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Cellular Based Aggregated Satellite System: The Design and Architecture of a Three Degree of Freedom Near-Frictionless Testbed for Ground Validation of CubeSat Operations

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ABSTRACT

As small and nano-satellite operations become more complex and increase in functionality, the need to validate new concepts prior to deployment in a low-cost and time efficient manner has further increased. While computer simulations have traditionally provided acceptable results for guidance navigation and control (GNC) algorithms, more complex actions such as rendezvous and proximity operations and docking (RPOD) require alternative methods, which often require ground-based platforms. The concept of on-orbit autonomous docking of small satellites has grown in popularity due to its broad range of applications. However, most existing ground testing platforms (GTP) are expensive due to the technologies used and large physical space required. Due to the importance of RPOD to nano-satellites specifically, the development of a low-profile GTP is a crucial component in the testing and validation of small satellite concepts. The Space Engineering Research Center (SERC) at the University of Southern California (USC) has designed and manufactured a GTP capable of validating various unique nano-satellite operations in a cost-effective and space-efficient manner. This paper will focus on the design and architecture of a three degree of freedom (3DoF) near-frictionless testbed for ground validation of RPOD in a microgravity environment and its use with various small satellite applications.

INTRODUCTION

Although GTPs are necessary for the validation of advanced small satellite RPOD concepts, the hardware is often replaced with complex and computationally intensive simulations. The cost, physical space, and time required to design, build, and maintain the suitable ground testing facilities (GTF) are typically more difficult than software solutions. A large body of work has focused on evaluating past GTF for frictionless testing.[1,2,3] USC's own large-scale Microsatellite Dynamic Test Facility (MDTF) showed the value of a large GTF, but also suffered from cost and complexity of the GTPs that were used to provide the frictionless testing.[1] Recently at the SERC, a new generation of GTPs has been designed and manufactured that reduces the amount of resources necessary to produce and mitigates testing errors so that the focus of its use can be on its validation purposes rather than problems in the hardware.

"Gen II" is a vehicle that is 24-centimeters long by 24-centimeters wide by 43-centimeters tall. Within the vehicle is a pneumatic system of pressurized air that feeds the propulsion and floatation systems. Propulsion is accomplished via eight solenoid valves, and flotation occurs via three air bearings below the vehicle. These air bearings produce a thin layer of air between their surfaces and the table beneath them, creating a near-frictionless environment. Gen II is powered via commercial off the shelf (COTS) electronic components contained within its control box and has variability with respect to the types of electrical hardware equipped.

This paper will focus on SERC's Gen II GTP and the aspects of its design and architecture that allow it to be a versatile and universal piece of testing infrastructure for the validation of GNC and RPOD algorithms.

PREVIOUS GENERATIONS

Generation 0

The concept of dedicating hardware specifically to the validation of GNC and RPOD algorithms of small satellites has been developed by a range of research groups in the past decade. These iterations have taken different forms targeting various aspects of testing, including increasing the number of degrees of freedom, observing long range behavior, and minimizing the amount of resources necessary for testing.[1,2,3] The closest relative of SERC's Gen I was created at USC's MDTF.[1] The MDTF consisted of a multi-room facility designed specifically for the testing and maintenance of Gen 0 vehicles. With a 66-centimeter diameter and a mass of

25 kilograms, Gen 0 could perform a variety of tests and complex maneuvers, but it required a high degree of resources and maintenance to keep operational.

Generation I

Gen I of a newly designed, scaled-down GTP was developed at USC's SERC to be used in validating a Cellular Based Aggregated Satellite System (or CBASS) concept.[4] The vehicle, seen in Fig. 1, featured similar components to that of Gen 0, including foam core composite sandwich platforms, flat air bearing pucks, and the use of a high-pressure composite wound air tank to feed solenoid valves used as cold gas thrusters.

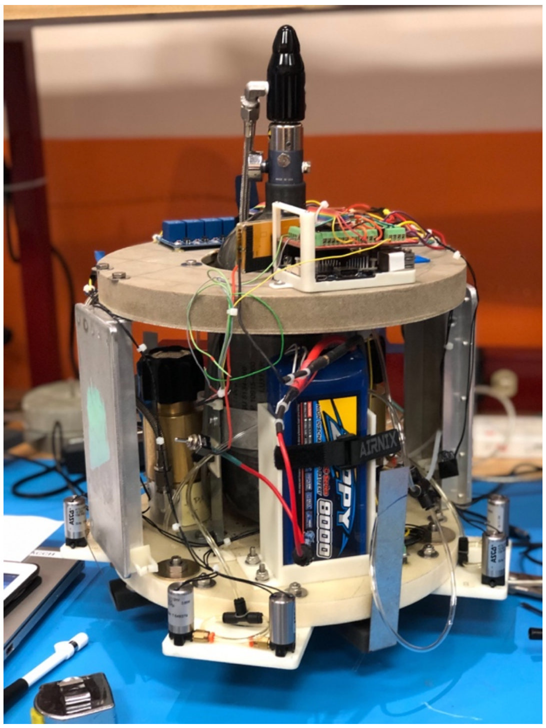


Figure 1: Gen I Assembled on Workbench

Because the focus of Gen I was on its short-term use, the design did not consider ease of reproducibility. Making multiple vehicles required stages of manufacturing including fiberglass layups, drilling hole patterns, and 3D printing mounting stands for each piece of electronic hardware. This process was time intensive and required the proper tooling to ensure the center of mass and moment of inertia values calculated from the computer models would not vary due to manufacturing errors. Due to its compactness in comparison to Gen 0, Gen I was more prone to these types of errors. Additionally, the circular shaped bases meant that a high level of precision was required to prevent error propagation when demonstrating multi-platform aggregation of multiple GTPs.

REDESIGNED PLATFORM: GEN II

As the CBASS project continued, a need arose to build multiple GTPs for the validation of the project's GNC algorithm and RPOD. However, Gen I presented issues during initial testing that required a redesign of the hardware. In order to isolate errors seen in the CBASS algorithms from errors due to the testing hardware, a new generation of GTP was designed.

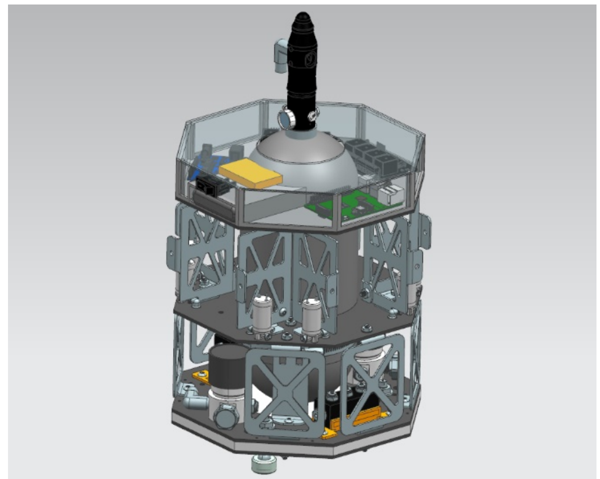


Figure 2: Gen II CAD Assembly

The redesign focused on improving the reproducibility of the vehicles while simultaneously allowing multiple projects with different requirements to be integrated onto the GTP without requiring major changes. This was accomplished through restructuring the architecture of the vehicle to isolate each subsystem, as seen in the full assemblies in Fig. 2 and Fig. 3, preventing changes on one system from affecting the others. Gen II subsystems are described below.

Figure 3: Gen II Assembled on Workbench

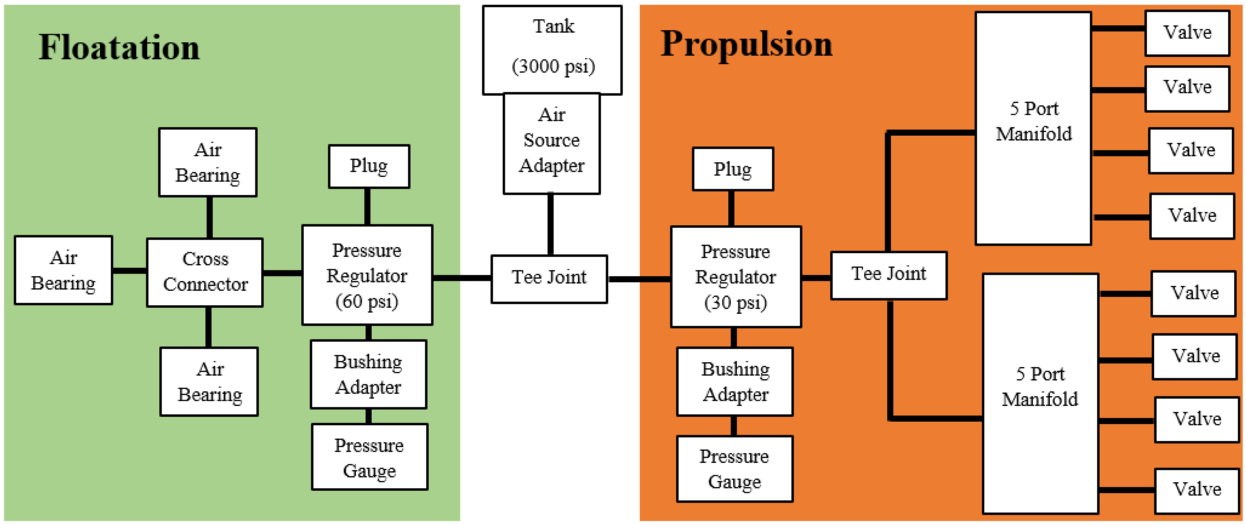


Figure 4: Block Diagram of Gen II Pneumatic System

Propulsion and Floatation

As a whole, the pneumatic system of Gen II remains similar to those of Gen I and Gen 0, seen in Fig. 4, with all components being COTS products. A common supply tank is pressurized up to 3000 psi, and feeds two separate TESCOM BB1 Series Regulators using high pressure braided hoses with 37° flared JIC fittings. Each regulator contains two outlets, one used for a miniature pressure gauge and the other for a push to connect fitting for tubing. From one regulator, the tubing feeds to the propulsion system. This consists of two separate manifolds, from which a total of 8 outlets provide pressure for each of the ASCO miniature solenoid valves. From the other regulator, the tubing feeds to the floatation system. This consists of the three, 25-millimeter diameter air bearings connected to the bottom of the GTP. When pressurized, these create a thin layer of air between themselves and the glass surface covering an optical table. Each bearing produces a 5-micron separation from the table when operating at 60 psi under a load of 80 Newtons, without a noticeable amount of instability due to pneumatic hammer, resulting in a near-frictionless testing platform.[5]

Octagonal Base

Due to its use with RPOD of multiple vehicles, the shape of the base needs to have a regular tessellation and allow the thrusters to be positioned so that the cold gas supply can be used most efficiently before and after aggregation. Requiring a regular tessellation in an attempt to utilize concepts of biomimicry limited the options to squares, triangles, and hexagons.[6] However, each of these presented its own problems.

Triangles were not space efficient when all components were required to be contained within its area. Additionally, linear movement of the GTP required components of thrust in directions non-parallel to its desired velocity vector due to their positioning. Squares, although favorable in terms of thruster positioning, prevented the vehicles from rotating freely after being translated to positions close to other objects. The original circular platforms were the optimized shape for space efficiency, allowing the platforms to translate to any spot, and rotate at that spot without regard to surrounding objects. But, as mentioned previously, circular patterns could lead to issues following aggregation if the mounting platforms are not aligned within a tight tolerance.

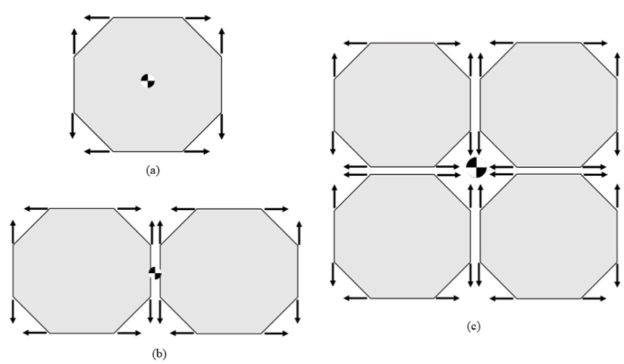


Figure 5: Illustrations of the octagonal base in various aggregate shapes with the corresponding thrust force vectors

After finding the problems with regular tessellations, it was decided that a semi regular tessellation would better serve the purpose of the GTPs: specifically, the aggregation pattern of octagons. Although octagons do not form a seamless tiling, the empty space between joined faces allows the thrusters to be positioned in ideal locations with no interference issues, as seen with the hexagon and triangle. Additionally, by positioning thrusters at each vertex of the octagon, an efficient firing pattern can be established for single vehicles and many combinations of vehicle aggregates, as shown in Fig. 5.

Increased Adaptability

To support its use with multiple projects, the platform needs to be capable of supporting various sets of hardware and testing mechanisms. This increase in adaptability was accomplished through its sub-plate design, the isolation of the subsystems, and the inclusion of designated payload bays.

The sub-plate design refers to the four plates which support the vehicle, as seen in Fig. 6. Each plate is made out of ⅛ inch thick plain weave carbon fiber sheets with identical hole patterns machined by a CNC waterjet. This level of precision allows any iteration of the vehicle to be replicated while maintaining constant and known center of mass and moment of inertia values. By having holes in each floor that are unused, it allows new pieces of hardware to be easily integrated onto the vehicle. If pre machined hole patterns on the hardware do not align with the sub-plate hole pattern, then a 3D printed adapter can serve as the interface, coupling the two. This design also decreases the time and cost of manufacturing since the plates can be ordered and machined in bulk, which is especially important when multiple vehicles need to be assembled for testing involving aggregation or RPOD.

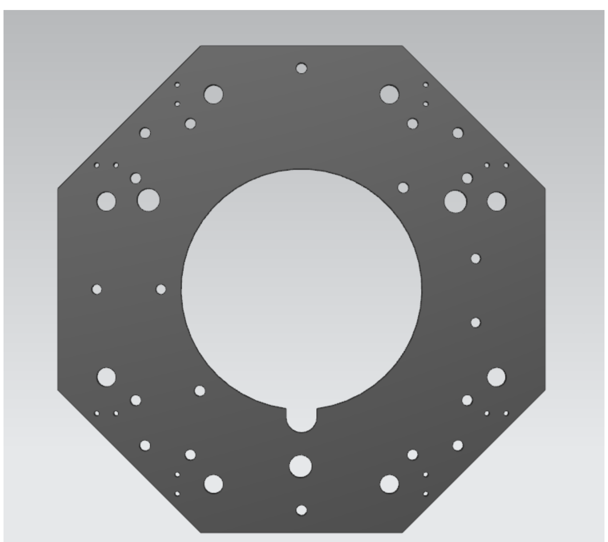


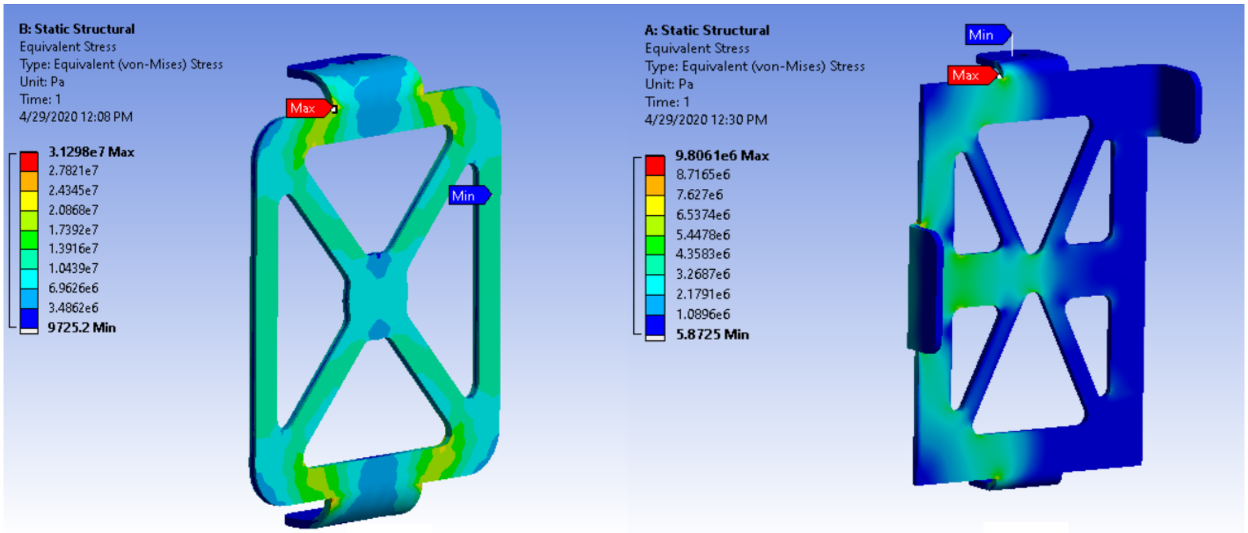
Figure 6: CAD model of a single sub-plate with the designated hole pattern

Previously, GTPs had only two levels, the bottom designated to all pneumatics hardware, and the top designated to all electronic components. While simple, this design was difficult to modify once assembled. The wires leading from the electronic hardware to the solenoid valves were intertwined with the pneumatic tubing connecting the inner workings of the cold gas system. Generation II mitigated this issue by dividing the platform into three levels, each containing its own subsystem. As seen in Fig. 2 and Fig. 3, the bottom tier is dedicated to the pneumatic components, the middle tier is dedicated to the solenoid valves and payload bays, and the top tier is dedicated to the electronic hardware. Where before the pneumatic lines were intertwined with the wires from the electronics, now the two are separated from each other. This allows the two systems to be modified and adjusted without interfering with other systems more easily.

As mentioned previously, the empty bays on the second level are reserved for payloads specific to the required testing hardware. Each of the four bays has a volume of 250 cm^3 that can be used in a variety of ways. With the hole patterns on the sub-plates above and below the payload bays, they have access to both the top and bottom floors without the need to feed supporting wires or tubes outside of the perimeter of the vehicle, potentially interfering with docking operations between multiple vehicles. The walls that support the second floor have flanges with hole patterns oriented so that panels can be fastened to them. These side walls are interlocked, creating a solid body when integrated onto the platform. This allows them to support the loads that may be seen during testing while maintaining an amount of strain that is negligible to the test results.

Reduced Weight

Gen I occasionally saw issues with friction between the air bearing pucks and the table due to the weight of the platform. By itself, Gen I performed nominally, but the addition of testing hardware for certain projects decreased its reliability of performance. Gen II combats this by establishing a lighter bare weight, allowing more heavy testing equipment to be added without exceeding the bearing loads of the air bearing pucks. This was accomplished through the use of sheet metal side walls, composite material sub-plates, and lightweight pneumatic components. The side walls are laser cut out of Aluminum 6061, chosen for its light weight and 1:1 ratio of bend radius to material thickness. ANSYS Academic Research Mechanical, Release 18.1 was utilized to conduct finite element analysis on the walls in order to determine the gauge necessary for expected loads, with results shown in Fig. 7. A single 2-millimeter-thick panel simulated to experience a load of 20 Newtons results in a maximum stress of 30 MPa, resulting in a factor of safety of 5. This result allows the side walls to be reconfigurable, either being added for additional structural support or taken away for additional space. This further increases the ability of the platform to adapt to various testing requirements. Additionally,



(a) (b)

Figure 7: FEA Results for (a) the bottom-floor side walls and (b) the second-floor side walls

the use of a high-pressure composite wound air tank and miniature pneumatic components, including high pressure regulators and solenoid valves, allowed weight reductions.

Isolated Control Box

Specific to controlling the GTP itself, there is a small number of COTS electric components that are required, as shown in Fig. 8. It is powered by a 14.8-volt lithium ion battery, chosen for its cycle life and sleek size and weight. The power is then split by a buck converter, specifically the UBEC Duo, with one path powering the microcontroller, a Raspberry Pi 3 Model B, and one path powering the two, four module relay boards, used for the actuation of the solenoid valves. On Gen I, these electronic components were mounted to the top floor via 3D printed stands. However, this made modifying the vehicle a tedious process to prevent dislodging any of the electrical connections. Due to the iterative nature of the testing performed with GTPs, much time would be spent fixing mistakes caused by this interference between the electrical and pneumatic wiring. By implementing a control box that isolates the electrical hardware from the rest of the vehicle, Gen II prevents testing to be affected by this. The control box is coupled to the top floor via fasteners utilizing the hole pattern on the sub-plate and connects to the solenoid valves using crimp plug connections. This allows the user to easily detach all electrical components from the GTP if necessary. HDMI, USB, and Micro-USB breakout cables connect to the Raspberry Pi and mount to the walls of the control box, allowing the user to access and modify the microcontroller without needing to remove it from its mounted position in the box. Additional tracking systems or other various components can be integrated as needed for testing, either within the control box itself or in the payload bays.

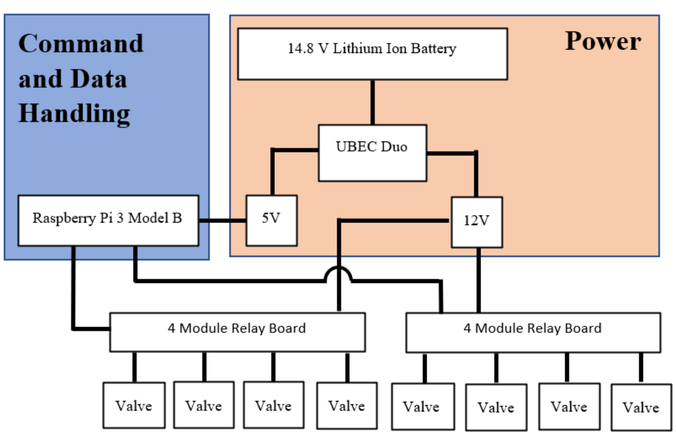


Figure 8: Block diagram of Gen II electrical system

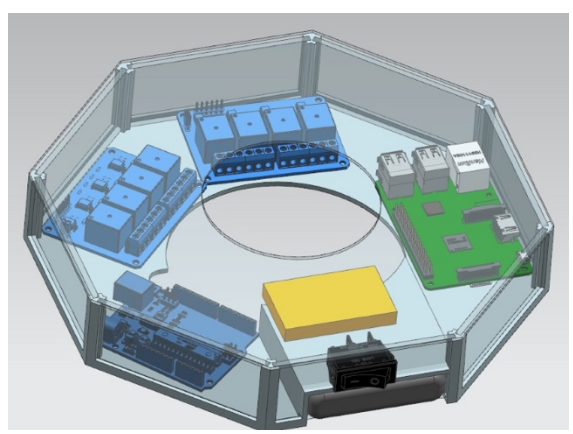


Figure 9: CAD of Gen II control box with supporting electrical components

(b)

The structure of the control box, as shown in Fig. 9, is 3D printed with ABS plastic, including all of the mounting supports necessary to fix the components to the box. The side walls and top are ⅛" thick acrylic sheets. These materials were chosen due to their lightweight and ability to change if required by testing.

APPLICATIONS AT SERC

CBASS

One of the recently sponsored projects at SERC is the development of an autonomous distributed software architecture to optimize the use of computational resources in nano-sat clusters. The redesign of our CBASS hardware is instrumental in validating the real-world feasibility of a new software architecture that may help pave the way towards cost-effective CubeSat commercialization in highly modular swarm applications.

REACCH

The REACCH project combined tentacle end effectors with formable electro-adhesion (EA) and Gecko adhesion capture cloth material, allowing for soft captures of different materials in-orbit in the future.[7] The previous generation of GTP at SERC supported testing the REACCH mechanism's capability to capture objects of different sizes, shapes, and surfaces through use of the microgravity simulated testbed and platforms. The previous platform was sent to JPL to add necessary fixtures to hold the prototype tentacles as well as a control box, to wirelessly actuate the tentacles and capture materials from a second platform.

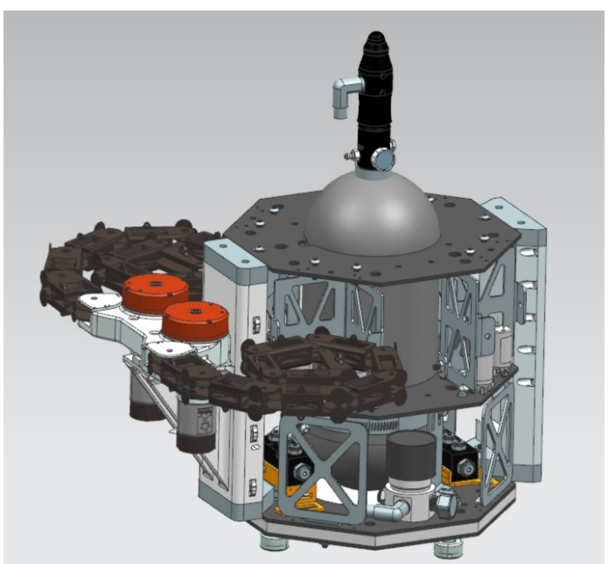


Figure 10: Configuration of Gen II with the appropriate REACCH testing hardware

Gen II will allow for future testing to continue, without the need of additional fixtures, as seen in Fig. 10. This will allow for any modifications to be done with ease as requirements may change with continued testing. Collecting more data and results on the effectiveness of the REACCH mechanism is necessary in order to proceed to future phases of testing, such as testing in a microgravity 6DoF environment and eventually applications in space.

Swarm RPO

The next big step forward in the exploration of space is the ability to manufacture and assemble in space, which will require large swarms of spacecraft cooperating in close proximity to each other, all subjected to the same laws of orbital mechanics. The autonomous assembly of micro-satellites has been previously demonstrated using USC's MDTF.[8] Currently, new methods for swarm RPO safety are being developed at the SERC, but have not yet been tested. The most promising type of swarm RPO safety utilizes real-time GNC algorithms coupled with a variety of sensor inputs giving the position, velocity, and pose of all satellites in the swarm, to constantly update the relative-motion orbits of all the elements in the swarm, while propagating these orbits forward in time to prevent conjunctions.[9] The Gen II GTP will allow real-time testing of these algorithms to simulate a cooperative swarm of spacecraft in low-Earth orbit.

CLING

CLING, created and patented by Dr. Berok Khoshnevis from USC, is a genderless electro-mechanical docking system designed for ground robotics, translated to join any vehicles or platform in the Space environment. The redesign of the platforms allows CLING to be attached to multiple faces of the platform, allowing for variation in testing of the mechanism. The ability to attach CLING to the newly designed platforms also aids CBASS testing, as a docking mechanism is needed to test the functionality of an aggregated system of platforms.

FUTURE WORK

Thrust Control

The new design still incorporates a binary thrust system which poses a challenge in controlling along all three axes of motion. Currently, we use a three-phase controller (rotation-translation-rotation), but would like to move to a single phase controller. To get there, the next generation will need continuous-control thrusters.

Incorporation of Reaction Wheel

Future work involving the incorporation of reaction wheels will be very valuable for any testing involving Guidance, Navigation, & Control (GNC) algorithms, as reaction wheels are one of the primary actuators used for satellites in Low Earth Orbit (LEO). In particular, for an autonomous network of satellites, ground-based testing using multiple platforms will need to include the use of more complex subsystems in order to consider the possibility of a real-world application. However, the current testbed available only allows for 3DoF and in order to utilize reaction wheels properly, a testbed allowing for 6DoF is needed. Therefore, the addition of reaction wheels is future work that involves other additions to the current GTP.

CONCLUSION

USC SERC's Gen II GTP was designed to allow GNC and RPOD algorithm and hardware validation with 3DoF without requiring excessive resources devoted to its production and maintenance. This readily available and modifiable design broadens the range of small satellite applications that can be reliably tested on the ground. This will allow users to focus the scope of their testing on its applications and results, as opposed to the testing hardware itself. Through its use with various unique projects at SERC, Gen II's ability to accommodate a variety of functions continues to be validated.

ACKNOWLEDGMENTS

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