Modular Solar Electric Space Tug

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Introduction

In order to reduce the barriers of space exploration, humanity must develop a low-cost method of delivering payloads beyond low Earth orbit (LEO). This paper presents an autonomous spacecraft capable of transferring payloads from LEO to lunar distant retrograde orbit (LDRO) and back using solar electric propulsion (SEP). A modular design was implemented for ease of maintenance and to allow the space tug to be modified for interplanetary missions. Costs were minimized and the mass that could be transferred to LDRO over the operating lifetime of the spacecraft was maximized. Computational tools were used to calculate and optimize spacecraft parameters while satisfying mission requirements.

Spacecraft Design

The reusable space tug, named Moonraker, will consist of a command module and cargo module. The command module will include all necessary subsystems for spacecraft operation, including the full solar array, chemical and electrical propulsion systems. The cargo module will consist of a modified version of the Orbital ATK Cygnus commercial vehicle. In order to reduce time between launches and procurement cost, the command module will be delivered by the Falcon 9 Full Thrust rocket and the cargo module by the Orbital ATK Antares 230 rocket.

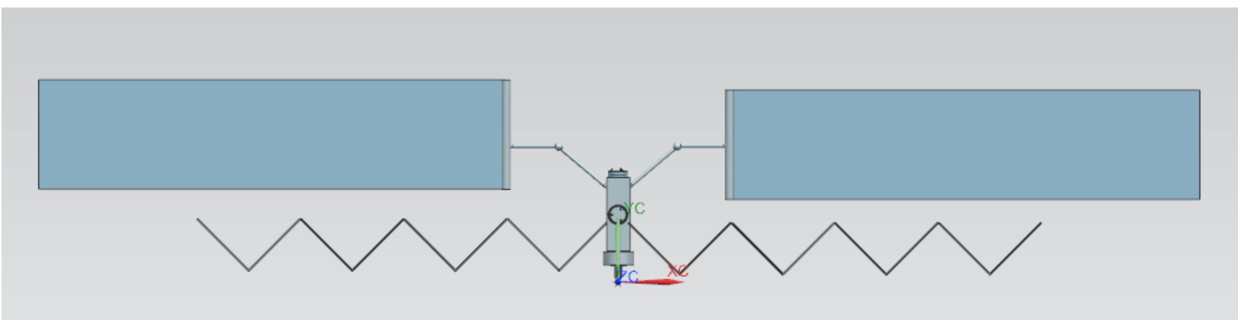


Figure 1: Moonraker in fully deployed configuration.

The command module will be launched with fuel necessary for the lunar return transfer and station-keeping during the assembly period and LEO loiter between transfers. The cargo module will supply the fuel necessary for the outbound trajectory. While the cargo module was designed with the Cygnus in mind, by launching the majority of the fuel with the cargo module and utilizing the NASA Docking System (NDS), the payload is only limited by flight time and the customer's budget. Additional solar and propulsion modules can link with the spacecraft allowing for increased performance and further its mission capabilities. In-orbit refueling and autonomous docking are critical capabilities for assembling and operating the space tug.

Propulsion for the command module will be supplied by the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) developed by Ad Astra. Specifications for the propulsion system were extrapolated from more than 10,000 firings of the VX-200 on Earth; however, testing on the ISS will be instrumental in determining in-orbit performance. These test firings demonstrated several properties of the VASIMR that make the engine ideally suited for a solar tug mission. These include a thruster efficiency of 72% and a specific impulse of 5102 s [1]. Additional capabilities of the VASIMR are a high operating voltage and the ability to use argon propellant, which is desirable due to its availability and low cost.

In 2015, Ad Astra received a $10 million grant through the NextSTEP program for the advancement of VASIMR to a Technical Readiness Level (TRL) of greater than five [2]. After the completion of the grant's three-year statement, the VX-200 will be a fully integrated system capable of operating at high power continuously for a minimum of 100 hours. The progression of the engine in addition to its funding is sufficient reasoning to affirm the use of the VASIMR as the spacecraft's main form of propulsion. With the allotment of 200kW to the SEP, alternative choices such as the NEXT Ion thruster and the NSTAR Ion thruster would be required in greater numbers: up to 26 NEXT thrusters or 87 NSTAR thrusters. Additionally, these thrusters use xenon propellant which is costlier and scarcer than argon.

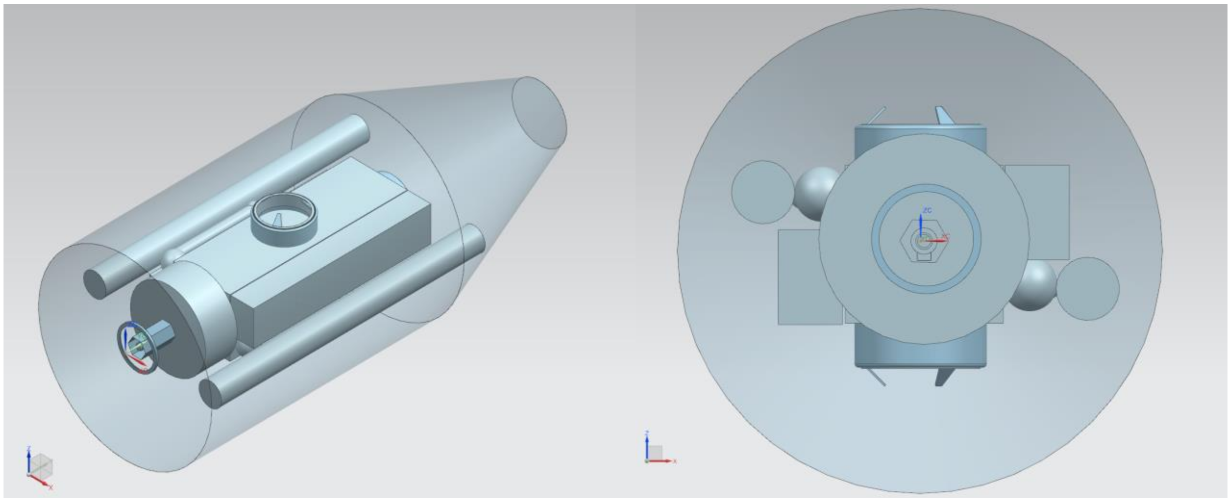


Figure 2: Moonraker in stowed configuration.

Power to the engine and other systems will be provided by inverted metamorphic multijunction (IMM) solar cells with a beginning of life (BOL) efficiency of 33% [3]. The cells will be fitted on Deployable Space Systems' (DSS) Stretched Optical Lens Architecture Roll Out Solar Array (SOLAROSA), which is at a technology readiness level (TRL) of four. A minimum of 700 m^2, divided between two arrays, will be needed to meet the 210 kW power requirement of the spacecraft. Assuming that the arrays have a BOL power to mass ratio of 0.4 kW/kg [4] with a coverglass thickness of 15 mil, the total mass of the arrays was approximated to be 700 kg. The actual thickness of the coverglass will likely be much higher than assumed value in order to reduce degradation caused when passing through the van Allen belts. The energy density of the array in its stowed configuration is 50 kW/m^3[5], which translates to a total stowed volume of 4.2 m^3. When deployed each array will be a flat blanket with dimensions of 7m by 50m, and when stowed a cylinder with radius 0.31m and height 7m. All components have a fundamental flexible body vibration mode that is higher than the minimum 0.05 Hz. Lastly, the arrays will be fitted on the command module using custom designed Diamond Roll-Rings that will provide the rotational freedom necessary to keep them continuously facing the sun. These rings have been in use on the International Space Station since 2001 and have not seen any failures, as such, they are well suited for use on this spacecraft.

The command module is equipped with enough fuel to allow for station keeping while in LEO and for the return trip from LDRO. The additional fuel required for the lunar transfer will be supplied from cargo modules. As a result, the cargo module will carry a majority of the compressed argon needed to operate the VASIMR beyond LEO. The command module will dock with the cargo module by utilizing the NDS, a mating mechanism that "supports low approach velocity docking" while also providing a "modular and reconfigurable standard interface”[6]. In its design, pneumatic legs extend outward, capturing the cargo vehicle and joining the two crafts. The design allows a margin of error during rendezvous which is critical when performing autonomous operations. Current working models of the NDS are ground proven and provide robust docking configurations along with mechanical operations, power transfer and command data & handling transfer. Future models will incorporate fuel transfer capabilities.

After docking with the command module, the fuel tank from the cargo module will connect to the command module’s propulsion system and the transfer to LDRO will begin. By utilizing this type of assembly, in which the command module is refueled with each subsequent cargo transfer, its initial launch mass can be significantly reduced; however, the command module will be dependent on cargo modules for refueling operations. Additional modules may be connected to the command module with the NDS to increase the performance of the space tug.

The command module will be fitted with a hydrazine reaction control systems (RCS). Furthermore, all extension modules will have their own RCS for rendezvous with the command module. This also facilitates modularity as the space tug can be easily extended with maneuverable extension modules. The larger BT-4 engine on the cargo module will provide enough thrust for docking with the command module in LEO.

The command module will be equipped with standard telemetry and position tracking equipment. The communications system of the command module will consist of multiple omni-directional antennas to receive instructions for in space autonomous assembly in LEO and operations in LDRO. If medium or high gain antennas are necessary for transfers beyond LDRO they may be added with cargo modules or expanded via extension modules.

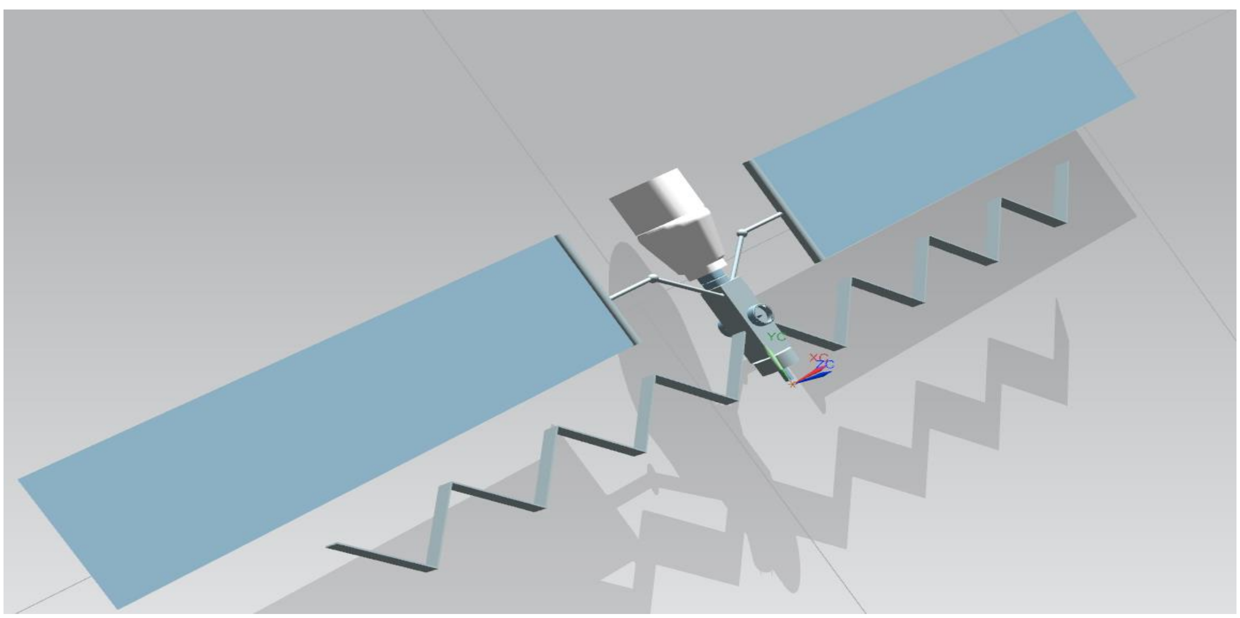


Figure 3: Moonraker with cargo module attached.

Two commercially available spacecraft were evaluated for the role of the cargo module, the Orbital ATK Cygnus Enhanced Version and the SpaceX DragonLab with Extended Trunk. Despite the smaller enclosed volume, the Cygnus was selected for its lower dry mass and ability to use interchangeable modules for pressurized and unpressurized cargo. The Cygnus has a capacity of 3,500 kg to the ISS, so it is reasonable to assume that a comparable cargo mass can be launched to rendezvous with the command module [7]. However, advanced capabilities must be developed, such as automated docking, fuel transfer, larger solar panels and antennae for operations in LDRO. Additionally, the BT-4 chemical engine on the Cygnus will be capable of inserting the cargo module into LDRO once it has separated from the command module.

Mission Design

While the focus of this paper is spacecraft design and assembly, mission design cannot be neglected. Especially in the case of a low-thrust transfer, the trajectory of the spacecraft greatly impacts the vehicle design and vice versa. A MATLAB script based on the Edelbaum algorithm was used to calculate flight time and propellant costs for the outbound and inbound lunar transfers.

The command module will be launched from Cape Canaveral Air Force Station to an orbit with an altitude of 400 km and an inclination of 5.145° relative the ecliptic. The assembly process for the command module will take 30 days to complete, including time for a systems check with Earth assistance. This process consists of extending the arms which deport the stowed solar arrays a sufficient distance from the plume of the VASIMR engine. Once the arms have locked into the deployed configuration, SOLAROSA will unroll into its deployed configuration. Simultaneously, the radiators will deploy in a configuration perpendicular to the solar arrays.

The cargo module will be launched from Wallops Flight Facility such that it reaches the command module when the assembly is completed. The cargo module will be using the BT-4 engine and the TriDAR sensor on the Cygnus. A V-bar approach was selected because it requires minimal propellant use and accommodates an end-to-end docking configuration. A final systems check will be performed over a period of 30 days before the completed spacecraft departs Earth under electric propulsion.

The outbound trajectory will consist of a SEP lunar transfer, separation of the modules in cislunar space, and an LDRO insertion of the cargo module with chemical propulsion. For the initial estimate, the dry mass of the command module was taken as 12,000 kg and the wet mass of the cargo module as 5,965 kg. A propellant margin of 10% was selected as per NASA standards for robotic spacecraft [9]. Because of the repeating geometry between Earth, Sun and Moon [10], an LDRO with 2:1 resonance and a semi-major axis of 70,000 km was chosen as the destination. A flight time of 188 days was calculated with a propellant mass of 2181 kg for the inbound trajectory of Moonraker. In order to deliver both modules along with enough propellant for the inbound trajectory, a flight time of 305 days and propellant mass of 3127 kg was calculated for the outbound trajectory. A powered lunar flyby was considered to insert the cargo module into LDRO. Despite the increased operational complexity, this maneuver lowers the total delta V for the insertion to 348 m/s with a flight time from fly-by to LDRO insertion of 8.5 days [10], which is within the capabilities of the BT-4 engine on the Cygnus. Propellant cost for this maneuver is 665 kg.

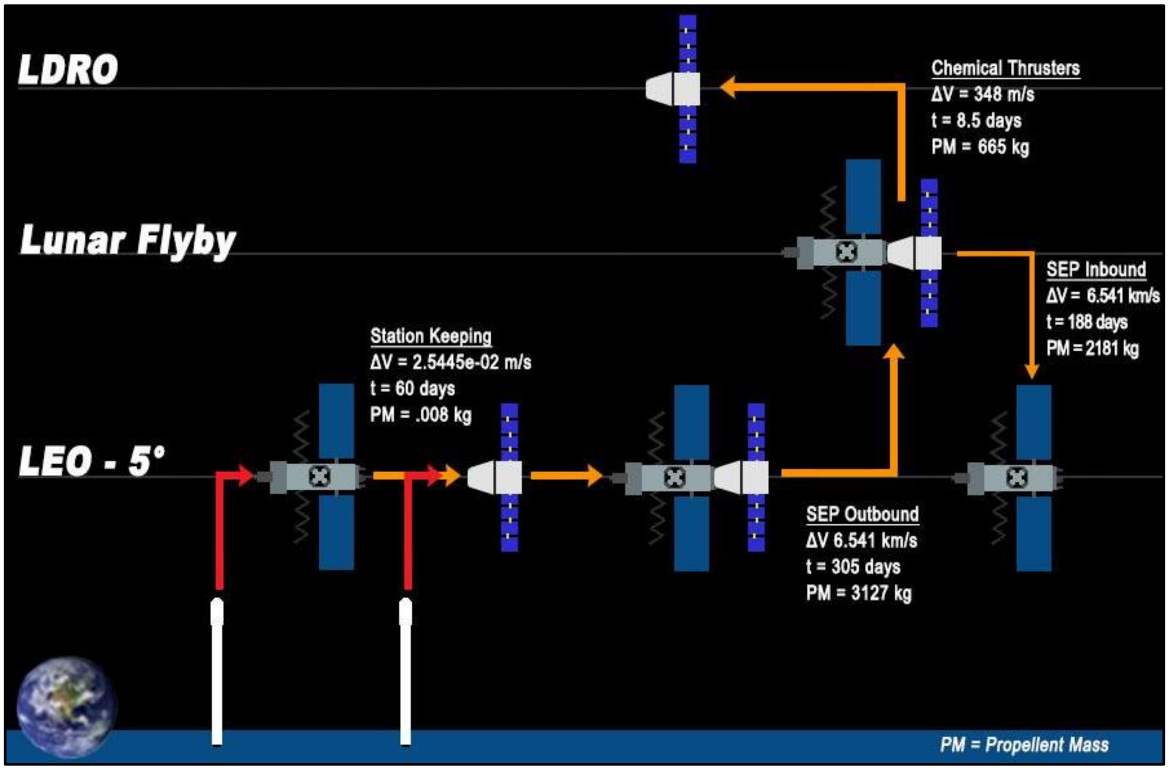


Figure 4: Design Reference Mission.

Because the space tug spends a large amount of time in LEO during the assembly period and between lunar transfers, station keeping costs were calculated. Occultation from the Earth leads to a 41% duty cycle for an orbit with an altitude of 400 km because it would be cost-prohibitive to include a battery large enough for the spacecraft to thrust while in shadow. As a result, the delta v required for maintaining altitude during the 60-day assembly period was calculated to be 2.5445×10^{-2} m/s. Since the VASIMR can be utilized at low input power levels, station keeping requires minimal propellant use. However, the command module must be launched with enough fuel for station keeping and tanks large enough to contain fuel for the return trip from LDRO to Earth. Figure 4 shows altitude of the spacecraft over ten days as impulsive burns are performed to maintain orbit.

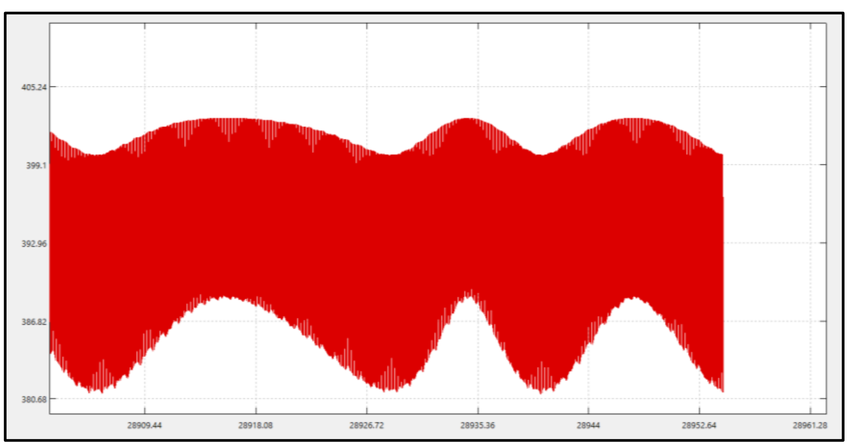


Figure 5: Spacecraft altitude during LEO loiter/assembly.

Design Analysis

SEP space tug systems are an efficient way of transporting large mass objects over long distances at the cost of travel time. While SEP systems have an advantage over chemical propulsion systems in terms of mission life, overall cost effectiveness and reliability, entities like subsystem mass, assembly, compactness, modularity, ground testability and mission extendibility need to be considered while designing the space tug.

The mass of the spacecraft was estimated using data gathered from other SEP tug proposals. Tugs of many different power requirements have been proposed in the recent past, ranging from scales of dozens of kilowatts to many hundreds of kilowatts, manned and unmanned. By comparing data and scaling it to the competition power requirements, a general mass estimate was acquired.

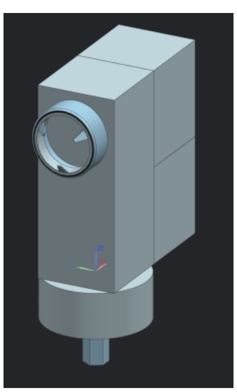
COMMAND MODULE	15379.2
Solar Arrays	**700**
Power System	**1177**
Propulsion System	**1005**
Propulsion Unit	685
Power Processing Unit	200
RCS	120
Propellant	**6313.4**
Argon	5308
RCS Chemical Propellant	700
Pressurant	40
Fuel Tanks	265.4
Communications System	**75**
Omni-directional antennae	75
Avionics	**582.8**
Command and Data Handling	75
Guidance, Navigation, and Control	25
Thermal Control	**1900**
Active Thermal Control	250
Passive Thermal Control	1150
Structure and Mechanisms	**3626**
Structure and Mechanisms	3100
NASA Docking System	526

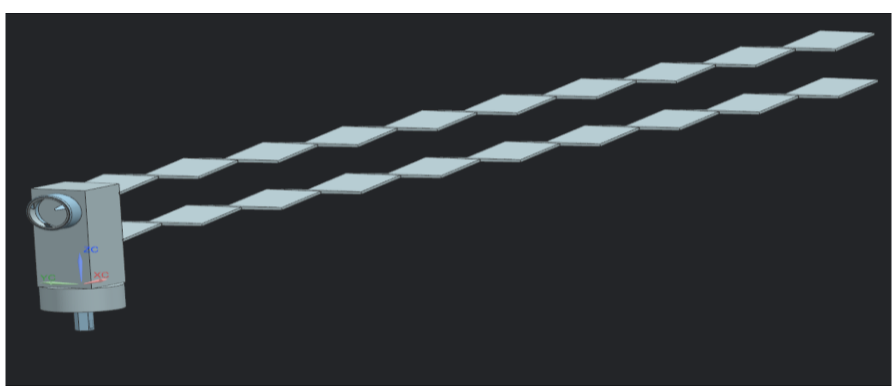
Figure 6: Table of mass estimates in kilograms.

The SOLAROSA provides for an affordable, lightweight and compact solution to the spacecraft's energy requirements. Solar cells contribute nearly 40% of the cost involved in the manufacturing of solar arrays; thus, by concentrating solar power onto straits of arrays fewer cells will be needed to produce the same amount of power, thereby reducing the overall cost of each array. IMM cells cost $50/W to manufacturer and the total cost of the arrays on the command module will be $26.25 million [5]. DSS will conduct structural, thermal and composites analysis on their systems. SOLAROSA is currently undergoing NASA funded phase I development, which aims to demonstrate concept feasibility and a TRL of four. Phase II development of this technology will further aim to achieve a TRL of six, which includes structural, thermal, radiation, composites testing and risk mitigation effectiveness. Comparisons were made between SOLAROSA, Mega-ROSA and Ultraflex, a disc shaped array; however, the latter two designs either did not fit in the launch vehicle in its stowed configuration, or did not exceed the capabilities of SOLAROSA. Thus, as stated by NASA Techport, it “is particularly suited for Space Science and Exploration missions that require game-changing performance in terms of affordability, high voltage operation, radiation tolerance.” [11]

The thermal subsystem must maintain all subsystems within their respective operating temperature ranges: batteries between -5 and 20˚C, electronic components between -10 to 45˚C, propulsion components between 0 to 50˚C, cameras between -30 to 40˚C, and solar arrays between -150 to 100˚C. Pressurized argon propellant must be stored below -150˚C because of its cryogenic properties [12]. In order to achieve those requirements both a passive cooling system (PCS) and an active cooling system (ACS) will be used. The PCS will consist of multi-layer insulation and thermal resistant coating while the ACS will be used heavily when operating beyond LEO. The ACS will utilize a 2 phase coolant that will be pumped and requires radiators with an area of approximately 60 m^2 to dissipate 56 kW of waste heat produced mainly by VASIMR’s power processing unit (PPU). These radiators will be placed on the same planes the solar arrays are mounted on and will extend outwards, in an accordion like fashion, after the solar panels have been deployed.

An important aspect of this spacecraft’s design is its modularity. Additional modules will allow the spacecraft to increase its thrust and power output, which are essential for missions beyond LDRO. The command module will be equipped with three NDS ports, one on the bow of the command module and two port and starboard of the command module to allow for the attachment of extension modules. The ports shall be labelled as following: A for the port on the bow of the spacecraft, B and C for the port and starboard ports; all will be labelled on the command module. Port A will be used to dock cargo modules or solar array extension modules as well as any potential scientific payloads. Solar array extension modules can be added to increase power generation or to replace degraded panels. The side ports, B and C, will be used to connect propulsion modules to increase the performance of the spacecraft. To maintain the relative symmetry of the spacecraft extension modules will have components similar in size to the command module’s. All modules come equipped with an RCS, communication systems and avionics to facilitate safe docking. The spacecraft’s modularity and extendibility will allow it to operate for extended periods of time and meet more rigorous requirements.





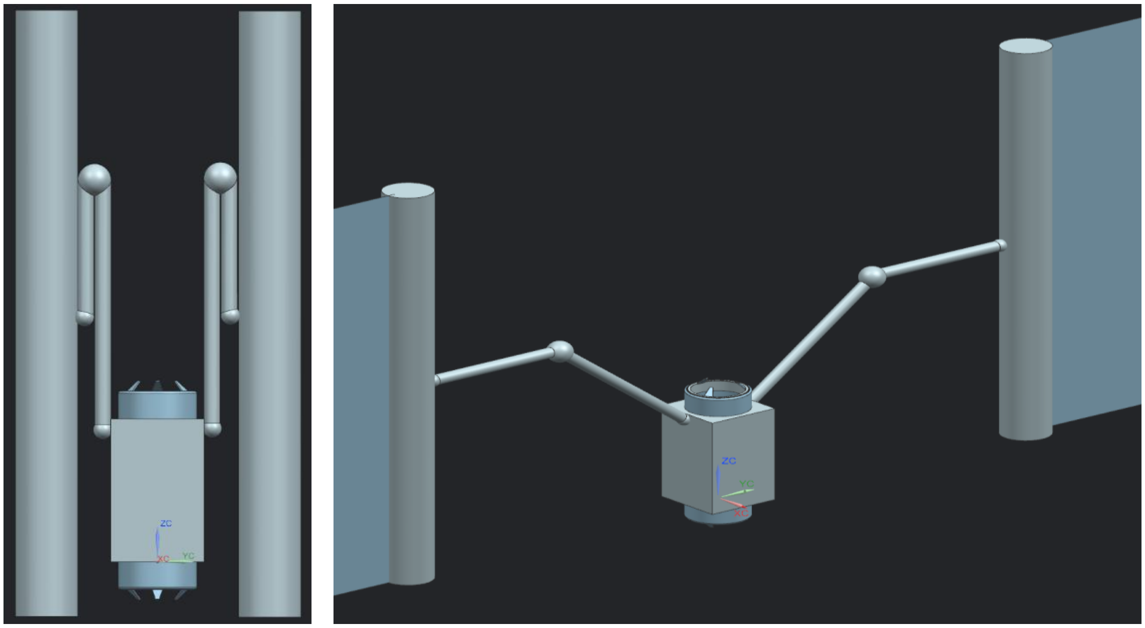


Figure 7: Propulsion and solar extension modules, stowed and deployed.

In order to meet the 500 kW power requirement listed for deep space operations a solar extension module (SEM) capable of producing 300 kW of power must be included. SEMs can be easily scaled to meet any power requirements due to its replicable design. The 300 kW SEM will incorporate two arrays, with properties identical to those on the arrays of the command module, of width 10m and length 50m. The additional power will be transferred to the command module and propulsion modules via the NASA Docking System, which allows for easy transferring of power, fuel and data. Each module is equipped with NDS ports on the stern and bow to allow for docking to the command module and connecting additional solar array extension modules or the cargo module respectively.

Furthermore, to account for the extension of the space tug from 200 kW to 500 kW, two propulsion modules, each carrying a VASIMR engine scaled down to 150-155 kW, must be included. The design of the VASIMR engine can be easily scaled. Moonraker is limited to two additional propulsion modules so additional upgrades must be accomplished by discarding previous propulsion modules. Though the propulsion module design could easily allow further modules to attach to it by adding an additional NDS, budget, mass and cost requirements showed diminishing returns after two modules. To preserve efficiency, cost and simplicity, it was decided the Moonraker will be limited to two propulsion modules. Additionally, adding extension modules will introduce various degrees of redundancy, as each propulsion module will add an additional avionics system and TCS, while each additional solar array extension module will add an extra power processing subsystem and TCS.

A 500kW Moonraker will incorporate the 300 kW solar array extension module and two 150 kW propulsion modules mentioned above. To do so, the solar array extension module will be launched first and docked to Moonraker. The solar array extension module will remain in a stowed configuration awaiting the installation of the propulsion module. The propulsion modules will be launched as a single unit to the same orbit of the space tug. After reaching the designated orbit, the unit will separate from the fairing and further divide into two separate modules. One module will be directed towards a lower orbit than the space tug, hence will have a higher traveling velocity, while the other module will be directed towards a higher orbit and will thus have a lower velocity. The RCS aboard each module will be used to control velocity and docking maneuvers onto the command module. The two modules will be docked at different times using the R-bar approach depending on their intersection times with the tug considering the difference in their orbital velocities. During approach the radiators on the command module will retreat back into their stowed configuration and will be considered as dead mass. Once the radiators aboard the command module have collapsed, the arms of the command module solar array will move to a lower position. Then, the solar extension module attached earlier will deploy. The propulsion modules that are added will then have their radiators extended and used as the main set of radiators for the space tug.

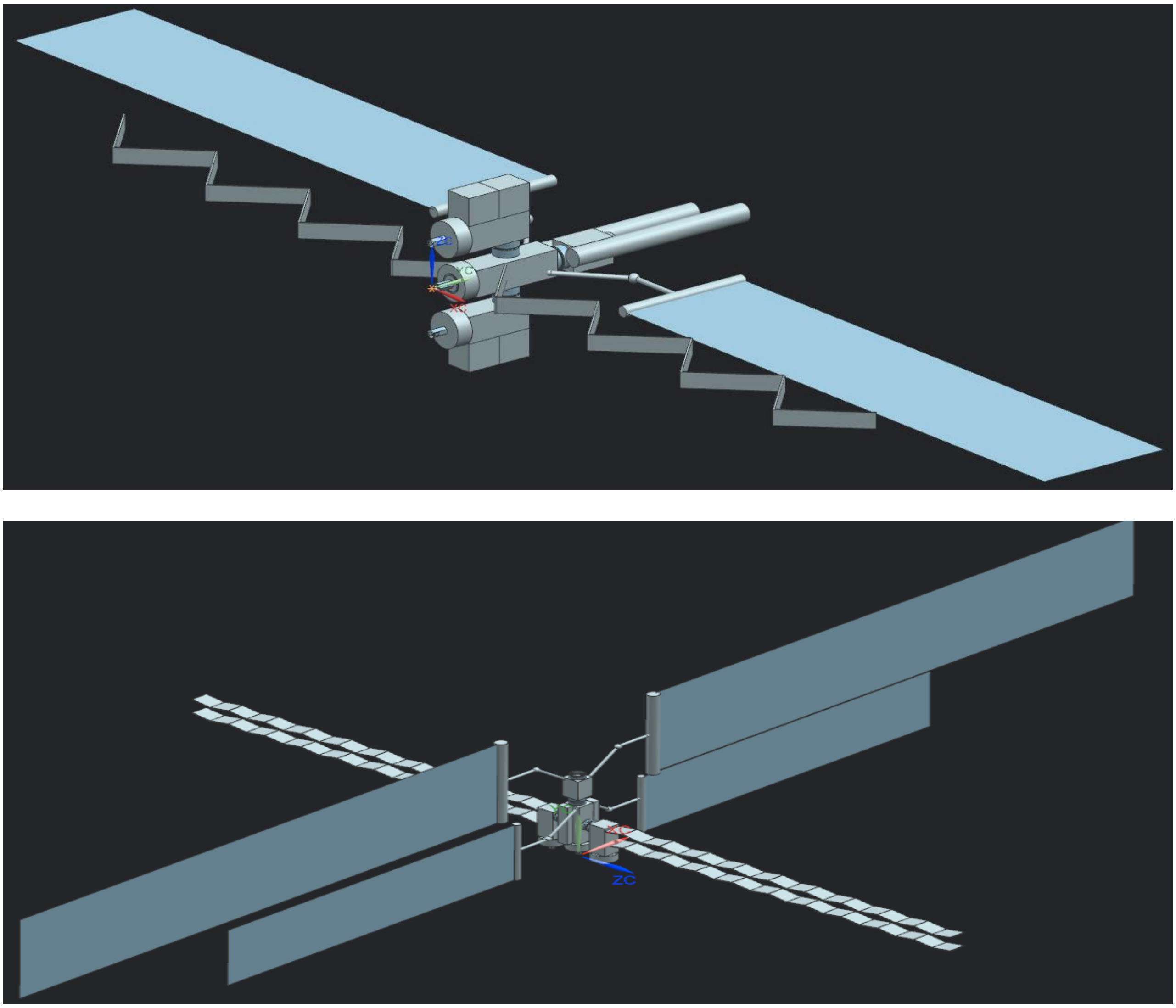


Figure 8: Moonraker with extension modules, stowed and deployed.

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