University of Colorado - Boulder

Department of Aerospace Engineering

ASEN 4018

Project Definition Document (PDD)

Bi-functional On Orbit Space Transfers

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3. Problem or Need

In the next decade, the number of satellites in orbit around the Earth is expected to grow by more than 800% [5]. This growth is in large part due to an explosion of commercial, government, and civil interest in the Cislunar domain and it's wide range of potential capabilities including improved terrestrial navigation and communication, on-orbit servicing for satellites, and future development and colonization of the lunar surface.

This surge in development within the Cislunar domain will cause a large need for improved transit within that space. In the future, satellites may need to change orbits, spacecraft may need to deliver materials from one satellite to another, and crews may need to transition from one space station to another, all within the Cislunar environment [8]. In the face of this development, there will be an increasing need for a transportation infrastructure system that can be widely used and deployed in Cislunar space and that provides satellites and spacecraft with the capability of moving between desired locations or orbits.

The Bi-functional On Orbit Space Transfer (BOOST) infrastructure system seeks to meet this need by developing a cost-effective space-based transportation system capable of providing spacecraft with the ability to conduct orbit transfers while simultaneously optimizing maneuver cost, power requirements, and civil space traffic management. By providing Cislunar missions with optimized transportation capabilities, project BOOST will not only yield a return on investment, but will also help enable the future development of Cislunar space.

4. Previous Work

While a complete transportation infrastructure has yet to be fully implemented in Cislunar space, several companies are currently developing space based transportation infrastructure systems. Project BOOST is not affiliated with any of these projects, but they constitute a portfolio of engineering designs BOOST can draw from for reference for many of its components.

There are two main types of space based transportation infrastructure that have been pursued previously: on-orbit refueling and transportation tethers. Recently, orbital refueling has been pursued more than tethers, with companies actually putting refueling stations in orbit. However, space tethers have been researched heavily since the 1990's. In this section, the previous work and research done on both of these potential infrastructure ideas will be discussed, as well as potential limitations of the idea.

The San-Francisco space-industry startup Orbit Fab (partly sponsored by Lockheed Martin) is currently designing and producing a series of 'gas stations in space:' refueling systems that can be used by satellites in the Cislunar domain. Specifically, Orbit Fab has developed a fluid transfer interface that, when incorporated into the design of a satellite, allows the satellite to easily refuel in orbit [4]. Orbit Fab's architecture design involves launching several fuel depot spacecraft into various orbits around the Earth and the Moon. Orbit Fab shuttles will dock with these fuel depots, extract fuel, and then carry the fuel to satellites that need refueling [7]. This service provides transportation infrastructure by lowering the amount of fuel that spacecraft and satellites have to carry, potentially letting the mission carry more payload and/or cutting down on spacecraft refuelling missions.

One limitation of Orbit Fab's infrastructure is that all spacecraft that wish to use it must have Orbit Fab's specific fuel port design. This greatly limits the users of the system as it prevents all spacecraft who don't elect to include Orbit Fab's fuel port as well as all spacecraft launched before Orbit Fab released their fuel port design. Furthermore, as with any fuel depot, the refueling satellites will have to be refilled eventually. However, possibly the largest limitation with the orbital refueling idea is space itself. It would take an incredibly large infrastructure network to adequately provide refueling services across large amounts of orbital space. These issues create additional logistical problems and add project objectives.

Space tethers, since being proposed in the late 19th century, have been researched and discussed extensively but have never been fully implemented. However, starting in the space shuttle era and continuing until today, space tethers of all kinds have been tested in orbit [5]. There are many kinds of space tethers, however the two types that allow for transportation are electrodynamic and momentum transfer tethers. Electrodynamic tethers are generally shorter than momentum transfer tethers, but can still be several kilometers long [2]. These tethers are conductive and use the interaction of the charged cable and the earth's magnetic field to either generate electricity or momentum. Momentum exchange tethers are two massive bodies, not necessarily of the same mass, tethered together and exchanging momentum [3]. Both of these tether concepts have been researched extensively and tested in orbit, however electrodynamic tethers have been tested much more extensively.

Notable space tether test missions include the Tethered Satellite System (TSS) in 1992, the Shuttle Electrodynamic Tether System (SETS) also in 1992, the second Young Engineers Satellite (YES2) in 2007, the Tether Technologies Rocket Experiment (T-REX) in 2010, and most recently the Miniature Tether Electrodynamic Experiment (MiTEE) in 2021. The TSS mission was flown during a Space Shuttle Atlantis flight, and the satellite deployed an electrodynamic tether of about 250 meters. The goal of this experiment was to prove that tethers could be deployed and retrieved, as well as provide some level of control. The results showed that the TSS was easier to control than expected, and the experiment revealed a lot of information about the dynamics of tethers. The SETS mission, also a NASA space shuttle mission, was similar to TSS in that it was a data gathering mission, however this time a longer tether was used and it was deployed for longer. The YES2 mission, a student led effort launched on a Soyuz mission, was the first official test of a momentum exchange tether in orbit, and is considered a general success. The goal of this mission was to de-orbit a payload package using momentum entirely from a swinging tether. The satellite deployed a tether with a total length of 31.7 km and successfully de-orbited the attached package [9]. The T-REX mission, sponsored by NASA, was the first successful test of a longer electrodynamic tether, successfully deploying a 300m tether that was entirely charged [1]. Finally, the MiTEE project is a student led effort to deploy miniature electrodynamic tethers to generate momentum in orbit. The mission is an experiment aimed to gather more information on this type of tether propulsion. It was launched in 2021, however no results have been published [6].

While space tethers are theoretically possible, implementing them in large scale transportation infrastructure is a daunting task. In order to gain a significant momentum transfer, the tether has to be incredibly long relative to the spacecraft being "picked up." This creates multiple issues, such as transporting the tether to orbit and deploying it to full length or using material able to sustain high levels of tension throughout the tether while remaining stable. There are less deployment limitations involved with electrodynamic tethers, and they have been researched significantly more than their momentum transfer sibling. However, due to the nature of interacting with Earth's magnetosphere as a means of propulsion, the control options are limited. These tethers seem to only be applicable for the boosting or decaying of orbits, not necessarily other orbital maneuvers. Furthermore, the buildup of charge in the tether can be hard to handle, with a voltage difference of 3,500V generated along the tether in one experiment.

5. Specific Objectives

The following tables outline the specific objectives that must be completed for the project to be considered a success (level 1 objectives) as well as desired objectives that are not directly required for the project to be a success (level 2 objectives). They are divided into four sub-categories aligned with the original objectives outlined by the project's sponsor: Dr. Marcus Holzinger. These four sub-categories are performance, energy management, space traffic management, and return on investment (ROI).

Performance	
Level 1	The infrastructure shall provide users with the capability of moving between two orbits
	The infrastructure shall provide users with the capability of transitioning into an orbit with a max altitude of TBD
Level 2	The infrastructure shall provide users the capability of moving bidirectionally between two orbits
	The infrastructure shall provide users the capability of entering a new orbit at a desired orbital velocity and orientation

Table 1 Specific objectives for the performance sub-category

Energy Management	
Level 1	The infrastructure shall have an energy consumption/use of TBD per unit mass of the spacecraft using the service
	The infrastructure shall faciltate a transfer of energy to/from the user
Level 2	The infrastructure shall enable users to transfer between two orbits using the minimum required amount of energy for the transfer
	The infrastructure shall have a maximum energy consumption of TBD per TBD orbit periods

Table 2 Specific objectives for the energy management sub-category

Space traffic Management	
Level 1	The infrastructure shall provide users with the ability to access/leave TBD high-use orbits
	The infrastructure shall allow at least one user to use it at a time
Level 2	The infrastructure shall provide TBD common flight paths/orbits for accessing/leaving TBD high-use orbits
	The infrastructure shall allow for TBD simultaneous users

Table 3 Specific objectives for the space traffic management sub-category

Cost and Return on Investment (ROI)	
Level 1	The infrastructure will have a total ROI of TBD
Level 2	The infrastructure shall have an initial cost of no more than TBD
	The infrastructure shall return a profit after TBD years

Table 4 Specific objectives for the ROI sub-category

6. High Level Functional Requirements

High level functional requirements of the system were developed from the customer's request and the analysis of required functions for successful mission. The requirements and rationale behind them are listed below in Table 5.

Req. ID	Requirement	Rationale
FR-001	The system shall provide the user with capability to transfer to a new orbit.	This corresponds to one of the high-level objectives provided by the customer: Civil Space Traffic Management.
FR-002	The system shall interface with user's spacecraft.	This is necessary to move customer's spacecraft.
FR-003	The system shall produce the energy to be self-sufficient throughout its lifecycle.	This corresponds to one of the high-level objectives provided by the customer: Space-based Power Logistics & Services. The system should be self sufficient in terms of providing power, since it will function as a semi-permanent on-orbit infrastructure.
FR-004	The system shall be capable of receiving and transmitting signals.	The system needs to communicate with third parties to obtain information about customer's spacecraft.
FR-005	The system shall survive at an altitude of TBD km from Earth's surface for TBD years.	The system needs to function as an infrastructure in Cislunar environment; therefore, the system needs to survive in the environment for an extended period of time.
FR-006	The system shall complete the operations for TBD number of cycles.	The system needs to operate as an infrastructure and survive for the entire duration of the operational period.
FR-007	The system shall comply with applicable space laws and policies.	This is necessary for the successful operation of the mission.

Table 5 List and Rationale of High Level Functional Requirements

As the above functional requirements reveal, the purpose of BOOST is to develop an infrastructure system capable of providing users with the ability of maneuvering between two different orbits. To accomplish this goal, a concept of operations (CONOPS) diagram is shown below showing the four main phases of the mission: response, interface, orbit transfer, and recovery. A more detailed CONOPS covering phases 2 and 3 of Fig. 1 will be developed once the final infrastructure design is selected.

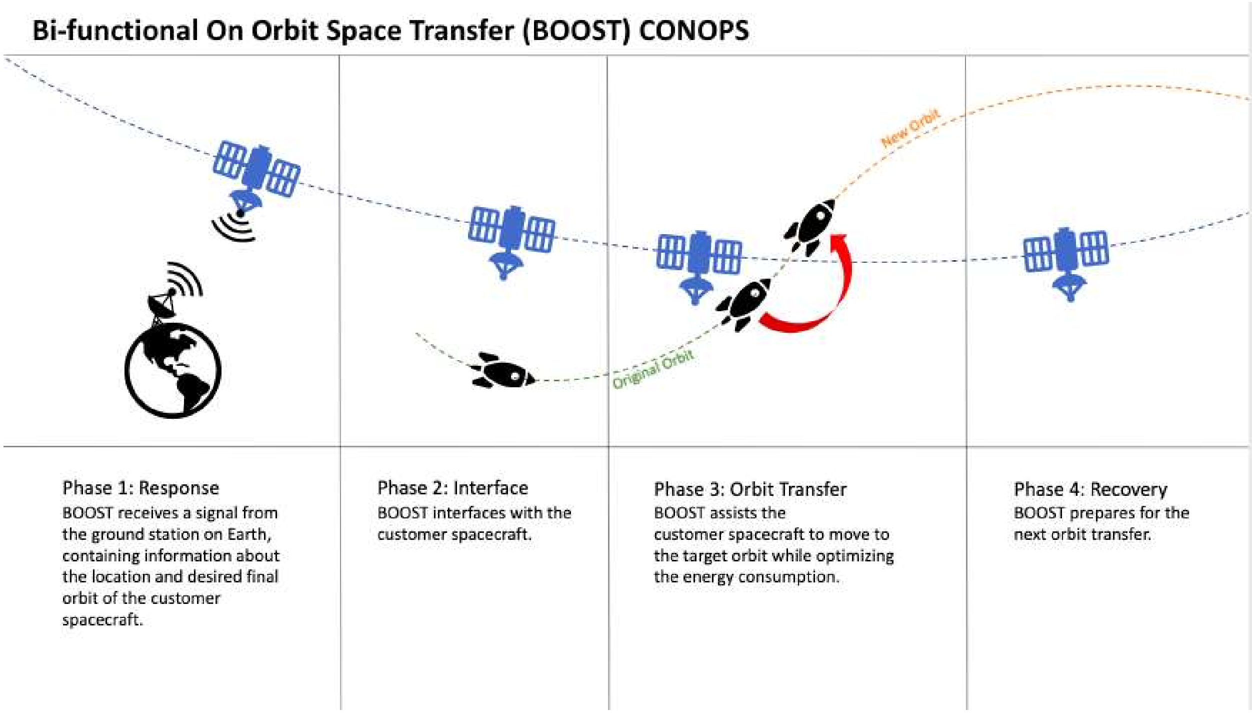

Fig. 1 Concept of Operations Diagram

7. Critical Project Elements (CPE)

Critical project elements reflecting the current scope of the entire infrastructure project are provided below in 6. Further critical project elements for the design of the spacecraft that will constitute the infrastructure are included in the Appendix.

CPE Number	CPE	Description
CPE.1	Trade Space Analysis	The team will conduct a trade space analysis to determine the optimal solution to our problem by balancing performance, upfront cost, maximal use, and Return on investment. The team will develop a cost function to determine the optimal solution for the selected problem. The cost function will take into account multiple performance parameters, including energy gained by target spacecraft and return on investment.
CPE.2	Orbital Simulation	The team will use STK (or comparable software) to model the orbital dynamics of our selected solution, and project trajectories of target spacecraft.
CPE.3	Power	The system will be able to facilitate an energy transfer to/from the target spacecraft.
CPE.4	System Dynamics	Extensive dynamics modeling will be done both to evaluate the performance of the selected solution, as well as to refine the CONOPS and specify the mechanics of the system to a higher degree of detail. These models will also be used to guide, design, and place constraints on our design space.
CPE.5	Policy Requirements	The team will present a paper detailing the policy environment necessary to facilitate the feasibility and success of the selected infrastructure.
CPE.6	Return On Investment	The selected system will attempt to optimize return on investment over the designed lifespan.
CPE.7	Hardware Demonstration	The selected system will have a critical component that can be used as a hardware demonstration and technological proof-of-concept.

Table 6 Critical Project Elements

8. Sub-System Breakdown and Inter-dependencies

While the final infrastructure design has yet to be selected for project BOOST, a diagram showing the expected general sub-system breakdown is shown below in Fig. 2. This diagram shows the expected power and data connections for the BOOST architecture.

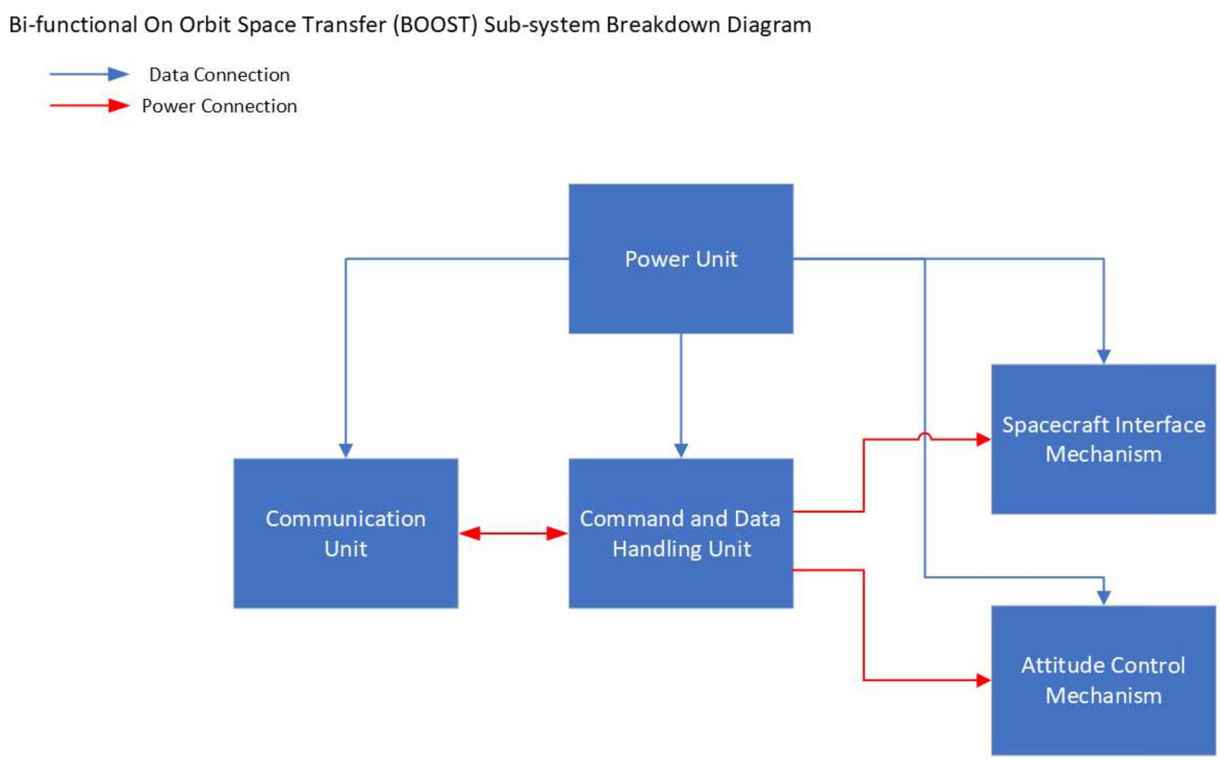

Fig. 2 Sub-System Breakdown Diagram

9. Team Skills and Interests

Team Member	Skills and Interests	Associated CPE
Riana Gagnon	Python, software, autonomy, Machine Learning	CPE.1, CPE.4, CPE.5
Chieri Kamada	SysEngineering, avionics, communications, wire harnessing	CPE.1,CPE.3,CPE.5,CPE.6
Colton Massic	Ansys, CAD, manufacturing,electronics,Business	CPE.3,CPE4,CPE.7
Zach Rochman	Structures, CAD, ANSYS, Mechanical Design, Business	CPE.1,CPE.4,CPE.5,CPE.6
Luca Herlein	Software(Dev/QA/Docs), electronics, geology minor, STK	CPE.1,CPE.2,CPE.3
Avery Gillespie	Electrical Engineering minor, machining and manufacturing	CPE.3,CPE.4,CPE.7
Tycho Cinquini	Software, electronics, soldering, autonomy, python	CPE.1,CPE.3,CPE.4,CPE.6
Rishi Mayekar	Computer science minor, ANSYS	CPE.1, CPE.4,CPE.6
Wesley Gilliam	CAD, mechatronics, prototyping, machine shop	CPE.4, CPE.7

Table 7 List and description of critical project elements

10. Resources

Critical Project Elements	Resources/Source
Trade Space Analysis	Python, Research papers, Advisors | Source: AES Dept
Power	ANSYS, Advisors, Multisim | Source: AES Electronics Lab
Orbital Simulation	STK, Matlab | Source: AES Dept
System Dynamics	Matlab, Solidworks, Advisors | Source: AES Dept
Policy Requirements	Research Papers, CU University Library, Advisors | Source: CU Boulder, UN Space Policy
Return on Investment	Python, Excel, Advisors | Source: AES Dept
Hardware Demonstration	Solidworks, SolidCAM, Lab Space | Source: AES Manufacturing shops

Table 8 List and Description of Project Resources

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I. Appendix

The following table details the critical project elements for the design of one of the component satellites/spacecraft that will be used in the BOOST system infrastructure.

Number	CPE	Description
CPE.1	Structures	The system will have structural redundancies and designed factors of safety to avoid single-point mission failure.
CPE.2	Power/EPS	The system will be able to provide electrical power for all onboard subsystems. The system will be able to generate its own power and store TBD minutes worth of reserve power.
CPE.2.1	Energy Transfer	The system will be able to transfer energy (chemical/electrical/kinetic - TBD) to the target spacecraft. This is necessary to facilitate the orbit transfers.
CPE.3	Controls	The system will be able to independently maintain attitude control to an accuracy of TBD.
CPE.3.1	Deployment	Upon arrival to the selected orbital path, the system will be able to deploy and initialize without the help of another required set-up mission.
CPE.4	Guidance	Using TBD technology, the system will be able to determine its position in space to a precision of TBD.
CPE.4.1	Relative Navigation	When interfacing with a target spacecraft, the system will be able to determine the relative attitude and position of the target to TBD precision.
CPE.5	Interface	The system will establish either a physical or wireless interface with the target spacecraft.
CPE.6.1	Communications with Earth	The system will receive commands from a ground station to update software and receive target spacecraft trajectory data.
CPE.6.2	Communications with Target Spacecraft	The system will be able to communicate wirelessly with the target spacecraft for either a physical interface (docking/connection) sequence, or a wireless energy/data transfer.
CPE.7	Assembly	The system will be able to fit in the launch vehicle, and will deploy upon on-orbit deployment. This functionality will be a critical part of the design phase.
CPE.8	Testing and Validation	The project will use hardware demonstrations and computer simulations to verify functionality of critical design elements.

Table 9 List and description of critical physical project elements