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On-Orbit Refueling Demonstration to Support Expanded Mission Operations

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Abstract

Orbit Fab has two upcoming missions to demonstrate their on-orbit refueling technology. Two identical payloads will be flying, with the first launching in 2026. One will be hosted on a free flying satellite bus and one will be hosted on a propulsive ESPA ring. These two payloads are equipped with GRIP and RAFTI and are designed to interact with three other RAFTI equipped spacecraft also operating in the same GEO + 300km environment. This cornucopia of RPOD equipped spacecraft will be able to interact with each other and demonstrate fuel transfer between spacecraft allowing for more dynamic space operations and extended mission life. The design and development progress of these two payloads will be described in detail and novel aspects of the fuel transfer system will also be discussed. These demonstration spacecraft will serve as crucial risk mitigation as permanent in-space refueling logistics architectures are deployed on orbit.

Keywords: Refueling, Remote Proximity Operations and Docking, Geostationary Orbit

Acronyms/Abbreviations

AFRL – Air Force Research Lab
AWS – American Welding Society
CDR – Critical Design Review
CoM – Center of Mass
COTS – Commercial Off The Shelf
DIU – Defense Innovation Unit
EDU – Engineering Development Unit
ESPA – EELV Secondary Payload Adapter
FCU – Fluids Control Unit
GEO – Geostationary Orbit
GCU – GRIP Control Unit
GRIP – Grappling and Resupply Interface for Products
ISS – International Space Station
LEO – Low Earth Orbit
LWIR – Long Wave Infrared
MLI – Multi-Layer Insulation
NASA – National Air and Space Agency
OAHU – Operationally Active Hub Unit
PIL – Processor-In-The-Loop
QR – Quick-Response
RAFTI – Rapidly Attachable Fluid Transfer Interface
RPO/D – Remote Proximity Operations and Docking
TCS – Thermal Control System

1. Introduction

The current paradigm for satellites is a single use architecture limited by the amount of propellant carried from the launch pad. This is while the remaining systems still have useful life remaining. This had led to the demise of many satellites, two specific examples are Telesat's Anik F2 [1] and NASA's Tropical Rainfall Measuring Mission [2]. There are five missions currently planned to interact with one another in the GEO belt starting in 2026. These missions include the twin Tetra 5 satellites [3], a DIU mission [4], an AFRL mission [5], and a fuel shuttle [6]. These demonstrations will show that building in refueling capability is critical for any satellite operator. The remainder of the paper will focus on the design and manufacturing of the two payloads owned by Orbit Fab, named Kamino (free-flying satellite bus) and Rancor (hosted on a propulsive ESPA ring). Specific considerations for docking and fuel transfer will be highlighted as unique contributions of these missions.

2. Background

Refueling satellites is a new frontier in satellite operation. Some examples include the ISS in LEO [7], Orbital Express in 2007 [8,9], and it's strongly suspected to have occurred between SJ-21 and SJ-25 in July of 2025 [10]. All of these are non-commercially available services and thus Orbit Fab was established to address the commercial market. The hardware interface comprises of RAFTI and GRIP. RAFTI, the passive side of the interface, was qualified in 2024 with a first flight expected in early 2026. GRIP is expected to complete qualification in fall of 2025 with a first flight expected in late 2026. To prove out this interface Orbit Fab is developing GRIP equipped payloads to dock with RAFTI equipped spacecraft. These payloads are not representative of the final Depot-Shuttle architecture discussed in a previous paper [11], however they serve as a key milestone in derisking several critical technologies needed to fully deploy the operational architecture. GRIP, the fluid transfer system, flight electronics, RAFTI ground fueling operations, and LWIR camera RPOD operations are just some of the key technologies that will be demonstrated by these payloads.

The remainder of this paper will discuss the key requirements that drove design. The design choices that were made as the conops were more fully understood, and the current status of the integration along with the final steps from the current state to the integration on the rocket along with a brief discussion of high level conops.

3. Theory

3.1 Mission Objectives/Requirements

The first step in developing any hardware is to identify the mission objectives. This is an ambitious mission and thus there are several major objectives we wanted to demonstrate.

- Demonstrate autonomous docking with another satellite in the GEO belt.
- Demonstrate the ability to establish a leak tight seal between two spacecraft propulsion systems.
- Demonstrate fuel transfer between two spacecraft.
- Demonstrate successful undocking and resumption of normal operations.

These objectives serve as the cornerstone of how the payload was designed. Unlike many other satellites, these payloads were designed to (slowly and carefully) collide with another spacecraft. This resulted in many conversations with the other programs that would dock with Kamino and Rancor. These resulted in unique requirements being generated around capture envelopes and alignment of the docking mechanisms with the center of mass of the spacecraft. Significant effort was also expended in understanding how two spacecraft cooperatively observe each other and approach with requirements established to increase the likelihood of a successful dock.

Moving from objectives to more actionable requirements to guide payload design. Several driving requirements were established to guide the design process.

- The payload shall be capable of transferring at least 50 kg of hydrazine
- It shall fit in the provided envelope (approximately a meter cube)
- The Rancor/Kamino payload shall be able to capture the docking spacecraft in the established capture envelope.
- The GRIP shall be integrated to minimize the distance between the center of the capture envelope and the center of mass of the spacecraft.
- The payload shall have cameras to detect the position of another spacecraft

3.2 Payload Design Overview

With these high-level requirements in place the initial design layout began. The five main subsystems of the payload are Electrical, Propulsion, Thermal, Docking Optics and Structural.

On the electrical side, the decision was made to have three electronics boxes. The dedicated flight computer, named OAHU, will operate the payload and manage communication between the host vehicle and the other payload systems. The other two electronics boxes are to control GRIP and the Fluids System respectively. These boxes will be accompanied with a full suite of Flight Software to bring life to all the electrical components.

One of the truly unique aspects of these payloads is the propulsion system. To transfer fuel all the usual components are required, but in a different context, and used in ways they weren't necessarily designed for. An additional component, unique to this system, is a catalytic vent assembly. This can be described as "the world's worst monopropellant thruster" due to the requirement to generate as little net thrust as possible. This is needed to clear the lines between spacecraft to minimize hydrazine leaked overboard on separation. This builds upon learning from the Orbital Express mission, however Orbital Express used a refurbished monopropellant thruster while this solution was purpose designed and built.

The thermal system is a critical portion of this payload to manage the temperature of the Hydrazine-Wetted lines and tank. Hydrazine has very similar properties to water, except it's much better at exploding. Keeping Hydrazine in the liquid phase is a key goal of any mission and thus tight thermal controls are key. Another key thermal component are the LWIR fiducials, essentially heated space QR codes that other spacecraft use to precisely locate another spacecraft.

The structural portion of the payload is more typical of other missions though a few curve balls were still thrown at the payload. The Vulcan loads are much higher than expected so managing those alongside a large tank that sloshes and a heavy grappling mechanism far away from the spacecraft attachment point all provided unique challenges to the design.

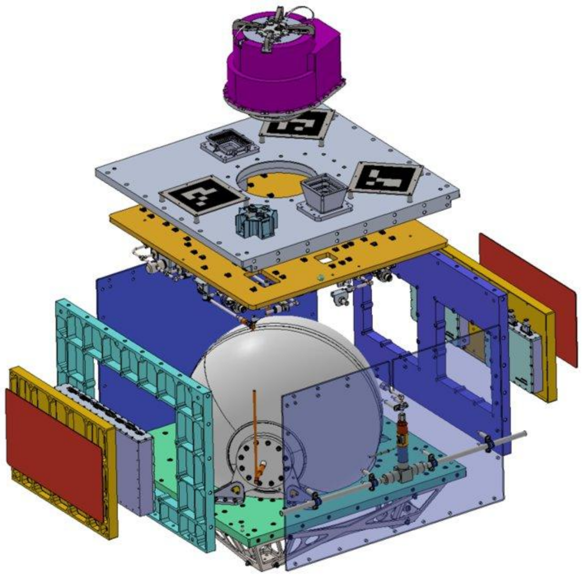

Fig. 1. Payload Exploded Model

3.2.1 Electrical Design

The electrical system consists of a main controller board, the OAHU and two function-specific boards, the GCU and the FCU. Each board is encased in an aluminium enclosure and mounted to the sides of the payload.

OAHU is the power and communications processor for all functions on the payload and was designed to be able to accommodate interface architecture differences across various spacecraft buses for more rapid integration without compromising safety. It also hosts the Q8S daughter board that holds the Trigger subsystem—the mission’s RPOD kit. Beyond those responsibilities, OAHU also manages the thermal control subsystem, has monitoring and bypass activation capabilities within the fluids subsystem, and has the ability to shut down GCU or FCU if needed.

FCU is the control board for the fluids subsystem components, including the nominal control solenoid valves, pressure transducers, and the pump.

GCU is the control board for the GRIP subsystem components, including the motors that drive GRIP. It takes an input from the RPOD system that also features a backup sensor option in cause of failure on the RPOD system.

For the entire electrical subsystem, a COTS+ hardware philosophy was adopted. For circuitry that is considered safety-critical, higher fidelity parts (better performance, more radiation hardness, etc) were chosen. For other circuits either less likely to fail or less critical to the mission, COTS parts were chosen. This was a balance of risk, lead time, and cost to enable us the highest chance of success while also not waiting months for parts to come in.

The flight software is an integral component of the electrical subsystem. Each board hosts a state machine architecture that prevents entry into hazardous states if a redline has been crossed, does not allow for “accidental” commands to change the state of the system, and handles the autonomous docking response on GRIP.

One of the lessons from Orbital Express that we were able to implement in our requirements planning was the ability to reprogram each of the boards while on orbit—and practicing that procedure early and often. As we go through each stage of the mission, we will undoubtedly learn new information about the performance, environments, and docking dynamics of our system, and reprogrammability will enable us to adapt to new information on the fly. Additionally, if a sensor goes “bad” and the safety mechanisms of the state machine are preventing us from moving into a state, we would be able to program in a workaround. Combined with our flatsat and processor-in-the-loop dev stations, we will be able to practice and debug the implementations of new software on the ground before we send them up to space.

3.2.2 Propellant System Design

The propulsion system is designed to move propellant from a tank to another spacecraft with as few components as possible, while providing some redundancy against the most severe failure modes. The system can transfer propellant via tank ullage pressure differential, at a slow and fast rate, as well as a closed-loop control pumped mode. It operates largely like a traditional propulsion system, except that the end point for the hydrazine is a client spacecraft instead of thrusters. Many components were sourced from the traditional supply base but the interfaces, RAFTI and GRIP, are internal developments.

RAFTI is used by client spacecraft as a refueling port and a Fill/Drain valve for loading operations, but on the Rancor and Kamino Depot Payloads, RAFTI is used only as a Fill/Drain valve. One isolation valve per RAFTI valve core is used provide an additional inhibit to overboard leakage on the pressurant and propellant sides. This arrangement meets range safety requirements and represents the typical client configuration, giving the client an ability to isolate or open the fluid connection regardless of depot configuration.

The depot uses a ~50L spherical bladder style tank with significant flight heritage. Pumped mode is enabled by a positive-displacement pump with a bypass valve. A rupture disc is used to provide a reliable, robust inhibit independent of valve control electronics. Ground loading operations are designed to maintain a factor of safety against rupture of over 4, and the disk is opened during flight using the pump, or via thermal conditioning of the propellant tank as a backup.

Downstream of the burst disc are redundant isolation valves which separate the always-wetted hydrazine section from what Orbit Fab calls the "Interstitial Volume" – which is the primary working volume of the refueling system. This volume is connected to the GRIP interface, redundant pressure transducers, an actively controlled vent valve, and a passive relief valve. The vent and relief valves both lead to the catalytic vent assembly, which is used to safely decompose vented hydrazine in a way that minimizes force and prevents deposition of liquid or solid hydrazine on sensitive surfaces. Hydrazine has a tendency to form unpredictably expelled ice deposits when liquid is vented at pressure directly to vacuum. Those ice deposits will typically sublimate, especially in sunlight, but can stick to warm surfaces they contact. With the optics needed for RPOD operations there are numerous surfaces that could be damaged by hydrazine contact. Some surfaces can also be damaged by deposition of ammonia vapor produced by the partial decomposition of hydrazine, so the catalytic vent assembly is designed to fully decompose hydrazine into its constituent elements of N_2 and H_2 and expel those effluents away from neighbouring spacecraft.

This is a robust system architecture designed to balance risk with simplicity to achieve low-cost hydrazine refueling. Forward-looking decisions have been made to ensure the system is compact, straightforward to manufacture, and transferrable to future distributed refueling architectures.

3.2.3 Thermal Design

The thermal control subsystem (TCS) is composed of heaters, temperature sensors, multi-layer insulation (MLI), and radiators. In reality, the entire payload is part of the TCS, but these are the components that are specific to it. This is one of the few subsystems that diverge between payloads because of the different power levels available from both hosting spacecraft. For simplicity this discussion will focus on Kamino as it's the first payload to launch and has more generous power requirements.

The primary goal of the TCS for this mission is to keep hydrazine in a liquid state and to keep all components from overheating. While quiescent, hydrazine is contained in the tank and on the lines of the fluid plate, both of which are closely monitored and actively heated to prevent freezing and ensure smooth thermal conditioning of the critical fluidic components. When operating, various component dissipate heat that must be rejected or stored by the payload to ensure components don't overheat.

Heaters are divided into two groups, survival and operational. Operational heaters are flight software controlled and run automatically during normal operations. Survival heaters kick in when the bus goes into a low power mode. Survival heaters are controlled by mechanical thermostats and don't require software to function. The thermostats mechanically connect the heating circuit when temperatures drop below a set point and mechanically disconnect that circuit after the component has reached a warm enough temperature. Employing both mechanical and software control of heaters gives redundancy and ensures a robust design while allowing precise temperature control of heated components.

Hydrazine freezing can be catastrophic to a fluid system. Like freezing and bursting pipes in your house, hydrazine expands when it changes phase. The big difference is that water expands when it freezes whereas hydrazine expands when it thaws. Freezing hydrazine isn't the main problem, the challenge begins when you try to thaw that frozen hydrazine back into its liquid form. Thawing uncontrolled can lead to bursting fluid lines and broken components. Having a thaw plan and having the infrastructure (heaters and temperature sensors) in place to thaw in a controlled manner allows you to recover if unplanned freezing does occur. Rancor and Kamino have strategically placed heaters to keep hydrazine from freezing and to allow for controlled thawing in off-nominal situations.

Due to low maximum temperature range requirements of certain components and high minimum temperature requirement for hydrazine, heat switches were considered for these payload's designs. Active cooling, like pumped cooling loops, is complex and costly which is why our payloads use radiators to passively reject heat. The problem with radiators is that they are rejecting heat all the time, even when you don't want them to. Sizing radiators to reject enough heat for hot components can lead to too much heat rejection and hydrazine freezing. Heat switches are one solution to this problem, they mechanically connect and disconnect thermal conduction paths so that you can stop rejecting heat when components start cooling down beyond acceptable limits. We ultimately decided to engage in a bigger analysis and design optimization effort to eliminate the need for heat switches on Kamino and Rancor.

Having a thick-walled aluminum structure means that the payload can remain relatively isothermal as well as hold its heat very well. When in a low inclination GEO orbit, spacecraft are heated by the sun for the majority of the orbit but eclipse earth for approximately one hour.

During eclipse, net heat loss skyrockets and temperatures can drop dramatically if heat storage is low. Having a high heat capacity, the aluminum structure of the payload can retain heat and more effectively maintain its temperature during eclipse. This minimizes heater power draw and battery storage requirements.

Overall, a robust thermal design effort was undertaken, and the proper components have been sourced and are in the process of being integrated.

3.2.4 Structural Design

The structural design of the spacecraft follows typical design choices to enable the survival of the payload components through the launch environment. Some interesting and unique challenges are presented given the intended operations of the payload.

The primary challenge was packaging of the payload. Docking, rather than berthing, drives tighter requirements on the alignment of the docking interface with the CoM of the overall payload. To achieve this, it required the axial alignment of the docking mechanism, GRIP, and the tank. This influenced the overall structural design to be stiffer than normal to compensate for drumming modes induced by the configuration.

Orbit Fab has learned several lessons on structural design and packaging in these initial payloads that can be carried forward to future architectures where maximizing wet mass will become more pressing as the ultimate goal is to carry as much sellable fuel as possible.

3.2.5 Docking Optics

"The TRIGGER subsystem comprises of a set of 2 LWIR cameras and associated software to generate a pose estimate of a RAFTI on another spacecraft by identifying and tracking the 2 heated LWIR Fiducial markers on either side of RAFTI. These two cameras are specifically designed for very close up operation, from 1.5m to spacecraft contact. This contrasts with current state of the art RPO systems that are designed around further away operations.

The companion missions will navigate to a holding point 1.5m away from our payload and will then hand over control to the Kamino and Rancor payloads. As the RAFTI equipped spacecraft makes its final approach for docking the cameras will precisely monitor the location of RAFTI to confirm when it had entered the roughly 3cm cubic capture envelope, and it will then send a signal to the payload to begin to actuate GRIP closed.

This will allow Kamino and Rancor to capture the other spacecraft and drive the GRIP mechanism through several different states until sufficient structural connection is created that will allow the combined stack of spacecraft to maneuver as one. Then the fluid systems will be mated, and fuel transfer will occur.

Once the fueling has been completed there will be communication between both spacecraft and the separation command will be issues. The cameras will then monitor the departing spacecraft noting if any adverse movement of the spacecraft is detected, which would then raise the need to quickly perform dynamic maneuvers to put both spacecraft in safe positions.

4. Results and Discussion

4.1 EDU Test Effort

Building a spacecraft or payload is no easy feat. While design and analysis will take you a long way, ultimately you need the hardware to truly understand the ins and outs of design. One of the first steps is a mock-up of the payload shown in the figure below. As the team moved towards CDR they started laying out all the major components of the payload to understand how they physically go together. One of the more important parts of this was laying out the fluids panel with a 1:1 model to ensure there was proper routing and room to route all the harnesses and place heaters. The Team was able to creatively 3D print many of the parts and in a moment of artistic genius craft a spherical tank model from a kids ball and wrapped in foam. This effort resulted a lot of great insights that fed back into layout and manufacturing concerns.

Fig. 2. Manufacturing Pathfinder

More technically relevant is the fluids flat sat. As refueling is not well understood in the context of fluid transfer between two satellites a 1:1 fluidic model was created to enable the simulation of all the fluidic conops and provide the electronics team a proving ground for the Fluid Transfer Subsystem control board. The system was designed with modularity in mind and uses a mix of flight like- and COTS components to mimic the operation on orbit including a client system simulated with a RAFTI core and solenoid with an inline orifice. The system is able to mimic all the main operations for the payload:

- Fill operations through RAFTI

- Blowdown fluid transfer
- Pumped fluid transfer
- Venting operations

More specifics around the Fluids Flat Sat will be discussed in a subsequent paper.

Electronics board EDUs were designed and fabricated to test all the relevant functionality and provide feedback to refine the designs.

The cameras that are hosted on the payload also underwent EDU testing to ensure their capability to sufficiently identify the client spacecraft fiducial markers and talk to OAHU. A particular challenge was ensuring the mechanism docking limits were not further limited by the pose estimation accuracy of the cameras. While the hardware used is modified COTS the software development and a series of fairly basic test setups built confidence in the optic system meeting the strict performance needs of the system. The docking part of RPOD is a relatively new field requiring a new paradigm in the design of the hardware and software enabling the close rendezvous of two objects, autonomously, in space.

Flight software was developed utilizing a PIL setup for each of the boards. These setups allowed for more rapid flight software development. Once the software passed all tests on the PIL, it was flashed to one of the three flight-quality boards that were set aside for development (referred to hereafter as Dev Boards). The dev boards enabled more testing with peripherals like sensors, active components, and even other boards. Only after the software was proven out on the development board was it then flashed to a Flight Unit for functional testing. Once the payload launches, the Dev Boards will be used on the ground to troubleshoot and test patches before they are deployed on orbit.

4.2 Payload Integration

Building off all the design and test efforts the team was finally ready to move to payload integration. The general integration flow is shown below.

The first section of work was to weld the propulsion system together. To support that effort Orbit Fab developed an in-house weld specification that pulls from the AWS 17.1D and NASA orbital tube welding spec. With the specification in hand the weld schedules for the system were created and qualified. Then the first set of tube welds were undertaken outside the clean room. Those were sent out for inspection and cleaning. The weld set up was them moved to the clean room and set up to perform the fluid component integration. After checking out the all the parameters still worked identically to the previous set up work began on the welding system.

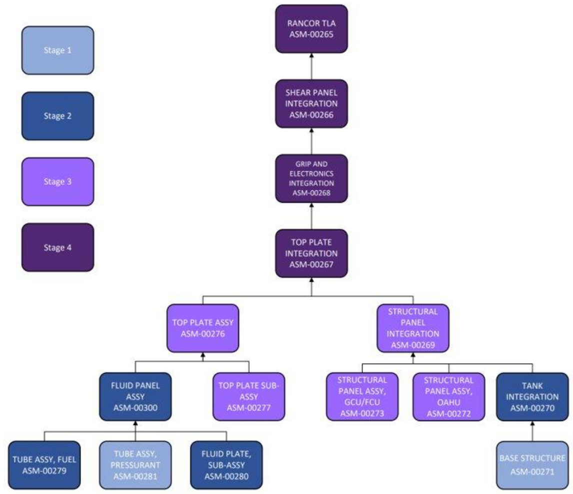

Fig. 3. Integration Flow

As of this writing the fluid transfer subsystem is currently in integration. The first structural panels have arrived and that will kick off the main structure build. The electronics boxes are moving toward their flight spins and will then go to bring up and testing. Ultimately, later this year the full payload will be assembled and ready for testing. The remaining build and testing of the payload will be shared in a future paper.

5. Conclusions

This paper walked through the first of its kind refueling payload. This payload is scheduled to launch next year and will demonstrate autonomous refueling in geostationary orbit. The efforts from design to EDU testing to the current flight build represents a great effort of creativity and perseverance from the Orbit Fab team to move in-space refueling from an idea to an everyday reality.

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