitrous oxide for the oxidizer and solid Plexiglas for the fuel grain.

The Busek Company, under a competitive SBIR contract managed by the AFRL Propulsion Directorate at Edwards AFB, is developing a backup PM solution. Busek is applying their successful Hall thruster technology developed under the TechSat 21 program to possible TUG thrusters. In this case, inert Xenon gas is the working fluid for the Hall thruster. Since a Hall thruster delivers thrust in the milliNewton (mN) range, it would fire continuously for the orbitraising maneuver. Busek estimates it could accomplish the required change in velocity in approximately one month. The competing PM technologies were selected based on the likelihood in meeting the advertised STP performance and stringent Shuttle mission safety requirements.

Guidance System: Current rocket flight control systems are highly accurate but costly. These systems are heavy (~45kg) and can cost anywhere from $150k to $500k depending on production lots and desired level of accuracy. The AFRL/VS is currently funding the development of reliable, GPS-aided, Inertial Navigation System (INS) guidance systems similar to the hardware shown in Figure 2. Low-cost accelerometers and gyros are augmented by the use of extremely accurate position/velocity measurements from GPS sensors to achieve accuracies similar to the more expensive systems. Using these lightweight sensors, and packaging all related equipment (GPS, sensors, and flight computer) in a single box, results in savings in volume, weight and power. The current systems being developed are designed for launch vehicles, but can easily be modified for use in the STP TUG.

Avidyne's GN&C unit (Fig. 2) was selected for use by the STP TUG program. This device offers excellent performance while meeting the strict mass and volume requirements of the TUG configuration. This unit is low-cost (~$100k) which also makes it an excellent choice for the TUG. The novel software that was developed for this system is designed as an open-ended architecture. This flexibility allows the software to host other guidance and navigation algorithms as determined by the user.

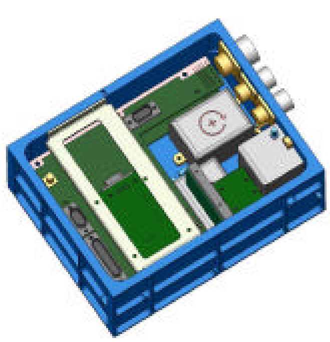

Figure 2: Avidyne's Guidance, Navigation, and Control System

This system is in the second year of its development under a Phase II SBIR as a launch vehicle controller. The system can easily be modified as a guidance system for the TUG. Before integration into the TUG, this system will have already been flight tested aboard STPSat-1 and also tested as part of an F-15 launch program.

Attitude Control System: The ACS requirements for this system are relatively simple. The Mark II TUG requires an ACS to initially orient the stack and ensure that the TUG moves in a safe direction without wasting impulse. After initial light-off, the Guidance System can control the thrust vector of the stack until engine cut-off and coast along the transfer orbit trajectory. The ACS also aligns the stack just prior to the propulsive maneuver to circularize the orbit at the higher altitude. This system is currently baselined to be a three-axis control system. A spinning vehicle would require careful mass balancing not only of the STP TUG, but also of the payload. In order to offer maximum flexibility to the users of this system, a three-axis stabilized vehicle is preferred. The Mark III TUG requires the same fidelity ACS system to perform its propulsive maneuvers to achieve the higher orbit. The Mark III TUG may require a higher fidelity ACS to support experiment operations at the target orbit. These requirements will be identified on a mission-by-mission basis.

Satellite Bus Systems: The AFRL is currently funding AeroAstro Inc. to design, fabricate, and flight qualify a flexible, low-cost satellite bus architecture that facilitates the integration of various payloads and spacecraft subsystems using modular assemblies. The modular satellite bus design is made possible by utilizing this "plug-n-play" hardware configuration. This satellite bus concept is ideal for the STP TUG program because of the flexibility of the design and ability to meet the strict requirements of the STP TUG program. This flexibility allows for the straightforward reconfiguration of the system for Mark I, Mark II, or Mark III flights, whichever is required by the user. The modular design is built around an open system architecture and a set of Spaceframe Blocks (SFB). The SFBs are satellite subsystem-level assemblies scaled to a number of discrete sizes that can be configured to meet the needs of a wide range of missions with minimal customization. The most compact versions of this hardware will be utilized by the STP TUG program. The SFBs provide standard electrical and mechanical interfaces for easy integration of spacecraft electronics, payloads, and other peripherals (Figure 3 and 4). The modular bus concept enhances reliability due to its Multi-Functional Structure (MFS) electronic circuitry design. The STP TUG bus will incorporate prefabricated flexible circuitry that can be fabricated by computer to a range of applications. This type of circuitry is much more efficient than conventional round-wire cabling that requires time-consuming soldering of each individual cable to the connector. Implementing the MFS electronics into the STP TUG bus design provides an 80% and 90% reduction in mass and volume over conventional round cable designs, and a 50% reduction in touch labor.

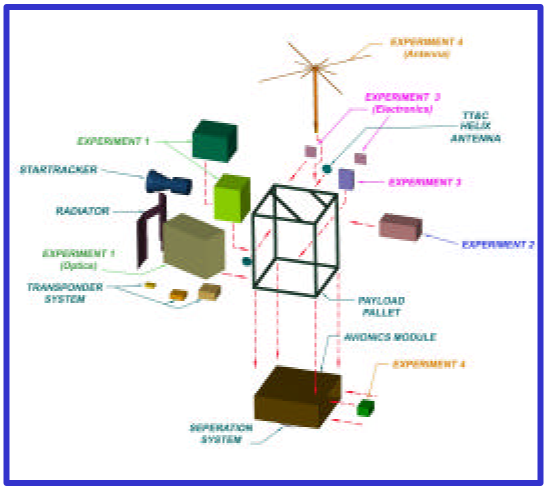

Figure 3. Modular Spacecraft Bus Showing Avionics Module and Payload Pallet

A micro-spacecraft avionics module will be the spacecraft control center. This avionics module will integrate and control all the SFBs and will support all electronics bus functions such as communications, data handling, ACS, power, etc. This core module combines flexibility with low cost by including only generic (Mark I, II, or III) electronics functions and eliminating artificial separations between electronics subsystems. The design leverages commercial off-the-shelf hardware and can be ready for flight just a few months after order. This avionics architecture is being flight demonstrated by AeroAstro on the SPORT and Encounter space systems.

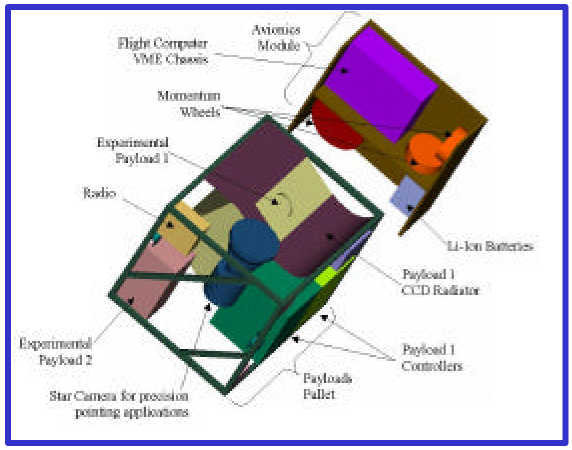

Figure 4. Assembled Spacecraft Utilizing SFB Concept

Payload Separation Systems: The AFRL/VS is funding the development of lightweight, low-shock, non-pyrotechnic separation technologies for small satellite deployment. The small size of the SHELS payload mass and volume provides challenges with regard to separation system mass and volume. These challenges are exacerbated by the STP TUG Mark II, which deploys its payload and therefore requires two separation systems (one with the Shuttle and one between the STP TUG and the payload). Both discrete point and marmon band systems are being considered for this program. One of the systems being considered is Planetary Systems Corporation "Lightband". The "Lightband," shown in Figure 5, is ideal for deployment of small satellites". These systems are also available in a range of shapes to satisfy many different designs.

Figure 5: Planetary Systems Corporation Lightband

TUG System Requirements/Issues

The greatest technical challenge for the TUG program is to develop a system that incorporates propulsion, control, communications, auxiliary equipment, and structure in a 56 kilogram package. Use of innovative technologies such as the Avidyne GN&C system, Multi Functional Structures, and a "plug and play" architecture are critical to achieving system performance with so little mass available. The following data outlines the TUG mass and volume requirements:

1. Stack Mass: 181 kg.
2. Stack Volume (cm): 106 X 66 X 114 (tall)
3. TUG Mass: 56 kg.
4. Satellite Payload Mass: 125 kg.

The Mark I TUG (PM attached to a satellite) is the lightest and simplest configuration. The Mark II TUG (full-up, short duration TUG and satellite payload) is the greatest mass and volume configuration and also requires two separation systems (one between the stack and the SHELS carrier and one between the TUG and the payload) further complicating the already tight mass and volume restrictions. This configuration is the focus of this development effort and qualification flight. The Mark III TUG (long-duration TUG plus experiments) uses TUG systems to support the experiments on orbit and should represent an intermediate requirement for mass and volume.

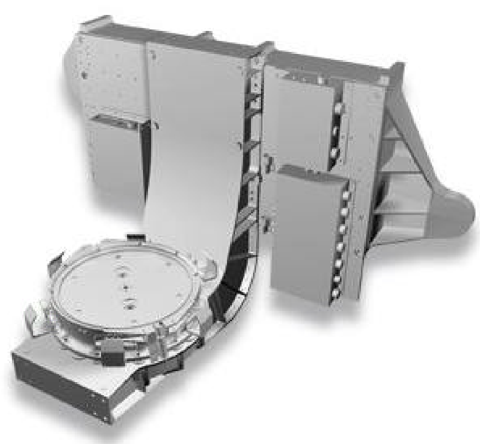

Figure 6: SHELS Carrier

The performance requirement for the TUG is to boost the stack from a typical Shuttle orbit of about 350 kilometers to a final orbit for the satellite payload of 700 kilometers.

Integration

The most difficult programmatic task of this project is ensuring that all of the various products and contractual vehicles mesh together. This project will integrate at least four different technologies, with each providing a critical component (i.e. propulsion, flight control system, structures, etc.) necessary to vehicle function. The AFRL is using existing bus technology and architecture contracts with AeroAstro to develop a small satellite bus as an integration approach to meet the TUG requirements. Grounding the TUG design to a specific set of bus and structure hardware represents the greatest probability of melding these various technologies and programs into the integration effort that ultimately will result in the TUG design. Our goal is to generate a strong integration team composed of an Air Force project manager and lead systems engineer to work the integration issues, supported by the Air Force project leads, the AeroAstro bus and integration lead, and contractor representatives from each SBIR program. This team will meet regularly to work integration issues and to ensure that each individual SBIR project is not doing anything that might be incompatible with the TUG program goals. This team will focus on the specific TUG program requirements while be aware of and supportive of other applications for the various SBIR projects.

Conclusion

The successful integration of these diverse technologies into a single vehicle with operational utility will be challenging. The TUG concept represented an excellent way to provide real world requirements to shape the path of these R&D activities, provide a technology transition path for each of the SBIR contracts included in the program, and provide a viable product of use to the Air Force small satellite community.

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