ORBITT:
Orbital Refueling By Internal Tank Transfer

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This paper presents ORBITT (Orbital Refueling By Internal Tank Transfer), a modular in-orbit servicing architecture to extend the operational lifetimes of satellites in low Earth orbit (LEO). Many satellites are limited by the onboard propellant; this can lead to premature mission failure even with fully functional systems. ORBITT addresses this limiting factor by a novel refueling approach that replaces depleted propellant tanks using an internal track-based transfer mechanism, rather than relying on direct fluid transfer. The system design operates from an existing servicing platform based on the ESPAStar. The ESPA ring is used to carry 6 independent Orbital Replacement Units (ORUs), each carrying three 30-liter tanks filled with Hydrazine. A rotary drum and track-based transfer system enables the exchange of tanks between the servicing vehicle and the client satellite. A compliant docking interface, designed around the International Docking System Standard (IDSS), provides alignment, capture, and a structural connection while supporting the integrated electrical and fluid interfaces. Mission analysis using representative Sun-synchronous orbit (SSO) satellites in the 500-700 kg range shows that a 30L replacement tank can increase the available delta-V from approximately 85 m/s to 118 m/s. This increase will enable for meaningful mission extension. Economic analysis indicates that refueling has the potential to reduce costs by up 85% compared to a complete satellite replacement. ORBITT provides a modular, scalable pathway towards sustainable servicing.

Nomenclature

IDSS	International Docking System Standard
LEO	Low Earth Orbit
ORU	Orbital Replacement Unit
RAAN	Right Ascension of the Ascending Node
RPO	Rendezvous and Proximity Operations
SSO	Sun-synchronous Orbit
QC	Quick Coupling

I. Introduction

The number of satellites operating in low Earth orbit (LEO), especially in sun-synchronous orbits (SSO), has greatly increased over the past several years because of a growing demand for Earth observation, communications, and scientific missions [1]. Although there have been continuous advancements in spacecraft subsystems, many satellites are retired due to propellant depletion and not to issues such as hardware failure. Once onboard fuel is depleted, satellites will lose the ability to perform station keeping, orbital corrections, and end-of-life maneuvers. This leads to limited mission duration and overall mission effectiveness.

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In-space servicing, assembly, and manufacturing (ISAM) is a promising approach to counter these limitations by allowing maintenance and life extension of in-orbit satellites. One of the capabilities within ISAM is in-orbit refueling, which has been identified as a key way to extend the lifetime of satellites and improve the flexibility of the mission. Traditional refueling approaches usually rely on direct fluid transfer between a servicing vehicle and a client satellite. Although effective, these systems can introduce significant technical challenges, including the need for precise fluid coupling, leak prevention, contamination control, and standardized interfaces [2]. In order to reduce the complexity associated with direct fluid transfer, there are alternative approaches to refueling. One approach involves replacing depleted propellant tanks rather than transferring fluid directly. This simplifies the mechanical interface and reduces operational risk.

The system proposed in this work, ORBITT, is designed to provide a modular and scalable solution for refueling in low Earth orbit. ORBITT will utilize an Orbital Replacement Unit (ORU) architecture where filled propellant tanks are stored within the servicing vehicle and transferred to a client satellite using an internal rotary and track-based mechanism. This approach reduces the need for complex fluid transfer systems while enabling a more robust and repeatable refueling process. The system is designed to operate from an existing ESPAStar-based service platform and will target satellites in sun-synchronous orbits at altitudes of approximately 600–800 km. Representative satellites in the 500–700 kg class are used to evaluate system performance and mission impact. By allowing the replacement of depleted propellant tanks, ORBITT has the potential to greatly extend the operational lifetime of satellites, reduce the need for replacement launches, and improve the sustainability of space operations.

In-orbit refueling has been identified as a valuable mission area within the COSMIC Capstone Challenge due to its ability to extend mission lifetimes and increase operational flexibility for spacecraft [3]. The modular ORU based approach presented in this work aligns closely with these objectives by providing a scalable and adaptable servicing architecture. This paper presents the system design, mission analysis, and key challenges associated with ORBITT, demonstrating its feasibility as an approach to in-orbit refueling.

II. Mission Overview

ORBITT, or Orbital Refueling By Internal Tank Transfer, plans to solve the issue of limited mission lifetimes with the aforementioned replacement of propellant tanks. ORUs stored within ESPAstar, along with each port's track mechanism will remove and replace the client satellite's tanks following the procedures outlined below.

A. CONOPS: Concept of Operations

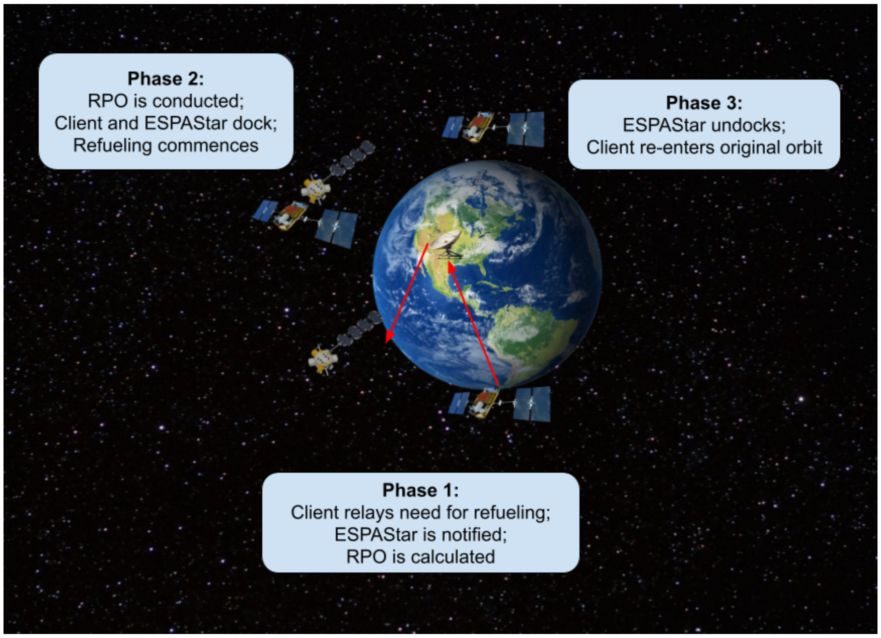


Fig. 1 ORBITT Concept of Operations

B. Mission Plan

The following phases detail how the expected mission will be conducted from start of ESPAStar's insertion into a parking orbit to the end of life maneuver for the ESPAStar. Note, some of the phases will be discussed in depth in the refueling sequence subsection.

Phase 1. Client Satellite Determines Need for Refueling
The Client Satellite's onboard fuel management system detects that propellant levels have dropped below the operational threshold. A refueling request is initiated and transmitted to ground control for authorization.

Phase 2. Client Satellite Determines Orbit Alignment with ESPAStar
The Client Satellite computes the relative orbital parameters of the ESPAStar servicing vehicle. ΔV requirements and phasing maneuvers are calculated to achieve rendezvous conditions.

Phase 3. Client Satellite Matches Orbit with ESPAStar
The Client Satellite executes a series of phasing and transfer burns to align its orbit with ESPAStar, achieving proximity operations range.

Phase 4. Refueling Sequence
See subsection below.

Phase 5. Client Satellite Confirms Refueling and Unlocks from ESPAStar
The Client Satellite's avionics confirm successful tank installation and nominal propellant system readings. Structural latches disengage in sequence, the two spacecraft separate safely. The Client Satellite executes departure burns to return to its operational orbit.

Phase 6. ESPAStar Mission Next Steps
If the ESPAStar has remaining tanks after the previous refueling, it will return to it's nominal parking orbit and the mission plan will return to Phase 1. If the ESPAStar has depleted all of its tanks, it will begin deorbiting maneuvers and a new vehicle will be launched for the continuation of a new mission.

C. Refueling Sequence

The following procedure outlines the nominal in-orbit refueling sequence between a Client Satellite and the ESPAStar servicing vehicle, including interaction with the Orbital Replacement Unit (ORU) carrying replacement fuel tanks.

Step 1. Client Satellite and ESPAStar Align Refueling Sections
Both vehicles perform fine attitude control maneuvers to align their respective refueling interfaces. Proximity sensors and visual cameras confirm geometric alignment of docking ports and fuel transfer couplings.

Step 2. Client Satellite and ESPAStar Lock Together
The two spacecraft mechanically dock and form a combined vehicle configuration. Structural latches engage, electrical and data interfaces connect, and the two satellites effectively operate as a single integrated platform for the remainder of the refueling sequence.

Step 3. Client Satellite and ORU Align Track
With the combined vehicle stabilized, the design of the docking and transfer track system results in alignment of the tracks. The Client Satellite's fuel tank bay forms a continuous line to the ORU's delivery track.

Step 4. Client Satellite Deposits Empty Fuel Tank
The spent, empty fuel tank is extracted from the Client Satellite and transferred along the track to the ORU for stowage. Once transferred from the Client Satellite to the open chamber of the ORU, retention mechanisms release under controlled actuation, and the empty tank is secured in the ORU's open chamber.

Step 5. ORU Rotates to Align Full Fuel Tank
The ORU rotates its tank rotary mechanism so that a full, flight-ready fuel tank is indexed to the transfer

track position, resulting in a complete and continuous line from the ORU delivery track to the Client Satellite's fuel tank receptacle.

Step 6. Full Fuel Tank Deposited into Client Satellite
The full fuel tank is transferred along the track and inserted into the Client Satellite's fuel tank bay. Mechanical latches engage, and fluid couplings seal automatically. A leak check and tank pressurization verification are performed. Once complete and secured, the Client Satellite can begin operations for another tank transfer or de-attach from ESPAStar, dependent on fuel requirements.

III. Mission Analysis

A. Orbit Requirements & Reference Satellite Selection

The first orbit parameter to be defined is the inclination of orbit. Sun-synchronous orbits (SSO) were chosen due to the high population density in low Earth orbit (LEO), minimal drag at higher altitudes, and the lower ΔV needed for coplanar maneuvers. Using data from Fig. 4 in [4], the most populated inclination in this band was 98 degrees. This choice is very important to minimize planar transfers, which cost large amounts of ΔV. The second parameter was the altitude to orbit. There are two large population bands on each side of 700-800 km (shown in Fig. 3 of [4]), so 800 km was chosen to minimize atmospheric drag while still maintaining a large client base near orbit. The drift of the right ascension of the ascending node (RAAN), a critical parameter for SSO orbits, was then determined to be 0.917 degrees per day with an orbit velocity of approximately 7.51 km/s.

The reference satellite selection was based on SSO spacecraft in LEO, with Orbital Focus used as the primary dataset for identifying representative vehicles within the target mission class [5]. Among the candidates considered, EO-1 emerged as the strongest baseline reference because it offers a relatively high level of publicly available technical information compared with other SSO satellites, allowing for more defensible estimates of spacecraft mass properties, propulsion characteristics, and maneuvering capability [6]. The comparison of EO-1, CALIPSO, and SMOS showed a consistent spacecraft scale, supporting a constrained reference mass range of approximately 500 to 700 kg and a propellant range of roughly 20 to 30 kg [7]-[8]. These bounds are important because they provide a realistic systems-level benchmark for designing a servicing or refueling architecture intended to operate with typical SSO spacecraft in LEO. Rather than selecting a reference satellite only by name, this approach ties the research to the broader objective of defining a representative client class, which helps guide assumptions for tank sizing, propulsion feasibility, and expected in-orbit servicing value.

To connect the satellite survey to propulsion performance, the analysis used the Tsiolkovsky rocket equation to estimate ΔV for both the original onboard propellant load and a refueled case based on the team's selected 30 L tank design. Using an assumed average specific impulse of 220 s for hydrazine monopropellant systems, the resulting estimates showed that the selected reference satellites occupy a narrow and useful performance band: original ΔV capability was approximately 85–97 m/s, while the refueled case increased this range to about 100–118 m/s [9]. Conceptually, this is important because it links satellite mass and propellant capacity directly to the practical benefit of refueling, showing that even modest propellant addition can produce a meaningful increase in maneuvering capability for orbit maintenance, mission extension, or limited repositioning. In this context, EO-1 remains the most valuable reference not only because of data availability, but because it represents a technically credible midpoint within the selected spacecraft class. Overall, the research supports the use of EO-1 and comparable SSO spacecraft as a rational foundation for estimating propulsion needs, validating tank-sizing assumptions, and framing the expected performance gains of a refueling mission architecture in LEO.

The atmospheric burn up of the satellite is the last stage of its life cycle. The orbit only decays around 126 meters per year according to the orbital energy equation, so the reentry must be induced. The rapid heating region (70-80 km) is where a large part of the melting and break up of the satellite occurs on reentry. The Sutton–Graves stagnation heating correlation calculates around 1 MW/m^2. Most external structures melt and detach in this region due to high pressures and heat. Until around 40 km, any material that cannot sustain this heating, such as the aluminum body, will be either melted into the atmosphere or dispersed into small fragments. The only material on the craft that can survive the heating would be any steel parts and the empty titanium fuel tanks. This leaves a mass of around 100 kg, or roughly 15% of the initial mass, landing on the ground [10].

B. Economic Considerations

The guiding principle behind the economic analysis of the ESPAStar refueling operation was to verify the efficacy of this business model. This economic framework hinges on the fact that it is cheaper for client satellites to pay the vendor to use the ESPAStar's refueling services than for the clients to launch a new satellite to replace their original. Therefore, to conduct this investigation, it was first necessary to determine the start-up cost associated with placing the ESPAStar in LEO. According to publicly available information from manufacturer Northrop Grumman, the ESPAStar has a dry mass of 470 kg and a fuel capacity of 330 kg [11]. Provided this craft carries 18 thirty-liter tanks of liquid hydrazine for refueling client satellites, the ESPAStar would have a total mass of 1333.5 kg. Following a thorough review of existing launch vehicles capable of placing client satellites in LEO, SpaceX's Falcon 9 rocket was selected as the most commercially viable rocket for this operation. Per SpaceX's publications, Falcon 9 has a client launch cost of $74 million and a maximum thrust payload of 22,800 kg [12]. Presuming a linear relationship exists between cost of launch and payload capacity, it was determined that the SpaceX Falcon 9 launch program charges $3250 per kilogram payload. Therefore, it would cost $4,333,875 to launch the ESPAStar into LEO to conduct refueling operations.

Secondly, this initial investment was used as a benchmark to calculate the price charged by the vendor to client satellites for refueling and to validate the profitability of this operation. Selecting the EO-1 as the target client for refueling, it was found that it would cost a prospective client an average of $2,275,000 to launch one of these satellites into LEO. This value was selected as the upper bound of the vendor price. If the price of refueling were set any higher, it would be cheaper for the client to simply launch another satellite instead of using the vendor's services. Assuming the ESPAStar sells all 18 tanks during its operation and that all other costs associated with the ESPAStar are trivial in comparison to the launch cost, the lower bound of the price charged by the vendor (the break-even point) would be $240,770. If the cost of refueling is any lower, the vendor would lose money by conducting this operation. In the current market, it is common for highly specialized contractors working on large-scale projects to implement markups of around 40% [13]. Taking the break-even point as the base rate and applying the 40% mark-up, it was decided that it would be reasonable for the ESPAStar vendor to set the price of refueling at $337,078, or approximately $350,000 for each hydrazine tank, ensuring a fair market price for the client and a strong return on investment for the vendor. These finalized numbers represent that refueling is around 85% cheaper than launching a new satellite.

IV. Subsystem Design

A. Docking Mechanism & Plumbing Interface Design

The proposed docking mechanism is a three-arm, compliant capture system designed to enable reliable, low-impact docking between a servicing spacecraft and a client satellite. This design draws directly from principles established in the International Docking System Standard (IDSS) and the NASA Docking System (NDS), particularly in the areas of soft capture, alignment, and structural attachment. The goal is to achieve a simplified, modular alternative to traditional ring-based docking systems while maintaining compatibility with proven docking behaviors.

(a) Female docking port.

(b) Male docking port

Fig. 2 Both sides of the docking port design.

At initial contact, the three spring-loaded arms act as a soft capture system, providing a large capture envelope and accommodating misalignment between vehicles. This approach is inspired by the NDS soft capture architecture, which is designed to “accommodate vehicle misalignments” and “attenuate the relative motion of the two vehicles” before rigid attachment [14]. The inclusion of compliance through spring mechanisms mirrors the function of actuators and damping elements in NDS. By distributing contact across three arms, the system achieves stability similar to the multi-petal capture mechanisms used in legacy and modern docking systems.

Following initial capture, guide pins and corresponding alignment holes ensure precise positioning of the two spacecraft. This feature directly reflects IDSS requirements for alignment guides, which use tapered holes or guide pins to bring docking interfaces into concentric alignment prior to hard mate . Proper alignment is critical not only for structural integrity but also for enabling subsequent electrical and mechanical connections. In this design, alignment is passively achieved through geometry, reducing reliance on complex control systems.

Once aligned, the arms transition into a hard capture role, locking into place to form a rigid structural connection. This function is analogous to the structural hooks used in IDSS-compliant systems, which engage to create a secure load-bearing interface between docked vehicles . While traditional systems separate soft and hard capture into distinct subsystems, this design integrates both functions into a single mechanism, reducing mechanical complexity while preserving functionality.

Finally, the docking interface includes provisions and space for electrical connections and servicing operations, such as power/data transfer and propellant tank replacement. This aligns with the NDS capability for post-docking umbilical connections, which enable power and data transfer between the docked spacecraft after structural mating is complete . By combining docking and servicing into a unified interface, the design supports the broader goal of modular, reusable satellite infrastructure.

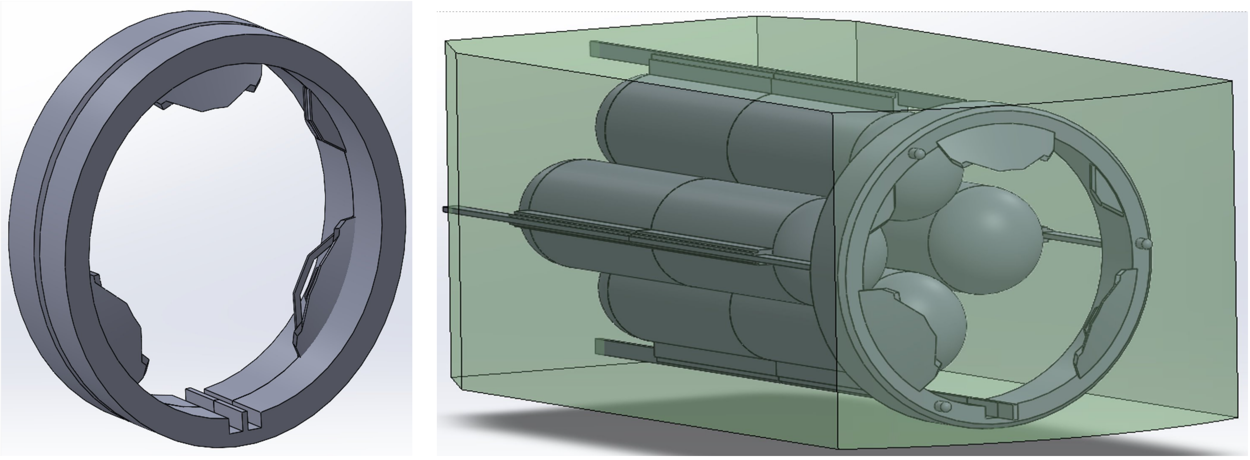

(a) Docking port assembly.
(b) Docking port assembled with tanks.

Fig. 3 Docking port CAD assemblies.

The plumbing system mating to the ORU after the empty tank is detached was designed around the following three requirements: First, the tank must be sealed upon detachment and must be opened with attached. Second, the plumbing system must be standardized to allow client satellites to integrate the system with minimal complexity. Third, the system must be compatible with the base design chemical hydrazine. These design requirements lead to the selection of a pioneer style quick disconnect. The trade off between air versus hydraulic QCs varies based on their disconnect process, some compressed air QCs only seal on one side while hydraulic QCs seal on both the male and female sides. This is crucial to meet the first design requirement and thus the ISO 7241-A QC was chosen for our system. The actuation of this QC will be discussed in the next section.

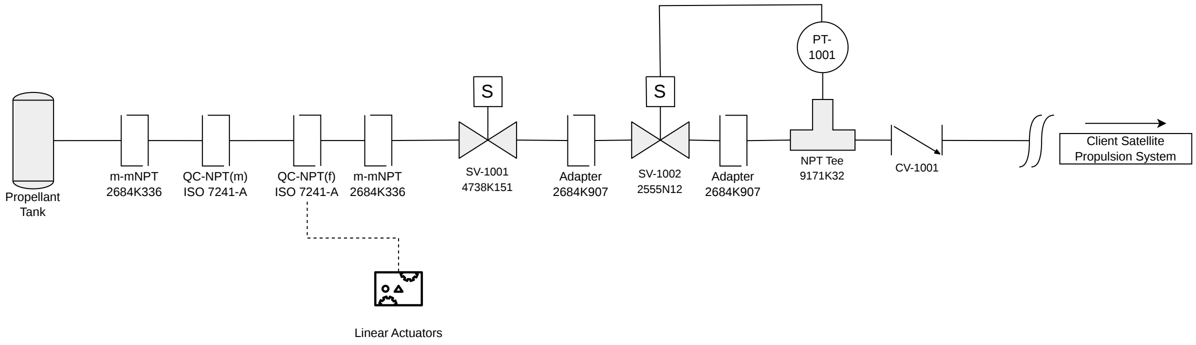


Fig. 4 P&ID for the system required by the client satellite to enable the use of ORUs.

Figure 4 shows the plumbing and instrumentation diagram (P&ID) of the system. The propellant tanks will all be equipped with a male QC fitting, and with this tank design a male to male 1/4" National Pipe Threads (NPT) fitting is required to mate the QC to the tank. The client satellites will either use this plumbing architecture or use our all-in-one plumbing system design to exchange and accept ORU tanks. The systems require a female QC fitting, along with our actuator module. The plumbing system itself contains a run valve for allowing propellant flow from the tanks. Followed by a flow control valve in a feedback loop with a pressure transducer to monitor the downstream pressure fluctuations. The system finishes off with a check valve to reduce backflow before connecting to the rest of the client satellite's propulsion system. Figure 5 on the next page shows the assembled CAD model of the plumbing system. The left side of the assembly represents the male QC where the tank would be attached. The right side shows the client satellite's front-end plumbing system. From left to right, the run valve and pressure transducer can be seen pointed downward and the flow control valve is pointed upwards.

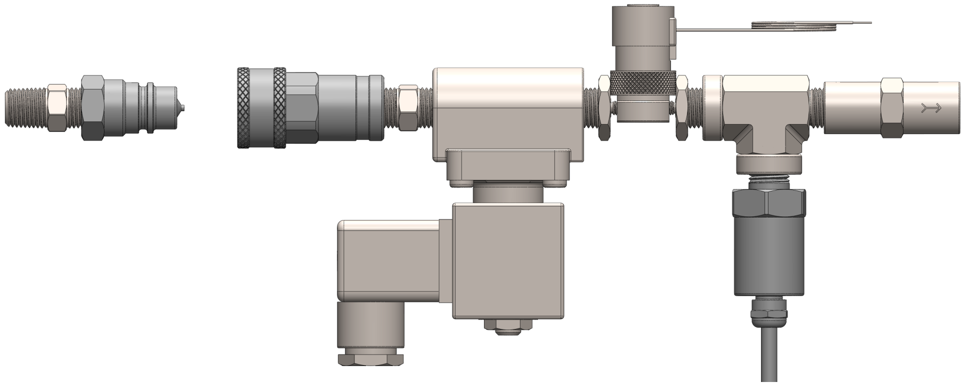
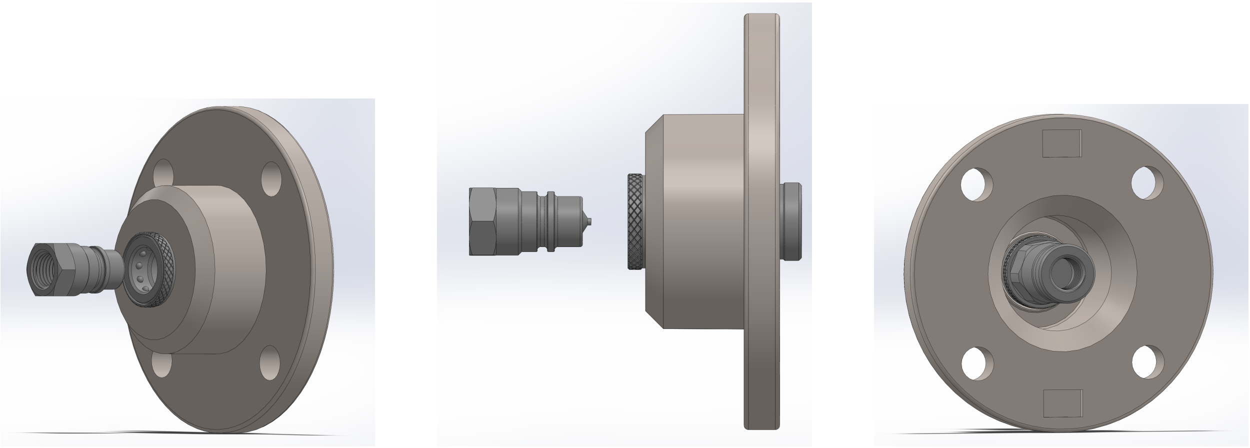


Fig. 5 CAD model assembly of the P&ID.

The fluid system attachment mechanism to the ORU would be achieved by actuating a quick-connect coupler on the client side, via linear movement of a coupler head over the female fitting end. The disc-shaped coupler head is moved by 2x 2-inch (12V) linear actuators attached at opposite ends of the disc, equidistant from the center, which will push it back and forth to allow the attachment and disconnection of an ORU tank. The mechanism will be aided by the internal spring in the female QC, which will return it to the neutral position once the linear actuator is retracted. This mechanism would ensure that no moment is imposed on the fitting head, allowing for successful actuation. There are also 4 holes equidistant to each other from the center to place guiding rods through to ensure the mechanism doesn't rotate or twist, which would either damage the linear actuators or the quick connect couplers. Working with hydrazine requires all stainless steel parts in the system and the chemical is not compatible with brass, copper, or bronze specifically. Stainless steel 316 is used for each of the components to reduce the risk of corrosion while operating with hydrazine.



(a) Front view.

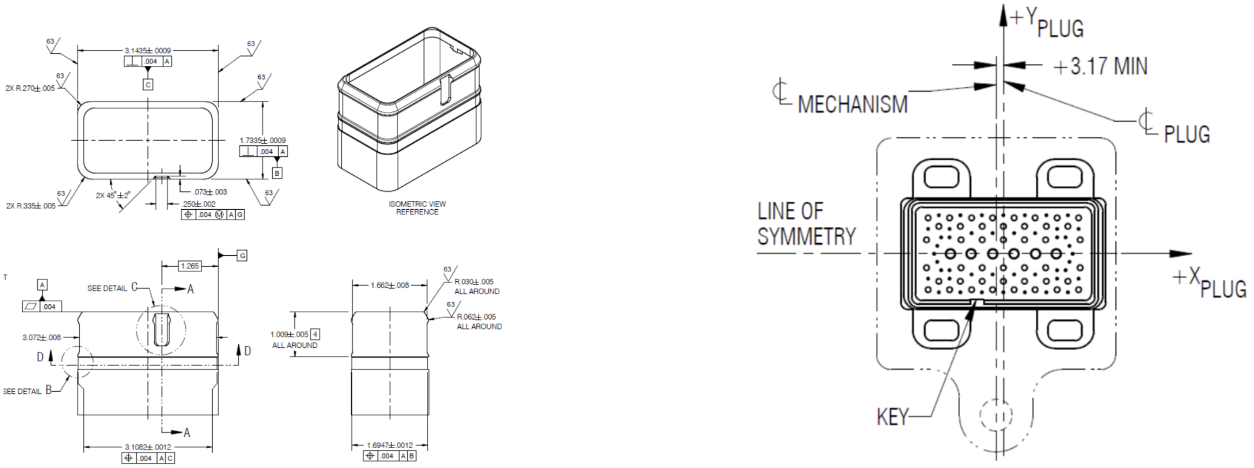
(b) Side view.

(c) Back view.

Fig. 6 Actuator plate assembled onto the female QC.

B. Controlling Electronics & Electrical Interface Design

The design for the docking system's electrical connector, similarly to the docking port, was inspired by NASA's IDSS bulkhead connector [15]. The bulkhead design will be the same as the IDSS design, but the pinout of the bulkhead will be much less crowded, since less than 20 wires are needed for full system communication between the ORBITT docking port and the client satellite's front-end plumbing system. Figure 7 on the following pagea shows the bulkhead design for the female and male sides with a key on one side. Figure 7 on the next pageb shows the NASA pinout that the ISS uses, however this can be further reduced in complexity for ORBITT's design since not as many communication lines are needed.



(a) (b)

Fig. 7 [15]

The system will be controlled through an ESP32 chip which will manage all of the motors, sensors, and processing required before, during, and after the ORU transfer. A buck converter is used to step voltage from a 24V battery down to a safe voltage for the ESP32, while another buck converter is used to drive linear actuators and servo motors. A time of flight sensor is utilized to determine the position of the ORU tank in order to actuate the QC at the correct moment.

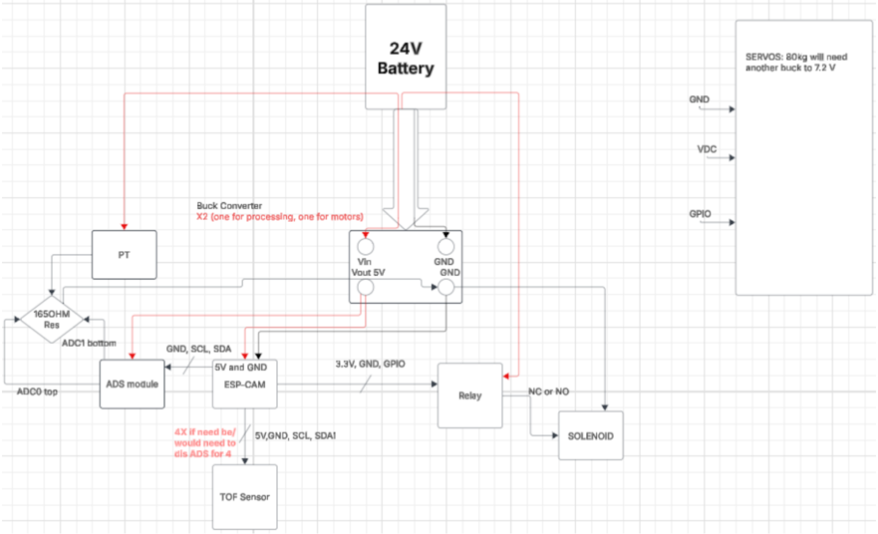


Fig. 8 Wiring schematic for the client satellite's ORU-acceptance and plumbing system.

After the QC is actuated and the tank is attached, the solenoid valve will be opened using a relay module. The pressure transducer will send data to the ESP through an ADS module for I2C communication. Figure 8 shows the electrical schematic as described above.

The data budget can be seen in Table 1 on the next page, where the data is grouped by main task. Motor updates from the linear actuators and solenoid valves will require 9 bytes of data per response. The tank status represents the data sensed from the time of flight sensor and the pressure transducer, yielding the status of the tank attachment and pressurization at any given time, requiring 7 bytes per response. The track mechanism status includes the motor and the time of flight sensor, specifically during ORU transfer operations which are highly critical on tank position. The status also includes the rotary position of the tank drums discussed later. This update status therefore produces 8 bytes of data per response. The background health of the client satellite's plumbing and electrical systems will utilize 5 bytes of data per response. Finally, the packet header leading the data transfer along with the cyclical redundancy check (CRC) will require 4 bytes of data per response. The CRC is a redundant data check used to verify data during a communication transfer for spacecraft due to higher likelihood of induced errors during transmission. The total data budget is 33 bytes per sample response, and therefore at a 10 Hz sample frequency the system would achieve a 2.64 kilobits per second (kbps). Utilizing a standard UART communication protocol, which can easily achieve a 115 kbps data transmission speed, this data budget is successfully closed.

Data Point	**Bytes**
Motor Updates	9
Tank Status	7
Track Mechanism Status	8
Background Health	5
Packet Header & CRC	4
Total	**33**

Table 1 Data Budget

C. ORU Design Philosophy

The orbital replacement unit distribution system was one of the major areas of concern regarding the ORBITT design. Unlike other systems, such as docking, which have numerous established designs available for review, there is a limited body of research focused on the refueling of satellites, particularly those with masses under 500 kilograms. One of the focuses of the design was how to store an empty fuel tank while still providing a large enough volume of fuel to client satellites to make the overall design beneficial for prospective clients. While one's first thoughts may jump toward a robotic arm for removing and restoring fuel tanks, the ORU team decided against this route due to the complexity of implementing a six degree of freedom (DoF) arm. This challenge, combined with issues of how to make each port serviceable, led away from a robotic arm as a means of refueling. Instead, two different systems were put forth, and their advantages and disadvantages were weighed. The first design was a track system with an internal storage area, similar to how a train station has a single track and then splits into multiple tracks via railroad switches. The other design consisted of a revolving mechanism similar to the final design.

The main advantage of the track design lay in its overall volume of storage, which, if designed correctly, could hold more fuel than most other designs. However, there were issues regarding the intake of the empty fuel tank and the best internal mechanism for switching it with a full tank for use in the client satellite. The rotary design solved this issue, but at the cost of less available fuel, as one chamber of the rotary system would have to be left empty at the start of operations to allow for intake of the empty client tank. Instead, the team opted for a combined design, which utilized the main rotary drum system, but also maintained a single track from the docking interface to each drum chamber. This track would also continue into the client satellite when connected, forming a full track from storage to client.

D. ORU Rotary Tank Drum Design

The primary tank storage mechanism of the orbital replacement unit we went with is the rotary drum design. The objective of this design is to store as many fuel tanks (of a size capable of servicing the desired client satellites) as possible within the ESPAStar payload restrictions at minimal complexity and with limited counterforce necessary. The rotary tank drum accomplishes this by keeping all alignment and tank motion either restrained to the geometry of the ORU itself or through a single degree of angular momentum. An image of the current design prototype is shown in Figure 9.

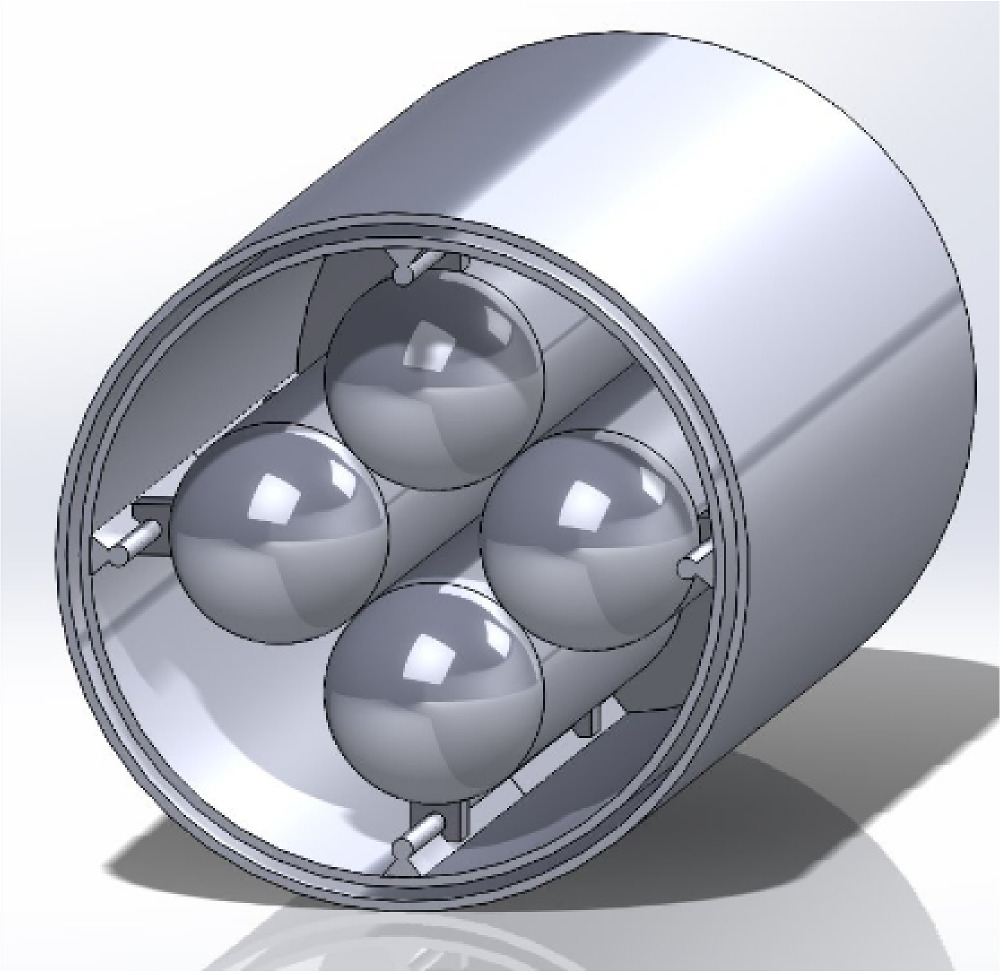


Fig. 9 Current rotary ORU design solution.

The current ORU design can store 4 total 30 Liter hydrazine refueling tanks. In real mission scenarios, one bay will be left empty for receiving the empty client satellite fuel tank. The client satellite and the ORU are aligned through the docking procedure, so the linear rail can be seamlessly traversed by the tanks. The main operational procedure is as follows:

1) Client satellite docks for refueling
2) ORU orients empty bay with the bottom linear rail of the docking mechanism
3) Crawler on empty bay traverses through ORU into the client satellite and retrieves the empty tank
4) Internal drum rotates 90 degrees
5) Crawler attached to a full fuel tank pushes the tank into the client satellite
6) Tank attachment confirmed through electrical connections from docking
7) Client satellite undocks and process repeats 3 total times

The linear traversal of the tanks will be covered in a later section of this paper. The rotation of the internal drum is accomplished by having a separate drum that contains both the rails and the tanks within a small air gap separate from the outer ORU that remains mounted to the EPSAStar. The inner drum remains horizontal with a series of bushings that hold its weight and permit its rotational movement. This allows the motor and major electronics that are critical for ORU operation to stay stationary and mounted to the ESPAStar, and for rotation of the tank to be possible with the client satellite still docked. Figure 10 shows the current design solution where the back end is hollow to contain components.

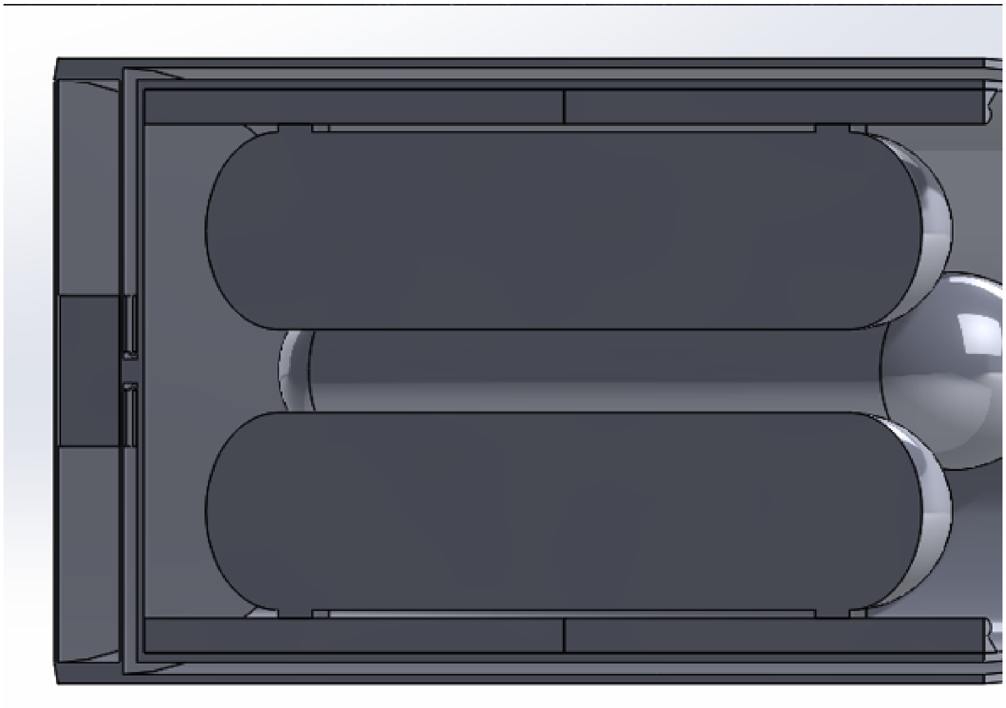


Fig. 10 Section view of ORU model. The left side of the image shows an empty cavity for component placement.

The central large mass represents the brushless DC-DC motor that will be used to rotate the internal drum. The small flat cylinders that surround the motor shaft's connection represent reflective optical encoders and a magnetic sensor for rotational position understanding and motor control. The reflective sensor allows us to keep all electronics on the stationary parts of the tank. An example of a reflective optical encoder can be seen in Figure 11.

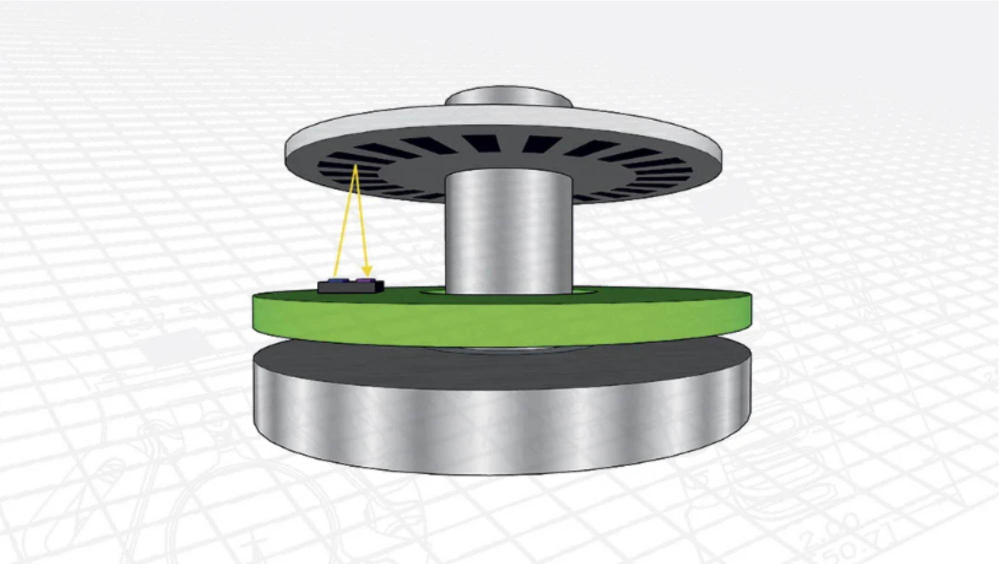


Fig. 11 Reflective optical encoder by Encoder Products Company. [16]

Therefore, with all systems put together, the rotary ORU design provides viable orbital refueling using systems that only have 2 degrees of freedom, lateral movement of the tanks, and the rotation of the internal drum. As a result, ESPAStar will only need to provide a slight rotational counterbalance when the rotary drum is in operation.

E. ORU Tank Design

The tanks within the ORU must be able to withstand the pressures from the onboard fuel, be light enough to be feasibly used in space, and have enough volume to resupply the chosen design satellites. In order to carry the expected volume of 30 Liters, the tanks must be long enough that with the rotary size requirements, 4 tanks of 30L internal volume can fit within. Assuming an industry standard 0.5cm wall thickness (thin millimeter-thick metal sheets with large reinforced plastic layers on top) of the tanks [17], we can design tanks that fit 4 abreast within the ORU volume. Figure 12 shows the dimensions of the tank that fits these criteria being 83cm long with an OD of 21.5cm and half-sphere end caps. Thus, the total internal volume of each tank is 30.264 Liters.

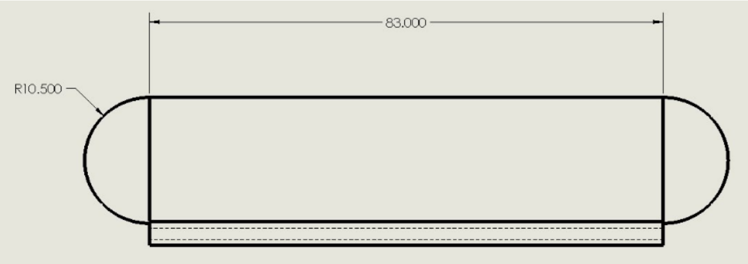


Fig. 12 Dimensioned drawing of basic tank dimensions.

To be strong enough, we assume a factor of safety of 2, such that the tank's material should be able to withstand the hoop and longitudinal stress generated from storing hydrazine at a pressure of 2.5 MPa (industry standard [18]). Thus to fulfill the propsed factor of safety of 2, we will assume the hydrazine is instead stored at 5 MPa, which with the aforementioned tank dimensions, produces a hoop and longitudinal stress of 100 MPa and 500 MPa, respectively. Based on the stress criteria and to keep the tank at a reasonable weight, we opted for the tank material to be made of Ti-6Al-4v titanium alloy. Not only is this titanium alloy extremely strong, but it is also lightweight and is an industry-standard material [19] for hydrazine storage in space, making it a fantastic option for tank material. With the chosen tank material, we can calculate the weight of a single tank to be 14.765 kg and approximately 45 kg while filled with fuel.

F. ORU Transfer Mechanism Design

The tanks within the ORU must be moved to and from the client satellite along the linear rails in some fashion. To accomplish this, we decided on a low-weight crawler that can be placed on every rail that uses a rack and pinion gear system, where the rack is incorporated into the side of the linear rail such that a small motor can be mounted onto each rail and can then attach and detach from tanks, pushing and pulling the empty and full tanks to and from the client satellite. The current small-scale prototype idea for these crawlers can be seen in Figure 13 with a servo mounted onto the top of a linear rail carrier, which connects to a large round gear that can mesh with the rack gear laid along the track.

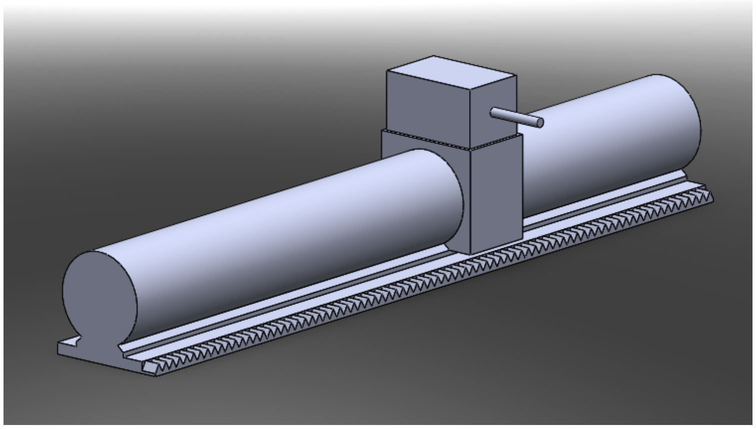


Fig. 13 Prototype tank crawler design concept.

In the space-faring prototype, the gear system will be much more rigidly mounted, likely including the rack gear being integrated into the sides of the linear rail that the tanks ride along. An example rack and pinion crawler that is self-contained and more rigid than the prototype design can be seen in Figure 14.

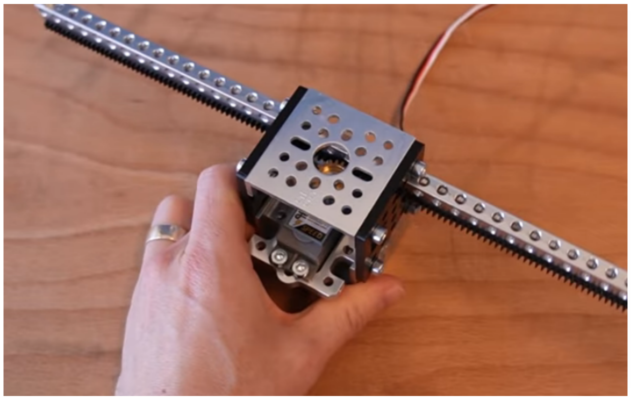


Fig. 14 Enclosed rigid rack and pinion crawler.

Fig. 15 Train car coupler. [20]

This crawler setup allows us to control the lateral motion of each tank into and out of a client satellite with a single motor that runs along the track. Each crawler will interface with the rear of each tank using either a railcar-esque linkage system (seen in Figure 15) or with technology similar to the quick connects seen in the plumbing system (seen in Figure 6). This will allow for 4 identical low-weight and low-cost crawlers to be mounted, which will handle all tank movement into and out of the client satellite, drastically reducing the complexity needed to move each tank compared to the other ORU design solutions.

V. Risks

While there are system specific risks and failures, it's important to consider external risks that exist that could hinder or entirely prevent the mission's success. One potential risk is orbital debris or collision. The impact of this would be loss of service vehicle and/or client satellite as well as mission failure. Additionally, a vital component of our mission is to mitigate orbital debris so this risk inherently goes against our design. To mitigate this, we will analyze debris trajectories and perform collision avoidance when possible. We will conduct station keeping and deorbit the service vehicle after its mission lifetime.

Other serious risks to consider are failing to rendezvous with the client satellite and a malfunction with autonomous operations. The impacts of this would include wasting propellant, loss of servicing opportunity, potential system damage, and conducting an incorrect mission/refueling sequence. To mitigate these risks, we plan to conduct pre-mission orbit planning, an incremental approach with abort capabilities, and fault detection, isolation, and recovery procedures. Additionally, an economic stipulation, such as an advance payment, can be used to entice customers to not waste servicing opportunities.

VI. Conclusion

In conclusion, the ORBITT (Orbital Refueling By Internal Tank Transfer) system presents a practical and innovative solution to one of the most significant limitations of modern satellites: finite onboard propellant. By utilizing a modular tank exchange approach, ORBITT reduces mechanical complexity and enables reliable in-orbit servicing. The integration of a track-based transfer mechanism, compliant docking interface, and standardized plumbing and electrical systems demonstrates a cohesive and scalable architecture suited for LEO operations.

Mission analysis confirms that even modest refueling can produce meaningful increases in available delta-V, directly translating to extended mission lifetime for client satellites. Furthermore, the economic assessment highlights the strong viability of this approach, offering substantial cost savings compared to full satellite replacement. While risks such as orbital debris, rendezvous challenges, and system malfunctions remain, the proposed mitigation strategies provide a credible path toward safe and effective implementation.

Overall, ORBITT represents a forward-looking step in sustainable space operations, supporting the broader goal of reusable, serviceable satellite infrastructure and a more efficient orbital ecosystem.

References

[1] Barato, F., Toson, E., Milza, F., and Pavarin, D., "Investigation of different strategies for access to space of small satellites on a defined LEO orbit," *Acta Astronautica*, 2024. https://doi.org/10.1016/j.actaastro.2024.05.045.

[2] Chato, D. J., "Technologies for Refueling Spacecraft On-Orbit," Tech. Rep. NASA-20000121212, NASA Glenn Research Center, 2000. URL https://ntrs.nasa.gov/api/citations/20000121212/downloads/20000121212.pdf.

[3] Mulvaney, John, "A Cross-Disciplinary Study of On-Orbit Refueling for Geostationary Satellites," Tech. Rep. COSMIC-E01-C002-2025-A, COSMIC, 2025. URL https://cosmicspace.org/wp-content/uploads/2025/12/COSMIC-E01-C002-2025-A-GEO-Refueling-Use-Case.pdf.

[4] Weeden, B., and Shortt, K., "Development of an architecture of sun-synchronous orbital slots to minimize conjunctions," *SpaceOps 2008 Conference*, 2008. URL https://doi.org/10.2514/6.2008-3547.

[5] Focus, O., "Sun-synchronous Orbits - Ordered by Age," , 2026. URL https://orbitalfocus.uk/Diaries/Launches/GeoSS/ss-Age.php.

[6] eoPortal, "EO-1 (Earth Observing-1)," , 2026. URL https://www.eoportal.org/satellite-missions/eo-1.

[7] eoPortal, "CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations)," , 2026. URL https://www.eoportal.org/satellite-missions/calipso.

[8] eoPortal, "SMOS (Soil Moisture and Ocean Salinity) Missions," , 2026. URL https://www.eoportal.org/satellite-missions/smos.

[9] NASA, "State-of-the-Art of Small Spacecraft Technology," , 2026. URL https://www.nasa.gov/smallsat-institute/sst-soa/in-space_propulsion/#:~:text=number%20of%20heritage%20hydrazine%20propulsion%20systems%20makes,200%20%E2%80%93%20235%20seconds%20for%201%2DN%20c.

[10] Rochelle, W., "Analysis of reentry survivability of UARS spacecraft," *Advances in Space Research*, 2004. URL https://doi.org/10.1016/j.asr.2003.01.011.

[11] Grumman, N., "ESPASTAR Flexible, Affordable Access to Space," , 2026. URL https://cdn.northropgrumman.com/-/media/Project/Northrop-Grumman/ngc/space/espastar/ESPAStar-D-Datasheet.pdf?rev=46b3e380e1f04d159f8502e8e65a2af2.

[12] MSN, "SpaceX raises launch prices before IPO," , 2026. URL https://www.msn.com/en-us/news/insight/spacex-raises-launch-prices-before-ipo/gm-GM2407345B?gemSnapshotKey=GM2407345B-snapshot-1&uxmode=ruby.

[13] Truitt, and White, "Understanding Contractor Markup on Materials," , 2025. URL https://truittandwhite.com/contractor-markup-on-materials.

[14] McFatter, J., Keiser, K., and Rupp, T. W., "NASA Docking System Block 1: NASA's New Direct Electric Docking System Supporting ISS and Future Human Space Exploration," , 2018. URL https://ntrs.nasa.gov/citations/20180004167, nASA Technical Reports Server, NTRS ID 20180004167.

[15] Donahoe, S. R., "International Docking System Standard (IDSS) Interface Definition Document (IDD), Revision F," , July 2022. URL https://ntrs.nasa.gov/citations/20220011643, nASA Technical Reports Server, NTRS ID 20220011643.

[16] Company, E. P., "Reflective Encoder Technology | What Are Reflective Encoders?" , 2026. URL https://www.encoder.com/reflective-encoder-technology.

[17] "Space - Propellant Tanks," , 2026. URL https://www.sbi.at/en/applications/aeronautics/space-fuel-tanks.

[18] "Hydrazine," , Mar. 2026. URL https://en.wikipedia.org/w/index.php?title=Hydrazine&oldid=1346413506, page Version ID: 1346413506.

[19] "Hydrazine Propellant Tanks for Satellites and Spacecraft," , 2026. URL https://www.space-propulsion.com/spacecraft-propulsion/hydrazine-tanks/index.html.

[20] "Train Car Coupler factory, Buy good quality Train Car Coupler Products from China," , 2026. URL https://www.rail-wagons.com/supplier-2697014-train-car-coupler.